PARTICLE GAS SIMULATION FOR PERFORMANCE PREDICTION OF COMMERCIAL SCALE FCC REGENERATOR CYCLONE SYSTEM

Review Report

Submitted by

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In partial fulfillment for the award of the degree of

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CHEMICAL ENGINEERING
(With Specialization in Process Design Engineering)

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Dated: **(Meenu Verma)**

Place: Dehradun

ABSTRACT

Cyclone separators are commonly used as solid gas separation devices. These devices are relatively cheap and have simple construction and also moderate pressure drop. This is the reason why they are used in many engineering processes such as dryers, coal gasifiers, and circulating fluidized bed combustion and also in the refineries for separating catalyst from flue gases and other reactor product in fluidized catalytic cracking (FCC). The driving force for the separation of particles is the centrifugal force. Separation efficiency is the amount of particles that are collected at the bottom. Efficiency of cyclone separation is affected by a number of factors such as gas inlet velocity, mass solid flux entering, and particle size and cyclone body dimension. Using computational particle fluid dynamics Barracuda software we performed simulations to understand the effect of vortex finder diameter on the cyclone performance through computational particle fluid dynamics Barracuda software. This software is well suited for simulating dense particle laden fluids due to its numerical solving methods for both particle and fluid. Simulations were carried out for two stage FCC regenerator cyclone system having 3D geometry and without any chemistry. Two cases of simulation are performed and the results of both are compared to predict the one which gives better cyclone particle collection efficiency.

DECLARATION BY SCHOLAR

I hereby declare that this submission is of my own, and to the best of my knowledge and belief that this document does not contain any content previously published by other person, or material which has been accepted for the award of any other Degree or Diploma of the University or other Institute of Higher Learning, except when the acknowledgement is made in the text.

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BONAFIDE CERTIFICATE

This is to certify that the report entitled "**PARTICLE GAS SIMULATION FOR PERFORMANCE PREDICTION OF COMMERCIAL SCALE FCC REGENERATOR CYCLONE SYSTEM"** submitted by Meenu Verma **(R670215009)**, to the University of Petroleum and Energy Studies, for the award of the degree of **MASTER OF TECHNOLOGY** in Chemical Engineering with specialization in Process Design is a bonafide record of project work carried out by her under our supervision. The results embodied in this project are based on literature and the research at IOCL REFINING TECHNOLOGY DEPARTMENT. IOCL is the sole owner of the data and hence only IOCL reserves all rights to patent, publish and present the data.

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CHAPTER 1

FLUIDIZED CATALYTIC CRACKING

Introduction

One of the most important conversion processes that are used in the petroleum refinery is Fluid Catalytic cracking (FCC). It converts the high boiling and high molecular weight crude oil into low boiling and low molecular weight high value product such as gasoline, diesel along with very important petrochemical products such as C4 gases like isobutylene, isobutane, butane (Huma Warsi Khan and Anali, 2015)

FCC has many important function is refinery and petrochemical industry (Ye-Mon Chen, 2003).

1. FCC is the main source of gasoline production.
2. It reduces the amount of residue in crude oil.
3. It provides flexibility to refining process. We can make changes in its operating conditions to produce gasoline, LPG etc.
4. It can produce light olefins for downstream refining process such as alkylation or any other petrochemical process.

1.1 Feedstock

Feedstock to FCC process can be Vacuum gas oil (VGO), Hydro-treated VGO, Deasphalted oil (DSO), Reduced crude oil (RCO) or Vacuum residue (VR). Typical feedstock consists of Vacuum or Atmospheric gas oil but it may also include other heavy stream. This feedstock contains contaminants which need to be removed before being sent for processing. Major contaminants in the feedstock include carbon reside, sulphur and other metals (NPTEL).

1.2 Process Description

Liquid hydrocarbon feedstock is preheated in the reactor /regenerator section of the FCC process and is brought in contact with steam and injected into the riser reactor through feed nozzles. Hot regenerated catalyst is withdrawn from the regenerator and is then contacted with feed. Because of interaction between the catalyst and the feed, catalyst reacts with feed and losses its heat to it and converts into vapor form with lighter products. During the process coke gets deposited on the catalyst and deactivates it. Product vapors and catalyst are separated by the cyclone separator inside the reactor. Product vapors then goes to fractionation section. Catalyst enters the stripper section where steam is introduced to further recover hydrocarbon product .Spent catalyst is fed to regenerator for recovery. Catalyst action is recovered by burning of the coke deposited. This process is an exothermic process. Heat released during the process is used to heat up the catalyst. Finally regenerated catalyst is separated from flue gases by passing the mixer through cyclone separator inside the regenerator. Catalyst is then returned to the reactor system and flue gas is sent to flue gas cleaning and power recovery system (Ye-Mon Chen, 2003).

Figure 1 shows the flow diagram of FCC process.

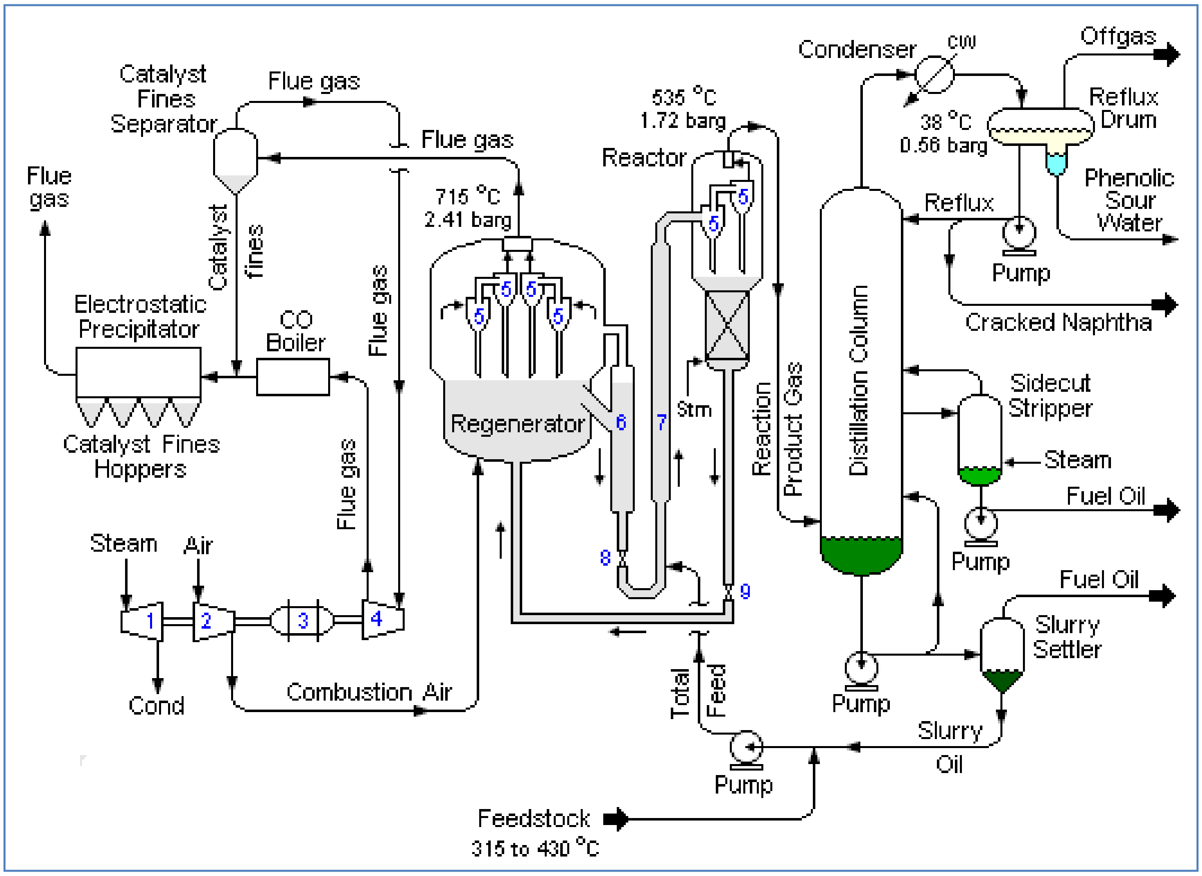


Figure 1.1 FCC process flow diagram (John W.McTernan and Issam Abu-Mahfouz, 2014)

1.3 FCC Catalyst

Catalyst holds an important position in FCC process. Physical and chemical properties of catalyst determine the design and operating conditions of the process. The catalyst used today is very fine catalyst with wide product size distribution which is mostly in the range of 10 to 150 microns and with the bulk product density of about 50-60 lb/ft^3 (Ye-Mon Chen,2003). The catalyst is solid sand like material that is made fluid by hot vapor and liquid fed into FCC. Because the catalyst is fluid it keeps on circulating between reactor and regenerator.

There are four major components of modern catalytic cracking catalyst.

1. Zeolite
2. Matrix
3. Filler
4. Binder

Zeolite: These are the most important part of the catalyst since they are responsible for the selectivity and activity of the catalyst. Performance of the catalyst is largely dependent on Zeolite. Zeolite has a well defined lattice structure and its basic building blocks are silica and alumina that are joined together in a tetrahedron structure with Si/Al at the centre and four oxygen atoms occupying the corner position.

Matrix: Matrix is a component of the catalyst other then Zeolite that has some catalytic activity. These have a significant role in the overall performance of the FCC catalyst. Alumina is the source of active matrix. Matrix provides the primary cracking site. These are not as selective as the Zeolite but they have the capability to crack the hydrocarbon that has certain hindrance from entering Zeolite pores.

Filler: Filler is clay that is incorporated into the catalyst to dilute its activity. Kaoline is the most common type of clay that is being used in FCC catalyst.

Binder: Binder serves as the glue which is used to hold all the other components together in the catalyst. Binder may or may not have any of the catalytic activity. Binder provides integrity and heat transfer medium to the catalyst (Reza Sadeghbeigi, Fluid catalytic cracking handbook).

CHAPTER 2

GAS-SOLID SEPARATION DEVICES

Introduction

Gas –solid is a heterogeneous type of mixture in which separation can be done physically by means of difference in their densities. For separation mechanical-physical forces acts on both solid particles as well as on gas stream. These forces include gravitational, centrifugal and kinetic forces. Solid particles are separated from gas stream because of the following reasons (Perry's Chemical Engineering Design, 8th edition)

1. To prevent the loss of expensive particles being lost to environment.
2. To clean the gas stream to comply with air-pollution regulation.
3. For the safety and health hazard elimination.
4. Product quality improvement.
5. Maintenance of equipment from getting deteriorated from the particle laden gas.

From the point of view of collector performance and design the most important property to consider is the solid particle size. Particles larger than 100 µm are easily collected by inertial or gravitational methods. For particles of size smaller than 100 µm in size the high collection efficiency is difficult to achieve.

There are five principle types of gas-solid separation devices. These include settling chambers, cyclone separators, liquid scrubbers, filters and electrostatic precipitators. The use of each one these depends on the size of the solid particles. Figure 2.1 shows classification of each of the separation devices on the basis of particle size.

