CYCLONE SYSTEMS IN CIRCULATING FLUIDIZED BEDS

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Abstract – Cyclones are an integral part of nearly all fluidized bed processes, and especially so for circulating fluidized bed (CFB) systems. Cyclones are extremely important to the successful operation of nearly all CFB processes. The two most important CFB processes - fluidized catalytic cracking (FCC) and circulating fluidized bed combustion (CFBC) - operate with different particle sizes and at different operating conditions. Therefore, the cyclone designs for each of these major CFB processes are also different. Cyclones for CFBC units are generally very large (8 to 10 m in diameter) and typically have only one stage. Cyclones for FCC units are much smaller (of the order of 1.2 to 2 m in diameter) and are designed for a minimum of 2 and as many as 4 stages in series. The average particle size flowing around FCC units is only about 70 microns, while the particles circulating in CFBC units are typically 150 to 200 microns. In this paper, how the differences in cyclone operation and design affect CFB system operation is described and discussed.

INTRODUCTION

Using centrifugal force to separate solids from a gas was first patented in the United States in 1885 by an employee of the Knicker Bocker company named John Finch (Finch, 1885). Since then, cyclones have been one of the most important devices in particulate processes. Cyclones separate solids from a gas stream at a low energy cost, are relatively inexpensive and because they have no moving parts are very reliable. In general, cyclones are used to separate solids from gases in approximately 99% of all fluidized bed processes. Processes without cyclones either use filters, inertial separators or in some cases use no solids/gas separation at all (Burdett et al., 2001; Maryamchik and Wietzke, 2010).

Cyclones are unique devices in that they can be used over extremely wide solid loading ranges and over extremely large size ranges. Cyclone sizes range from 1 to 2 cm in diameter for laboratory units, up to 8- to 10-m diameter cyclones in circulating fluidized bed combustion (CFBC) units. Cyclone solids loadings can range between about 0.0002 kg/m^3 (0.00013 kg$_s$/kg$_g$) and nearly 50 kg/m^3 (42 kg$_s$/kg$_g$). This is a factor of 250,000!

Cyclone operation is not the same over this wide loading range. For example, secondary cyclones operating in catalytic processes at low loadings experience erosion in their cones, while at higher loadings they do not. The dependence of pressure drop with increasing loading is different depending on whether the cyclone is operating in the high or low loading regime. In addition, the type of cyclone inlet (tangential or volute) can greatly influence efficiency at high loadings, but is not quite so important at low loadings. Also, the operation of cyclone diplegs is significantly affected by whether the cyclone is a high-loaded or a low-loaded cyclone.

Cyclone loadings have traditionally been expressed on a weight basis in one of two ways: 1) in kg of solids (kg$_s$) /kg of carrying gas (kg$_g$), or 2) in kg of solids per m^3 of carrying gas. Either one of these two methods is generally a satisfactory way of expressing and comparing loadings if the particle densities of the solids are relatively close. However, if the solids differ widely in particle density, the concentration of the solids in the carrying gas can vary significantly when the loading is expressed on a weight basis (Knowlton and Karri, 2008). This can be seen in Table 1. This table compares three materials with different particle densities (600, 1500 and 3600 kg/m^3). The low-density material is representative of a resin, the middle-density material that of a coal char or a dense FCC catalyst, and the high-density material is similar to the density of an ore (iron, titanium, etc.). If each material is added to a cyclone at the same weight-based loading of 18 kg/m^3, the "volumetric loading" expressed as solids volume fraction (1-ε) varies from 0.03 (3% solids) for the resin to 0.005 (0.5% solids) for the ore. Thus, the material with a particle density of 600 kg/m^3 has a solids volume fraction 6 times the solids volume fraction of the material with a particle density of 3600 kg/m^3.

However, because the traditional way of expressing loading is on a weight or mass basis, loading will be expressed as a mass loading in this paper – recognizing that solids volume fraction or solids concentration is probably a more realistic way of expressing loading - especially for comparing materials of widely differing particle densities.

Table 1. Comparison of Loadings Based on Volume and Weight

Material	Loading, kg/m^3	Particle Density, kg/m^3	Solids Volume Fraction, $1-\varepsilon$
1	18	600	0.030
2	18	1500	0.012
3	18	3600	0.005

Cyclones are generally classified as either low-loaded or high-loaded cyclones. The demarcation between high and low loading is arbitrary, and, in general, high-loaded cyclones are primary (first stage) cyclones, and low-loaded cyclones are secondary (second stage), tertiary (third stage) or even fourth stage cyclones. Particulate Solid Research, Inc. (PSRI) classifies cyclones with a loading of greater than 1 kg_s/kg_g, as high-loaded cyclones. Cyclones with a loading less than 1 kg_s/kg_g, are classified as low-loaded cyclones.

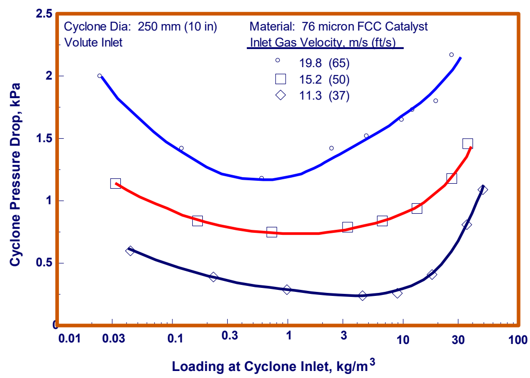

Fig. 1. The effect of loading on cyclone pressure drop

Another way to define low-loaded and high-loaded cyclones is to specify that cyclones are low-loaded cyclones when their pressure drop decreases with an increase in solids loading (Fig. 1, Knowlton and Karri, 2008), and high-loaded cyclones when their pressure drop increases with solids loading.

The reason that the cyclone pressure drop initially decreases with increasing loading is that the solids on the cyclone wall effectively "roughen" the wall and increase the frictional resistance to gas flow. This causes the tangential velocity in the cyclone to decrease, thus decreasing the pressure drop (Yuu, et. al., 1979), as can be seen in Fig. 2. In this figure, the tangential velocity decreased from 16 to 13 m/s at the wall, and from about 34 to 17 m/s at its maximum value as solids were added to the cyclone. At higher loadings, the pressure drop due to the solids acceleration becomes so large that the total cyclone pressure drop then increases as solids loading increases.

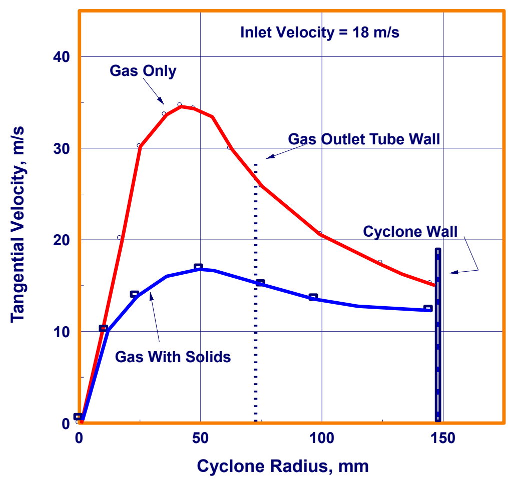

Fig. 2. Cyclone tangential velocity with and without solids flow in the cyclone

CFB Systems

In commercial CFB systems, the two dominant technologies using cyclones are the fluidized catalytic cracking (FCC) and the circulating fluidized bed combustion (CFBC) processes. There are significant differences in the two processes that are summarized in Table 2. One of the primary differences is that FCC processes use Geldart Group A solids, and CFBC processes use Geldart Group B solids. Another area utilizing CFBs is chemical looping, with several different types of chemical looping processes being developed. Many of these processes use Geldart Group A solids, and so their cyclone design and operation will be similar to FCC cyclones.

One type of an FCC unit is shown in Fig. 3. In an FCC unit the circulating fluidized bed is the riser. In the riser, oil is added to the hot circulating catalyst (approximately 70 microns in size) at the bottom. The hot catalyst cracks the oil into various components (kerosene, gasoline, diesel oil, etc.). The catalyst and the products are then routed into cyclones at the top of the riser. Post-cracking of the product gases (which is detrimental) can occur if the solids and the gases are not separated quickly. Therefore, the gas and solids are separated as quickly as possible by routing them through close-coupled cyclones or other inertial separators (such as an RSS or a VSS vortex separator, etc.). The loading in the close-coupled cyclones can be very high (up to 24 to 32 kg/m^3). These close-coupled cyclones are some of the highest loading cyclones in the world, and generally have significantly higher solid inlet loadings than CFBC cyclones. If close-coupled cyclones are used, the FCC riser discharges into generally 4 to 6 parallel cyclones located close to the riser. A second stage of cyclones in series with the first stage is also used.

