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ANALYSES OF THE RADIAL SEPARATOR

By
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February 6, 1962

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TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	5
II. SUMMARY AND CONCLUSIONS	6
III. SPREAD ON RADIAL SEPARATOR VANE CAUSED BY CENTRIFUGAL FORCE.	7
VI. BUBBLE SEPARATION ANALYSIS	10
V. REFERENCES	19

I. INTRODUCTION

This memorandum presents some mathematical analyses of the performance of the radial or vane type of steam separator. A previous report (Reference 2), to which this is an addendum, described air-water and steam-water tests of radial separator models.

The radial separator is a primary steam separator which is being developed for superheat reactor use. Radial vane separator assemblies generally consist of a number of curved vanes installed between the core flow discharge plenum and the reactor vessel wall. The inlet mixture enters the vanes through nozzles inside the plenum wall and is separated into steam and water by the centrifugal force generated by the curved surface of the vane and by the buoyancy of the steam. Steam flows upward between the vanes, and water discharges from the vane ends into the downcomer annulus formed by the vane ends and the downcomer shroud or vessel wall.

The radial separator operation depends upon the interaction of many parts. These include the entrance to the nozzle, nozzle flow, discharge or jetting from the nozzle, separation of vapor from liquid on the vanes, flow of separated steam between vanes, discharge of separated water from the vanes, and flow in the downcomer. Complete analysis of this system is not now achievable, and, in fact, is unlikely because of the complexity. However, simplified analyses are possible and can be of considerable use in supporting and guiding tests.

II. SUMMARY AND CONCLUSIONS

The analyses presented in this report are both concerned with flow on the vane. The first is concerned with the spread of flow on the vanes due to centrifugal force, which necessitates making the vane height greater than the nozzle. The second analysis deals with the separation of the vapor from the liquid.

The following conclusions are indicated:

1. Spread on the vane due to centrifugal force is not severe and amounts to about 4 inches above and below the nozzle for a 4-inch radius vane with an 18-inch $\frac{1}{2}$ -inch wide nozzle. Nozzle velocity does not affect the spread due to centrifugal force.
2. Further experimental work on drag coefficients and bubble sizes is necessary to prove or disprove the equations derived for bubble separation. The conclusions from the analysis are now strongly dependent on many assumptions.
3. The analysis of bubble separation shows that nozzle velocity can be increased without exceeding the limits for separation if:
 - a. The vane radius is increased
 - b. The film thickness is decreased
 - c. The available arc length is increased
4. The analysis tends to indicate that complete separation on the vane was to be expected in the range of air-water tests conducted. Lack of knowledge of drag coefficients in 545°F water makes a similar calculation difficult for the steam-water tests. The analysis also strongly suggests that separation on the vane is not likely to be a major limitation or problem for the radial separator.

III. SPREAD ON RADIAL SEPARATOR VANE CAUSED BY CENTRIFUGAL FORCE

After the film of mixture leaves the nozzle of the radial separator, it will tend to spread out on the vane because of the centrifugal force. It is desirable to predict this spread effect so that the vane height can be made sufficiently greater than the nozzle height so fluid does not escape from the top and bottom of the vanes. An analogous hydraulics problem is the determination of the water surface in flat bottom open channel flow following a sudden expansion in the walls. The solution is presented in the form of a graph in Reference 1 in which:

x is distance in the direction of flow in the channel before expansion or in the nozzle of the separator.

y is the depth of the fluid in the channel or on the vane.

y₁ is the depth of the fluid before expansion or the nozzle width for the radial separator.

z is the distance from the channel or nozzle center plane measured in the direction perpendicular to nozzle flow. z is the measure of spread on the vanes.

B₁ is the width of the channel or the nozzle height before expansion

F₁ is the Froude number = V_1

For the radial separator, instead of $\sqrt{gy_1}$, we have a centrifugal field of $\frac{V^2}{R}$ where R is the vane radius. Consequently, the "Froude" number for the radial separator is: $F_1 = \sqrt{\frac{R}{y_1}}$

With these changes, Figure 55 can be used to determine the contours $\frac{y}{y_1}$ as a function of distance from the nozzle. Figure 55 has lines of constant $\frac{y}{y_1}$ between 0.1 and 0.9 for Froude numbers of 1, 2, 4, and 8.

