TECHNICAL SUMMARY
DRY SCRUBBERS

1. General Description

The Peerless Dry Scrubber is a multiple element centrifugal type separator intended for the high efficiency separation of liquids and/or solids from gas in pressurized process systems.

The Dry Scrubber consists of a cylindrical shell, which may be either vertical or horizontal, in which is installed a section of multiple small diameter cyclones. The cyclone tubes are compartmented within the shell so that all entrained liquids and/or solids entering with the gas are forced to pass in parallel flow through the tubes. The centrifugal action of each tube forces entrained particles to the wall of a lower cone section of each tube, where the separated material runs downward and drains out of each tube to a storage section in the lower part of the vessel. Clean gas moves vertically upward out of each tube into an outlet chamber in the vessel and out the gas exit nozzle. Separated material accumulated in the lower section of the vessel is ultimately removed from the separator by either automatic or manual blow-down.

2. General Type of Application

The Dry Scrubber is used in applications where liquids and/or solids are continuously present in a gas and must he removed with high efficiency with a minimum of maintenance and attention.

The most extensive use of Dry Scrubbers is probably in natural gas transmission service. In this application, the Dry Scrubber is installed in the gas piping immediately preceding the natural gas compressors in the pumping station and removes pipe line scale, dust, and hydrocarbon liquids which condense in the pipelines between compressor stations. High efficiency removal of entrained material, liquid or solid, is essential to prevent damage to the gas compressors, whether reciprocating or centrifugal.

Dry Scrubbers are also used in process systems where dry solids must be removed from gases and where the necessity for shutdown and maintenance of filter type separators cannot be tolerated. The high efficiency removal of solids where particles may be down to 10 microns or less, which is accomplished by the use of multiple small diameter cyclones, makes the Dry Scrubber suitable for numerous applications where otherwise only filters would be considered.

Dry Scrubbers are used to advantage in oil and gas production applications where sand or other solids are produced with condensate and gas. As a rule, solids and liquids in these applications will occur in moderate quantities within the handling capability of the Dry Scrubber.

3. Principle of Operation

All material entrained in the gas which enters the Dry Scrubber must pass into the cyclone tubes for removal. As the gas flows into the two entrance slots of each cyclone, the tangential velocity imparted develops a centrifugal force action on the gas and entrained particles. Since the entrained material is much heavier than the gas, this material is thrown to the cylindrical walls of the lower portion of the tube. By gravitational action the still-rotating solids and/or liquids move down to an opening in the bottom of the conical section of the tube and fall into a storage section beneath the cyclone tube section. The clean gas rises through a smaller diameter tube, which is centered in the lower cone and exits from the cyclone.

In any cyclone type separator, the size particle, which can be separated, depends on the particle density, the gas density, and the magnitude of the centrifugal force, which must be developed to throw the particle out of the gas stream. In the service where the Dry Scrubber is usually applied, a wide difference nearly always exists in the gas density and the entrained particle density, whether liquid or solid. The centrifugal force thus is a primary determinant of the size particle, which can be effectively separated by a cyclone type separator.

In the cyclone separator, the centrifugal separating force is directly proportional to the square of the gas velocity and inversely proportional to the radius of curvature of the gas stream. A high centrifugal force can be created by employing a high rotational gas velocity, by using a small diameter tube, or by some combination of the two. While using a high velocity is desirable since centrifugal force increases as the square of velocity, the higher velocity also

produces a pressure drop, which increases with the square of the velocity. The approach used by Peerless in the design of multiple cyclone tubes for Dry Scrubbers is to combine relatively small diameter tubes with moderate rotational gas velocities to, achieve separation of particles down to the sizes
which comprise essentially all the entrainment in the type of applications for which Dry Scrubbers are predominantly used.

4. Operational Characteristics

A. Gas Capacity

The gas capacity of an individual cyclone tube is the gas flow rate range within which the acceptable separation effectiveness can be achieved. Since the radius of curvature of the gas stream is a fixed dimension for a particular size cyclone, the only other variable of consequence is the rotational velocity of the gas, which is directly proportional to gas flow rate.

The allowable gas flow rate for a cyclone has an upper limit above which re-entrainment of separated material will occur, even though a high centrifugal force is being developed. The lower gas flow rate limit is the point below which the centrifugal force is inadequate to separate particles of the size normally expected to be present in the gas. For the size cyclones used in Peerless Dry Scrubbers, the upper and lower gas flow rate limits are in a ratio of four to one.

