14

Foam-Breaking Cyclones

14.1 Introduction

Foams consist of cellular liquid structures, or lamellas, that are filled with gas. Some type of surfactant is required in order for foams to form—they cannot occur in pure liquids. If a gas, such as air, is sparged into a liquid containing a surfactant, the surfactant will form a double layer around the gas bubble, creating a collection of spherical foam bubbles. Such foams tend to be unstable and readily coalesce or break due to their high liquid content. More stable polyhedral foam, of most interest to us, is formed as a result of mechanical stresses, and is much more stable or difficult to break. Breaking of foam occurs in three stages: drainage of the cellular liquid comprising the walls, breakage of the foam walls, and diffusion of the gas out of the foam cells.

At the consumer level, most of us enjoy or find useful products that produce foams. This includes, for example, saving foams, bubble bath products, kitchen detergents, carpet cleaners, cappuccino, beer and other beverages, whipped cream toppings, foam insulation, and many others. At the industrial level, some foams are also useful—indeed essential—to the process. Froth flotation, wherein a foam is artificially created to remove organic pollutants, is one such example. Another is the use of foams to recover valuable minerals from ore. In both of these cases, the process takes advantage of the tendency of certain substances to migrate preferentially into foam. Foams are also used to help prevent fuel fires on airport runways during certain emergency landings. Such foams are created deliberately. In many industrial or processing units, however, foams are often unwanted and troublesome to operations.

Various types of equipment and techniques have been employed to suppress foam formation in biological and process equipment. These include both chemical and mechanical methods. Chemical methods include various defoaming chemicals (silicone oils, non-ionic surfactants, etc.) Mechanical methods employ sprays, wire mesh elements, heat, live steam injection, air or steam-operated ejectors, sonic horns, vacuums, centrifuges, and the use of large retention time vessels. Defoaming chemicals enjoy widespread industrial use but they have the disadvantage of changing the chemical and physical properties of the system. They can also be quite expensive. Thermal methods can damage the product. Centrifuges, though costly, can be effective but most have narrow passages spread out over a large area. Such passages can plug and are difficult to clean. It turns out that one of the most effective ways of breaking many types of process foams is through the application of centrifugal force, and the shear associated with the use of such force. Thus, what we wish to describe herein is the use of cyclonic type devices for suppressing or breaking process foams. This type of equipment that has become quite popular in recent years although the concept of using a cyclone to break foams dates back to at least 1951, Fraser (1951).

Relatively little fundamental information on the design and performance of foam-breaking cyclones appears in the literature. What little is known about them, at least from the user's point of view, is more descriptive than quantitative. This chapter reflects the state of affairs. Even so, it is the writers' hope that the information contained herein will provide the reader who is unfamiliar with these, most interesting separators, with a basic understanding of the art and practice underlying their application and performance.

We shall begin by noting that, if a cyclone is fed a fluid mixture consisting of a heavy phase and a light phase, the light phase will tend to be displaced radially inward by the heavier phase as the latter attempts to make its way to the outer walls in the centrifugal field. If the incoming mixture happens to be a 'foam' or 'froth' (mixtures consisting of less than about 20 volume percent liquid) the gas bubbles will tend to concentrate and form a continuous gas phase along the central axis of the cyclone. In addition to concentrating the less dense foam phase along the cyclone axis, the shear stresses created within the cyclone leads to a distortion of the cellular structure of the foam which appears to result in an increase in the liquid drainage rate. Thus, the combined effects of centrifugal force and shear can be used to separate an incoming foam into its component vapor and liquid phases so that, in principle, only liquid reports out the bottom of the cyclone and only gas out the top.

Such cyclones are known as 'foam-breaking' or 'defoaming' cyclones or separators. A simple illustration of a defoaming cyclone installation is presented in Fig. 14.1.1. The separator itself is seen to consist of a tangentially fed cylindrical tube mounted vertically within a vapor/liquid separator. The cyclone's underflow opening is sealed in the vessel's liquid phase. Vapor reports out the top of the cyclone and liquid out its underflow. The separator may or may not feature a conventional vortex tube. If not, the roof plate will usually have a circular opening that is somewhat smaller than the inside diameter of the body tube. The resulting roof 'ring' serves to help prevent liquid from exiting out the top. The individual separator tubes are typically fabricated from 150 to 250 mm (6 to 10 inch) pipe.