To determine the spread on a vane of a particular radius and nozzle, points of $\frac{Z}{B_1}$, from Figure 55 (at a value of x corresponding to the vane length) can be plotted versus $\frac{y}{y_1}$ and extrapolated to $\frac{y}{y_1} = 0$. For example take a 4-inch radius vane with an arc of 130° and a nozzle 18 inches high and $\frac{1}{2}$ -inch wide.

$$F_1 = 4$$

$$B_1 = 18 \text{ inches}$$

$$\frac{x}{B_1 F_1} = 0.125$$

$$y_1 = \frac{1}{2} \text{ inch}$$

From the graph the values of $\frac{Z}{B_1}$ are found for $\frac{y}{y_1}$.

$\frac{y}{y_1}$	$\frac{Z}{B_1}$
0.1	.65
0.2	.58
0.3	.53
0.4	.51
0.5	.51
0.6	.50
0.7	.49
0.8	.47
0.9	.39

Extrapolating to $\frac{y}{y_1} = 0$ gives $\frac{Z}{B_1} = 0.72$ or $Z = 13$ inches. Since the nozzle half height is 9 inches, the fluid will spread $13-9 = 4$ inches by the end of the arc.

According to the analysis, the nozzle velocity does not affect the amount of the spread.

This analysis has been derived for single phase flow. It may also be conservative for a separator which will operate with two-phase flow. In two-phase flow, separation of vapor will tend to reduce the effective depth to less than the nozzle width. The smaller the initial depth, the less will be the spread.

Fanning out of the flow after it leaves the nozzle may also be caused by various nozzle exit conditions, but these are not considered in this analysis

which is limited to centrifugal force. Because of these nozzle conditions, it is not possible to use the test results to confirm the analysis. It can be said, however, that the observed spread on the 4-inch radius vanes was not substantially different from the analytical prediction.

IV. BUBBLE SEPARATION ANALYSIS

A. Symbols and Diagram of Model for Bubble Separation Analysis

D Bubble diameter

θ Angle bubble travels along vane before separation

t Water thickness for bubble to traverse

V Circumferential velocity of water and bubble

U Radial velocity of bubble relative to water

F_D Drag force

C_D Drag coefficient

ρ or ρ_f Liquid density

ρ_g Vapor density

g_c 32.2 lb. ft./# sec.²

R Vane radius

F_B Centrifugal force on bubble

σ Surface tension

a Characteristic acceleration

C Constant describing geometry before separator

R_e Reynolds number for bubble

K Constant - depends on fluid and R_e

n Constant - depends on fluid and R_e

μ Viscosity

B. The Model and Derivation of Conditions for Separation

The analysis is concerned with the bubble which will travel the farthest and will be the last to be separated, since it indicates the capacity limit of the separator. This bubble has a diameter D , starts its travel from the separator wall, and travels an angle θ to pass through a thickness t before complete separation.

The equation of motion for the bubble can be found by equating the forces. In the range of interest it is possible to neglect gravity force and to assume that the time for the bubble to reach a steady state velocity U is negligible. Slip of the bubble relative to the water in the circumferential direction is assumed to be zero. Turbulence in the water is neglected. With these assumptions, the equation of motion is obtained by equating the drag force with the centrifugal force.

$$F_D = \frac{C_D \pi D^2}{4} \rho_f \frac{U^2}{2g_c} \quad (1)$$

$$F_B = \frac{1}{6} \pi D^3 \frac{(\rho_f - \rho_b)}{g_c} \frac{V^2}{R} \quad (2)$$

$$F_D = F_B \quad (3)$$

For conditions of interest $P_f - P_g \approx P_f$

so that (1), (2), and (3) combine to give: $U^2 = \frac{4V^2 D}{3RC_D}$ (4)

Next, consider the time τ required for the bubble to separate.

$$\tau = \frac{R\theta}{V} \text{ and also } \tau = \frac{t}{U} \text{ so that } \frac{R\theta}{V} = \frac{t}{U} \quad (5)$$

To eliminate U, solve (5) for U and substitute in (4) to give the equation for the conditions at which the bubble just leaves the liquid.

$$\frac{t^2}{R\theta} = \frac{4D}{3C_D} \quad (6)$$

Equation 6 is in terms of separator dimensions, the angle at which separation is completed, the bubble diameter D, and the drag coefficient C_D . The rest of the analysis and the conclusions are dependent upon assumptions concerning the bubble diameter and the drag coefficient.

C. Determination of Bubble Diameter, D

The bubble diameter may conceivably be determined in many ways and a complete solution would require a knowledge of the number of bubbles of different sizes present in the mixture entering the separator. This knowledge is not available but useful results can be obtained by considering the following possibilities.