Since gas velocity in the cyclone tube is the primary determinant in separation effectiveness, the gas capacity of a tube is a function of the actual volumetric flow rate of gas rather than a flow rate as normally expressed in standard terms. For proper cyclone performance, then, the flow of gas in the tube must be kept within the range limits in actual volume per unit of time terms, regardless of the flowing pressure of the gas. For the 2 inch standard Dry Scrubber cyclone tube, the effective flow rate range is 10 to 40 actual cubic feet per minute. For the 4-1/2 inch tube, the range is 50 to 200 actual cubic feet per minute.

B. Liquid and Solids Capacity

The cyclone tubes used in Dry Scrubbers are intended to handle moderate quantities of either liquids or solids or combinations of the two. The 2 inch tube will handle liquid quantities ranging from 2.0 gallons per minute (per tube) at 10 ACFM per tube to 0.5 gallon per minute at 40 ACFM per tube. The 4-1/2 inch tube will handle 4.5 gallons per minute (per tube) at 50 ACFM to 1.25 gallons per minute at 200 ACFM per tube. These capacities apply for free-flowing liquids in a 40 to 70 pound per cubic foot density range.

Solids can be effectively removed by the 2 inch tube in quantities up to 0.25 pound per minute (per tube) over the 10 to 40 ACFM range. The 4-1 /2 inch tube will handle 0.56 pounds per minute in 50 to 200 ACFM range. These capacities apply for solids in a particle size range from 2 microns to 1500 microns and with bulk densities from 60 to 120 pounds per cubic foot.

C. Pressure Drop

The pressure drop in the individual cyclone tube is primarily a function of the resistance coefficient of the tube, of the gas velocity in the tube, and of the density of the flowing gas. The resistance coefficient is a characteristic of the particular tube design and is a constant. In cyclones as used in Peerless Dry Scrubbers, the gas velocity should be maintained within the four-to-one flow rate range. Gas density, which is directly proportional to gas absolute pressure, thus becomes the primary determinant of the pressure drop which will occur with the cyclone type separator element.

The total pressure drop, nozzle-to-nozzle, in a given Dry Scrubber consists of an inlet nozzle loss, loss across the cyclone tubes, and an outlet nozzle loss. Standard nozzle sizes in Dry Scrubbers limit gas velocities such that nozzle losses comprise only about 15% of the total pressure drop as shown in capacity tables.

A look at capacity table pressure drops for Dry Scrubbers with 2 inch cyclones shows the manner in which pressure drop varies with flow rate and pressure. For example, with a flow of 10 ACFM/tube at 0 PSIG through a Dry Scrubber, the nozzle to-nozzle loss is .011 PSI. With 40 ACFM/tube, still at 0 PSIG, the pressure drop has increased to .176 PSI, an increase of sixteen times. The pressure drop increase thus has varied as the square of the 40 to 10 ACFM/tube flow increase.

Looking at the variation in pressure drop with pressure, the .176 PSI pressure drop at 40 ACFM/tube and 0 PSIG is seen to increase to 7.38 PSI at 600 PSIG. This increase of 41.9 times is in direct proportion to the ratio of absolute pressures, 614.7 PSIA. to 14.7 PSIA.

Nozzle-to-nozzle pressure drops shown in capacity tables are based on operation with a 0.6 specific gravity gas at 60° F. and with a compressibility factor of 1.0. In the Sizing Procedure Bulletin for Dry Scrubber, No. 21000-5-1.0, note that pressure drop also varies with change in flowing temperature, specific gravity, and compressibility of the gas.

The 4-1/2 inch cyclone tubes also used in Dry Scrubbers are designed to have the same pressure drop characteristics for their 50 to 200 ACFM/tube flow rate range that the 2 inch tubes have in their 10 to 40 ACFM/tube range. The nozzle-to-nozzle pressure drops shown in capacity tables for the 2 inch tube are thus also applicable for the 4-1/2 inch tube at flow rates increased by a factor of five.

D. Separation Efficiency

The 2 inch cyclone tube used in the Dry Scrubber will remove 100% of all solid particles 10 microns and larger at all gas flow rates within the 10 to 40 ACFM/tube range. Particles less than 10 microns in size will be separated with decreasing effectiveness, with some variation in efficiency depending on the actual flow. For example, 84% of 3 micron particles will be separated at a flow of 40 ACFM/tube, but only 70% of the same size particles are separated at 10 ACFM/tube. The decreased efficiency at the lower flow is due entirely to the reduction in centrifugal separating force achieved at the 10 ACFM/tube flow. Separation efficiency versus particle size for the 2-inch cyclone is shown in the curves of Figure 6, dated July 1, 1960. Efficiencies are based on separation of solid particles having bulk densities in the 60 to 120 pounds per cubic foot range.