Since the design of defoaming cyclones is based largely on tests and experience, it is difficult to provide any firm design guidelines herein. However,

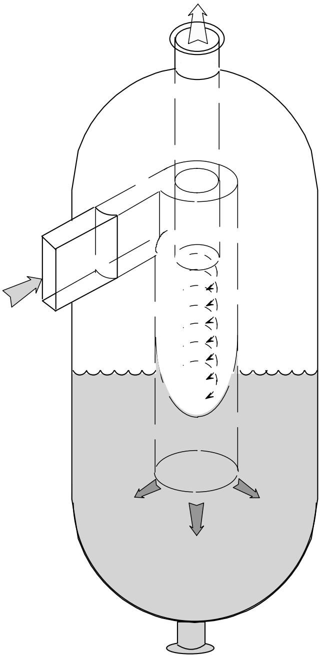

Fig. 14.1.1. A simplified illustration of a defoaming cyclone system

Mohan and Shoham (2002) report that their cylindrical-bodied three-phase gas/water/oil cyclone separator (CLCC separator, see Fig. 14.1.2) was able to break foams at gas entrance velocities in excess of 40 ft/s (12 m/s). Foam breaking was not effective at low gas velocities, i.e., 10 ft/s.

As mentioned earlier, foam-breaking or defoaming type of cyclone separators have enjoyed considerable commercial success in recent years, especially in refinery and drilling/wellhead installations handling dirty and/or heavy crudes. This is largely due to:

1. their demonstrated effectiveness in this application area,
2. their relatively low initial and operating cost,
3. the fact that they normally can be built off-site then retrofitted relatively quickly within existing gravity separators and secured in place without hot-welding and,
4. their simple construction and lack of moving parts or small openings that could plug during service.

To the industrialist faced with a production-limiting foaming problem defoaming cyclones can be a very attractive solution. Any process-related downside risks with these devices are normally deemed minor. When it comes to "selling" their use to management, their relatively low cost and potential to solve the foaming problem will normally offset any process risk concerns. They may

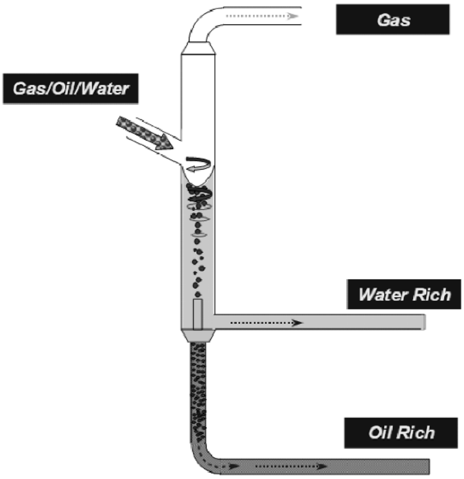

Fig. 14.1.2. A three-phase "GLCC" cyclone separator (adapted from Mohan and Shoham, 2002)

even be viewed as an improved version of an inlet distributor—something which is needed anyway.

Excessive amounts of foam in a vessel can result in a host of operating and production problems, including reduced product throughput, level control problems, excessive liquid entrainment out the vapor outlet piping, excessive vapor out the liquid underflow piping, and underflow pump cavitation problems. If foaming occurs in a compressor knockout drum it can easily flood a mesh pad or vane (chevron) separator. When this occurs, the foam carryover from the drum can severely damage the gas compressor downstream.

The traditional approach to handling foam problems involves the use of one or more commercially available antifoam chemicals. This, however, requires one to install and maintain a special chemical injection system and the on-going purchase of chemicals, which can significantly increase production costs. Foam-breaking cyclones can often significantly reduce, if not altogether eliminate, the dependency upon such chemical injection. In one Gulf of Mexico platform for which the writers are familiar, a defoaming cyclone separator eliminated the use of chemicals for an annual cost saving of about 400,000 USD.

14.2 Some Design Considerations and Factors Influencing Behavior

One of the problems in applying foam-breaking cyclones is that it is difficult to quantitatively predict, a priori, just how well they will perform in practice.

If the liquid phase viscosity is too high (greater than approximately 50 cp, for example), the dispersed foam bubbles may not respond well to the applied centrifugal field within the cyclone. Likewise, if the bubbles are too small or form a 'micro-dispersion', the separation will be ineffective.

On the other hand, the production or process engineer often is only interested in knowing if his or her unit is going to have a foaming problem or not—"yes or no?" Whether the separation efficiency is 99% or 99.8% is of less consequence. Under these conditions, experience with similar processes can be extremely valuable and, if such experience is not available 'in-house', the equipment vendor's experience may prove very helpful.

