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LARGE SCALE GAS SEPARATORS

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Large Scale Gas Separators

by

J. A. Hafford

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OAK RIDGE NATIONAL LABORATORY

Operated By

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Previous work done on gas separators has been done on a small scale.⁽¹⁾

In view of the anticipated progress of the homogeneous reactor program, a need for large scale gas separators is expected. This report deals with experiments with separators an order of magnitude larger than those heretofore tested. Attempts are made to set up some criteria for design of any size separator needed.

Several specific problems were investigated, such as void size, inlet disturbances, entrainment behavior and flow patterns.

General Information

The entire system was of low pressure carbon steel construction. The separator proper consisted of two sets of fixed vanes. One set for creation of a vortex, and one set for recovery of rotation energy. The recovery vanes had a reversed curvature from the rotation vanes, and the inlet, or leading, edge had an angle slightly less than the rotation vanes to allow for decay of the vortex. The separator was placed in a 14-in. diameter pipe and pumps capable of 6000 gpm at 100 psi head were used to move water through the system. Figure 1 is a schematic layout of the equipment.

Two different sets of vanes were used at different times. The vanes of the first set were compound curved in order to come as close as possible to a constant angle discharge. Figures 2 and 3 are photographs of these sets of vanes. This set of vanes was also designed around a hub to be used only with a large void. Two different ells were placed before the rotation vanes to determine the influence of the inlet disturbance; first a long-radius ell and later a vaned miter ell.⁽²⁾ There was provision for injecting air directly to the void of the vortex created by this vane system while the radius ell was in place but not when the vaned ell was in place.

A second set of vanes was a simple geometric scale up of the separator vanes reported on as Model II in ORNL-1602. These vanes have a simple

curvature of nominally 45 degrees, and were inaccurately analyzed in that report. In Appendix A is the development of the expression for the angle of discharge as a function of pipe radius for these vanes, as well as the theoretical flow patterns. Figures 4 and 5 are photographs of these vanes prior to installation.

The simple curved vanes are much easier to fabricate. The compound curved vanes require special forms and a high degree of skill to build. Figure 6 is a photograph of the form necessary to shape the compound vanes. Figure 7 is a photograph of the system prior to assembly for the first time and Figures 8 and 9 are sketches of the separator in place with the different vane systems.

The gas take off line was standard 5-in. pipe inside the separator and standard 6-in. pipe outside for the compound vanes, with a run of 30-ft., including two 90 degree ells to a 500 gallon hold up tank where the entrainment could be dropped out and metered. The simple vanes had a 3-in. line from the separator to the holdup tank and it was only 20-ft. long.

An island or "frog" was used in the gas takeoff line of the compound vane system to prevent the total collapse of the void if gas flow ceased. Figure 8 shows the location of this frog. It was actually mounted about 1 pipe diameter downstream within the recovery vane hub, leaving an annulus for the air and entrained water to pass. The ratio of the cross sectional area of the annulus to the cross sectional area of the pipe was 0.28. Later the ratio was increased to unity by increasing the I.D. of the pipe at the annulus. Manometers were used to measure the various pressure drops throughout the system. The water flow was measured with an orifice. Air was measured at two points; the air flow was metered into the void through an orifice and metered directly into the stream of water through a flowrator. Some pitot tube measurements were made to estimate the existing flow patterns. These are considered to be crude and only useful for approximate analyses.

Gas removal efficiency was estimated by observing visually the amount of bypassing of the gas in the liquid stream. This estimate was standardized by observing the appearance of deliberately bypassed gas of known volume.

Test Operation

The separator was operated both at 5000 gpm and 3000 gpm of water during routine runs at from 1 to 2 atmospheres of pressure. For stability limit tests, it was necessary to operate at flow rates as low as 2400 gpm where the void then lost stability. The change in flow rate was achieved by manipulating the discharge valve on the circulating pump. The pump had a discharge head of some 100 psi gauge and for small variations in pressure, a valve on the discharge line from the separator was used to provide back pressure, thus raising the separator pressure.