As noted previously, the 4-1/2 inch cyclone tubes are designed to have the same pressure drop characteristics as the 2-inch tubes. Uniformity in pressure drop is accomplished by maintaining geometrical similarity of the two sizes and is accomplished by keeping the rotational velocity of the gas the same in the 4-1/2 inch tube as in the 2-inch tube. With centrifugal separating force in the cyclone directly proportional to the square of the gas velocity and inversely proportional to the radius of curvature of the gas stream, the 4-1/2 inch tube has the same velocity component as the 2-inch tube, but has only 1/2.25 of the radius component. The centrifugal force in the 4-1/2 inch tube, therefore, is less than half that achieved in the 2-inch tube at comparable flows within the allowable range of the tubes.

The effectiveness of separation of small particles by the 4-1/2 inch tube is not substantially reduced by this apparently substantial reduction in centrifugal, however. This is because particle weight as well as size is a major determinant in the effectiveness which a given centrifugal force has in separating solids from gases. Thus where the 2 inch cyclone separates 100% of 10 micron particles (and larger) over its full 10 to 40 ACFM/tube flow rate range, the 4-1/2 inch tube will separate 100% of particles with 2.25 times the weight of the 10 micron (and larger) particles. With density assumed the same for all particles, weight is proportional to volume and spherical volume, in turn, proportional to the radius cubed ($V = \frac{4}{3} \Pi R^3$).

A spherical particle having 2.25 times the weight of another shperical particle of the same density will therefore have a radius which is greater only by the cube root of 2.25, or 1.31. The minimum size particle which the 4-1/2 inch tube will separate with 100% efficiency will be 13.1 micron diameter. The separation efficiency of the 4-1/2 inch tube for particles less than 13.1 microns will follow the same pattern as the 2 inch tube for particles less than 10 microns. For example, where the 2 inch cyclone separates 95% of 5 micron particles at 40 ACFM /tube, the 4-1/2 inch tube will separate 95% of 6-1/2 micron particles at 200 ACFM/tube.

The 2 inch and 4-1/2 inch cyclone tubes have slightly lower separation efficiencies for liquid particles of a given size as for solid particles of the same size. As a rule, liquid densities are less than solids densities and the centrifugal force acting on the liquid particle will he less when moving in a cyclone at the same radius and with the same radial velocity. For liquids normally entrained in gas flows where Dry Scrubbers are principally used, carryover of liquid will be limited to no more than 0. 1 gallon per million standard cubic feet of gas, with gas flow through the Dry Scrubber maintained within the capacity flow rate limits of the individual cyclones.

5. Design Characteristics

A. Nozzle Velocities

With standard size nozzles installed on the inlet and outlet, nozzle velocities in Dry Scrubbers will vary from about 20 feet per second at the low end of the per-tube flow limit to about 80 feet per second at the upper limit of per-tube flow. At these velocities, nozzle pressure losses constitute about 15% of the total pressure drop across the Dry Scrubber.

B. Cyclone Tube Capacities

The per-tube capacities have previously been given as 10 to 40 ACFM for the 2 inch tube and 50 to 200 ACFM for the 4-1/2 inch tube. Both the 2 inch and 4-1/2 inch tubes will maintain their separation efficiencies for given particle sizes at flows up to 120% of the upper capacity rating limit. As a general rule, the appreciable increase in pressure drop which accompanies increased flow becomes unacceptable, however.

At flows below the lower limits specified for each of the two tube sizes. the centrifugal force developed decreases to the extent that separation of either liquids or solids tends to result more from impact and impingement. Where small particle entrainment is still present, rather uncertain separation efficiencies will be achieved when per-tube gas flow is below the lower capacity limits.

C. Effectiveness of Use of Vessel Volume

The Dry Scrubber with either 2 inch or 4-1 /2 inch cyclones is one of the most effective separators in its use of shell volume of all the types of separators available for removal of both liquids and solids. The most effective working pressure range is from about 500 PSIG to about 1500 PSIG. In this pressure range, the Dry Scrubber provides high separation efficiency at high gas flow rates in relatively compact size vessels with acceptable pressure drops.

As an example, the 30 inch Dry Scrubber with sixty 2 inch cyclones will hand 3.44 MMSCFD per cubic foot of shell volume, when operating with a 0.60 specific gravity gas at 800 PSIG and 60° F, and with only a 2 PSI pressure drop. By comparison, a 30 inch Horizontal Filter/Separator will handle 2.29 MMSCFD per cubic foot of upper shell volume, with gas flow at the same conditions and with a 1-1/4 PSI clean condition pressure drop.