As with all foam-related problems, surface tension and surface chemistry play an important role with defoaming cyclone-type separators. Yet, in most cases of practical interest, our understanding of the coalescence process is poor. This is because many industrially important processes for which foam is a problem are characterized by heavy, 'dirty' feeds consisting of a complex heterogeneous blend of gas, oil, water, dissolved salts and, often, solids. Operating pressures and temperature may also be far removed from ambient conditions or from that which can be readily studied in a laboratory setting.

In many situations, it is not even clear if the foam is entering the feed line or if it is being generated in the receiving vessel that is having a 'foaming problem', or both. Independently of how it arises, cyclonic type separators can, in many applications, either coalesce an incoming foam or degas the incoming liquid phase so that it cannot produce a rate-limiting foaming problem downstream. In addition, since defoaming cyclones eliminate conventional "splash plates", they also eliminate this common cause of foam formation.

In certain applications, an incoming liquid stream is saturated with gas, and any decrease in static pressure will result in the liberation of gas bubbles. If this liquid is injected in a cyclonic type separator, the drop in static pressure within the core of the separator will tend to release or 'liberate' the dissolved gas so that a gaseous core is formed. A similar air core is also observed to occur in traditional hydrocyclone installations in the minerals industry. The creation of this gas core is similar to popping the cork on a bottle of one's favorite champagne or other carbonated drink. The static pressure within the core of a defoaming type cyclone type separator can easily drop to 700 mm of water column (1 psi) below inlet pressure in low or moderate pressure applications. At high gas densities, the drop in static pressure can exceed 10 times this value. The point we wish to make is that the cyclone, itself, has the potential of 'degassing' the incoming feed by reducing its static pressure. If the liquid phase is not too viscous (less than about 50 cp), the gas bubbles thus liberated may then be separated from the liquid phase.

As the liquid spirals down the walls of the cyclone and travels deeper into the liquid pool, the static pressure increases. This pressure increase is due to the increased hydrostatic head and to the loss of spin. This tends to halt the liberation of gas and helps to explain, at least in part, the workings of defoaming cyclones.

A spontaneous production of foam may be triggered by simply injecting a stream that has a propensity to foam into a conventional liquid knockout vessel. This is likely to happen if the feed stream experiences an abrupt pressure decrease upon entering the vessel. It is also likely to occur if the feed stream's incoming kinetic energy is abruptly dissipated through impact with a 'splash' or 'deflector' plate or some other device (a dished-head, for example) that is capable of generating a large amount of surface area. Ideally, one wishes to avoid splash plates and utilize the incoming momentum of the feed in a more productive way. Such cyclones can serve one of two functions. They can:

1. act as excellent inlet diffusers by eliminating the splashing that can produce a foaming problem or
2. utilize the feed stream's incoming momentum to generate high G-forces (100 to 200 G's, or more, in some applications) which act to separate any gas bubbles from the liquid phase. These same G-forces may also be helpful in separating two incoming liquid phases that may also be present in the feed stream. If the feed stream is comprised of a gas and two immiscible liquid phases, the inlet velocity may be limited by the need to prevent the formation of a liquid/liquid emulsion.

The designer has the task of sizing a foam-breaking cyclone system so that it can physically handle the combined vapor and liquid volumetric throughput without excessive liquid 'carryover' and excessive gas 'carryunder'. For example, the gas-phase vortex (shown in Fig. 14.1.1 above) must not be allowed to dip below the bottom opening of the cyclone—a condition known as gas 'blow out'. Gas blow out is most likely to occur at maximum gas rates and low liquid rates.

The designer must also be able to estimate overall gas phase pressure loss as a function of gas and liquid throughput at operating conditions. The defoaming cyclone system must sometimes be designed to handle incoming slugs of liquid so that they neither upset the process nor physically harm the equipment.

As with all such centrifugal separators, one would not normally scale up a foam-breaking cyclone by simply increasing its diameter to accommodate an increase in flow rate. From a pressure drop point of view it may be acceptable to increase (or decrease) the cross-sectional area of the cyclone body in proportion to any increase (or decrease) in feed volumetric flow rate, as discussed in Chap. 4. However, other factors being equal, the separation performance will decrease with increasing diameter and, for this reason, body tube diameter is normally held reasonably constant and the number of tubes is chosen to accommodate the total flow rate. Thus, one large 480-mm diameter separator would not be installed in place of ten 150-mm diameter separators running in parallel unless one was only interested in capturing 'slugs'. Most commercial designs appear to consist of a parallel arrangement of 2 to 6 defoaming cyclones symmetrically arranged off a common, centrally located header.