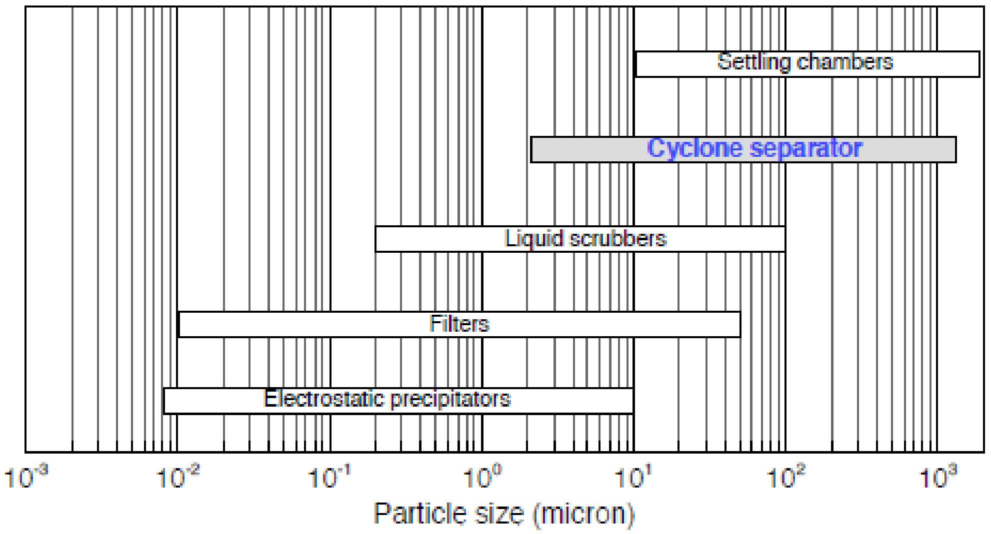


Figure 2.1 Suitable methods for removing particles from a gas stream (Khairy Elsayed , PhD Thesis ,2011)

2.1 Settling Chambers

Settling chambers are one the simplest type of gas cleaning equipment which are suitable for coarse particle usually in the size range of 100-150µm. In these type of equipment solid particles gets settled by gravitational force and is then removed from the bottom. Settling chamber can be operated at high temperature and pressure since they offer very little resistance for gas to flow (Coulson and Richardson’s Chemical Engineering Design, 4th edition).

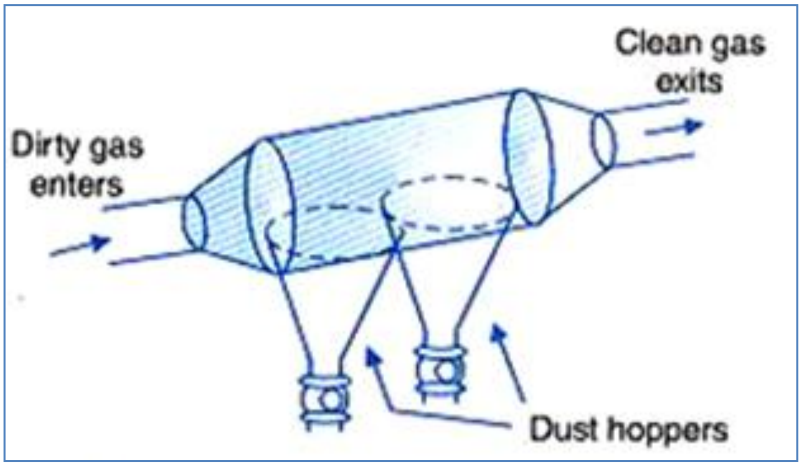


Figure 2.2 Gravity Settling Chamber (Useful notes on Gravitational settling chamber-important air pollution control)

2.2 Wet Scrubbers

In wet scrubbing dust particles are removed by washing it with a liquid which is usually water in a counter-current direction. The principle mechanism involved is impact on the solid particles and water droplets. Particles of size as small as .5µm can be removed by wet scrubbing. In addition to removing particles these can also neutralize the gas and remove any kind of corrosive material in it.

Spray, packed and plate are the most common types of wet scrubber units. Sprays towers cannot be used to remove very fine particle where as packed and plate tower are more efficient for such particles but at an expense of high pressure drop (Coulson and Richardson's Chemical Engineering Design, 4th edition). Figure 2.3 shows a systematic diagram of wet scrubber.

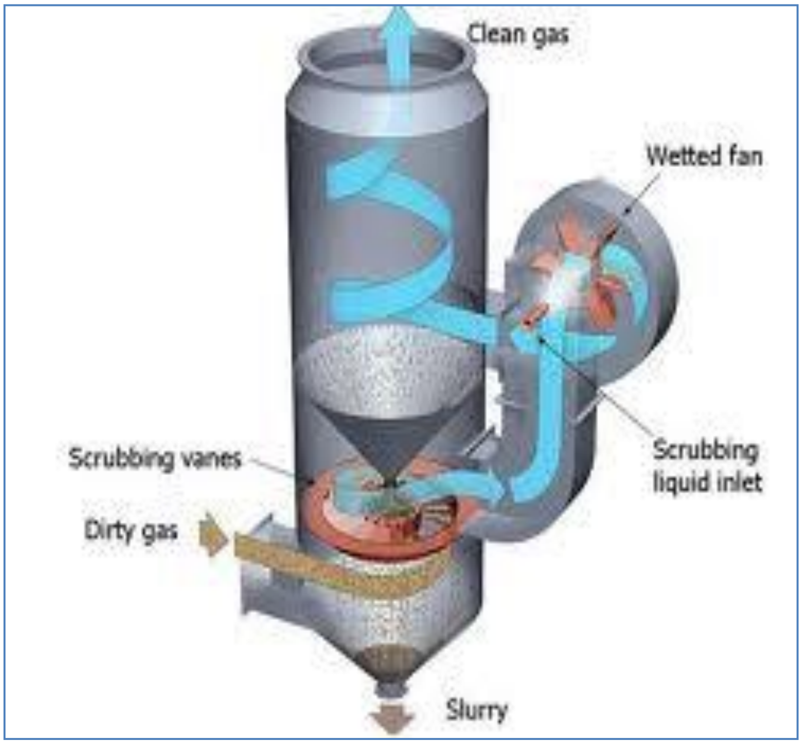


Figure 2.3Wet Scrubber (https://blog.oureducation.in/wet-scrubbers/#!prettyPhoto)

2.3 Filters

Filters use filtration to separate solid particles from gases. These are one of the most efficient separation devices. In filtration process suspended solid particles in gas or liquid stream are removed by passing the mixture through a porous medium that retain the solid particle and let the liquid or gas stream to pass through it. Filtration is performed by vacuum, pressure or centrifugation.

Most frequently used filter medium is woven cloth. Filter aids are used to increase the collection efficiency of filter medium. Industrial filters use vacuum, pressure or centrifugal force to carry out the filtration process. Filtration process is usually a discontinuous process (Marja Nappa and Lotta Sorsamäki, 2015).The pores of the medium are usually many times the size of the dust particles so that the collection efficiency is low until some of the particles are collected to form a precoat in the pores. Because of high collection efficiency of filter to collect the particles of almost all the size ranges these have been used for the collection of fine dust and fume (Perry's Chemical Engineering Design, 8th edition). Figure 2.4 shows a type of filter used in industry.

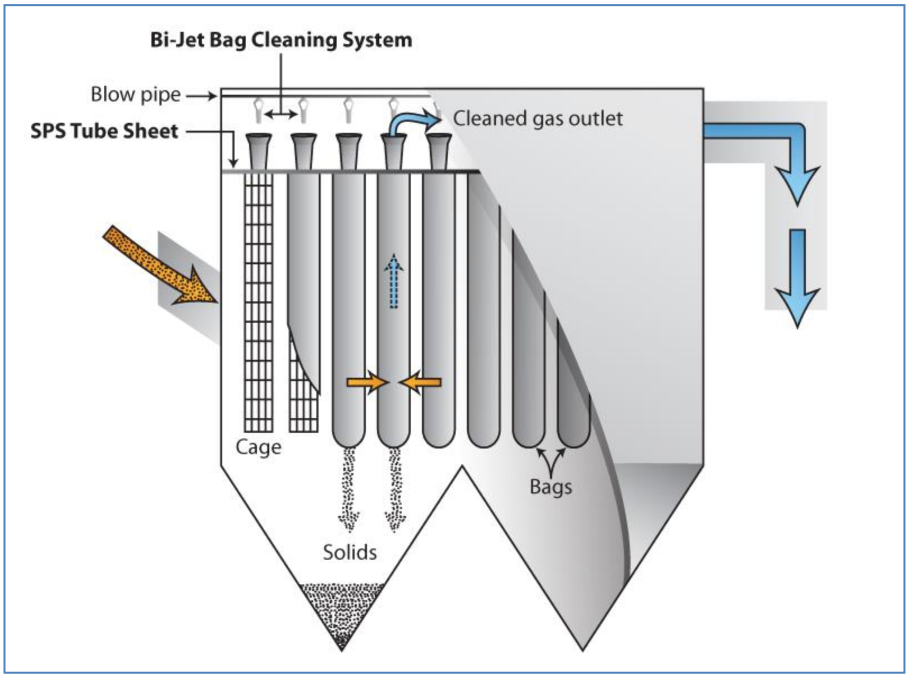


Figure 2.4 Bag Filter(http://www.redecam.com/bag-filters/)

2.4 Electrostatic Precipitator

Electrostatic precipitators can collect very fine particles of size <2µm with high efficiency. The main disadvantage of these is that they operate at high capital and operating cost. This type of equipment is being used in metallurgical, cement and electric power industries. They find their application for the removal of fine fly ash which is formed by the combustion of pulverized coal.

In electrostatic precipitator, gas gets ionized when it is passed through high – voltage electrode and grounded electrode. Dust particles get charged during the process and get attracted towards the grounded electrode. Dust is removed from electrodes mechanically usually by vibration or washing. Wires are being used as high voltage electrode and plates / tubes as grounded electrode (NPTEL).

Figure 2.5 shows a typical design of electrostatic precipitator used in industries.

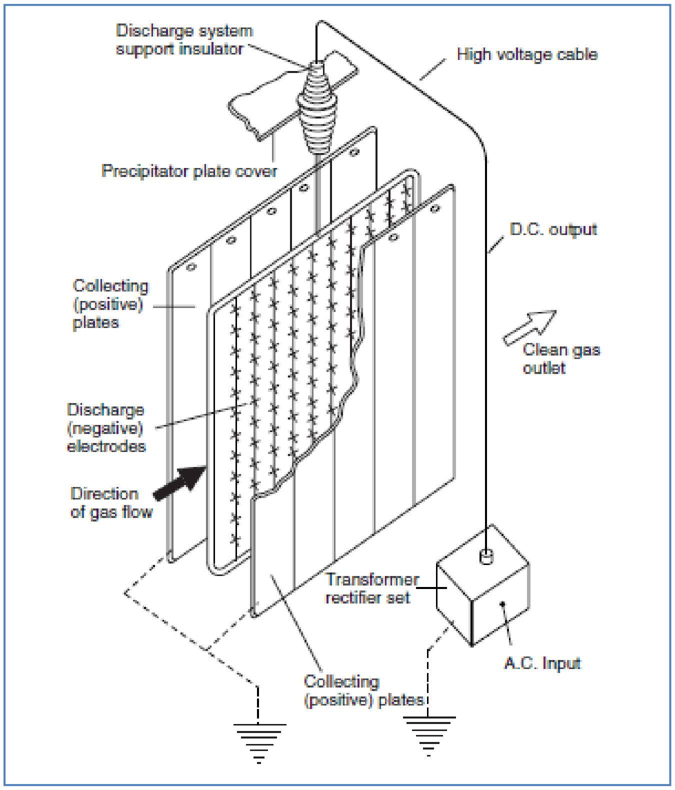


Figure 2.5 Electrostatic Precipitator (http://www.redecam.com/electrostatic-precipitators/)

2.5 Cyclone Separator

Cyclone separator provides a method of removing particulate matter from the gas stream at a low cost and low maintenance along with high collection efficiency. Cyclone is centrifugal separators which consist of an upper cylindrical part referred as barrel and lower conical part cone as cone. Figure 2.6 shows a typical design of cyclone separator.