The air used for actual separation tests was injected into the water about 10 ft. upstream from the inlet vane. The maximum amount of air available for injection into the water was about 100 scfm. On the first runs, while testing the large void, an additional 400 scfm was available for injection directly to the void. This air was introduced through the rotation vaned hub and could be injected only while the radius ell was in place. It would have required quite an extensive extra effort to modify the vaned ell to provide direct air injection to the void and was not felt to be worthwhile.

The runs made were as follows:

1. Operation at 5000 and 3000 gpm of water with compound curved vanes. Air from 0 to full, this with the radius ell in place. Void stability and gas removal was observed and entrainment measured. These tests were repeated at slightly higher pressure.

2. The annulus around the frog was enlarged. Runs described under 1 repeated.

3. Operation at 5000 and 3000 gpm. No air being injected so that pitot tube measurements could be made.

4. Radius ell removed and replaced with vaned miter ell. The rotation vanes were fitted with a plug to prevent bypassing of water through the center. Stability observations made and gas removal observed. Entrainment measured and pitot tube measurements were made at both 5000 and 3000 gpm.

5. New vanes constructed of simple curvature and installed. Small void takeoff and higher degree of rotation. Gas removal and void stability observed. No pitot tube measurements were made. All runs made with vaned miter ell. Liquid flow rates were 5000 and 3000 gpm, and gas up to 100 scfm and, as before, the pressure was varied up a few pounds.

During all of the operation of the separator, the carbon steel system was protected against corrosion by the use of sodium hexa meta phosphate. This protection was quite effective for the system except for the region within the vanes where the intense degree of turbulence apparently removed the protective film from the steel and permitted corrosion to take place.

Results

In all of the tests with the compound curved vanes, it was quite apparent that the degree of rotation was inadequate to give best results. Particularly, with the radius ell in position, the inlet disturbance was too great for any real degree of stability and permanence of the void. In spite of this, the gas removal was reasonable; definitely better than 90 per cent of the gas injected to the water and all that was injected to the void. However, the primary purpose of the large void separator was to provide a stable void which would persist even upon the loss of gas flow. In the case where the separator was installed with the radius ell, prior to the rotation vanes, the void would immediately disappear upon loss of air, completely cancelling any value of the frog. When the radius ell was replaced with a vaned miter ell, this condition was corrected. The void became much more stable and persisted for several minutes when the gas flow was cut off.

In spite of the improved stability and persistence of the void, the entrainment of water in the gas takeoff line was still rather large. It was then

decided that a more intense void or vortex would be necessary.

With the compound curved vanes operated at a water flow of 5000 gpm and a variety of gas flow rates, the gas was adequately removed, in every event, although with excessive water entrainment in the range of 125-200 gpm. This minimum of entrainment was achieved by restricting the flow through the gas takeoff line. The pressure in the system was varied up to about 35 pounds gauge but this simply served to give more control to the gas removal. This system was operated at about 1/2 the previous flow, that is 3000 gpm. The same tests were run and indications were void stability was adequate even at this low rate, and approximately the same entrainment was experienced. Gas separation was perhaps not quite as good, however.

The pitot tube measurements at 5000 and 3000 gpm were quite rough. Figure 10 shows these velocity results.

The radius ell was removed and replaced with the vaned miter ell. The runs taken under these conditions did not have gas injection directly to the void; however, 100 standard feet of cubic air per minute was injected into the water upstream from the vanes and the efficiency of the separator was tested. The performance as a separator appeared to improve considerably. About 95 per cent of the air was removed.

Again, entrainment was measured and pitot tube measurements made at both 5000 and 3000 gpm. Entrainment was slightly less and pitot tube measurements showed little deviation. The main difference was in the ability of the void to persist after the gas flow had been stopped and water and gas still being removed from the separator. The void persisted for perhaps several minutes after the discontinuation of gas injection to the water.