When one views the inlet configuration of some of the commercially available designs, one may question the uniformity of the gas and liquid distribution to the individual separator tubes. The gas and liquid cannot be expected to divide perfectly uniformly among the various separator tubes when injected through the feed header. However, unless there is reason to suspect some gross maldistribution, one does not have to be overly concerned about this. As we found in the previous chapter, maldistribution stemming from a nonsymmetrical inlet velocity profile in the inlet manifold leads to a rather small pressure differential at the bottom (gas-liquid interface) of the individual separators. In addition, the individual tubes are effectively isolated from one another because their underflow openings are independently sealed in the vessel's liquid pool. Hence, they do not 'communicate' with one another. This does not mean that the gas distributes itself uniformly, only that the nonuniformity does not significantly affect the liquid level within the individual separator tubes. This would not be the case if the underflow seal were lost, however. The other rather obvious factor that bears mentioning is that experience with hundreds of commercial installations has proven that the feed headers that are typically used, actually work in practice.

An even more challenging task facing the designer is the prediction of separation or defoaming performance. Here, manufacturers of defoaming cyclones must rely heavily on experience with processes similar to that under consideration. By comparing 'oil-to-gas' ratios, operating temperature and pressure, liquid phase viscosities, gravities, interfacial tensions and other such properties and operating conditions, equipment vendors are usually able to design a 'new' system that will meet the customer's process needs. In some cases, however, the vendor may not have a good reference point for comparison and a unit will be installed as a test case. This is often appropriate since the cost of equipping a separator vessel with foam-suppressing or degassing cyclones is generally not a major expenditure compared to the potential benefit.

Foam-breaking cyclones can be installed in either vertical or horizontal vessels. In some offshore drilling operations, certain vapor-liquid separation vessels are routinely retrofitted with defoaming separators if there is a known or suspected foaming problem. This is usually possible since the individual tubes can pass through existing manways and be assembled inside the main separator vessel. If necessary, the separator assembly can be supported off the inside walls of the main vessel, as well as the vessel's inlet, thereby avoiding 'hotwork'.

In tall, vertical vessels, the distance from the vessel inlet to the liquid level may far exceed the height required by the foam-breaking cyclones. This is especially true at low liquid levels within the main separator vessel. Under these conditions the cyclone body tubes may need to be extended so that their bottom openings are always submerged and sealed.

In critical applications, where one must minimize entrained liquid carryover, wave-plate or chevron type separators can be inserted ahead of the gas outlet pipe to capture any mist that may escape capture by the foam-breaking cyclones. Demisting pads, though highly effective from a separations point of view, may only be used if the system is sufficient 'clean' so that there is little or no possibility of their plugging by solids or from wax or coke deposits.

Before startup, the foam-breaking separator assembly should be thoroughly inspected for alignment, gasketing/sealing, bracing, bolting, flow obstructions, et cetera, by an inspector familiar with the design and purpose of this type of equipment.

14.3 Applications

Some typical applications for defoaming cyclones include:

- Onshore and offshore platforms
- 2 and 3-phase production separators
- Geothermal separators
- Test separators
- Flash drums
- Flare/vent scrubbers
- Free-water knock-out drums (FWKO) or slug-catching drums
- Overhead accumulators
- Underbalanced drilling separators
- Produced water degasser separators
- Recycle hydrogen vessels
- Atmospheric separators
- Gas diverter vessels
- Certain chemical processes

Manufacturers of foam-breaking or foam-suppressing separators each have their own special experience, preferred design methods, and specialized equipment offerings. Some of the equipment offered by several manufacturers is presented in Figs. 14.3.1 through 14.3.7. Hopefully, these illustrations will help reveal some of the many design details and configurations that are possible.