1. The bubble size D may be constant in the separator and not a function of the flow rate or dimensions of the separator.
2. The bubble size may be determined by Taylor instability so that we

can write:
$$D \sim \sqrt{\frac{\sigma g_c}{(P_f - P_g) a}}$$

where a is some characteristic acceleration. This acceleration may be due to flow on the curved separator vane so that $a = \frac{V^2}{R}$. Another possibility is that the acceleration occurs because of a change in flow velocity before the flow reaches the vane. In this case $a = \frac{V^2}{C}$ where C describes the determining geometry before the separator.

In the subsequent work, these three cases of bubble diameter will be considered by using equations (7)

$$D = D_0 = \text{constant} \quad (7a)$$

$$D = 2 \sqrt{\frac{\sigma R g_c}{\rho V^2}} \quad (7b)$$

$$D = 2 \sqrt{\frac{\sigma g_c C}{\rho V^2}} \quad (7c)$$

D. Drag Coefficient, C_D

Extensive investigations have been made of the drag coefficient by Haberman and Morton³. Many fluids were considered and curves presented of the bubble drag coefficient vs. Reynolds number. However, all tests were for bubbles rising in a one g field and no tests were performed with fluids with an M value (descriptive of fluid properties) as small as that of 1000 psi saturated water.

The curves of C_D vs. R_e for any fluid on log log paper can be approximated by three straight lines with transition curves connecting them.

On any straight line section, we can approximate the curve by the equation $C_D = KR_e^n$ where K and n will vary for the three different regions and will be different for different fluids. The analysis will concern itself with one fluid at a time. However, for most fluids,

in region I $n = -1$

in region II $n = 1/2$

in region III $K = 2.6$ and $n = 0$

The Reynolds number is defined by:

$$R_e = \frac{UD\rho}{\mu} \quad (8)$$

E. Effect of Parameters on Reynolds Number

From the definition of bubble Reynolds number $R_e = \frac{UD\rho}{\mu}$ and equation (4) which equated drag force to centrifugal force, the Reynolds number can be expressed as:

$$R_e = \frac{2VD^{\frac{3}{2}}\rho}{3^{\frac{1}{2}}\mu R^{\frac{1}{2}}C_D^{\frac{1}{2}}} \quad (9)$$

If bubble diameter D is assumed to be determined by Taylor instability and the vane radius or the inlet geometry (equations 7b and 7c) the Reynolds number can be expressed as:

$$R_e = \frac{2^{\frac{5}{2}}\rho^{\frac{1}{2}}\sigma^{\frac{3}{4}}R^{\frac{1}{4}}}{3^{\frac{1}{2}}V^{\frac{1}{2}}C_D^{\frac{1}{2}}\mu} \quad (9b)$$

$$R_e = \frac{2^{\frac{5}{2}}\rho^{\frac{1}{4}}\sigma^{\frac{3}{4}}g_c^{\frac{3}{4}}C^{\frac{3}{4}}}{3^{\frac{1}{2}}V^{\frac{1}{2}}R^{\frac{1}{2}}C_D^{\frac{1}{2}}\mu} \quad (9c)$$

The equations show that an increase in inlet velocity, V, increases Reynolds number if the bubble diameter is not velocity dependent

through Taylor instability, but increasing V decreases Reynolds number if Taylor instability is determining.

F. Equations for Bubble Separation with Generalized Drag Coefficient and Alternate Assumptions for Bubble Diameter Origin

Equations describing the conditions at which the bubble separation takes place are arrived at by combining $C_D = KR_e^n$, and equations 4, 5, 7a, 7b, and 7c.

1. If we assume the bubble diameter is not affected by velocity and vane radius (Equation 7a):

$$V = \left(\frac{4}{3K}\right)^{1/n} \frac{R^{n+1} \theta^{n+2}}{t^{n+2}} \frac{\mu}{\rho} D^{1-n} \quad (10)$$

$$\text{if } n = 0, \quad \frac{3K}{4D} = \frac{R\theta^2}{t^2} \quad (10a)$$

2. If we assume bubble diameter is determined by Taylor instability on the vane (Equation 7b):

$$V = \left(\frac{4 \times 2^{1-n}}{3K}\right) \left(\frac{R^{n+1} \theta^{n+2}}{t^{n+2}}\right) \left(\mu^n \rho^{-\frac{n-1}{2}} \sigma^{\frac{1-n}{2}} g_c^{\frac{1-n}{2}}\right) \quad (11)$$

3. If we assume bubble diameter is determined by Taylor instability in some geometry before the vane, (Equation 7c):

$$V = \left(\frac{4 \times 2^{1-n} C^{\frac{1-n}{2}}}{3K}\right) \left(\frac{R^{n+1} \theta^{n+2}}{t^{n+2}}\right) \left(\mu^n \rho^{-\frac{n-1}{2}} \sigma^{\frac{1-n}{2}} g_c^{\frac{1-n}{2}}\right) \quad (12)$$

These equations have V , the inlet velocity, as the dependent variable, since the higher the value of V , the greater the separator capacity.