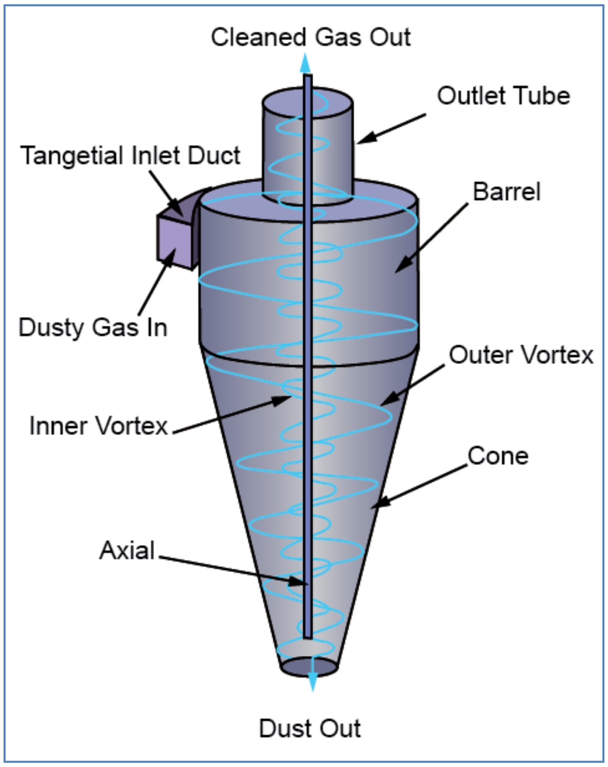


Figure 2.6 Systematic Diagram of Cyclone Separator (NPTEL)

Gas along with solid particulates enters the cyclone separator tangentially and movers down through barrel and cone forming a swirl pattern. Due to the centrifugal force acting on the particles the solid particles separates from the gas and falls down in the dust hopper. In the inner region of the cyclone gas stream reverses its direction and moves upward and exits at the top as a clean air.

2.6 Difference between solid-gas separating devices

Table 2.1 shows the difference between the different gas-solid separation equipments on the basis of particle size, loading, gas velocity, collecting efficiency and space required.

Type Of Equipment	**Minimum Particle Size(μm)**	**Minimum Loading (mg/m^3)**	**Approx. Efficiency (%)**	**Typical Gas Velocity (m/s)**	**Maximum Capacity (m^3/s)**	**Space Required (Relative)**
Settling Chamber	50	12000	50	1.5-3	None	Large
Cyclone	10	2500	85	10-20	25	Medium
Multiple Cyclone	5	2500	95	10-20	100	Small
Wet Scrubber (Centrifugal)	5	2500	90	10-20	50	Medium
Electrostatic Precipitator	2	250	99	5-30	1000	Large
Fabric Filters	0.2	250	99	0.01-0.1	100	Large

Table 2.1 Difference between Gas–Solid Separation Equipments (Coulson and Richardson’s Chemical Engineering Design, 4th edition)

CHAPTER 3

CYCLONE SEPARATOR

Introduction

Cyclone separator provides a method for removing the particulate matter from air stream at low capital and maintenance cost. Cyclone separators belong to the class of centrifugal separators. They use cyclonic action to separate solid particulate matter from gas stream. These are one of the most efficient and robust type of gas-solid separation equipment. Its robustness is because of the lack of moving parts and ability to withstand harsh operating conditions. Cyclone separators can be used for high temperature and pressure applications. These are one of the least expensive separation equipment.

3.1 Applications of Cyclone Separator

Cyclone separator finds its application in a number of industries because of its ability to work at high temperature and pressure operating conditions and have high collection efficiency. Cyclone separators are found in (Khairy Elsayed, PhD Thesis,2011):

1. Fluidized catalytic cracking (FCC).
2. Synthetic detergent producing units.
3. Food processing plants.
4. Power stations.
5. Spray dryers.
6. Crushing, separating, grinding and calcining operations in mineral and chemical industries.
7. Vacuum cleaning machines

3.2 Advantages of Cyclone Separator

Advantages of cyclone separator are (A. C. Hoffmann and L. E. Stein, 2008)

1. Low capital investment and maintenance cost is also low.
2. Robust: No moving parts.
3. Can be used under extreme operating conditions of high temperature and pressure.

4. Collected particles are dry and useful for further application.
5. Can be equipped with corrosion resistant or erosion such as Teflon.
6. High collection efficiency upto 99.99%.

3.3 Disadvantages of Cyclone Separator

Disadvantages of cyclone separator are (A. C. Hoffmann and L. E. Stein, 2008)

1. Low efficiency for particles below their cut off diameter when operated under low solid loading condition.
2. Can be erosive and fouling if the material under processing is abrasive or sticky.
3. It operated below the desired collection efficiency if not designed or operated properly.

3.4 Cyclone Nomenclature

Figure 3.1 shows the important parts that forms a cyclone separator.

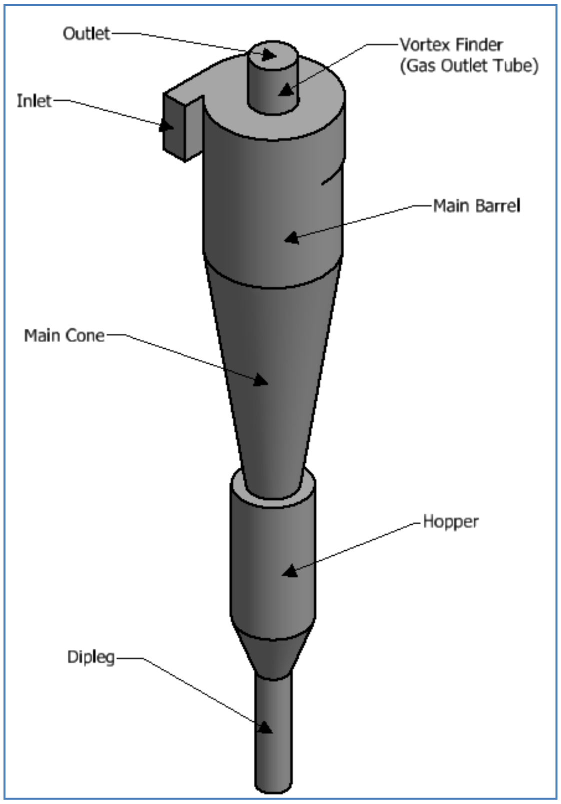


Figure 3.1 Parts of Cyclone Separator (John W McTeran ,2014)

3.5 Cyclone Operating Principle

Dust laden air enters the cyclone separator tangentially through the cyclone inlet at the top and follows a vortex flow pattern as it moves downwards helically. Centrifugal force is generated from the tangential velocity profile of cyclone. This centrifugal force forces the heavier dust particles to move radially outward towards the cyclone wall forming an outer vortex. When these particles reach the wall, friction and gravity force then to fall downwards and gets discharge from the bottom outlet. The gas reverses its direction at the bottom and forms an inner vortex and moves upwards and exits from the top (M.Heumann, 1983). Figure 3.2 below explains the operating principal of cyclone separator.

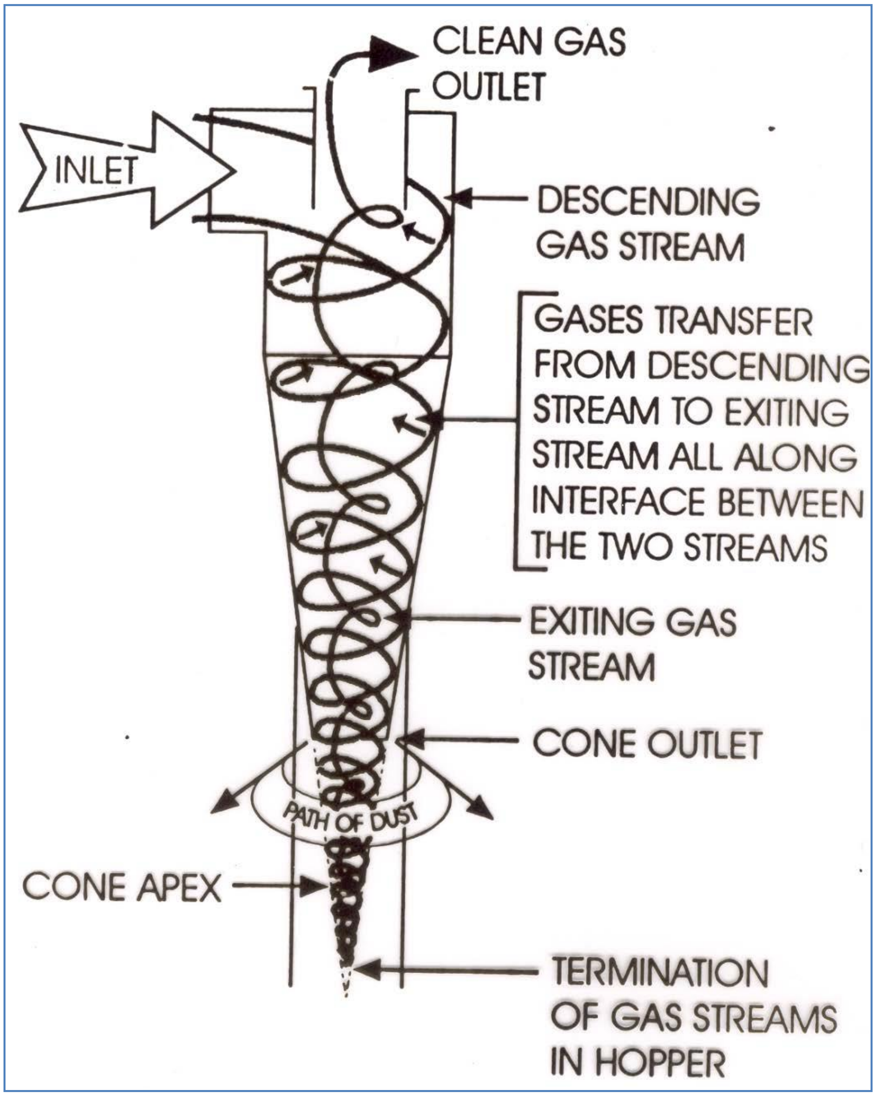


Figure 3.2 Operating Principal of Cyclone Separator (John W McTeran, 2014)

3.6 Basic Arrangement of cyclone System

There are two basic types of cyclone system arrangement as shown in figure below.

1. **Series Arrangement:** A typical series arrangement is shown in the figure 3.3 below. In such arrangement larger particles can be collected in first cyclone also called primary cyclone and smaller particles can be collected in the second cyclone called secondary cyclone. This reduces the dust loading in secondary cyclone and also reduces the problem of abrasion and plugging. Also if primary cyclone is plugged separation is still possible in secondary cyclone.

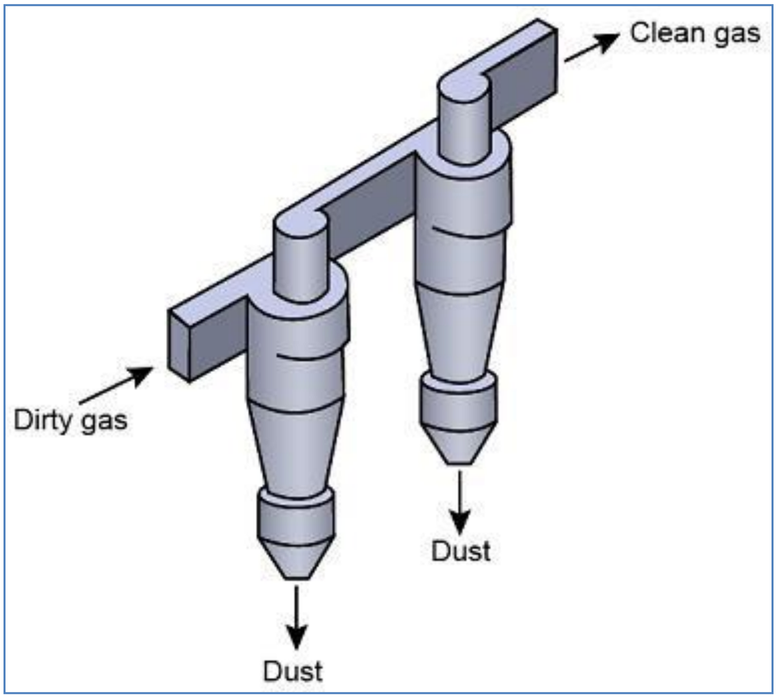


Figure 3.3 Series arrangement of cyclone separator (NPTEL)

2. **Parallel Arrangement :**

   The gas and solid stream is distributed evenly between the various units in parallel. This type of arrangement leads to excellent separation performance relative to larger unit handling the volumetric flow.