After enlargement of the annulus around the frog, the pressure drop across the frog was very little more than ordinary pressure drop through the pipe itself. Prior to enlargement of the annulus, the pressure drop had been rather high, although no exact figures could be arrived at. The final set of runs were made without a frog in place at all. It was observed that the

void was still large and in fact there was no difference as long as the gas was flowing. Of course, the void immediately disappeared upon discontinuation of gas flow; however, when the gas takeoff line was closed and the gas flow stopped, the void did persist as though the frog was still there. This indicates that the controlling factor on void size is not the frog but the actual inner diameter of the gas takeoff line. An actual system could probably be designed so that the frog would be unnecessary.

The second set of vanes constructed was of simple curvature as previously described. These were installed in the same fashion as the first set of vanes after the miter ell was in place. The void here was much smaller and there was no effort made to maintain it. That is, there was no frog in the takeoff line. Figure 9 is a sketch of this system as it was operated. These vanes gave a much higher degree of rotation, according to the analysis. Gas removal and void stability were correspondingly better. At least 98 per cent of the air was removed.

No tests were made with the radius ell in front of the rotation vanes, although it is almost certainly true that stability of the separator would not be quite as good. However, with a higher degree of rotation, it is felt that the separator would function adequately even with the radius ell in place except with perhaps a greater entrainment in the gas take off line.

Entrainment experienced with the second set of vanes was very low (about 10 gpm). The entrainment was approximately 0.15 per cent of the throughput of water through the gas separator, whereas with a previous set of vanes, the entrainment was an order of magnitude greater. Although no pitot tube measurements were made, pressure drop observations indicated that flow patterns were very similar to those experienced with the smaller separators.

The shape of the vaned hubs was found to be somewhat critical for stability of the void; that is, the leading edge of any obstruction in the flowing stream should be made a paraboloid to aid in stabilizing flow. This

is evidently an important consideration as the performance of the separator improved markedly with the change from spherical to parabolic shape. This would indicate that all leading edges of vanes, if the vanes are thick, should be parabolic in cross section. This may become important as the separators are further increased in size.

The efficiency of the vanes tested was not directly calculated; however, the smaller systems demonstrated an efficiency of 90 per cent for the rotation vanes and 80 per cent for the recovery vanes. These efficiencies represent the per cent of static pressure energy conversion to and from kinetic energy. Pressure drop measurements on the large separator indicate that the same efficiencies exist that were measured on the small separators, at the same average actual velocity. The compound curved vanes appeared to have slightly better efficiency than the simple curved system, thus implying less turbulence and perhaps less of a corrosion problem.

The recovery vanes functioned very well. From experiments on small gas separators, it was apparent that reversed vanes would be adequate, evidently, for both types of vanes. This is borne out by the large system. The tangential velocity pattern decays slowly and retains its shape. The axial flow pattern seems to fluctuate but not sufficiently to disturb the efficiency of the recovery vanes. The cause of the extreme difference in entrainment between the two sets of vanes was not firmly established. It is felt to be a result of both the difference in void size and vortex strength of the two vane systems.

Two Phase Flow

In the gas takeoff line a condition of two phase flow was met. The behavior of the flow was investigated as to pressure drop and flow type, in view of the increase in pipe size over any known published data.⁽³⁾ Unfortunately, it was not possible to accurately measure the pressure drop conveniently. The errors involved in measurement were probably 50 per cent

plus or minus; however, the data indicates that the ratio of measured ΔP over calculated ΔP increased with pipe size. For the 3-in. pipe the ratio was about 3 to 1 and for the 6-in. pipe it was about 6 to 1. Calculations merely consisted of extrapolating the published data on small pipe to the size used here. More tests should be run on large pipe before design of two phase systems is made. Table I gives the data collected.

A section of glass pipe was included in the takeoff line to permit observation of the flow type. In the 6-in. pipe the flow was largely stratified. The water layer very slightly slugged at times and had a very frothy surface. The annular type of flow was definitely not observed. For the 3-in. line the flow was definitely into the annular region although not fully developed. That is the thickness of the lower layer of water was larger than the upper layer. Occasionally, very light frothy slugs would pass through the system.