6. Allowable Variations in Standard Design

All sizes of Dry Scrubbers from 6-5/8 inch O.D. to 96 inch I.D. in either Vertical or Horizontal design are available with 2 inch cyclones. Vertical Dry Scrubbers with 4-1/2 inch cyclones are available in sizes 30 inch I.D. and larger. The use of 4-1/2 inch cyclones in Vertical 42 inch I.D. and larger allows about a 12% increase in allowable gas flow in the same size vessel and with the same pressure drop as with 2 inch cyclones, and with only slightly lower separation efficiency.

Horizontal Dry Scrubbers are designed to use 2 inch cyclones in sizes 30 inch I.D. through 96 inch I.D. size vessels. Horizontal Dry Scrubbers, with either tube size, are usually employed only where very large gas volumes must be handled in a single vessel. For example, a 60 inch I.D. Horizontal Dry Scrubber with 140 - 4-1/2 inch cyclones could handle 875 MMSCFD of a 0.60 specific gravity gas at 600 PSIG and 60° F. with only a 2 PSI pressure drop. A gas flow of this magnitude would seldom be encountered other than in natural gas pipeline transmission service. Standard nozzle locations for Vertical Dry Scrubbers are a horizontal side inlet and a vertical top outlet. The Vertical DS can be designed to allow a horizontal side outlet by adding extra shell length to the upper portion of the vessel.

Standard shell lengths for Vertical DS units are the minimum that should be used. Shell lengths can be increased if extra storage capacity is necessary.

As discussed previously, nozzle sizes in Dry Scrubbers are selected to keep inlet and outlet pressure losses to a low level, about 15% of total pressure drop across the vessel. A reduction in nozzle size will produce an appreciable increase in inlet and outlet loss and in total pressure drop. Nozzle sizes can be increased with some decrease in total pressure drop across the vessel. Separation effectiveness will not be affected by either an increase or a decrease in nozzle size.

Applications will occasionally be encountered where the necessary variation in gas flow rate exceeds the four-to-one ratio specified for the cyclones, or where a flow rate below the lower capacity limit for the vessel may occur. In such a case, individual cyclones may be blanked off to keep the per-tube flows within the desired limits. Access to the lower section of the vessel through a manway is necessary for cyclone tube plugging. Plugging of both the gas exit tube and the bottom cone outlet is essential to prevent by-passing of gas flow.

Removable cyclone tube sections can be furnished in the smaller size Vertical Dry Scrubbers. The 24 inch O.D. vessel is usually the upper size limit in which removable tubes are available.

Standard materials for cyclones are carbon steels. Parts subjected to erosive wear are either of forged materials or of special erosion resistant finish. Stainless steel cyclones are available for corrosive gas or liquid service.

7. Limitations in Applications

The pressure drop characteristics inherent in any centrifugal type separator usually become one of the limiting factors in applying the Dry Scrubber. At flowing pressures above 1000 PSIG, the pressure drop can exceed 10 PSI when operating with a 0.60 specific gravity gas at the upper per-tube flow limit. Such a pressure drop will usually be unacceptable.

At flowing pressures above 2000 PSIG, consideration must be given to the difference in densities of the gas and of the liquid and/or solid material to be separated. At this pressure level and higher, the density of most gases is becoming sufficiently large enough to affect the necessary movement of the material to be separated through the gas by the centrifugal force in the cyclone. Reduction in separation efficiencies obtainable by the Dry Scrubber may occur with dense gases at high pressures. As noted above, the increased pressure drop at elevated pressures will usually preclude the use of Dry Scrubbers for such applications.

The normal separation efficiency in removal of liquids will not be achieved by the Dry Scrubber when operating the unit at the upper gas flow limit with two immiscible liquids present. Where immiscible liquids such as oil and water are known to be present in a gas stream, the Dry Scrubbers should be sized so that per-tube gas flow will not exceed 70% of the upper flow limit specified for either the 2 inch or 4-1/2 inch cyclone tube. With gas flow limited to the 70% level, liquid re-entrainment of immiscible liquids will not exceed 0.1 gallon per million standard cubic feet of gas flow.

Where Dry Scrubbers are to be located in the piping systems of reciprocating gas compressors, consideration should be given to the pulsation levels produced by the compressors. The Dry Scrubbers, in either the Vertical or Horizontal design, have acoustic characteristics with respect to the gaseous medium which usually tend to dampen pulsation levels, but which can conceivably amplify pulsation. The internals of Dry Scrubbers are designed to withstand fairly high pulsation levels. Further, no effect on separation effectiveness will normally be produced by the presence of pulsation in the piping. The principal concern would be with the possibility of excessive vibration and possible failure of piping leading to or away from the Dry Scrubber.

Charles B. Valliant
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