Table 2. Comparison of FCC Riser and CFBC Processes (Typical Values)

Parameter	FCC Riser	CFBC
Temperature, °C	550	850 - 900
Pressure, Bar(g)	2	0.1
Particle Size, microns	70	150 - 200
Geldart Group	A	B
Riser Solids Flux, kg/s/m^2	500 - 1000	20 - 50
Riser Suspension Density, kg/m^3	8 to 32	2 to 10
Velocity, m/s	14 - 20	3 to 5
Riser Geometry	Circular	Rectangular
Riser Diameter, m	0.9 - 1.5	----------
Boiler Dimensions (large)*, m	---------	28 x 11
Height, m	28 – 35	48*

*Lagisza CFBC (460 MWe)

As the catalyst flows up the FCC riser, carbon is deposited on the catalyst, reducing its activity. Therefore, the catalyst is routed to a fluidized bed regenerator, where the carbon is burned off of the catalyst using air to restore its activity. However, if the catalyst is sent to the regenerator directly after passing through the cyclones, the valuable product gases in the interstices of the solids would be burned up. Therefore, the catalyst is passed through a steam stripper to remove product gases. After most of the product gases are removed, the catalyst is then routed to the regenerator. The regenerator is a large unit (usually 10 to 16 m in diameter) and contains many cyclone stages in parallel. Typically, the number of parallel stages of cyclones in the regenerator ranges from about 4 for small units to 22 for very large units. Because each primary cyclone has a secondary cyclone associated with it, for the largest unit indicated above, 44 cyclones are suspended in the freeboard of the regenerator. These cyclones can take up as much as 33 to 50% of the area in the freeboard.

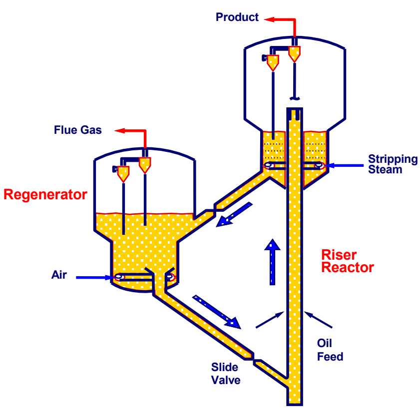

Fig. 3. Schematic Drawing of a Side-by-Side FCC Unit

Because particulate emission limits are very low (of the order of 50 mg/Nm^3), a third stage cyclone separator (TSS) is generally added downstream of the secondary cyclones. Most TSS units are composed of smaller multiclones with axial inlet vanes in parallel (Fig. 4, Weaver and Geiger, 2002). In large units, more than one hundred multiclones (also called swirl tubes) may be in one TSS shell. To enhance the performance of the TSS, about 3% of the cyclone flow is “pulled” out of the bottom of the cyclone with the solids. This higher loading gas stream is then sent to either a fourth stage separator (FSS), which is also typically an axial inlet type of cyclone, or to a filter – depending on the emission requirements.

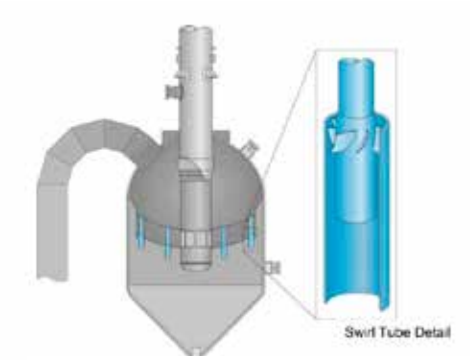

Fig. 4. Third-Stage Separator (Shell type) with axial inlet swirl tubes

Important differences in operation, scale and configuration between FCC unit cyclones and CFBC cyclones are shown in Table 3. CFBC systems have fewer and larger cyclones than in FCC units (Table 3). Most of the CFBC cyclones are also external to the riser, whereas most of the cyclones in an FCC unit are internal cyclones. One type is not really better than the other. Whether you use an internal or an external cyclone really depends on what is better for the process.

A schematic drawing of one type of CFBC unit is shown in Fig. 5. In this unit, coal is fed into the bottom of the rectangular CFB riser with limestone, which absorbs much of the SO_2 given off during combustion of the coal. The coal is combusted in the riser using air, and the solids and the combustion gases pass into the large cyclone(s). The solids are returned to the bottom of the riser via a dipleg and, usually, a loop seal. The CFB combustor units are rectangular and, depending on their size, have only one large cyclone if relatively small, or 2 to 8 cyclones in parallel if they are larger units. Only one stage of cyclone (or solids separator) is typically used in CFBC systems. The particles entering the cyclones are larger (150 to 200 microns vs. 70) and denser than in FCC units. Particles in CFBCs have particle densities ranging from 1800 to 2400 kg/m^3 while FCC catalyst densities are typically 1200 to 1500 kg/m^3.

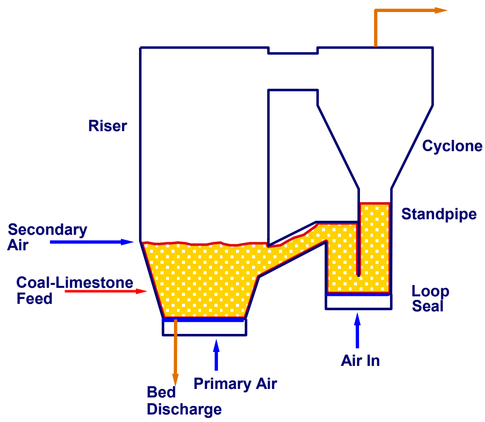

Fig 5. Schematic Drawing of a CFBC

Table 3. Comparison of FCC and CFBC Cyclones

Cyclone Parameter	FCC	CFBC
Diameter*, m	1.2 – 2.2	5 - 10
Inlet Velocity, m/s	13.5 - 20	18 - 28
Outlet Velocity, m/s	20 - 25	22 - 38
Number of Stages in series	2 – 4	1
Number of parallel stages	4 - 22	1-8
Loading, kg/m^3	10 – 35	2 - 10
Operating Temperature, °C	550	850 - 950
Average particle size in incoming gas, microns	70	150 - 200
Primary Cyclone Efficiency, %	99.95+	99.9+
Secondary Cyclone Efficiency, %	Up to 98%	NA

*Some CFBC “cyclones” are actually solid separators and can be rectangular, hexagonal, etc.

Cyclone Types and Configurations

There are several different cyclone configurations used in CFB systems, and they are generally classified by inlet type. The two most commonly-used cyclones are the tangential and volute inlet cyclones (Fig. 6). The volute-inlet cyclone has been found to be more efficient for highly-loaded cyclones than the tangential inlet. This is because the tangential inlet cyclones can produce an interference eddy near the inlet of the cyclone. This eddy causes fluctuations in the inlet solids stream that can cause the inlet solids to impact the gas outlet tube. This results in lower efficiency, and can cause erosion of the gas outlet tube as well. If a tangential cyclone is used for a highly-loaded cyclone, the inlet should be located such that the distance between the cyclone inlet and the wall of the gas outlet tube is great enough so that the fluctuating solids do not impact the gas outlet tube. This generally means that this type of tangential inlet cyclone will have a larger diameter than a typical tangential inlet cyclone.

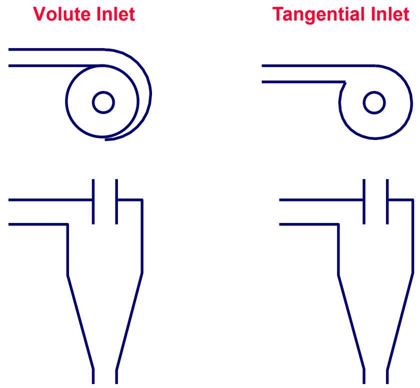

Fig. 6. Schematic Drawing of Tangential and Volute Cyclone Inlets

A highly-loaded, volute inlet cyclone does not suffer from this problem. With the volute inlet, the solids have experienced a significant centrifugal force before entering the cyclone barrel, enter the cyclone at an angle and, therefore, the entering solids do not experience the interference from the rotating solids stream in the cyclone barrel. This difference is depicted in Fig. 7. Therefore, in almost all highly-loaded cyclones (essentially all primary cyclones) a volute inlet is used. For low-loaded cyclones, the loading is so low (approximately 1/1000 or less of that of the primary cyclone) that the interference with the inlet solids stream does not occur, so tangential inlet cyclones are satisfactory designs for low-loaded cyclones. Volute cyclones are equally satisfactory as well, but quite often tangential cyclones are used for secondary cyclones because tangential inlet cyclones are less expensive than volute inlet cyclones.