3.7 Classification of Cyclone Separator

Cyclone separator can be classified on the following basis (Alex C Hoffmann, Gas cyclones and swirl tubes principle design and operations):

1. **Inlet Configuration**

   Tangential Inlet: Tangential inlets are widely used in chemical and petroleum processing industries. The cross section of tangential inlet is rectangular. These have a very good performance.

   Axial Inlet: In this the dust laden gas enters the cyclone parallel to the axis of the cyclone. This type of inlet is positioned between the vortex finder and the outer body of the cyclone.

   Scroll / volute Inlet: Volute inlet is used for high solid loading and it prevents the inlet jet from impacting the vortex finder and disturbing the flow and causing erosion problems. Volute inlets are usually used for the primary cyclones. This inlet reduces the angle of attack of the incoming stream with the cyclone barrel. The scrolls can be of 90, 180,270 or 360 deg depending upon the requirement. 360 deg scrolls are referred to as the full scroll and the others as partial scroll. Figure 11 below shows all the most commonly used Cyclone Inlets.

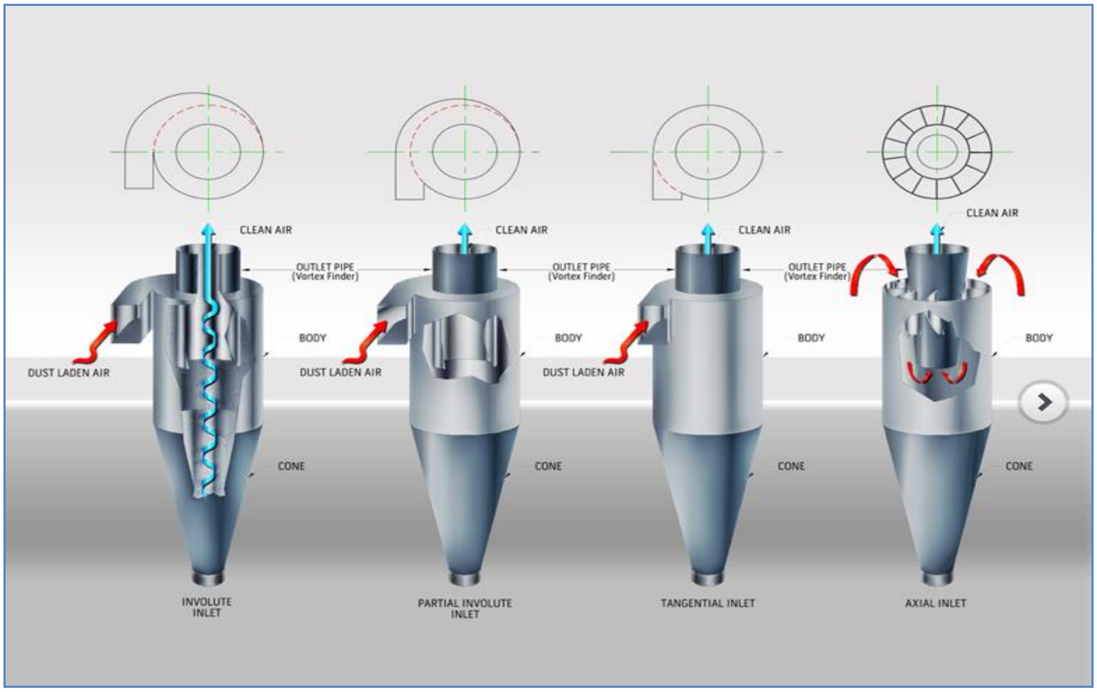


Figure 3.4 Common type of Cyclone Inlet (Ted Knowlton, 2015)

2. **Flow direction in and out of them**

   There are two possible configurations of the cyclone as shown in figure 12 below. The gas may leave the cyclone at the top roof which the "reverse flow cyclone" and the most common type of cyclone being used. Other possible configuration is that of gas leaving at the bottom in the same direction from where the dust particles exit and is referred to as the "straight through" cyclones. This type is less frequently used in industry because it is a much less practical design in most cases.

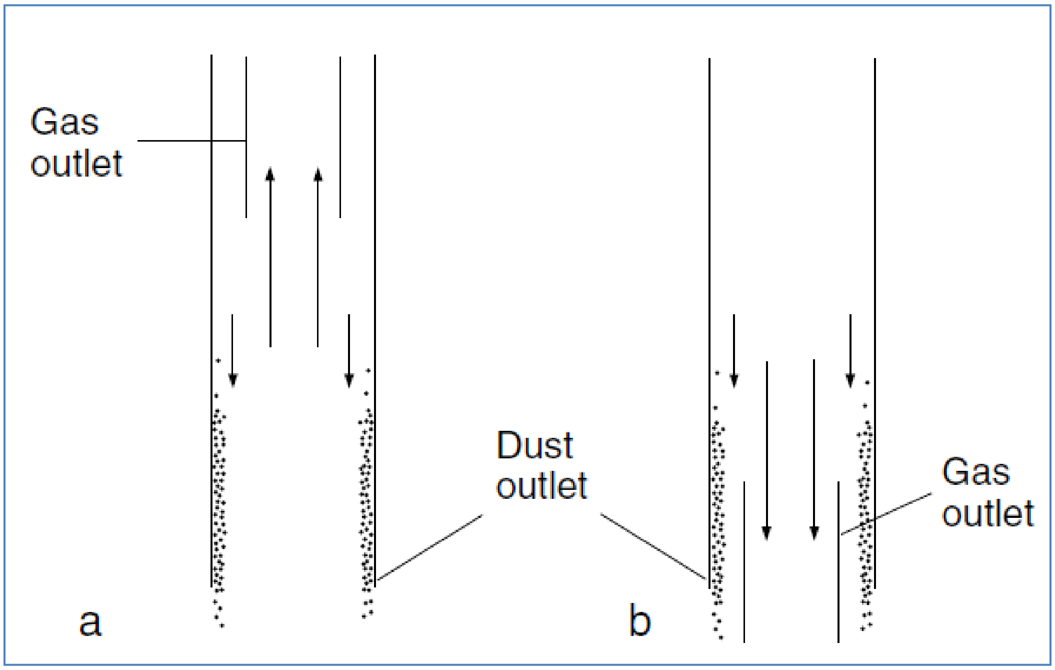


Figure 3.5 (a) Reverse Flow Cyclone (b) Straight through Cyclone (Alex C Hoffmann Gas cyclones and swirl tubes principle design and operations)

3. **Positive and Negative pressure cyclone**

   Positive pressure cyclone does not have the catalyst flow up the dipleg except at the startup and or a low flow rate. The diplegs are inserted in the bed for positive pressure system in an attempt to create a backpressure and minimize the gas flow down the dipleg.

In the negative pressure cyclone the pressure in the cyclone is less than the pressure in the vessel. This pressure drop in the cyclone closes the flapper valve. In order to balance this pressure catalyst level in dipleg needs to be build up (D.F Shaw, 2007).

3.8 Reason for High Catalyst losses inside cyclone separator

Following are the reasons for catalyst loss in cyclone (Fluid catalytic cracking cyclone design and modifications, Buell refinery cyclone):

1. **Mechanical Failures:** When there is a sudden loss of catalyst the first reason for that may be the mechanical failure which includes leaks, holes formed by erosion in cyclone or dipleg malfunctioning or damaged dipleg.
2. **Catalyst attrition:** Catalyst attrition in cyclone occurs because of improper design of cyclone, excessive inlet velocity and high turbulence.
3. **Excessive mass flow in cyclone and dipleg:** When the amount of flow rate in the primary cyclone is greater than the maximum amount that it can withhold then the cyclone level backs up into the cyclone from the bottom to the hopper and reaches a level where its gets reentrained along the gas flow upwards and to the secondary cyclone.
4. **Dipleg Length:** In cyclone the dipleg length have to long enough so that the catalyst level in the dipleg has to be well below the hopper so that none of the particles is reentrained in the existing gas stream.

3.9 Jet streaming and flooding in cyclone

Diplegs are the pipes that are attached to the conical bottom of the cyclone that return the collected solids back to the system. These can discharge the solids above the fluid bed (suspended dipleg) or directly into the fluid bed (submerged dipleg). During the start up process, fluidizing gas flows up the secondary cyclone dipleg until a solid level is reached to provide a seal to it. Primary cyclone generally has enough solid flow that they do not require any seal. Splash plates are used in the primary cyclone to prevent the gas to flow upwards. However, in the secondary cyclone sealing device is necessary since the flow rate is very low in them. They are provided with trickle valve to prevent the gas flow through the diplegs. This phenomenon of gas flow is known as jet streaming.

Flooding occurs if the solid flow into the dipleg is greater than the solids being discharged from the dipleg causing the dipleg to fill with solids and back-up into the cyclone. If the cyclone dipleg are located in a poorly fluidized region of gas bypassing, solid discharge from them will be hindered and will lead to flooding inside the dipleg (S.B Reddy Karri).

CHAPTER 4

Literature Review

4.1 Performance parameters of cyclone

There are two parameters which measure the performance of cyclone.

1. Particle Collection Efficiency
2. Pressure Drop

4.1.1 Particle Collection Efficiency

Collection Efficiency is defined as the fraction of particles of a given size that is retained by the cyclone. It depends on the nature of the process. If process stream particles are larger and free flowing collection is relatively easy. The collection efficiency of cyclones varies as a function of density, particle size and cyclone design. Cyclone efficiency will generally increase with increases in particle size and/or density; inlet duct velocity; cyclone body length; number of gas revolutions in the cyclone; ratio of cyclone body diameter to gas exit diameter; inlet dust loading; smoothness of the cyclone inner wall. The cut diameter of the cyclone is defined as the size of the particles collected with 50% collection efficiency. It is an indicator of the size range of particles that can be collected. It is a convenient way of defining as it provides information on the effectiveness for a particle size range.

4.1.2 Cyclone Pressure Drop

Pressure drop is an indirect measure of the energy required to move the gas through the system and is directly related to the operating cost. Pressure drop occurs in the cyclone because of the following reasons:

1. Frictional and entrance losses usually, which is usually 10% to30% of total pressure drop
2. The rest is pressure gradient generated by vortex.

Total pressure drop across the reverse flow cyclone between the inlet and the outlet is determined as the sum of five pressure drops as follows:

$$\Delta P = \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4 + \Delta P_5 \qquad (1)$$

1. **Pressure drop due to inlet contractions**

   Pressure drop due to gas acceleration from the inlet contraction at the inlet.

$$\Delta P_1 = \frac{1}{2}\rho_g((1+K)u_{inlet}^2 - u_f^2 \qquad (2)$$

Where,

u_f = superficial velocity in the region before the inlet of the cyclone.

K = Compression Correction factor

2. **Pressure drop due to particle acceleration**

   As the particle-laden gas stream enters the cyclone inlet, the gas is accelerated which, due to the drag force, accelerates the particle.

$$\Delta P2 = \lambda u_{inlet}\ (V_{inlet} - V_{outlet}) \qquad (3)$$

Where,

V_{inlet} = Particle velocity at inlet.

V_{outlet} = Particle velocity at outlet

3. **Pressure drop due to barrel friction**

   As a particle enters the cyclone barrel, centrifugal forces push the particle towards the wall. Wall friction slows down the particle which translates into an additional pressure drop.

4. **Pressure drop due to gas flow reversal**

   As the gas and particles spiral down the reverse flow cyclone, particles fall through the cone region into the dipleg. The gas, however, reverses flow and heads up to the gas outlet tube, hence the name “reverse-flow” cyclone.