Vane Theory

Flow through stationary vanes has been discussed in previous reports⁽¹⁾ and there is some literature on the subject available.⁽⁴⁾ The second set of vanes tested and reported on in ORNL 1602 were described as having a constant angle discharge. This was an error. The compound curved vanes herein reported do have a constant angle discharge and the theoretical velocities follow the curve given by $V = \frac{K}{\sqrt{r g c}}$. These measurements are not considered accurate enough to permit any conclusions.

The set of vanes with simple curvature are analyzed in Appendix A. The discharge angle is given as a function of pipe radius and the subsequent flow patterns are given in Figure 11. No measurements were made to compare with the theoretical curve. The measurement techniques were not felt to be accurate enough and during installation, several of the vanes were damaged, causing doubt to be thrown on the results. However, the bent vanes could only create void instability, and hence performance of an undamaged set should be better.

TABLE I
TWO-PHASE FLOW DATA IN GAS TAKEOFF LINE

6-in. Line

<u>Air Flow</u> <u>Lb./Sec.</u>	<u>Water Flow</u> <u>Lb./Sec.</u>	<u>Calculated</u> ΔP <u>"Hg</u>	<u>Measured</u> ΔP <u>"Hg</u>
0.395	20.7	0.39	2.1
0.257	24.2	0.90	2.0
0.146	29.5	0.94	2.5
0.674	20.0	0.28	2.5
0.373	37.0	0.22	2.1
0.384	51.8	3.9	3.0
0.262	34.3	0.17	0.8
0.392	29.6	0.20	1.5
0.614	19.9	0.16	1.5

3-in. Line

0.17	19.2	0.37	0.7
0.17	9.8	0.23	0.8
0.17	18.8	0.37	0.8
0.17	45.7	0.83	3.0
0.17	63.8	1.15	5.0

These vanes are very similar to the vanes described in ORNL 1602 as having constant angle discharge, and the analysis of these vanes would be very similar to a correct analysis of the vanes described previously.

Fluid Mechanics

No attempt is made here to solve the basic behavior of the fluid dynamics of the system. It was not felt that time or personnel were available for a long term study of these problems. It is apparent from the frequent peculiar behavior of the system that much is to be learned about the detailed internal mechanics of the vortex. The question of radial flow and negative flow were not touched on. Calculations of static pressure from measured tangential velocities indicate that a negative flow may possibly exist at the center of the vortex. Certainly, detailed studies of the flow within the vanes themselves would give interesting and perhaps useful information. The deviations of the actual flow patterns from theoretical predictions would be worth investigating. There are undoubtedly many more problems that are deserving of study. Volutes and helical vanes are possible mechanisms for handling vortices. These were not looked into from the standpoint of use in large equipment. In a long range program, these mechanisms may offer advantages which should not be ignored.

A study of any vortex reveals the pressure distribution existing due to centrifugal forces. This pressure distribution will act in favor of self control of a gas separator. The fixed maximum radius causes the pressures at the interface to be dependent on the void diameter. That is, the larger the void, the higher the pressure. It can be readily seen that with a larger void, more gas is to be removed and the extra pressure is automatically provided. Also, the entrainment would be less and thereby creating less pressure loss in the off gas line, again contributing to the effective removal of gas. Thus, a gas separator of this type may well be self-controlling.

In any event, before one endeavors to design a gas separator, one should study the existing literature carefully in order that he can understand as much as possible of the behavior of the vortex.

Length Between Vanes

The removal of the gas from the stream is a function of a number of variables. These are set forth in reports by F. N. Peebles⁽⁵⁾ and J. O. Bradfute.⁽⁶⁾ Most of the variables are known, but in any system, the velocity patterns and bubble sizes will be difficult if not impossible to fix. If we assume the velocity patterns measured for the compound curved vanes are correct, then it can be approximated that bubbles larger than 0.15 inches in diameter will adequately migrate to the void. The longer the vortex, the greater the chance of removal of gas. Appendix B gives the calculation for showing length of the separator required.

General Design Limits

In the design of an actual gas separator, one can be confident of the performance up to a certain degree. There are a few limitations that must be carefully observed but, in general, a great deal of latitude is available. Several rules can be made which will describe these limits.