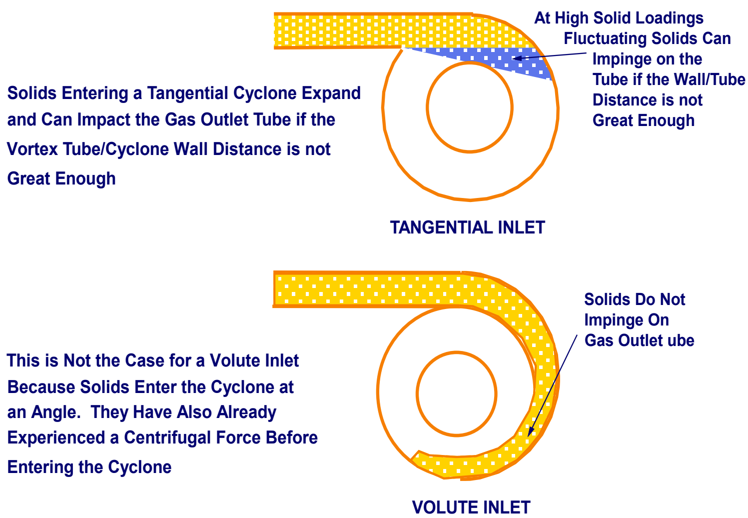

Fig. 7. Tangential and Volute Inlet Operation at High Solids Loading

In CFBC cyclones, the inlet to the cyclone has a slightly different configuration than for FCC cyclones. The inner wall of the inlet is angled toward the wall of the cyclone. To keep the area of the inlet approximately constant, the bottom of the inlet is angled downward at approximately 30°. This type is inlet is depicted in Fig. 8. This inlet configuration is also used in non- CFBC cyclones as well, and especially so in Europe. This inlet is a superior inlet compared to the straight tangential inlet tangential inlet shown in Fig. 6, because it directs the solids to the wall of the cyclone where you want them to be for high solids collection efficiency.

An axial inlet cyclone of the type shown in Fig. 4 uses axial swirl vanes to impart centrifugal force to the particles. This type of inlet is generally used for smaller-diameter cyclones, such as the multiclone TSS units also shown in Fig. 4.

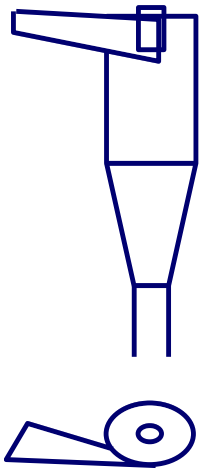

Fig. 8. Angled Inlet

Cyclone efficiencies of CFBC primary cyclones can be very high, 99.9%, and nearly rival the efficiencies of the FCC primary cyclones (even though the cyclones are much larger in diameter and the centrifugal force on the solids is significantly less with the larger cyclones). The particles in the CFBC units are both larger and more dense, which partly explains why the larger-diameter cyclones are so efficient. However, another factor comes into play with primary cyclones. The solids loading is generally so high that the primary cyclone operates like an inertial separator for much of the solids as explained by Muschelknautz et. al. (1996). In their model, the gas can carry only a maximum amount of solids (up to what is called the critical loading). At any solids loading in excess of this critical loading, the solids are immediately separated from the gas at the inlet to the cyclone as indicated in Fig. 9. The solids remaining in the gas are then separated in the cyclone barrel and primarily in the inner vortex below the gas outlet tube as if the cyclone were operating at a low solids loading. However, the inner vortex separation is reduced as the solids loading increases (Muschelknautz, 2010).

Because the solids at high loading are separated largely by inertial separation, the efficiencies of a high loaded, large-diameter cyclone can approach that of a smaller cyclone. This inertial "unloading" effect has been noted visually at PSRI in a 53-cm diameter Plexiglas cyclone. The solids enter the cyclone and then immediately "fall" down to the solids outlet. The solids entering high-loaded cyclones have only about 1.5 turns as they "fall" down the cyclone from the inlet to the solids outlet. A low-loaded cyclone was visually observed to have approximately 5 to 7 spirals in the same cyclone. High loading also affects the vortex below the gas outlet tube. The large mass of solids attenuates, or reduces, the spin rate of the vortex in high-loaded cyclones. Hoffman et. al., 1995 reported that the vortex length (swirl intensity) decreased with increasing solids loading, and was a strong function of the cyclone length as well.

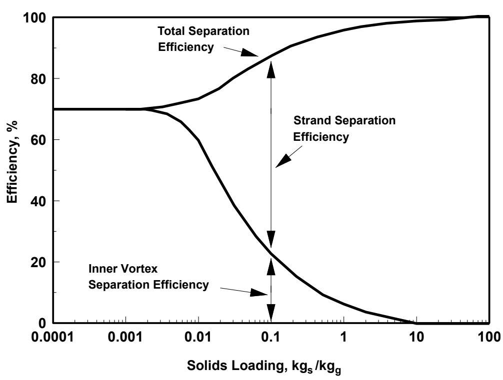

Fig. 9. Muschelknautz et al., 1996 critical loading plot

As mentioned above, FCC and other Group A catalyst processes have several internal cyclones in parallel. The parallel cyclone configuration is used to reduce the length of the reactor vessel. Large-diameter cyclones also are very long cyclones. If a single internal cyclone were used inside the reactor vessel, the freeboard above the fluidized bed would be very tall. This would increase the length of the vessel and result in a tremendous increase in cost because the vessels are large in diameter. Therefore, several parallel cyclones are used. Also, a single external cyclone would return the solids to only one side of the bed, and the solids may not distribute well from this one feed point throughout the fluidized bed. The external cyclone would also have to be a pressure vessel, and insulated much more than for the internal cyclone. Essentially all internal FCC cyclones have a refractory hex-mesh lining, approximately 2.5-cm thick, used primarily to minimize erosion of the cyclone.

CFBC processes use large external cyclones which (if not water-cooled) have refractory linings of the order of 300 mm thick. For cyclones with water-cooled walls, the wall is covered with a high-conductivity refractory that is about 5 cm thick. The cyclones are very large in diameter (up to 10 m) and correspondingly very long. However, the riser furnace is also very tall, and can accommodate the large, long cyclone as well as the dipleg and loop seal below it. For the Lagisza CFBC referenced in Table 2, the height of the riser is 48 m. External cyclones have an advantage over internal cyclones in that there is access to the cyclone and diplegs without going inside the unit. Often there is an extra layer of erosion-resistant lining in the CFBC cyclones where the incoming solids first impact the wall of the cyclone.

There is another advantage of using a single large cyclone when using one cyclone is possible. When using parallel cyclones, the gas and solids flow into each cyclone is generally not the same (Whiton, 1941; Smellie, 1942; Koffman, 1953; Broodryk and Shingles, 1995; Grace, 2005; Knowlton et. al., 2016). This unequal flow of gas and solids manifests itself in different erosion rates, unequal buildup of coke (and different collection efficiencies) in the parallel cyclones. Whiton, 1941 using small 5-cm diameter cyclones, found that the efficiency of a single cyclone for his system was 96%, while 7 cyclones in parallel and 14 cyclones in parallel gave lower efficiencies of 94.1 and 92.2%, respectively.

For large CFBC units, it is also necessary to use parallel cyclones. One type of parallel arrangement is shown in Fig. 10 for four cyclones in parallel. Because of differing solids flows through parallel cyclones, differences have been noted.

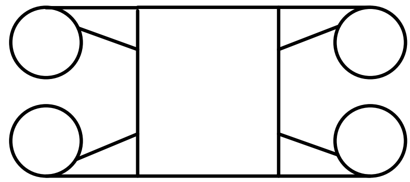

Fig. 10. Typical CFBC configuration for four cyclones in parallel

Kim et al., 2007 and Stringer and Stallings, 1991 both found unequal erosion occurring in parallel CFBC cyclones. Hartge et al., 2005, observed that the temperatures near the bottom of CFBC parallel cyclone return lines were different. Smellie, 1942 found that the solids flow rate through parallel cyclones could vary by a factor of 2. Knowlton et al., 2016 found that with 4 parallel, 300-mm diameter cyclones using 156-micron coke, measured solids flow rates through parallel cyclones could vary by a factor of 4.

Unlike the axial-inlet cyclone, the tangential and volute cyclone inlets cause asymmetric flow in the cyclone. As a result, eddies form near the back of the gas outlet tube (GOT), also called a vortex finder, in the area approximately 200 to 250° away from the inlet. For FCC cyclones, this eddy formation leads to coke buildup on the back side of the GOT. If not addressed, the coke can fall off and block the dipleg. One method for addressing this problem has been to add anchors (similar to refractory anchors) on this area of the GOT wall so that the coke will be held in position as it forms and not fall off to plug cyclone diplegs.

For CFBC cyclones, one way this asymmetric inefficiency has been addressed is by changing the position of the GOT. Trefz, 1992 found that moving the axis of the GOT away from the axis of the cyclone a short displacement along the radius of the cyclone at a position approximately 255° away from the inlet to the cyclone, significantly reduced these eddies, and improved cyclone efficiency. The resulting GOT offset has been called the eccentric GOT (Fig. 11). In this figure, the GOT has been moved from the center (dotted circle) to its final location (continuous line circle) used for the eccentric GOT. Subsequent implementation of the eccentric GOT in commercial units has been proven successful (Muschelknautz and Muschelknautz, 1999). Ipsen et al, 2014 reported that adding an eccentric GOT (as well as reducing the GOT diameter) to one of the CFB boilers operated by Stadtwerke Flensburg GmbH improved cyclone efficiency as well as the operation of the boiler. Before the improvements, they could not operate at full load. With the improvements to the cyclone, they could operate at full load, and the size of the circulating ash in the boiler was reduced by 60 microns – improving the heat transfer in the unit and increasing the amount of circulating ash so that much less sand was required to be added to the unit to maintain enough circulating solids for adequate thermal efficiency.