5. **Pressure drop due to exit flow reversal**
   As with the inlet contraction pressure drop, additional pressure drop is required for the compression of gas as it goes from the barrel to the outlet tube or vortex finder.

4.2 Factors affecting cyclone performance

Different factors that affect cyclone performance are as follows:

1. **Particle properties**
    a) Density
    b) Mass Loading
    c) Particle Size distribution
2. **Gas properties**
    a) Velocity
    b) Viscosity
    c) Temperature and pressure
3. **Cyclone Dimensions**
    a) Inlet height and width
    b) Cyclone total length
    c) Cylinder length and diameter
    d) Cone length and Diameter
    e) Vortex Finder diameter
    f) Dipleg Length

4.2.1 Effects of Cyclone Inlet Dimensions

Khairy Elsayed et al., (2003) studied the effect of inlet dimension on the cyclone performance using CFD. He investigated that the tangential cyclone inlet velocity decreases with the increase of inlet dimensions. Also increasing the inlet dimension decreases the pressure drop. The reason for pressure drop is accounted on the basis of the overall pressure drop occurring in the cyclone. Overall pressure drop is the sum of three pressure drop occurring in cyclone and theses are 1. Pressure drop at the inlet section of cyclone 2. Pressure drop in the cyclone body 3. Pressure drop at the exit. The main pressure drop is the drop at the exit and that depends on the maximum tangential velocity. Since maximum tangential velocity decreases due to increase in the inlet dimension hence pressure drop also decreases.

4.2.2 Effect of Gas inlet velocity

Jingxuan Yang et al., (2015) used the hard sphere model and Newton's law to predict radial motion of particle in a cyclone. They predicted a new model MEIV model that provides a new insight into the motion of particle in the cyclone. In this model they predicted at as the particles are centrifuged to the walls of the cyclone they are bounced back into the vortex as high speed as with which they enter the cyclone. So If the inlet velocity of the gas laden with particle is increased the particles with get accelerated and by the effect of centrifugal force will impact the wall of the cyclone and will be bounced back and into the inner vortex and will escape along with the gas. This will decrease the collection efficiency of the cyclone.

Shaw et al., (2006) in their paper used the Texas A & M method to design cyclone. According to this method 1D3D and 2D2D (where D is the diameter of barrel and first number represents the cyclone length and second number cone length) must have ideal inlet velocities of 974 ±120 m/min and 914±120 m/min. For both the cyclones they reported the collection efficiency greater than 99% regardless of inlet velocity.

4.2.3 Effect of mass loading

JJ Derksen et al., (2006) studied the mass loading effect of stairmand high efficiency cyclone. They demonstrated through simulation that as mass loading has impact on both the swirl motion and turbulence of cyclone. Because of the increase in mass loading swirls motion inside the cyclone decreases. This decrease in the swirl motion lowers the driving force on the particles and hence lowers the separation efficiency.

Fa´bio Lu´ıs Fassani and Leonardo Goldstein Jr(2006) carried out experiment with FCC catalyst with particle size distribution to study the effect of solid loading in the cyclone performance. They carried out experiment at three different velocities of 7 m/s , 18 m/s and 27 m/s and increasing solid loading. They noted the decrease in the pressure drop with the loading. They attributed this phenomena could be due to the reduction in tangential velocity caused by increase in wall friction. They also noted an increase in collection efficiency for velocities 18 m/s and 27 m/s upto 12 kg/s but after that they observed a decrease in efficiency.

4.2.4 Effect of temperature

Jianyi Chen and Mingxian Shi (2003) conducted an experiment on reverse flow cyclone of 300 mm diameter and with tangential volute inlet with air at a temperature of 973 K to provide the effects of temperature on the cyclone collection efficiency. Keeping the inlet velocity same they found out that both collection efficiency and pressure drop decreases with increase of temperature. The fall in collection efficiency was relatively higher at high temperature range of over 800 K. The reason for the decrease in efficiency is that as the temperature increases the viscosity of gas stream also increase leading to an increase of drag force on the moving particle. They also found a decrease in tangential velocity with increase of temperature.

Jolius Gimbun et al., (2004) predicted the effects of temperature and inlet velocity on the pressure drop inside the cyclone using CFD. They used Reynolds stress turbulence model to determine the pressure drop. They observed a very little pressure drop of upto 3%.

4.2.5 Natural Turning Length

In a reverse flow direction at a certain distance from vortex finder outer vortex changes its direction. This is known as “natural length” or “vortex length”. At this point all the gas in the cyclones reverses its direction and moves towards the exit. Also entrainment of the particles occurs at this stage. Cortes and Antonia Gil (2007) calculated numerically the appropriate vortex length for a cyclone. They found that for a properly operated cyclone vortex end should be stable and should be located well inside the dipleg. If the vortex is short, cyclone collection efficiency will fall.

4.2.6 Effect of Cone Dimension

Zenz et al., (1983) observed that if the vortex formed touches the cone wall the entrainment will occur and this can decrease the cyclone efficiency.

K.W Lee et al., (2001) experimentally studied the effect of cone dimension on the performance parameter of cyclone. He carried out the study with three different cyclones having cone bottom opening of 19.4 mm, 15.5 mm, and 11.6mm. They found out that the particle collection efficiency with smaller cone opening is higher than that of the cyclone with a larger cone opening. This shows that as the cone diameter keeps on decreasing particles gets more and more accelerated in that region. Since the cross sectional area decreases and hence this results into higher tangential force and ultimately greater centrifugal force acting on the particles. Also with the decrease of cone diameter the spacing in the cone decreases and the chances of vortex touching the cone increases. This will decrease the collection efficiency as the entrainment of particles will take place. But the effect of entrainment of the particles is less pronounces in comparison to enhancement of cyclone performance.

4.2.7 Effect of Cyclone Length

Hoffmann et al., (2011) predicted the effect of increasing cyclone length on the performance of Cyclone. The performance of cyclone is improved when the cyclone length is increased along with a huge drop is pressure. Lengthening of cyclone improves the performance of cyclone but upto a critical point because after that the natural length of vortex may end way before the cyclone length and may end up forming a gap and this decreases the collection efficiency of cyclone.

Lakhbir Singh Brar et al., (2015) carried out CFD study to predict the cyclone performance by changing the cylinder and cone length of standard cyclone design. They found that cyclone length greatly affects the pressure drop and collection efficiency of cyclone. They found that increasing the cylinder length by upto 5.5 times the cyclone diameter reduces pressure drop by almost 34% and increase collection efficiency by 9.4%. On the other hand increasing the cone length by upto 6.5 times the cyclone diameter shows a pressure drop reduction by 29% and increase in collection efficiency by 11%.

4.2.8 Effect of Dipleg Length

Kaya et al., (2009) through CFD simulation showed that the performance of cyclone can be improved by adding correct dipleg length. A prolonged cyclone gives higher cyclone collection efficiency by providing enough separation space. According to results provided approximate length for dipleg is half of that of height of cyclone. The main reason for this is natural vortex length. If the vortex end reaches the bottom of the dipleg this leads to high collection efficiency. Further increase in dipleg length makes the vortex shorter. If vortex end attaches to the wall and causes instability this will cause re-entrainment of collected solid particles and will lower the collection efficiency.

4.2.9Effect of Vortex Finder Dimensions

Khairy Elsayed et al.,(2011) analyzed the convention cyclone design by changing the vortex finder length and diameter. Nine different types of cyclone designs were analyzed using CFD. They used LES model in CFD. They obtained that 40% reduction in vortex finder diameter will increase the pressure drop by 175%.

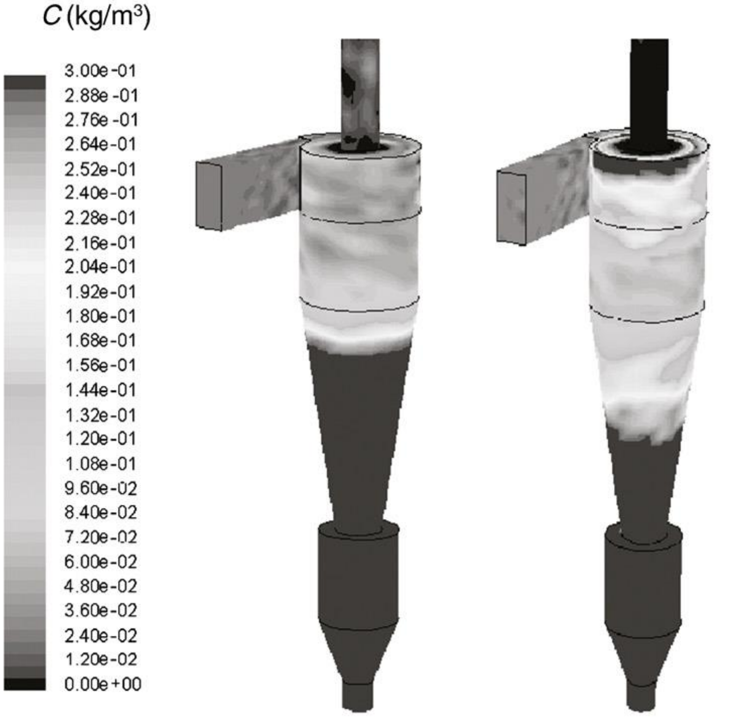
Vedat Ari et al., (2014) experimented with cyclones of different vortex finder diameter of 80 mm, 120 mm and 160 mm to investigate the effect of various lengths of vortex finder , inlet velocities and concentration of inlet particle on the collection efficiency of cyclone. They saw that when the vortex finder diameter is increased from 80 to 120 mm particle collection efficiency decreases. If the diameter is continued to increase the collection efficiency will decline constantly.

Kim et al., (2007) found out that the role of exit tube size is important on the particle collection efficiency because it controls both inner and outer vortex pattern. If we have a very large exit tube whose size almost same as that of the size of cyclone body the spiral pattern will not be sharp and some of the particles may exit through the exit tube without even reaching the lower part of cyclone. When the exit tube size is smaller a well defined outer and inner spiral flow are formed forcing the particle to travel to the lower part of cyclone.

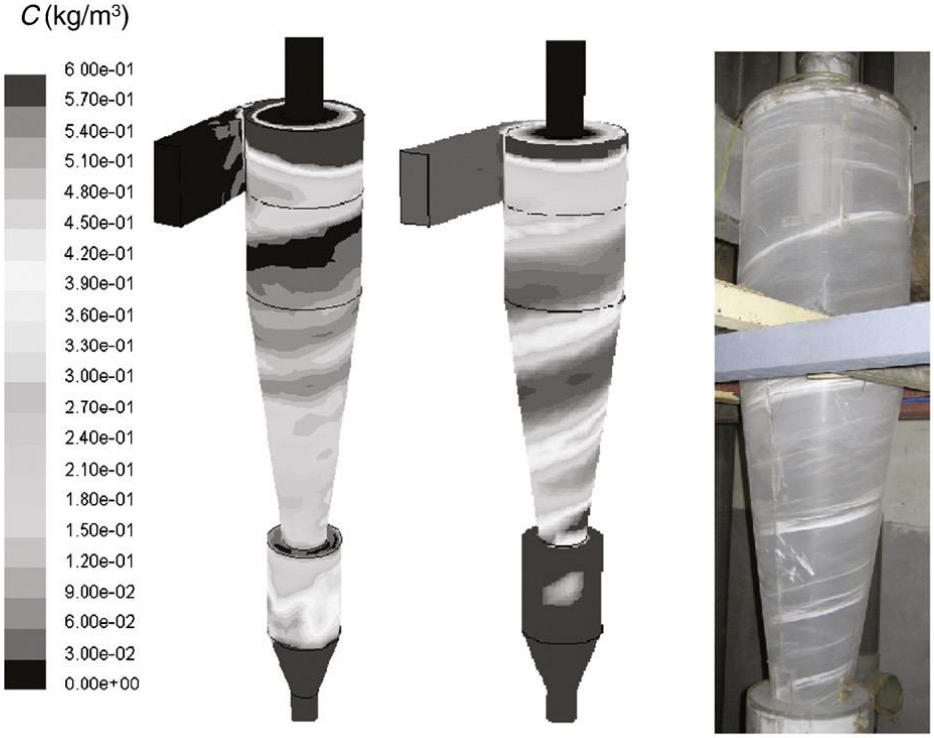
Reza et al., (2008) carried out experiment with three vortex finder of different diameters of 15, 11 and 7mm. Through CFD simulation they found out that the tangential velocity profile has similar same for the all the cyclone of different vortex finder diameters nut the magnitude of each of them is different. The tangential velocity in the inner region of cyclone decreases when the cyclone vortex finder diameter is increased from 7 mm to 15 mm and hence cyclone separation efficiency also decreases.