1. Stability of the void can be reached by providing sufficient rotation to overcome gravitational forces. Any means of rotation can be used to accomplish this.
2. Leading ends or edges of obstructions should be smoothly shaped parabolic surfaces.
3. The ends of the gas void should always be stabilized on fixed convex surfaces. This is particularly important on the downstream end.
4. Inlet disturbances should be minimized as much as possible, depending on other requirements for the separator.

The above rules merely are guides to assist in avoiding basic flaws in separator design; any given design should be tested prior to use, as there

are many problems untouched on which could have a strong influence on separator performance.

The test determining minimum limits on void stability definitely established the following criterion.

$$F = \frac{V_t}{\sqrt{rg}} \geq 1$$

where F is the modified Froude number, V_t is the tangential velocity and r is the pipe radius. For conservative design, F should be calculated for a number of radii and the smallest value used. It has been found that if F is greater than or equal to 1, the void will be stable and it should be about 4 for safety. With the flow at 5000 gpm, the compound curved vanes $F \approx 4$; for the simple curved vanes $F \approx 5$.

Conclusions

It is quite definite that large gas separators can be successfully operated. There appears to be a mathematical expression describing a stable void for any given set of vanes.

Whether or not compound vanes are to be preferred would depend upon the possibility that compound curved vanes created less turbulence in the system and perhaps thereby cause less corrosion. Unless this is the case, simple curved vanes would definitely be more desirable from the standpoint of ease of fabrication.

It seems apparent that the separators tested were not long enough. Another 4 or 5 feet would be necessary for truly complete separation; however, virtually a 100 per cent separation of gas is definitely possible.

Estimates indicate that the separator rotation vanes are approximately 90 per cent efficient and the recovery vanes are about 80 per cent efficient. This efficiency is based on a percentage of successful conversion of energy.

Any final design must be tested before use. The details of the separator (i.e., elbows preceding it, rotation and recovery systems, large or small void, etc.) must be tailored to fit into the flowsheet and layout of a

particular plant.

Entrainment in the gas takeoff line may be dependent on a number of things. A high degree of rotation would undoubtedly decrease entrainment, although entrainment is also a function of void size.

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Analysis of Simple Curved Vanes

The angle of discharge of a vane at any radius r of the pipe within which the vane is located, is the angle between the plane surface of the trailing edge of the vane and the element, e , of the cylinder, r , that passes through the plane p . In order to see this angle better and to derive an expression for it, one must lay out the intersection of cylinder of radius r and plane p .

From Figures 12, 13, and 14, we define.

ϕ = nominal discharge angle of vane

r_h = hub radius

r = given cylinder radius

R = inner radius of pipe

e = element of cylinder r that intersects trailing edge of vane

p = plane surface fixed by trailing edge of vane

θ = throw of trailing edge of vane

s = arc of throw θ at cylinder r

Now it can be shown that

$$y = r \tan (90 - \phi) \sin \frac{s}{r}$$

and $\frac{dy}{dx} = \tan (90 - \phi) \cos \frac{s}{r}$

for $\phi = 45^\circ$

$$\frac{dy}{dx} = \cos \frac{s}{r} \text{ or } \cos \theta$$

$$\tan^{-1} \frac{dy}{dx} = \phi'$$

and actual vane discharge angle is

$$90 - \phi' = \phi_t$$

where ϕ_t = time discharge angle and $\phi' = 90^\circ - \phi_t$

In any vane system, the relationship

$$(1) \quad \frac{V_t}{V_a} = \tan \varphi_t \quad \text{where } \varphi_t \text{ is a function of } r$$

From vane theory, we get the relationship

$$(2) \quad V_t \frac{V_t}{r} \frac{dV_t}{dr} + V_a \frac{dV_a}{dr} = 0$$

for a set of fixed vanes with no prerotation and assuming a flat axial velocity distribution. As an example of the use of the above equation, we will solve the case of the simple curved vanes.

$$(3) \quad \text{set } \tan \varphi_t(r) = K(r)$$

then a solution of the above equations yields

$$(4) \quad \frac{dV_a}{dr} = - \frac{C_1}{C_2} V_a$$

where

$$(5) \quad C_1 = \frac{K^2}{r} + K \frac{dK}{dr}$$

and

$$(6) \quad C_2 = K^2 + 1$$

Now equation (4) is solved by trial and error for various values of r .