Werther, 2005 reported that using an eccentric cyclone GOT as well as adding the angled cyclone inlet shown in Fig. 8, improved the operation of the Ceran B CFB steam generator significantly. The original Ceran A CFB boiler was not able to prevent the loss of fine inert material. The Ceran B boiler was an exact duplicate of the Ceran A boiler except for the cyclone design. Adding the improved angled inlet and using the eccentric GOT, improved the cyclone efficiency by such a degree that the median diameter of the circulating material was reduced to 75 µm from 180 µm. The improved cyclone efficiency resulted in finer circulating solids, an improved heat transfer coefficient and lower NO_x and SO_x emissions. Although using an eccentric GOT (and angled inlet) has proven to be beneficial for CFBCs, the FCC industry has not yet adopted these improvements.

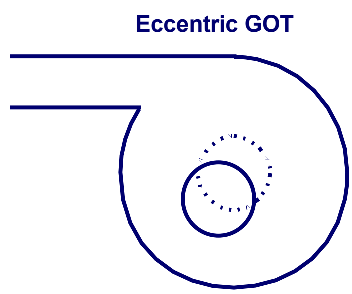

Fig. 11. Eccentric Gas Outlet Tube

Kobylecki and Bis, 2008, also showed how increasing cyclone efficiency reduced the emissions of NO_x and SO_x. They showed that increasing the cyclone efficiency from approximately 99.779 to 99.930% reduced the emissions of NO_x from approximately 200 to 100 mg/Nm^3, and the emissions of SO_x from approximately 450 to 200 mg/Nm^3.

As noted above, increasing the cyclone efficiency in CFBCs can lead to improved operation. However, sometimes improved cyclone efficiency is not what is desired. When high ash materials are being combusted, often the amount of material being circulated is too much. This can cause a decrease in temperature in the combustor because of too high of a circulation rate around the system. If the ash content of fuels in a CFBC varies widely, then it is desired to have some means of regulating the solids circulation rate. Muschelknautz and Roper, 2008, developed a method of adjusting the circulation rate by changing the amount of material lost by the cyclone.

This was accomplished by adding a gas flow (about 1.3% of the total flue gas flow) through a nozzle, located on the outside wall of the cyclone, that was angled/directed to inject solids rotating on the wall into the vortex just below the GOT (Fig. 12). This technique reduced the inventory of the bed significantly. The pressure measured at the bottom of the bed decreased from about 62 to 50 mbar in one test with the nozzle, and from 88 to 55 mbar in another.

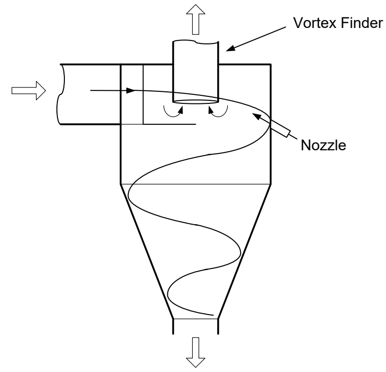

Fig. 12. Gas nozzle to regulate solids flow out of a cyclone

Normally, most cyclones are designed so that the exit velocity through the GOT is higher than the gas inlet velocity. The high centrifugal force then throws many of the fine particles not collected by the outer vortex to the wall, where they are collected. The higher the outlet gas velocity, the faster the inner vortex spinning rate and the higher the cyclone efficiency. Therefore, the inner cyclone vortex is an important element in cyclone operation.

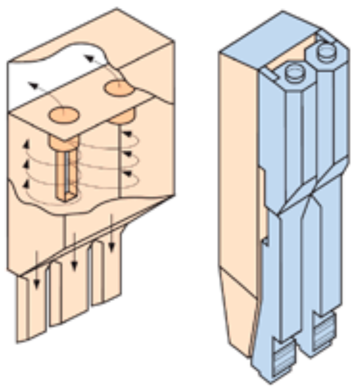

Fig. 13. Compact Solids Separators

Because the cyclone inlets in most cyclones are asymmetrical (with a single inlet), the inner vortex tends to precess or "wobble". The inner vortex also does not taper down to a small tip (as you would see with a tornado). Visual observation at PSRI in a Plexiglas™ cyclone has shown that the inner vortex has a diameter of approximately 75 to 85% of the diameter of the GOT, and this diameter is essentially constant throughout the length of the inner vortex. These observations were made by operating the cyclone with no solids flowing into it, and then adding a small amount of fine solids to the cyclone. The fine solids would escape the cyclone through the GOT, so the shape of the vortex could be seen.

Foster Wheeler and others have developed what is termed a compact CFBC (Chen and Jian, 2011). This CFBC uses rectangular or octagonal solids separators instead of a conventional circular cyclone. This type of design has several advantages: 1) no expansion joint is required between the reactor and the solids separator, 2) the footprint of the unit is reduced, 3) it is simpler and less costly to build, and 4) the water-cooled flat panels can be covered with a thin, 5-cm layer of abrasion-resistance refractory like water-cooled cyclones. The thin refractory layer allows faster startup and shut down times of CFBC units. The elimination of the expansion joint also significantly reduces the down-time of the CFBC - which is a problem with large, hot refractory-lined cyclones.

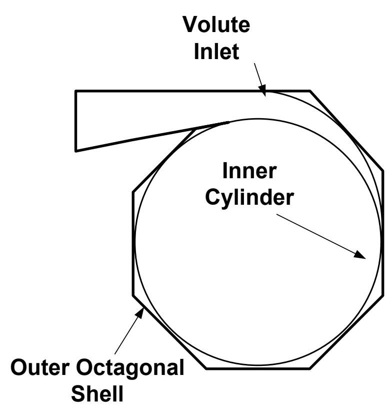

Fig. 14. Schematic Drawing of an Octagonal Cyclone

A drawing of two CFBs with Foster Wheeler-type compact solids separators is shown in Fig. 13 from Zhu, 2013. The drawing on the left shows a rectangular type of solids separator with two vortex finders, and the drawing on the right shows a

Fig. 15. Cone Erosion in a low-loaded cyclone

most erosion is observed where the solids impinge upon the cyclone wall near the inlet, and perhaps some erosion will occur on or in the GOT. In FCC units, most often the critical erosion area is in the cone of the secondary cyclone. A low-loaded cyclone (although a non-FCC cyclone) that has undergone erosion in its cone is shown in Fig. 15.

In an FCC primary cyclone, if the solids flow into the cyclone is at a rate of 10,000 arbitrary units per hour and the efficiency of the cyclone is 99.95%, then only 5 units per hour (5/10,000, or 0.05%, of the material flowing into the primary cyclone) will flow into the inlet of the secondary cyclone (Fig. 16). It seems counter-intuitive that this low solids flow rate would cause such severe erosion in the cone of the secondary cyclone. However, secondary cyclone cone erosion is one of the primary problems in the shutdown of FCC units.

The reason for the erosion in the FCC secondary cyclone cone can be seen with the aid of Fig. 17.

multi-panel solids separator. The corners of the rectangular cyclone are smoothed with refractory to improve separation efficiency, but the rectangular solids separators have a lower collection efficiency compared to a cylindrical cyclone. The Lagisza CFBC plant in Lagisza, Poland has an octagonal cyclone (Fig 14), which has an improved solids collection efficiency relative to a rectangular solids separator (Nowak and Mirek, 2013). It would appear that an octagonal separator is a good compromise between a cylindrical cyclone and a rectangular solids separator with regard to solids collection efficiency, cost and ease of construction.

Cyclone Erosion

In CFBC processes where only primary cyclones are used,

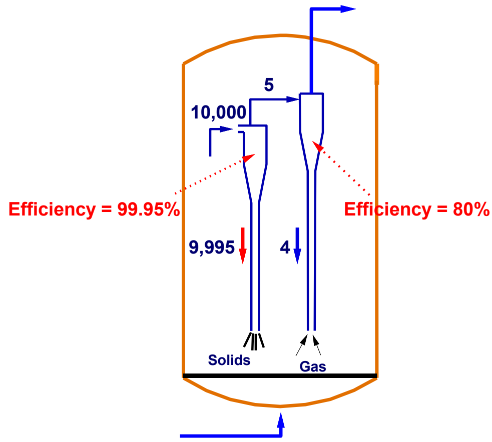

Fig 16. Relative loading in primary and secondary cyclones

The primary cyclone has many more solids flowing through it, but the solids rapidly drop down through the cyclone after inertial separation from the gas as shown in Fig. 9. Also, the vortex spin rate is decreased because of the high solids inlet loadings as discussed above, so the solids are not accelerated at high velocity in the conical region. It is also likely that the effective vortex length is shortened in highly-loaded cyclones. For these reasons, there is essentially no erosion on the primary cyclone cone. The important erosion zone for primary cyclones is on the wall opposite the solids inlet.