4.2.10 Effect of particle size distribution

Solid concentration of different particle size in a scroll cyclone separator was numerically simulated in CFD software using Lagrange approach by Gujun Wan et al.,(2008).Figure below shows the particle concentration. From the figure it is clear that particles generally move outward and downwards. Smaller particles get dispersed throughout the cyclone. In the upper, annular and cylindrical region small particles are dragged by gas flow and are escaped through vortex finder and on the other hand they are moved outwards and downwards by centrifugal force and gravity force. In the lower section of the cone separation process is dominant. For the small particles the small particle accumulation is seen across the wall only in the conical section. Whereas for the larger particles accumulation is greater at the wall but accumulation height is low. For large particles like that of 18 µm the accumulation is seen mostly in the lower section of cone.



(a) d_p=4μm (b) d_p=8μm



(c) d_p=18μm (d) particle group

Figure 4.1 Different diameters particle concentration distribution on walls (Gujun Wan et al.,2008)

CHAPTER 5

CPFD SIMULATION OF CYCLONE – OPTIMIZATION OF DESIGN

Introduction

The particle fluid flow simulation of commercial scale fluidized catalytic cracking (FCC) unit regenerator two stage cyclones has been conducted using CPFD Barracuda software. Barracuda is based on Multi-phase particle-in-cell (MP-PIC) implementation of computational particle fluid dynamics, which uses Eulerian approach for fluid field and Lagrangian scheme for particle flow. This study is not concerned with the numerical study of CPFD.

The simulation is three dimensional and no internal complex geometries were included in it. Study of hydrodynamic behavior is our main aim for carrying out the simulation so thermal and chemical reactions effects are neglected in this study. Simulation is carried out at quasi steady state operating conditions. The result of simulation includes the cyclone collection efficiency and pressure drop.

5.1 Motivation of this work

Cyclone separators are the most widely used gas solid separation devices being used in industries. The aim of this work is to understand the flow of solid gas mixture inside the cyclone and the design of optimum cyclone separator operation (minimum pressure drop and maximum separation efficiency).The performance parameter of cyclone is governed by many operational parameters and geometrical parameters. This study focuses only on the effect of geometrical parameter on the performance of cyclone.

The specific goals of the work are following:

1. Study affect of geometrical parameter (cyclone gas outlet duct/vortex finder diameter) on the performance of cyclone separator.
2. To obtain optimum cyclone design for minimum pressure drop and maximum solid separation efficiency.

5.2 Scope and Objective

The scope of the project includes the simulation of FCC regenerator two stage cyclone system using CPFD Barracuda software. Main objective of simulation is the prediction of:

1. Cyclone particle collection Efficiency
2. Pressure drop across the cyclone.

Simulation model consists of commercial scale fluidized bed with continuous solid particle (catalyst) and gas entering the cyclone inlet and the separation of gas and solid particles taking place inside the system. Cyclones are included as solid body and inside of the cyclones are modeled.

The entire project is subdivided in to three parts namely,

a) Development of Cyclone 3D model
b) Problem setup
c) Post processing of data for estimation of desired parameters

In actual plant there are 3 pair of two stage cyclone and all are symmetrical, therefore, we have consider only one pair of two stage cyclone system and accordingly solid loading and gas rate to cyclone of the total system are reduced to one-third.

The scope of work includes the following:

1. Problem definition
2. Collection of input data
3. Gridding of 3D geometry
4. Defining boundary conditions (Pressure and Flow),
5. Defining Flux planes and transient data for monitoring the desired parameters
6. Post Processing of results for estimating the desired parameters such as cyclone efficiency, pressure drop etc

5.3 Problem Definition

During the FCC process coke gets deposited on the catalyst surface. Catalyst needs to be regenerated to be used again in the process. They are being sent to regenerator for its activation.

Inside the regenerator catalyst particles enters the cyclone along with flue gas and they are required to be separated. Catalyst particles get separated by the action of centrifugal force and then they are returned to the reactor through the cyclone dipleg. Catalyst particles are collected at the bottom and flue gas exits at the top. However particles which are very fine (size<10 µm) or due to some upset inside the cyclone particles exits at the top along with the flue gas. This reduces the collection efficiency of the cyclone and causes a huge loss to the industry. The collection efficiency of the cyclone is defined as the percentage of the total particles collected inside the cyclone. The collection efficiency of the FCC cyclone is usually 99.999%.

Separation of gas and solid inside the cyclone depends on a number of factors. These include operational and geometrical parameters. Operational parameters include inlet velocity, mass solid flux, gas viscosity whereas geometrical parameters are cyclone dimensions. Most important dimensions are inlet width and height, barrel diameter and length, cone length and diameter, dipleg length, gas outlet duct diameter (vortex finder diameter).

Vortex finder is an especially important dimension which significantly affects the cyclone performance as its size plays a critical role in defining the flow field inside the cyclone including the pattern of outer and inner spiral flows.

This study is intended to computationally investigate the effect of decreasing the vortex finder diameter on particle collection efficiency and pressure drop.

5.4 3D geometry

Cyclone model contains the FCCU regenerator two stage cyclones. First cyclone is called primary and another one is secondary cyclone. One small tub of catalyst bed (rectangular box) is provided at end of cyclone diplegs for immersing it, to simulate the realistic dipleg conditions in regenerator dense bed. Entrainment of the catalyst from the tub is ignored .Another tub/ box is also provided at outlet /vortex tube of second stage cyclone to allow gas and catalyst particle to escape from the vortex tube. Regenerator primary and secondary cyclone are having splash plate and flapper valve assembly respectively at the end of dipleg bottom.

The 3D CAD geometry is developed using AUTODESK INVENTOR software and imported in Barracuda software for simulation in the form of ‘.stl’ file.

5.5 Assumptions

Following assumptions are being taken to carry out the simulation.

1. No chemical reaction takes place during the process.

2. Isothermal conditions exits inside the cyclone.
3. Flapper valve has 7deg opening.
4. Uniform velocity at bath tub.
5. Wen-Yu drag model is considered for this simulation. The drag model in Barracuda determines the force acting on a particle by a fluid in the model. The Wen-Yu drag model is the default particle to fluid drag model used by Barracuda.
6. Wear due to impact of particles is neglected.

5.6 Operating Conditions

Typical operating conditions used in the simulation are shown in the table below.

Parameter	**Value**
Pressure	420000 Pa
Temperature(Isothermal)	990 K
FCC catalyst particle density	1450 Kg/m^3
Initial bed catalyst mass	32500 Kg
Bed Density	464 Kg/m^3
Superficial velocity in fluidized bed	1.1 m/s
Particle flow rate at inlet	122.5 Kg/sec
Velocity at the outlet of primary cyclone	**Initial Velocity : 17 m/sec** **Changed Velocity : 27.7 m/sec**

Table 5.1 Operating Conditions

For our study we have decreased primary cyclone gas outlet tube diameter by .2 m as described in the original cyclone design. This changed the gas outlet velocity from 17m/sec to 27.7 m/sec.

5.7 Computational grid and particles

The first step of simulation is defining the computational grid. The computational cells defined by the grid are used to solve the fluid transport equations, the results of which are strongly coupled with particle momentum equations. A finer grid gives higher degree of computational solution, but requires a longer calculation time. Barracuda uses a regular rectangular grid. The computational grid contained 595650 real cells.

In a large commercial vessel such as the regenerator cyclone currently under consideration, there could be on the order of 10^{15} individual particles in the system. With current computers, it is not feasible to model the detailed motion of this many individual particles in a simulation. Barracuda uses so-called computational particles, which allows for useful engineering results in reasonable solution times. Each computational particle represents a group of real particles that share physical properties such as material, radius, and density. The number of computational particles used the simulation affects the accuracy of the results. As with the grid, using more computational particles gives more accuracy, but also requires longer run-times.

FCC Catalyst particles are used to carry out the current simulation with particle size distribution as shown in figure 5.1 below.

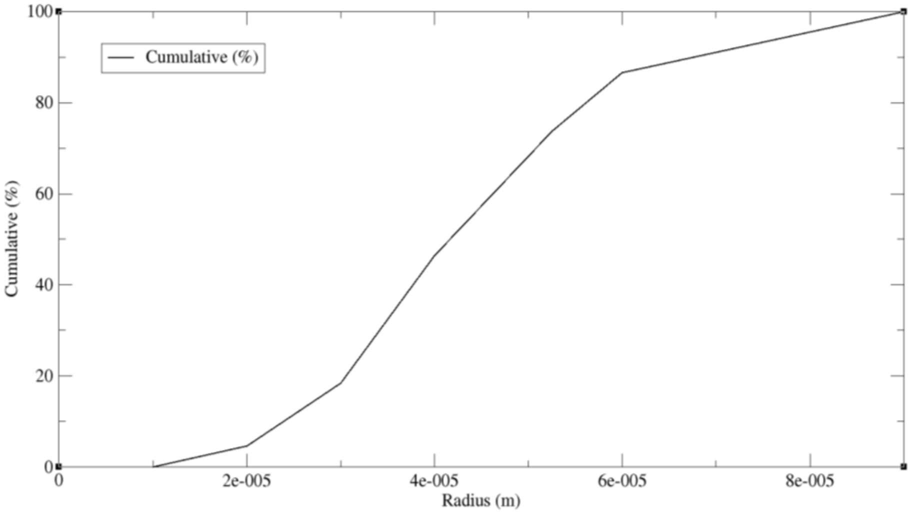


Figure 5.1 Particle Size Distributions of catalyst particles

5.8 Initial and Boundary conditions

Barracuda solves for the motion of particles and fluid by solving conservation equations for all computational cells and particles in the simulation. The initial conditions provide a starting point for all calculations, while the boundary conditions (BCs) specify where fluids and particles are entering or leaving the system. The initial condition for the simulation was specified such that the tub is filled to a target level with FCC catalyst particles at rest.

The pressure and temperature of the system were set to match the desired operating conditions. Flow BCs that brought in both gas and particles were defined at the bottoms of the primary cyclone diplegs and at the FCC catalyst particle feed at the inlet. Pressure BCs were defined at the bed top surface provided at the cyclone dipleg and other at the upper tub provided at the gas outlet duct (vortex finder).

Particles were allowed to exit at all pressure BCs, and the overall system mass was maintained at a constant value by using a particle feed controller, which adjusted the flow rate of particles at the cyclone diplegs as needed to maintain a constant system mass.

5.9 Post Processing

Simulation was set up to collect various types of data, including transient pressure at specific locations, time-averaged gas and particle mass fluxes, and particle residence times for FCC catalyst particles entering through the cyclone. Flux planes and transient data points are provided at the dipleg and gas outlet duct of both the primary and secondary cyclone.

CHAPTER 6

RESULTS AND DISCUSSIONS

The simulation model is run for 20-40 second of simulation time. Approximately, in a day the simulation program is run for only 1-2 second simulation time. The simulation is completed for the following two cases.