The resultant curve is tested by averaging the V_a for continuity and V_t is found from equation (1). Figure 11 shows the curves for the simple curved vanes.

Using equation (2) again, this time for the compound curved vanes, and since

$$\frac{V_t}{V_a} = \tan 45^\circ = 1$$

$$\text{then } V_a = V_t = \frac{c}{r}$$

C was evaluated to be 0.401.

The theoretical curve is shown in Figure 10.

APPENDIX B

The required length of a gas separator may be calculated if a number of variables are fixed., i.e., bubble size, velocity profiles, fluid properties, etc. These variables may not be known accurately, but approximations can be made.

If we assume that the bubbles are all large, above 1/4-in. in diameter, then the equation 29d, from the report by F. N. Peebles will hold.

$$\bar{U} = 0.825 \left[\frac{N_G^4}{g} \right]^{0.083} \left[\frac{\gamma g c}{1} \right]^{0.250}$$

where $\bar{U}$ = radial velocity of the bubble relative to the fluid

g = gravitational constant

γ = surface tension of the liquid

ρ_1 = density of the liquid

and
$$N_G = \frac{8V_t^2 (\rho_1 - \rho_2)}{3R \rho_1}$$

where V_t = tangential velocity at R

R = radius in question

ρ_2 = density of gas

The tangential velocity measured for the compound curved vanes averaged about 15.6 ft./sec.

$$\frac{\rho_1 - \rho_2}{\rho_1} \cong 1$$

$$\bar{V}_t \cong 15.6 \text{ ft./sec.}$$

$$\bar{R} = 0.442 \text{ ft.}$$

$$\gamma = 0.00513 \text{ lb./ft.}$$

$$\rho_1 = 62.4 \text{ lb./ft}^3$$

thus

$$N_G = 1470$$

and
$$\bar{U} \cong 1.6 \text{ ft./sec.}$$

Since the bubble must move through 0.202 ft., the time required is
 ~ 1.3 sec.

The residence time between vanes is greater than 1.3 sec., therefore, all large bubbles will reach the void in time.

If we further assume that 0.2 ft./sec. is the minimum radial bubble velocity for separation, (this is based on residence time), we can estimate the minimum bubble size that will migrate to the void regardless of where it enters the vortex. Using equation 29c from Peebles's report

$$U = 0.155 N_G^{0.758} \left[\frac{\rho_l}{\mu} \right]^{0.515} R_b^{1.272}$$

where μ = viscosity = 8.8×10^{-4} lb./ft./sec.

$$\bar{U} = 0.2 \text{ ft./sec.}$$

and R_b = bubble radius.

Solving this equation, we get

$$R_b \cong 0.08 \text{ in.}$$

Therefore bubbles of less than 0.08 in. in radius will not all be removed from the flowing stream of the separator as built.

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Fig.1. Schematic Diagram of Test Equipment.

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PHOTO 20949

Figure 2. Compound Curved Rotation Vanes.

Figure 3. Compound Curved Recovery Vanes.

Figure 4. Simple Curved Rotation Vanes.

PHOTO 22860

Figure 5. Simple Curved Recovery Vanes.

Figure 6. Forms Used to Shape Compound Curved Rotation Vanes.

Figure 7. Gas Separator Prior to Initial Assembly Showing All Parts.

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Fig. 8. Arrangement of Separator with Compound Curved Vanes and Radius Ell.

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Fig. 9. Arrangement of Separator with Simple Curved Vanes and Mitred Ell.

Fig. 10. Theoretical Curve for Compound Curved Vanes and Some Data Points.

Fig. 11. Theoretical Flow Patterns for Simple Curved Vanes.

Fig. 12. Plan View of Vane Showing Discharge Angle.

Fig. 13. End View of Vane Showing Angle of Throw.

Fig. 14. Intersection of Cylinder, r , and Plane, p .