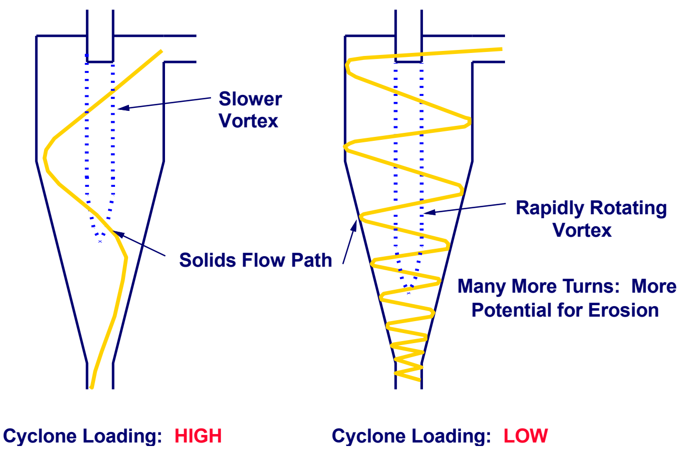

Fig. 17. Solids flow in low- and high-loaded cyclones

In secondary FCC cyclones, the inner vortex spins at a higher velocity than in a primary cyclone, and it is also longer. As the swirling solids move into the cone in a secondary cyclone, the high-velocity vortex accelerates the solids and increases their velocity. It is this high-velocity, concentrated-solids stream that causes the significant erosion seen in secondary cyclone cones (Fig. 15) and in the upper part of the secondary cyclone diplegs.

There are several things that can be done to mitigate this erosion: 1) increase the length of the cyclone (cone, barrel or both), 2) add a dust hopper, or 3) add a vortex stabilizer. A cyclone with one common type of dust hopper is shown in Fig. 18. Of these different solutions, it was found that the most effective method of reducing the secondary cyclone cone erosion was to add a vortex stabilizer in the bottom part of the cone of the cyclone. Shell has used the vortex stabilizer for over 20 years to prevent excessive erosion in their secondary cyclone cones (Chen, et al., 2013).

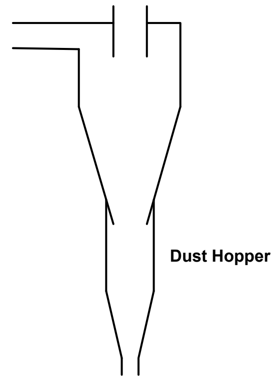

Fig. 18. Cyclone with Dust Hopper

The vortex stabilizer minimizes the precessing of the inner cyclone vortex, but primarily prevents the vortex from extending below the vortex stabilizer. If the vortex stabilizer is placed in the cone a certain distance away from the bottom of the cone, the rapid swirl of the inner vortex is reduced to a very low velocity below the vortex stabilizer, and the cyclone erosion produced at the bottom of the cone is significantly reduced. The larger the diameter of the vortex stabilizer, the more effective it is in reducing erosion. A plot showing the relative effectiveness of increasing the vortex stabilizer diameter for a flat plate cyclone vortex stabilizer is shown in Fig 19. Superimposed on the plot are data points showing how increasing cyclone barrel length, increasing cone length or adding a dust hopper reduces the secondary cyclone cone erosion rate. All of these methods reduce the erosion rate in the secondary cyclone cone, but adding a vortex stabilizer in the cyclone cone region is significantly more effective than the other methods. The effectiveness of using a flat plate vortex stabilizer relative to having no vortex stabilizer is shown in Fig. 20. In this figure, the erosion rate on the secondary cyclone cone is shown as a function of the gas velocity in the GOT, at a constant inlet velocity in the cyclone of 19.8 m/s and at a constant solids loading of 0.032 kg/m^3. The velocity in the GOT was varied by changing the diameter of the GOT. This figure shows that the cyclone cone erosion was significantly reduced using the flat-plate vortex stabilizer vs. no vortex stabilizer as the velocity in the gas outlet tube was increased. It was also found that the insertion of the vortex stabilizer into the bottom of the cone did not increase nor decrease the collection efficiency of the cyclone.

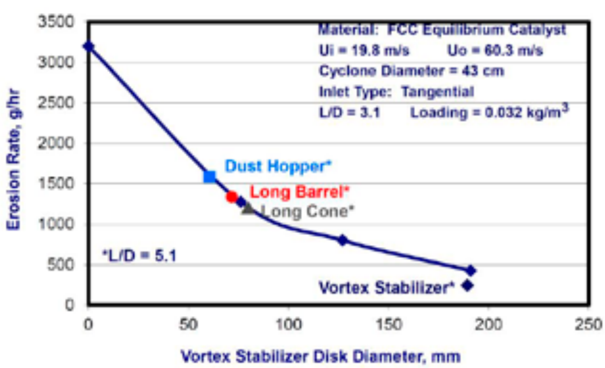

Fig 19. Effect of Flat Plate Vortex Stabilizer Diameter on Erosion Rate

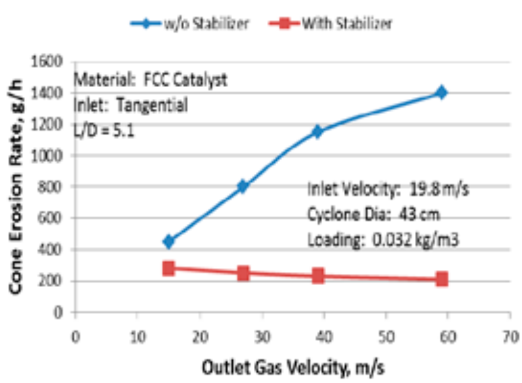

Fig.20. Cone Erosion Rate vs. gas velocity in the GOT for a flat-plate vortex stabilizer

The erosion rates shown in Figs. 19 and 20 were measured by coating a Plexiglas™ cone with drywall joint compound and weighing the amount of drywall joint compound lost to

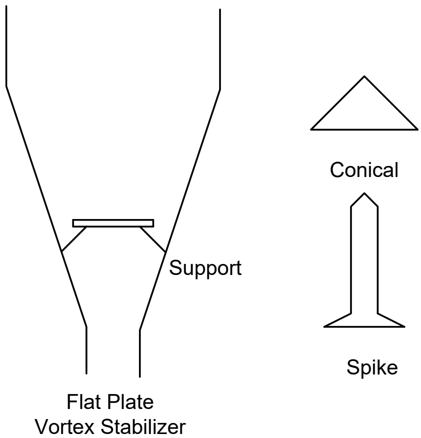

Fig. 21 Types of Vortex Stabilizers

erosion after a test. Specifically, three different layers of the compound were added to the cone, and the weight of the cone and drywall joint compound measured. After the cyclone was operated in a recirculating solids system for several minutes, the cyclone was then removed from the system and the cone and remaining drywall joint compound weighed to determine the erosion rate (Chen, et al., 2013).

Several types of vortex stabilizer configurations can be used. The flat plate, cone and "spike" type of vortex stabilizer configurations are shown in Fig. 21. Equivalent base diameters of these different configurations appear to give the same effectiveness in reducing erosion. As shown in Fig. 19, the larger the diameter of the vortex stabilizer, the more effective it is in reducing erosion. For best operation of the vortex separator, the diameter of the bottom of the vortex separator should at least be equal to the diameter of the inner vortex, which is approximately 75 to 85% of the diameter of the GOT, as discussed above. However, it should not be made so large in diameter that it affects the flow of solids down the wall of the cone. Surprisingly, the top of the vortex stabilizer does not erode, as minimal erosion was observed on the top surface of each type of vortex stabilizer. When supporting the vortex stabilizer from the wall of the cone, the supports should be below the vortex stabilizer. Adding supports above the base of the vortex stabilizer will result in erosion of the supports.

The vortex stabilizer has another advantage when it is used in FCC secondary cyclones. The vortex stabilizer modifies the pressure profile in the cyclone so that the pressure at the solids discharge of the cyclone is higher than without the vortex stabilizer (Muschelknautz and Grief, 1997). This means that the required pressure build in the dipleg below a cyclone containing a vortex stabilizer will be less than in a dipleg below a cyclone without a vortex stabilizer, requiring shorter diplegs.

The pressure drop across CFBC primary cyclones can be significantly reduced by adding swirl vanes into the outlet of the GOT (Ipsen et al., 2014). Adding swirl vanes to the outlet of a commercial CFBC reduced the pressure drop by approximately 30 to 40% for cyclones with inlet loadings above 0.5 kg/m^3, and by up to 60% for inlet cyclone loadings below 0.1 kg/m^3

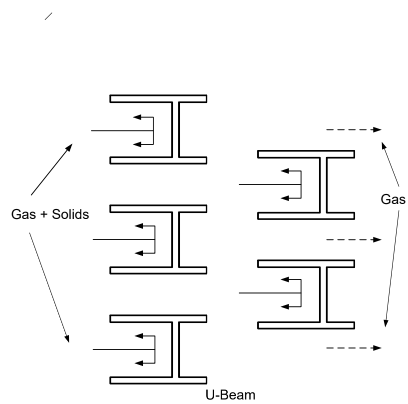

Fig. 22. Top View of U-beams

Another approach to reducing the pressure drop across solid separators in a CFBC is to not use cyclones at all. B&W uses U-beams (Fig. 22) in their CFBCs to separate the solids from the exit gas (Maryamchik and Wietzke, 2010). The collection efficiency of the U-beams (generally between about 95 and 97%) is not as high as for a cyclone (which is about 99.9% or a little more) or the compact separators (perhaps 98 to 99%). Therefore, a multiclone type of cyclone is generally used as a second stage of solids collection. U-beams are used because of their low pressure drop. Pressure drops as low as 1kPa have been reported with U-beams.