1. Case-I: Simulation of two stage cyclone with reduced primary cyclone gas outlet tube diameter

2. Case-II: Simulation of two stage cyclone with reduced primary cyclone gas outlet diameter and increased tub height

CASE-I: Simulation of two stage cyclone with reduced primary cyclone vortex finder diameter

Grid Model Of two stage cyclone system

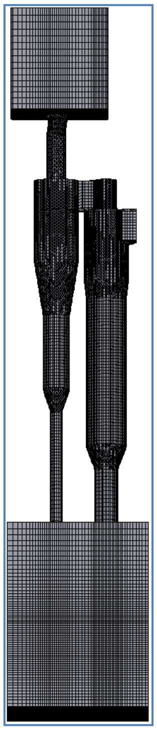


Figure 6.1 Grid view of Cyclone System

Estimation of particle mass at the 2nd- stage cyclone outlet

To estimate the solid particle mass at secondary cyclone outlet, the integrated mass of catalyst particles is plotted with respect to time scale. Below is a plot of time-integrated particle mass at the 2nd-stage cyclone outlet. The slop of the line provides the mass of particles leaving the cyclone.

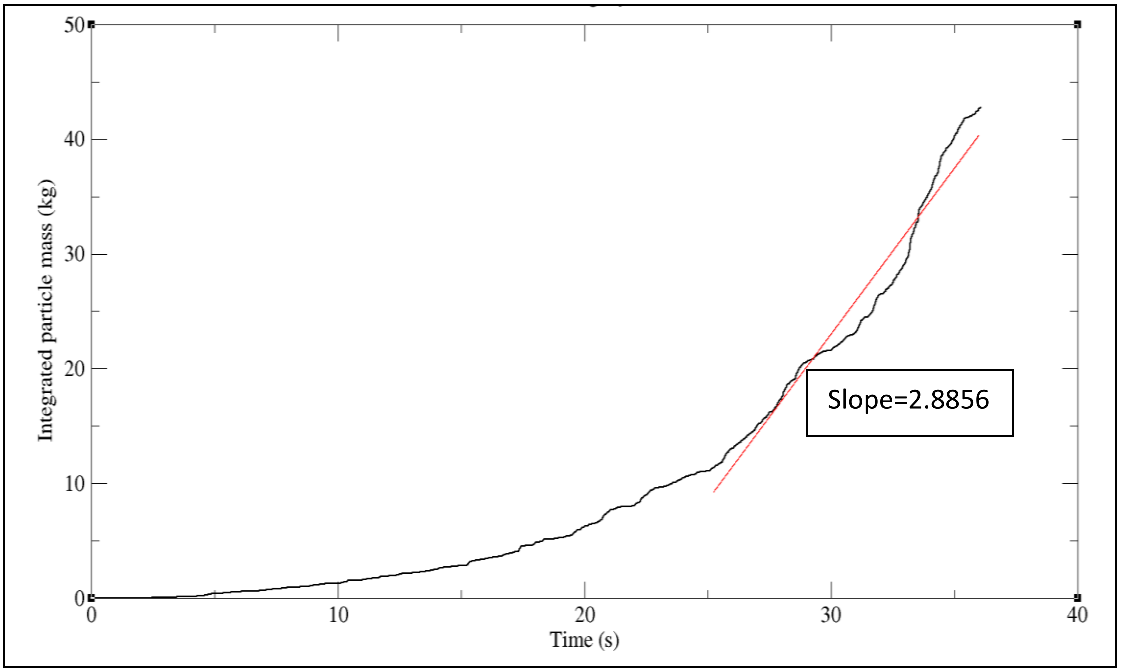


Figure 6.2 Secondary cyclone outlet particle mass

The regression feature of the simulation software is used to calculate the slope of the graph. This slop gives the particle flow rate. 2.885 kg/sec of the catalyst particles are going out the cyclone system per sec. Therefore, the solid particle exit from cyclone outlet is 249 MTPD which is higher compared to plant value.

Residence time of solid particles inside the two stage cyclone

Below is a GMV snapshot of the particles in primary and secondary cyclones, colored by residence time.

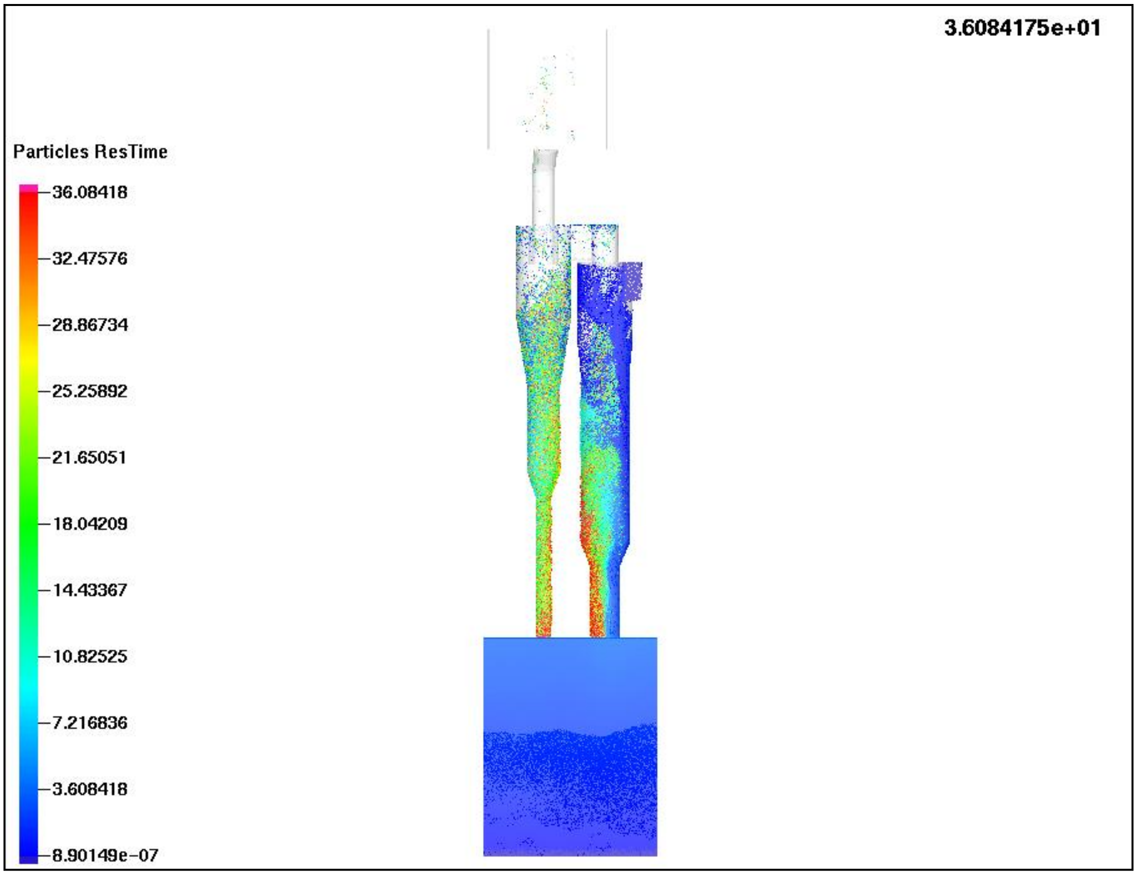


Figure 6.3 GMV of particle residence time

From the above, it is observed that the residence time of solid particles inside the primary and secondary cyclone is very high especially in the dipleg region. This increased residence time of particles causes flooding in the dipleg and hence particles get entrained with the inner vortex and reduce the collection efficiency.

Particle solid concentration inside the two stage cyclone

Below is a GMV snapshot of the particle volume fraction in cyclone.

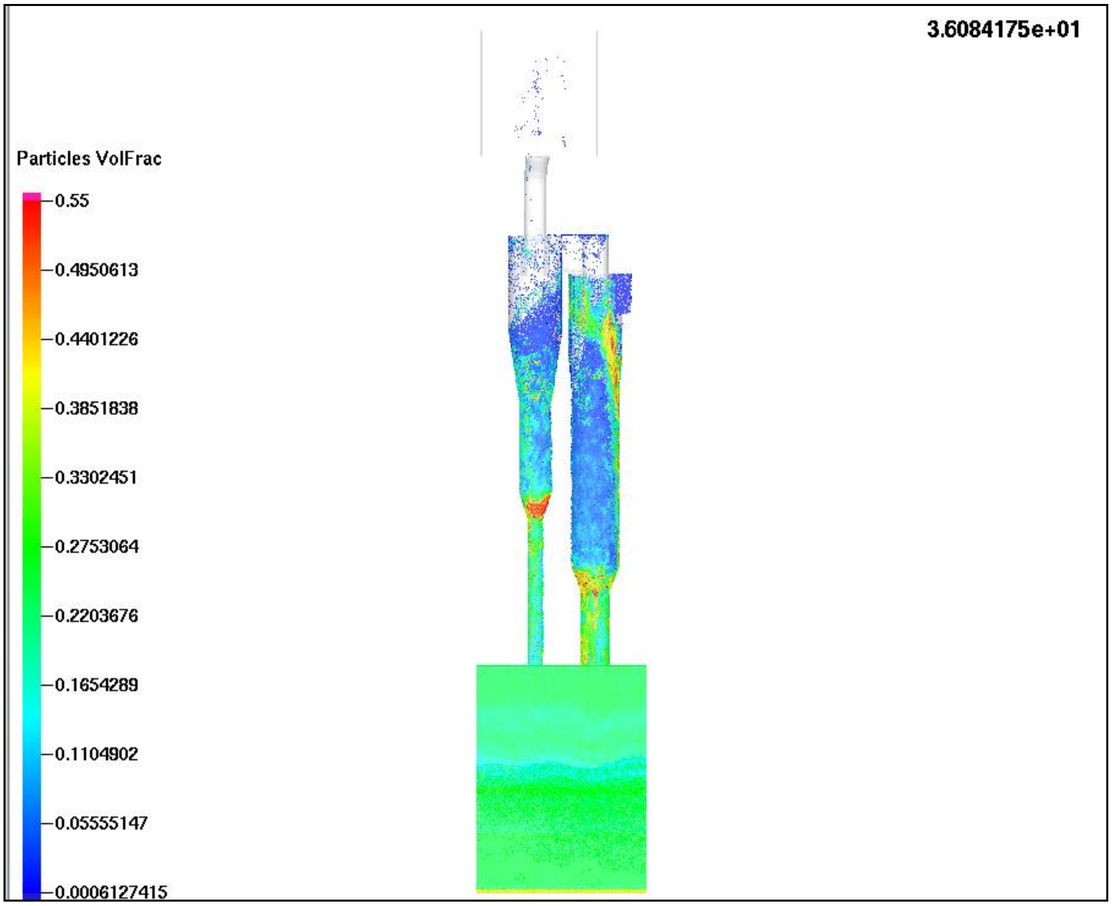


Figure 6.4 GMV of particle volume fraction in cyclone system

The above figure shows that particles are more concentrated at the dipleg forming a flooding situation inside the cyclone and hence reducing the particle collection efficiency.

Overall Efficiency of two stage cyclone system

Based on the slope of the time-integrated particle mass exiting at the secondary cyclone (presented above, slope 2.8856 kg/s) and the known inlet mass flow rate of particles being fed into the primary cyclone inlet (122.5 kg/s, as specified in the main particle feed Flow BC), cyclone system efficiency is calculated, which is given below.

$$\boldsymbol{Overall\ Collection\ Efficiency = \left(1 - \frac{2.8856}{122.5}\right) \times 100 = 97.6\%}$$

CASE-II: Simulation of two stage cyclone with reduced primary cyclone vortex finder diameter and increased tub height

Grid Model of cyclone System

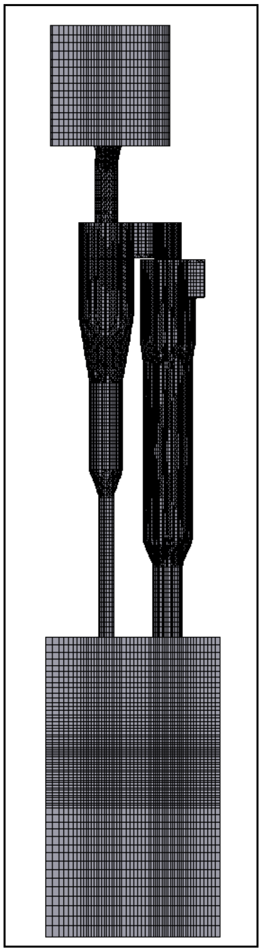


Figure 6.5 Grid view of cyclone system

Estimation of particle mass at the 2nd- stage cyclone outlet

Below is a plot of time-integrated particle mass at the 2nd-stage cyclone outlet.