14.4 Estimating Submergence Required to Prevent Gas 'Blow Out'

In this section we shall present a simple method for estimating the submergence required to prevent incoming vapor from escaping out the bottom opening of a defoaming cyclone. From fluid statics, we know that the hydrostatic pressure at the bottom opening of the cyclone, at elevation $z = 0$ (see Fig. 14.4.1), must equal the hydrostatic pressure at this same elevation outside the cyclone. This leads directly to the relationship:

$$p_{uf} + \rho g h = p_{of} + \rho g H \tag{14.4.1}$$

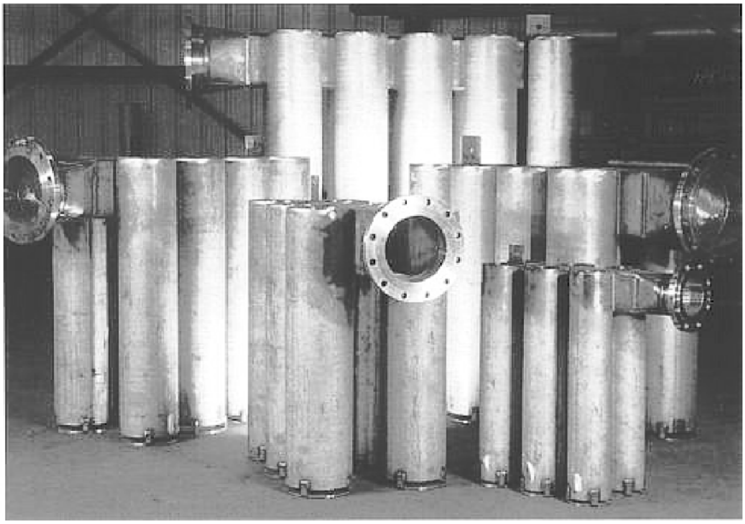

Fig. 14.3.1. A collection of Porta-Test Revolution 'defoaming' separators of various size and capacity. Courtesy Natco Group

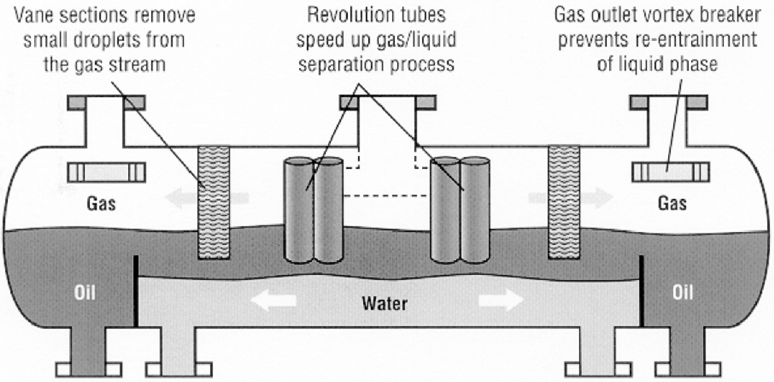

Fig. 14.3.2. A high-capacity horizontal separator featuring 'foam-breaking' Porta-Test Revolution separators as the first stage separator. Courtesy Natco Group

where p_{uf} is the gas phase pressure at the bottom of the cyclone directly above the cyclone's liquid level; p_{of} is the gas phase pressure upon exiting out the top of the cyclone (equal to the gas pressure in the vessel); ρ is the liquid phase density, and H, h are the elevations above the $z = 0$ reference plane as indicated in Fig. 14.4.1.

The cyclone's underflow and overflow pressures can be expressed as:

$$p_{uf} = p_{in} - \Delta p_{in-uf} \tag{14.4.2}$$

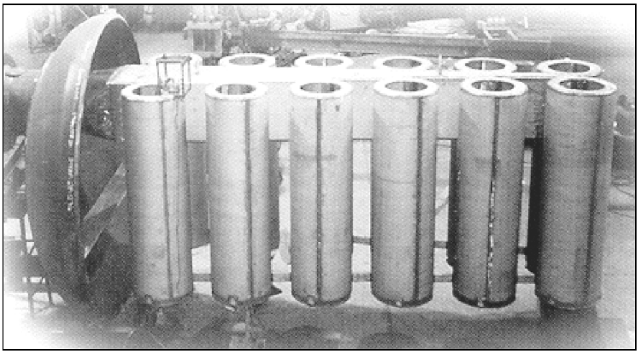

Fig. 14.3.3. A twelve-tube cluster of Porta-Test Revolution separators being installed in a horizontal vessel. Courtesy Natco Group