Cyclone Diplegs and Dipleg Terminations

FCC primary cyclone efficiencies can achieve cyclone efficiencies of 99.95 to 99.99%. Secondary FCC cyclones can achieve cyclone efficiencies of 98 to 99%, if the secondary cyclone dipleg is designed and operated correctly. In all processes utilizing a cyclone, the cyclone should be thought of as part of a system, and not separately. The operation of a cyclone will depend on how the rest of the system (especially the dipleg) is designed. If the secondary cyclone dipleg in FCC units is not designed correctly, too much gas can flow up the dipleg and reduce the efficiency of the cyclone significantly. In CFBC cyclones, it is also possible to have too much gas flow up the dipleg and reduce the efficiency of the primary cyclone (Muschelknautz and Grief, 1997). For cyclones operating in FCC units, the secondary cyclone dipleg is required to have a device such as a trickle vale or counterweighted flapper valve (Fig. 23) at the end of the dipleg. Primary FCC cyclone diplegs do not require trickle valves or flapper valves because of the high solids fluxes in their diplegs. However, some FCC primary diplegs have trickle valves on them to try to prevent catalyst loss upon startup.

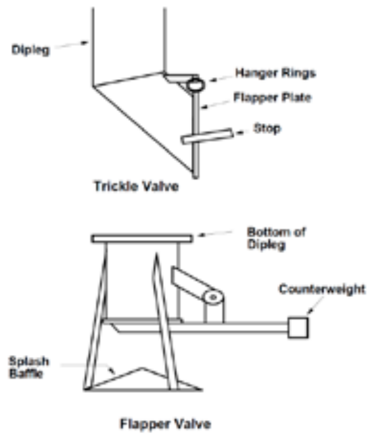

Fig. 23. Schematic Drawing of Trickle and Counterweighted Flapper Valves

A trickle valve or counterweighted flapper valve is required at the end of secondary cyclone diplegs at the startup of the FCC unit, which starts up with the fluidized bed empty. As the solids are added to the FCC unit, the solids pass through the primary cyclone. As shown in Fig. 16, for 10,000 arbitrary mass units of solids entering the cyclone per unit time (assume the units are kg/min), only about 5 kg/min will enter the secondary cyclone. If the efficiency of the secondary cyclone is 80%, then only 4 kg/min will flow down the secondary cyclone dipleg.

Fluidizing gas is being added to the vessel below the FCC cyclone during startup. The solids flux down the primary cyclone dipleg (generally designed to have a solids mass flux of between about 500 to 750 kg/m^2/s) is so great that the gas cannot flow up the primary dipleg against this large flux, and will be carried down the primary dipleg with the solids (Karri and Knowlton, 2001). However, for the case illustrated in Fig. 16, the solids flux down the secondary cyclone dipleg will only be 4/10,000 of the primary cyclone dipleg flux (if the same dipleg diameter as the primary dipleg is used), or only 0.2 to 0.3 kg/s/m^2. This is 2500 times less than the flux in the primary dipleg. Using a smaller-diameter dipleg to try to increase this flux to values similar to those in the primary dipleg leads to impractically-small, secondary cyclone diplegs.

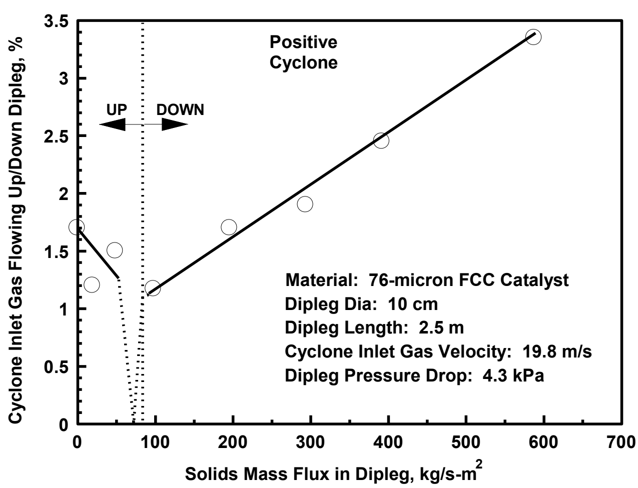

Fig. 24. The Effect of Solids Mass Flux in the Dipleg on the Direction of Gas Flow for FCC Catalyst

This extremely low flux of solids down the secondary dipleg is not enough to prevent gas from flowing up the secondary dipleg in amounts great enough to prevent solids flow down the secondary dipleg. This large gas flow upward prevents a solid seal from developing in the secondary dipleg. Therefore, a device such as a trickle valve or a counterweighted flapper valve is added to the end of the secondary cyclone dipleg to prevent most of the gas from flowing up the dipleg. This allows a solids seal to develop in the dipleg. However, even with the trickle valve or counterweighted flapper valve at the bottom of the dipleg, gas will still flow up the secondary dipleg as shown in Fig. 24, Karri and Knowlton, 2001.

If the FCC secondary cyclone dipleg is not designed and operated correctly, a significant amount of gas can flow up the dipleg and reduce the efficiency of the secondary cyclone and increase the emissions from the FCC unit. PSRI has found that if the upward gas velocity in the FCC secondary cyclone dipleg is greater than about 1 m/s, then the cyclone efficiency can decrease from about 98 to 99% to about 75 to 80% (Karri, 2015). This effect is shown in Fig. 25, and is similar in effect to what was found above for excessive upward dipleg gas flow affecting cyclone efficiency for CFBC cyclones. Many FCC secondary cyclone diplegs have their solids discharging into the dilute-phase freeboard above the

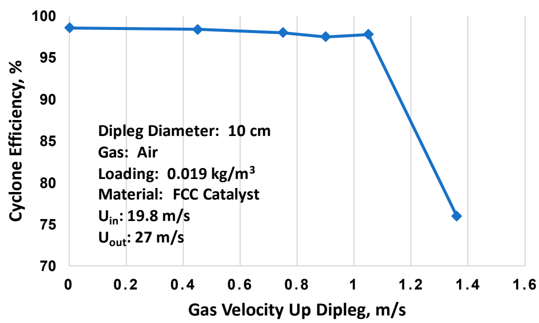

Fig. 25. Cyclone Efficiency vs. Gas flow Up the Dipleg

fluidized bed. Therefore, the tolerances between the trickle valve (or counterweighted flapper valve) plate and the dipleg should be as small as possible to prevent an excessive amount of gas from flowing up the dipleg and reducing the secondary cyclone efficiency. However, a better way of reducing the amount of gas flowing up the dipleg is to immerse the secondary dipleg into the fluidized bed (Fig. 26). This increases the height of the solids seal required in the dipleg, increases the "resistance" to gas flow up the dipleg, and significantly reduces the gas flow (and the velocity) up the dipleg. Immersions of about 1 m into the fluidized appear to be satisfactory to reduce this gas flow. However, if immersions are too deep, then the solids seal height will be too close to the bottom of the cyclone.

CFBC diplegs can also have gas flowing up the dipleg, even with relatively high solids fluxes. The solids in the dipleg of the CFBC cyclone dipleg are larger (approximately 120 to 200 microns vs. about 65 to 70 microns) than in the FCC primary cyclone dipleg. Tracer studies at PSRI with 120-micron sand material flowing through a dipleg above a loop seal have shown that for solids mass fluxes less than about 300 kg/s/m^2 through the dipleg, gas flowed up the dipleg. This is a much higher mass flux than the limiting flux shown in Fig. 24 (about 75 kg/s/m^2) required for gas to flow up the dipleg for FCC catalyst. The reason is that the surface area-per-unit-volume of the larger sand is much lower than that of the smaller FCC catalyst, so it takes a much higher mass flux (velocity) in the line to carry the gas down with the solids. The sand also has a greater flowing density in the dipleg than the FCC catalyst (approximately 1500 kg/m^3 for the sand vs. about 750 kg/m^3 for the FCC catalyst). The velocity in the dipleg where gas flow in the FCC catalyst suspension approximately transitions from up to down in the dipleg is 75 kg/s/m^2/750 kg/m^3 = 0.1 m/s. The velocity in the sand dipleg where the solids carried the gas down the dipleg was about 300 kg/s/m^2/1500 kg/m^3 = 0.2 m/s. Because of the difference in particle size and particle density, comparing velocities is a more accurate way of comparing differences in dipleg operation. However, this analysis shows that gas can travel up the dipleg at higher gas/solids suspension velocities in CFBC diplegs than in FCC diplegs, primarily because of the difference in the particle sizes in the two processes. The higher upward gas velocities in the dipleg below CFBC cyclones can also affect CFBC cyclone efficiency as (Muschelknautz and Grief, 1997) indicated above. However, the amount of gas flow up the dipleg below CFBC cyclones is also largely a matter of how much the loop seal is aerated. Unless the flux in the dipleg is high enough to prevent upward gas flow, if the loop seal is overaerated it can affect not only the operation of the loop seal, but the efficiency of the cyclone above the loop seal as well.