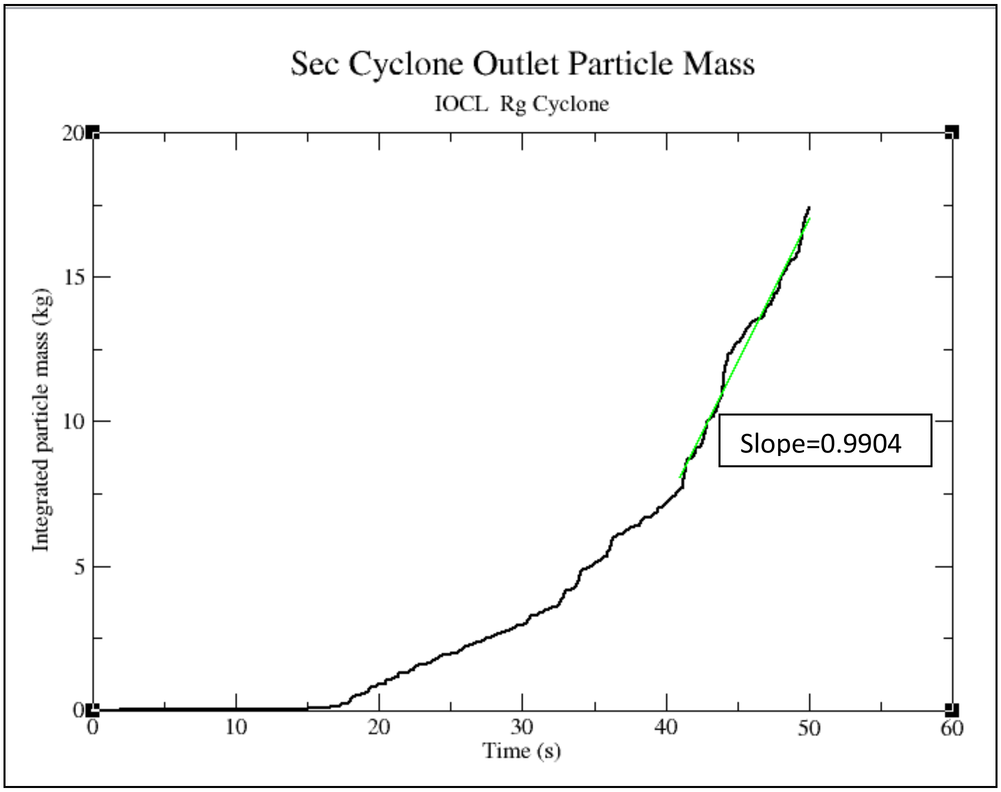


Figure 6.6 Secondary cyclone outlet particle mass

The slope of the graph is 0.9904. Therefore the total catalyst lost in the system is 11 MTPD which is higher compared to plant value.

Residence time of solid particles inside the two stage cyclone

Below is a GMV snapshot of the particles in primary and secondary cyclones, colored by residence time.

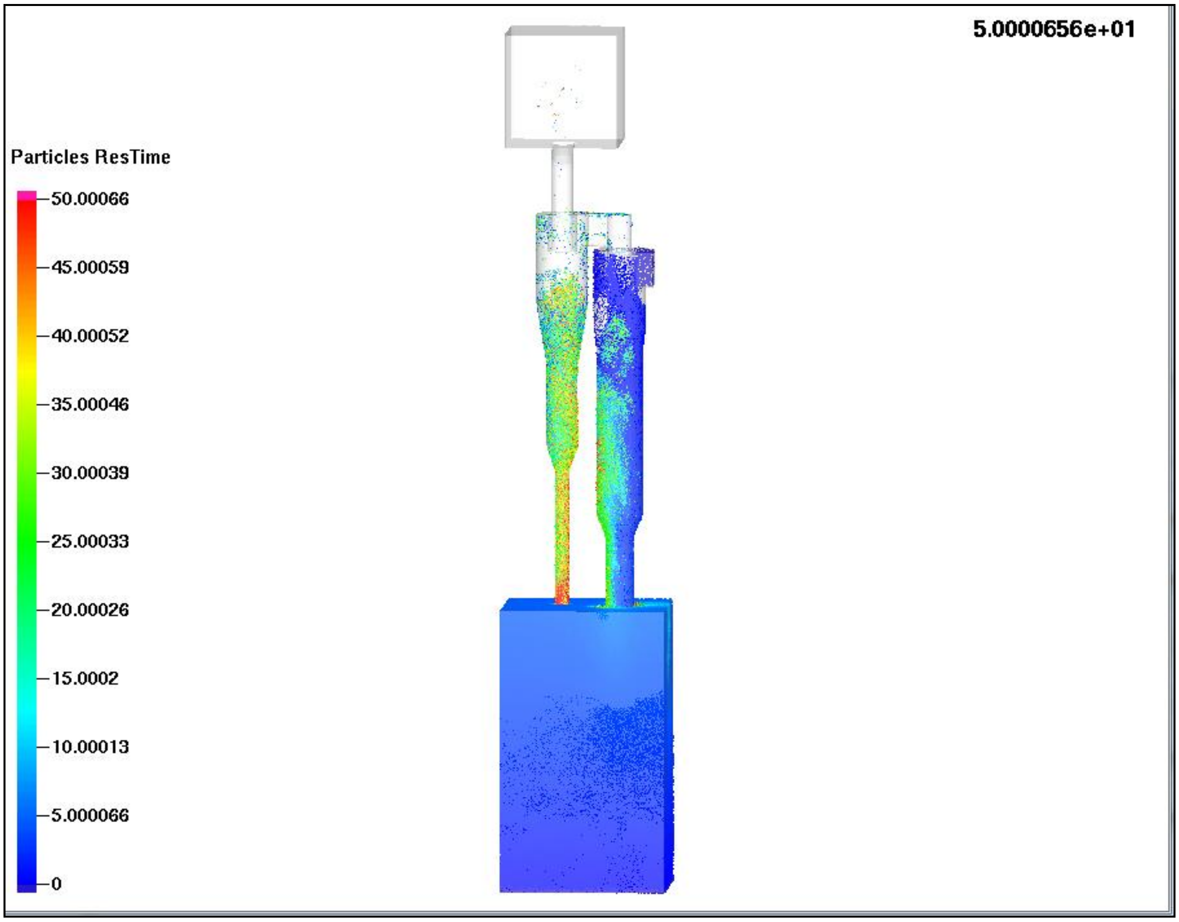


Figure 6.7 GMV of particle residence time in cyclone

As can be seen from the figure above the residence time of particles in this case is less than that of case 1. Residence time of particle is less in primary cyclone. But the time for secondary is greater than that of primary cyclone.

Particle solid concentration inside the two stage cyclone system

Below is a GMV snapshot of the particle volume fraction in cyclone system.

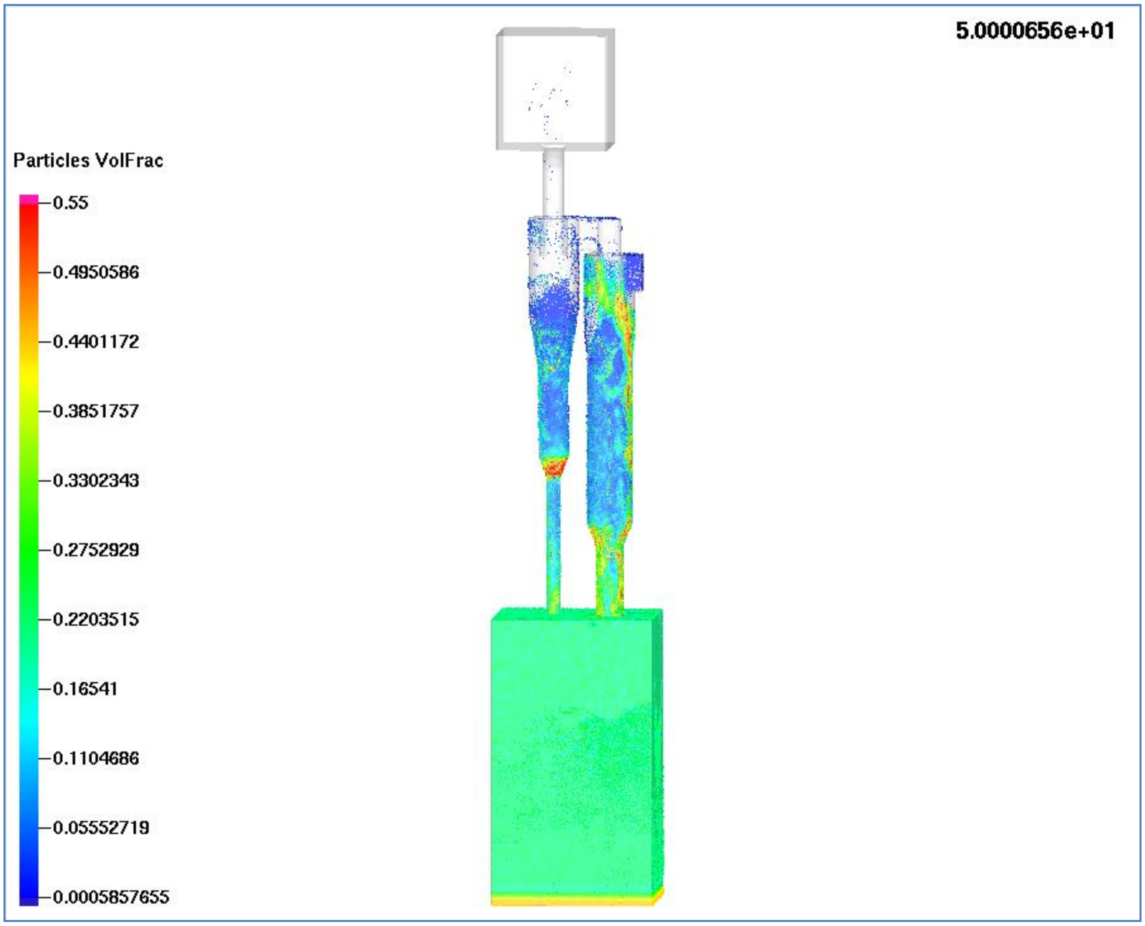


Figure 6.8 GMV of particle volume fraction inside cyclone system

Efficiency of two stage cyclone system

Based on the slope of the time-integrated particle mass exiting at the secondary cyclone (presented above, slope = 0.99044 kg/s) and the known inlet mass flow rate of particles being fed into the primary cyclone inlet (122.5 kg/s, as specified in the main particle feed Flow BC), cyclone system efficiency is calculated, which is given below.

$$\boldsymbol{Overall\ collection\ efficiency = \left(1 - \frac{0.99044}{122.5}\right) \times 100 = 99.10\%}$$

Conclusion

1. Estimated catalyst lost in both the cases is very high and cyclone collection efficiency is very low as compared to the commercial plant data.
2. Particle collection efficiency for case I and case II is found to be 97.6% and 99.10%.
3. Performance is better for case II as compared to case I but the efficiency level of cyclone 2 is also very low.
4. The higher pressure drop across cyclones resulting in sucking of more particles from the primary. In future studies the cyclone simulation is to be carried out using a lower pressure drop.

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