G. Relation of Test Conditions to Analysis

The test performance of air-water may be predicted from the equations which use Taylor instability and the vane radius to determine bubble size. In the tests with the 4-inch radius vane, the inlet velocity ranged from about 35 to 210 ft/sec. For these velocities, equation (7b) predicts bubble diameters of 0.0017 and 0.00028 feet, respectively. Equation (9a) or (9b) can be used with the curve of C_D vs. R_e for room temperature water to determine what region of the curve these operating conditions fit. With these assumptions, the air-water tests are determined to have been in Region II of the C_D vs. R_e curve and the exponent n equals plus 2. An increase in velocity above about 220 ft/sec., however, would place operation in Region I with n equal to minus one with these same assumptions. Equation 11 with $n = -2$ and $K = 8.3 \times 10^{-7}$ is the appropriate equation for predicting the arc length required for separation with the air-water tests. On this basis an arc length of 44 degrees was required for complete separation with the highest velocity tested in air-water. This is about one-third of the available arc length.

If the velocity is increased beyond the test conditions, operation would be in Region I of the drag coefficient curves. Equation 11 with $K = 16$ and $n = -1$ would then be appropriate for predicting performance if Taylor instability on the vane radius determines bubble size. The maximum inlet velocity for complete separation is calculated to be about 3,000 feet per second for air-water and $R = 4$ inches

$$t = \frac{1}{2} \text{ inch}$$

$$\theta = 130 \text{ degrees}$$

Similar calculations for the 1000 psi steam-water tests are not possible because the drag coefficient is not known for water at this temperature.

On the basis of the calculations, it appears probable that separation of the air from the water on the vane is not a limiting problem of the radial separator. Speculation on the effect of fluid properties on drag coefficients suggests that bubble separation is probably not limiting in 1000 psi steam-water, but much more evidence is needed.

H. Effect of Parameters on Bubble Separation

1. Effect of Vane Radius, R

The curves of Haberman and Morton for drag coefficient vs. Reynolds number show that in the equation $C_D = KR_e^n$, n is always equal to or greater than minus 1. If $n = -1$, equation 10 and equation 12 have an exponent of zero for R , indicating vane radius has no effect. If $n > -1$, V increases as R increases. It may be concluded from the equations that increasing vane radius will probably increase the maximum allowable inlet velocity, and will not decrease it.

2. Effect of Film Thickness t and Arc Length θ

The film thickness t will be determined by several factors including the nozzle width, the inlet quality, and the spreading caused by centrifugal force. The maximum arc θ for separation is the vane arc which should be not more than about 130-150 degrees to allow space for the separated water to leave the vane.

In all three equations (10, 11, and 12), the parameters t and θ appear as a fraction $\frac{t}{\theta}$ to some exponent. This means that to maintain the same maximum inlet velocity, a change in t must be accompanied by the same proportionate change in θ . The maximum allowable ve-

velocity V will be increased by decreasing t and increasing θ , with one exception. If the Reynolds number is low so n is negative and the bubble diameter is not determined by velocity, V will decrease if θ or t is increased.

3. Effect of Fluid Properties

Equations 10, 11, and 12 can be used to determine the effect of fluid properties on separation provided the drag coefficient vs. Reynolds number curve is known so that values for n and K can be established for each fluid. Unfortunately, the comparison of air-water and 1000 psi steam-water can not be definitely made because of the lack of knowledge of the drag coefficient in high temperature water.

It is interesting to note that the fluid properties do not appear in equation 10a, nor does the inlet velocity. This says that if (1) the Reynolds number is high enough so drag coefficient is constant, and (2) bubble diameter is not affected by velocity or vane radius, then the relationship between vane radius, separation arc length, and film thickness for a given bubble diameter is not a function of fluid properties or inlet velocity.

V. REFERENCES

1. Rouse, Bhoata, Hsu, "Design of Channel Expansions", ASCE Proceedings, November 1949, pp 11-49. See Figure 55.
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3. W. L. Haberman and R. K. Morton, "An Experimental Investigation of the Drag and Shape of Air Bubbles Rising in Various Liquids", Navy Department, David Taylor Model Basin, Report 802, NS715-102, 1953.