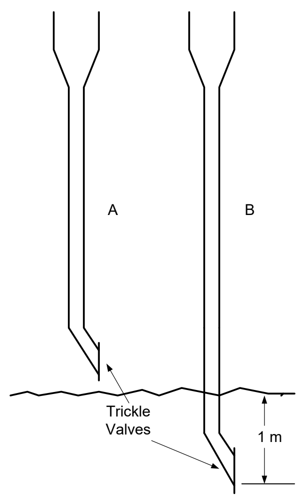

Fig. 26. Immersed and Non-immersed Trickle Valves

In FCC units, a recurring problem is the loss of fine material from the process. Nearly always, this is not the fault of the cyclone itself, but a problem with the secondary cyclone dipleg. In this dipleg, the solid flux is so low, and the particle size so small, that solids flow through this dipleg can be blocked, or so much gas can flow up the secondary cyclone dipleg (because of the reasons discussed above) that a significant amount of material can be lost. Often the problem is with the trickle or flapper valve plate not sealing well (because of poor design or warping), causing too much gas to flow up the dipleg which affects cyclone efficiency as indicated above. As also indicated, immersing the trickle or flapper valve in the bed a short distance can mitigate this problem.

Normally, a trickle or a flapper valve on the outlet of a secondary cyclone dipleg operates in an intermittent discharge mode. Solids will build up into the dipleg to a height which will provide enough "head" to generate enough force to open the flapper plate. Often there will be a continuous, small trickling flow of the solids through the trickle valve or flapper valve which constitutes approximately 10% of the solids flow rate. (Geldart and Kerdoncuff, 1992). Superimposed upon this constant trickling is the intermittent discharge mode, which discharges the other 90% of the solids flow rate. At times, the solids flow rate is so low, that the solids in the secondary dipleg can defluidize (deaerate) before the solids reach the height necessary to produce the pressure required to open the flapper on the trickle or flapper valve. If this occurs, then the defluidized bed of solids above the valve cannot produce enough head to open the flapper of the valve, and solids flow out of the dipleg will stop. If this occurs, the dipleg will flood, which means that the dipleg will fill up with solids to the bottom of the cyclone. When this occurs, the solids flowing into the cyclone will bypass out through the cyclone exit.

One way to solve this problem having defluidized solids in the dipleg is to add aeration into the dipleg. The best location to add aeration for the trickle valve is to add it in the mitered section at the bottom on the centerline of the dipleg Karri and Knowlton (2004). This location is shown in Fig. 27. They also found that adding aeration such that the superficial gas velocity in the dipleg was around 0.03 m/s gave good results.

However, adding aeration to a dipleg in a hot unit is not easy to do. There are usually between about 6 and 22 sets of cyclones in an FCC unit, and adding aeration lines to all of their secondary diplegs with the associated thermal expansion problems, is complicated. Therefore, it is easier to reduce the size of the cyclone dipleg so that the solids level will reach the required height to open the flapper before deaeration occurs.

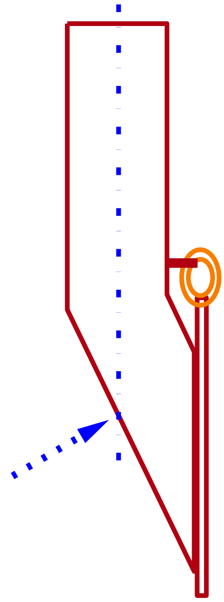

Fig. 27. Optimum Aeration Location for a Trickle Valve

Loop seals at the bottom of the cyclone dipleg in CFBCs are very reliable. For a loop seal to operate correctly, the upleg of the loop seal must be fluidized (Fig. 28). The downleg of the loop seal should also be fluidized for best operation, although the loop seal can operate with a non-fluidized downleg. However, it is strongly recommended that the downleg be fluidized for best operation of the loop seal.

In CFBC processes, the loop seal is the most extensively-used device to return solids collected by the cyclone back into the reactor. The FCC process does not make use of loop seals thus far – primarily because the cyclone diplegs are internal to the process. Loop seals can be used with both Geldart Group A or Geldart Group B solids. However, it would be difficult to start up an FCC unit with an empty loop seal instead of a trickle valve or flapper valve. The loop seal would have to be filled with solids before startup, so that the gas would not flow up the secondary dipleg and prevent a solids seal from forming due to the low secondary cyclone dipleg solids flow as indicated in Fig. 16.

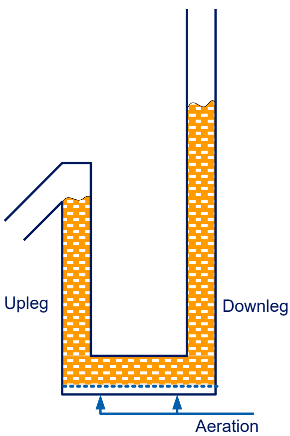

Fig. 28. Schematic Drawing of a Loop Seal

Attrition in Cyclones

One issue associated with cyclones is particle attrition. The solids enter the primary cyclone at a high velocity and impinge on the wall of the cyclone. This can cause substantial particle attrition. In FCC units, cyclone attrition is almost always of the surface abrasion type where the small surface nodules and asperities are abraded off of the surface of the FCC catalyst. These surface asperities are small, of the order of about 0 to 10 microns, and are mostly lost into the cyclone exit stream as the FCC cyclones have poor collection efficiencies for these sizes of particles.

In CFBC systems, attrition can be due to thermal stress, chemical reaction (which weakens the particles as they are reacted), as well as mechanical attrition. Mechanical attrition is what occurs in the cyclones, but the thermal shock or chemical reaction can weaken the particles so that they can more easily be broken.

Scala and Chirone, 2013, found that when a CFBC cyclone inlet gas velocity exceeded a certain threshold velocity, that the attrition produced by the cyclone increased significantly. They attributed this sudden increase to a chipping of material off of the particle surface (a type of fragmentation). However, the authors also noted that for typical cyclone inlet velocities found in CFBC cyclones, this type of fragmentation would not occur, and the primary mode of attrition would be particle abrasion. This is because high cyclone velocities cause the cyclone pressure drop to increase to values higher than desired, as cyclone pressure drop is proportional to inlet gas velocity squared.

Reppenhagen and Werther, 1999 developed a correlation for attrition in a cyclone based on their work with FCC catalyst. They found that the attrition in their 90-mm ID cyclone using this catalyst was essentially surface abrasion. The correlation they developed for this type of attrition is:

$$r_c = C_c \, d_{pc} \, \frac{U_i^2}{\sqrt{\mu_c}}$$

This correlation predicts that the attrition rate in a cyclone is proportional to the inlet velocity squared, and inversely proportional to the square root of the mass loading (kg_s/kg_g) entering the cyclone. In catalytic FCC systems, this large dependency of attrition on inlet gas velocity has been recognized and used to reduce particle attrition in cyclones. Because particle emission requirements are becoming more and more stringent, and a significant contribution to the emissions is material attrited in the cyclones, in the authors' experience, there is a growing trend toward designing primary FCC and other catalytic process cyclones with lower inlet gas velocities. This is because of the strong dependency of attrition on gas inlet velocity.

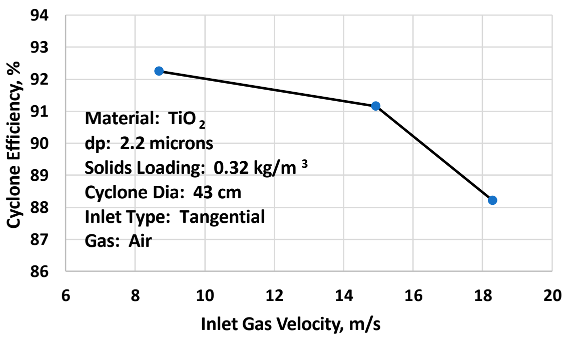

Fig. 29. Cyclone Efficiency vs. Inlet Gas Velocity for TiO_2

As can be seen from Fig 16, the loading is so high in the primary cyclone relative to the secondary cyclone that, practically, all attrition occurs in the primary cyclone. The solids flow rate into the secondary cyclone is typically between 1/1,000 to 1/10,00 of the flow rate into the primary cyclone, so relatively little attrition occurs in the secondary cyclone. Typical primary cyclone inlet gas velocities for FCC units have traditionally been in the range of 18.3 to 19.8 m/s (60 to 65 ft/s). Several primary cyclones have now been designed to operate in the range of 13.7 to 16.8 m/s (45 to 55 ft/s). Reducing the inlet gas velocity from 18.3 to 15.2 m/s, will reduce particle attrition caused by the cyclone by approximately 31% if cyclone attrition is proportional to inlet gas velocity squared. However, reducing the inlet gas velocity will also increase the size of the cyclone, or may require increasing the number of cyclones. Using the same relative dimensions of the cyclone with a reduced inlet gas velocity, the cyclone would have to be increased in diameter by approximately 10%. As well as reducing the attrition produced in the primary cyclone, the erosion of the cyclone impact area would be reduced as well by the reduction in the inlet gas velocity. To counteract the effect of the lowering of the inlet gas velocity, the GOT diameter can also be reduced to increase the rotational speed of the inner vortex, and increase the cyclone collection efficiency.