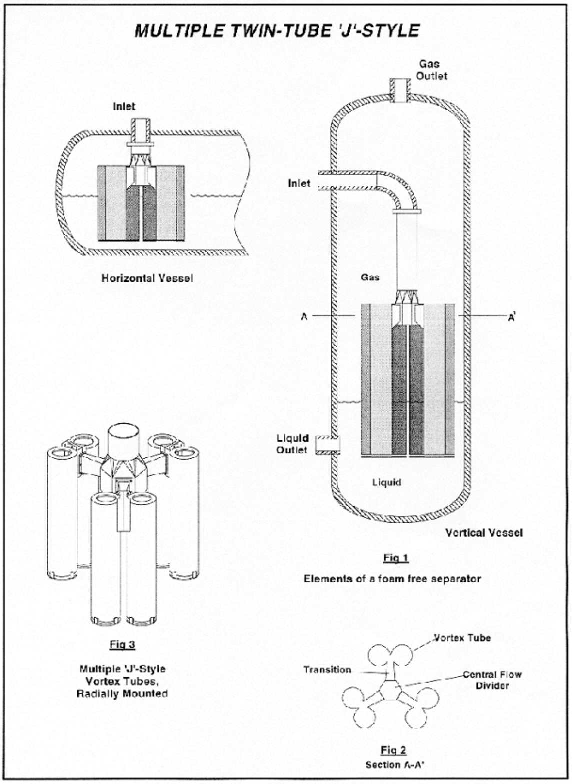

Fig. 14.3.4. A top-fed, multiple 'J' style 'Foam-Free' vortex tube assembly shown mounted in a horizontal and vertical vessel housing. Courtesy EGS Systems, Inc.

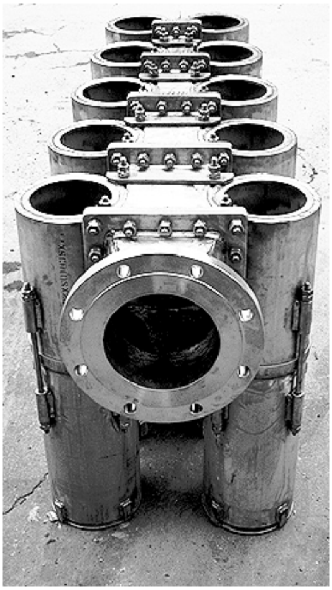

Fig. 14.3.5. A 10-tube parallel assembly of 'Foam-Free' vortex tubes shown bolted together off a central manifold inlet duct. Courtesy EGS Systems, Inc.

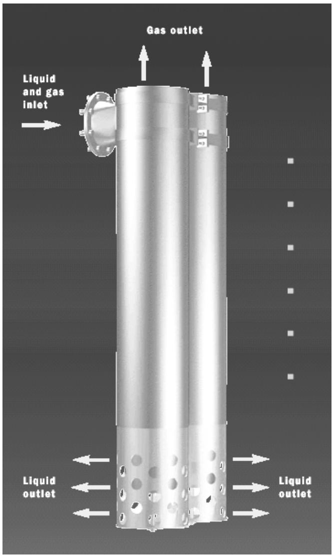

Fig. 14.3.6. A twin-tube G-Sep CCI foam-breaking cyclone cluster. Courtesy Kvaerner Process Systems

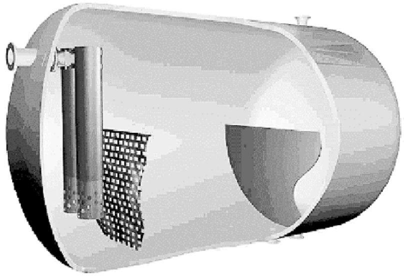

Fig. 14.3.7. A three-dimensional illustration of a twin-tube G-Sep CCI foam-breaking cyclone within a horizontal vessel. Shown also is a perforated vertical plate for improved distribution of the liquid phase(s) and a downstream, light-phase 'spill-over' baffle. Courtesy Kvaerner Process Systems

$$p_{of} = p_{in} - \Delta p_{in-of} \tag{14.4.3}$$

where p_{in} is the pressure at the cyclone inlet, and Δp_{in-of}, Δp_{in-uf} are the pressure drops from inlet to overflow and inlet-to-underflow, respectively.