Agglomeration of fine solids can also affect cyclone efficiency for these very fine solids (generally smaller than 10 microns). In general, agglomerate of these fine particles result in an increase in cyclone efficiency. The fine particles clump together (agglomerate) because of interparticle forces. Evidence of this clumping can be seen in Fig. 29. In this figure, very fine TiO_2 solids with an average particle size of approximately 2.2 microns, were directed into a

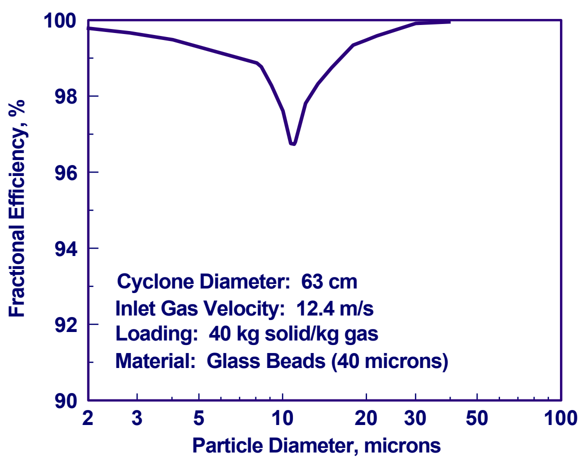

Fig. 30. Cyclone Efficiency vs. Particle Size With Indication of Small-Particle Clumping

tangential inlet cyclone at several gas velocities ranging from approximately 8.2 to 18.2 m/s. The gas velocity through the cyclone was varied at a constant inlet loading of 0.32 kg/m^3. A very low cyclone collection efficiency was expected for these particles, as cyclones generally cannot collect solids of this size at a high efficiency. However, a very high collection efficiency (over 92 %) was obtained for these very small particles at an inlet gas velocity of 8.2 m/s. As the inlet gas velocity was increased, the collection efficiency for these particles decreased. The reason for this counter-intuitive result appeared to be that the small TiO_2 particles clumped together in hydrodynamically stable, but relatively fragile agglomerates. As the gas velocity was increased, the increased impact force of the agglomerates with the cyclone wall caused an increased percentage of the agglomerates to break up into smaller particles, which could not be collected by the cyclone. Therefore, the cyclone efficiency decreased as the gas velocity increased.

The effect of particle clumping at small particle sizes can also be seen in Fig. 30. In this figure, the fractional collection efficiency of glass bead particles is plotted as a function of particle size (from Hugi and Reh, 1998). This fractional efficiency plot shows that the collection efficiency of 2-micron particles is greater than or equal to the collection efficiency of 20- to 30-micron particles. This is because the smaller particles clump together to form larger agglomerate particles which can be collected at higher efficiencies than larger particles that do not agglomerate (at least to the same extent).

Positive and Negative-Pressure Cyclones

A negative-pressure cyclone is a cyclone where the pressure in the barrel is less than the pressure in the freeboard of the bed into which it is discharging. A positive-pressure cyclone is a cyclone where the pressure in the barrel is greater than the pressure of freeboard of the bed into which it is discharging.

All CFBC cyclones are negative-pressure cyclones. However, some FCC cyclones can be either negative - pressure or positive-pressure cyclones. FCC close-coupled cyclones at the exit of the FCC riser can be either negative-pressure or positive-pressure cyclones. These cyclones are generally located above the stripper section of the FCC unit. Whether they are positive-pressure or negative-pressure cyclones depends on how the gas from the stripper enters the cyclone system. If the gas enters before the inlet of the primary cyclone, the cyclone is a negative-pressure cyclone. If the gas from the stripper enters between the primary and secondary cyclones, the cyclone is generally a positive-pressure cyclone. This difference is shown in Fig. 31. The secondary cyclones are not shown in this figure.

As shown in Fig. 31, if the cyclone is a positive-pressure cyclone, the level of the solids seal in the dipleg will be below the level of the stripper bed. If the cyclone is a negative-pressure cyclone, the level of the solids seal in the dipleg will be above the level of the stripper bed.

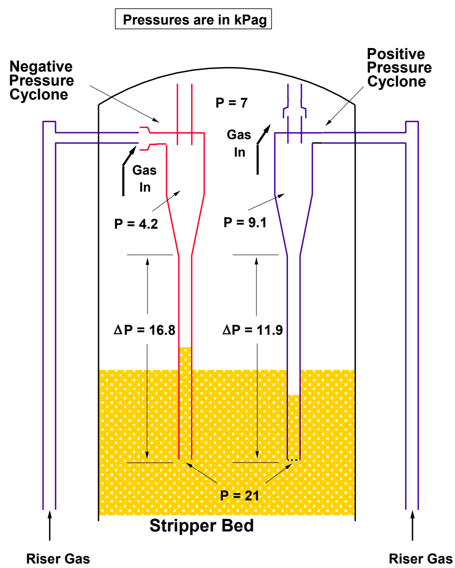

Fig. 31. Positive and Negative Cyclones

A positive-pressure cyclone is also more likely to have a dipleg that operates in what is called the streaming mode (Karri and Knowlton, 2001; Dries and Bouma, 1996; Sun, et al., 2001). In this mode, the solids stream down the primary cyclone dipleg and drag a significant amount of gas with them. Fortunately, this not a common occurrence, as a dipleg operating in the streaming mode is almost always non-desirable as it increases the "load" on the stripper. The dipleg streaming mode is more likely to occur if the pressure drop across the primary dipleg is low. The pressure drop across the primary dipleg for a positive-pressure cyclone can be significantly lower than the pressure drop across the primary dipleg for a negative-pressure cyclone, as shown in Fig. 31.

SUMMARY

The two most important CFB industrial processes that use cyclones are the FCC and the CFBC processes. The cyclones from these two processes have important differences. One difference is in the size of the solids which pass through the cyclones. The FCC process uses a catalyst which is a Geldart Group A material (about 70 microns in diameter), and the CFBC process uses a larger, Group B material (typically 150 to 200 microns in diameter).

The size and configuration of the cyclones in the two systems are also different. FCC cyclones are approximately 1.2 to 2 m in diameter, are mostly parallel, internal cyclones that have at least two and can have as many as four stages. CFBC cyclones are much larger (up to 10 m in diameter), are mostly external cyclones, and have only one stage.

The efficiencies of the multi-stage FCC cyclone system can be as much as 99.999%, whereas the larger, single stage CFBC cyclone efficiencies are more typically about 99.9%. CFBC systems which use "square" or multi-panel non-cylindrical cyclones for lower costs and reduced maintenance have efficiencies somewhat less than this.

CFBC units almost always use a loop seal at the bottom of their external cyclone dipleg to seal the differential pressure between the cyclone and the reactor. This type of dipleg return system is not used in FCC units. FCC units use either trickle valves or flapper valves at the bottom of their secondary cyclone diplegs to allow the units to startup with an empty bed.

Most erosion in CFBC cyclones occurs in the cyclone barrel opposite the point where the solids enter the cyclone. The most severe cyclone erosion in FCC cyclones, occurs in the cone of secondary cyclones, and adding a vortex stabilizer to the appears to be the best way to mitigate this erosion.

For CFBC cyclones, it has been found that using an eccentric GOT and an angled inlet can both improve the collection efficiency of the CFBC cyclones. These configurations have not been tried in FCC cyclones.

Both types of cyclones can have their collection efficiencies affected if there is too much gas that flows up the cyclone dipleg. This primarily occurs in the secondary cyclone diplegs for FCC cyclones, and for lower-flux CFBC cyclone diplegs.

NOTATION

C_c attrition rate constant, s^2/m^3
d_{pc} surface mean particle size, m
D cyclone diameter, m
L cyclone overall length, m
kg_g kilograms of gas
kg_s kilograms of solids
r_c attrition rate, fines mass rate produced in the cyclone/fines mass rate entering cyclone, (-)
U_i, U_{in} cyclone inlet gas velocity, m/s
U_o, U_{out} cyclone outlet gas velocity, m/s
U_c cyclone inlet gas velocity, m/s
ε voidage, (-)
μ_c solids to gas mass loading ratio, kg_s/kg_g

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