Substituting Eqs. (14.4.2) and (14.4.3) into Eq. (14.4.1) and simplifying:

$$\rho g\,(H - h) = \Delta p_{in-of} - \Delta p_{in-uf}. \tag{14.4.4}$$

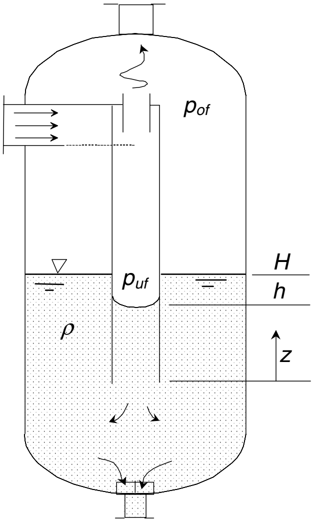

Fig. 14.4.1. A cyclonic type separator with liquid sealed underflow

This equation relates the elevation of the liquid level in the cyclone, h, to the submergence, H, and the inlet-to-overflow and inlet-to-underflow pressure drops across the cyclone. If conditions are such that h (measured upwards from the reference elevation $z = 0$) becomes 0, gas will begin to blow out the bottom opening of the cyclone. Setting $h = 0$ and solving for H, Eq. (14.4.4) becomes

$$H = \frac{\Delta p_{in-of} - \Delta p_{in-uf}}{\rho g} \tag{14.4.5}$$

This equation provides a relatively simple method for computing the minimum submergence, H, required to prevent gas from blowing out the bottom of the cyclone. An example calculation is presented in Appendix 14.A.

'Blow out' is to be avoided since it can lead to several problems, including:

- product gas exiting out the vessel's liquid underflow pipe
- cavitation of the underflow pump
- liquid entrainment out the top of the vessel (as the result of rising bubbles)
- foam generation, and
- disturbance of any hydrocarbon/water separation that may be occurring in the liquid phase of the main vessel.

The pressure drops appearing in Eq. (14.4.5) should be computed on basis of gas-liquid cyclone pressure loss correlations developed for the particular design geometry and operating conditions that apply. Lacking such data, one may use a more 'generic' pressure drop correlation—at least for the computation of the inlet-to-overflow pressure loss.

Very few correlations are available for predicting the inlet-to-underflow pressure loss. This is also the case for gas-solids cyclones but is especially true of gas-liquid cyclones. The Muschelknautz method described in Chap. 6 for gas-solids cyclones may be used for rough estimation purposes if one substitutes the friction factor for gas-liquid cyclones (see Chap. 13) in place of the gas-solids friction factor. However, as a word of caution, the writers have observed that this correlation tends to overpredict actual pressure losses. Clearly, neglecting the inlet-to-underflow pressure loss altogether in Eq. (14.4.5) will lead to a conservative estimate of the minimum submergence, H.

If the separator under consideration is a commercially available design, one should consult the manufacturer regarding expected pressure losses. Manufacturers normally develop their own correlations for pressure loss and other key system performance measures—applicable to their particular line of equipment. This information, understandably, is not generally reported in the open literature.

One should normally submerge the bottom opening of the cyclone (or cyclones) sufficiently to handle a gas flow rate 50% greater than 'design' operating conditions—more in some applications. In addition, the cyclone bodies may have to be extended (beyond that required for separation or normal sealing purposes) if the liquid level in the vessel housing the cyclones is likely to drop significantly during operation.

14.A Example Computation of Submergence Required to Prevent Underflow Gas 'Blow Out'

A defoaming cyclone-type separator is to be installed to prevent excessive foam-related problems in a commercial high-pressure 'test separator' handling a heavy crude feed. We wish to use Eq. (14.4.5) to estimate the submergence required to prevent gas from blowing out the separator's underflow opening. The cyclone's pressure drops and the liquid density at design conditions are:

$\rho = 750\ \mathrm{kg/m^3}$
$\Delta p_{in-of} = 5200\ \mathrm{Pa}$
$\Delta p_{in-uf} = 1200\ \mathrm{Pa}$

Solution

Substituting into Eq. (14.4.5):

$$H = \frac{\Delta p_{in-of} - \Delta p_{in-uf}}{\rho g}$$

$$H = \frac{(5200 - 1200)\ \mathrm{Pa}\frac{\mathrm{N}}{\mathrm{m^2Pa}}\frac{\mathrm{kg\ m}}{\mathrm{N\ s^2}}}{750\frac{kg}{m^3}9.81\frac{m}{s^2}} = 0.54m(1.8ft)$$

Thus, at 'design' conditions, the bottom opening of the separator should be submerged no less than 0.54 m below the vessel's normal liquid level. In practice, we would want to apply a safety factor of 1.5 (or more) and increase the submergence to 0.8 m or 2.6 ft.