Design Approach of Steam-Water Separators and Steam Dryers For Geothermal Applications

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ABSTRACT

An approach is given for designing steam-water separators and steam dryers for geothermal applications. The theory, design parameters and recommendations discussed here, enables the design engineer to calculate the size of the equipment and to estimate its performance under several operating conditions. An illustrative example is also presented.

INTRODUCTION

The steam-water separator (inlet mixture quality < 95 percent) and the steam dryer (inlet mixture quality > 95 percent) are equipment of major importance during the development, exploitation and electric generation of a "liquid-dominated" geothermal field. Generally speaking, a well delivers at the wellhead a water-steam mixture which normally falls in the 15 to 35 percent dryness fraction range which is separated in a separator. The saturated steam obtained at each well is piped to the main steam line which reaches a dryer where the moisture of the steam is removed in order to avoid scaling and corrosion at the turbine. The water can be rejected or flashed to provide vapor, which upon expansion yields additional power. This may be done several times at each well or in a flash plant; but, in any case, there will be several steam-water separators and two or three steam dryers. The dryer also removes the condensate formed along the steam-line length and acts as a safety element for the turbine in the case of failure of the system separator-ball float valve.

Since 1953, when the 26 MW plant of Wairakei New Zealand was designed, the steam-water separator has evolved due to modifications (Smith and Hoe, 1958 and Bangma, 1961) that have been integrated as result of operation experience and the need for improving the dryness of the separated steam to protect steam lines, equipment, turbine, etc.

The experience acquired in many liquid-dominated geothermal fields (New Zealand, Mexico, El Salvador) has demonstrated that the Webre-type cyclone separator is the best for geothermal applications (Smith and Hoe, 1958 and Bangma, 1961).

For removing moisture, several types of dryers (horizontal, chevron-type, etc.) are operating at different geothermal power plants. Unit 5 of Cerro Prieto I has 3 Webre-type steam dryers. The operating results have been so good that they allow for the next dryers (Cerro Prieto II, III - 4 x 110 MW) to accept the same design. Figure 1 shows a schematic diagram of triple-flash plant where the role of the separation equipment can be appreciated.

DESIGN

When selecting a separator or a dryer, there are several design parameters that should be taken into account. They are, among others:

- Steam quality of the separated steam
- Steam pressure drop
- Facility of operation and cleaning
- Space requirements (dryers)
- Cost

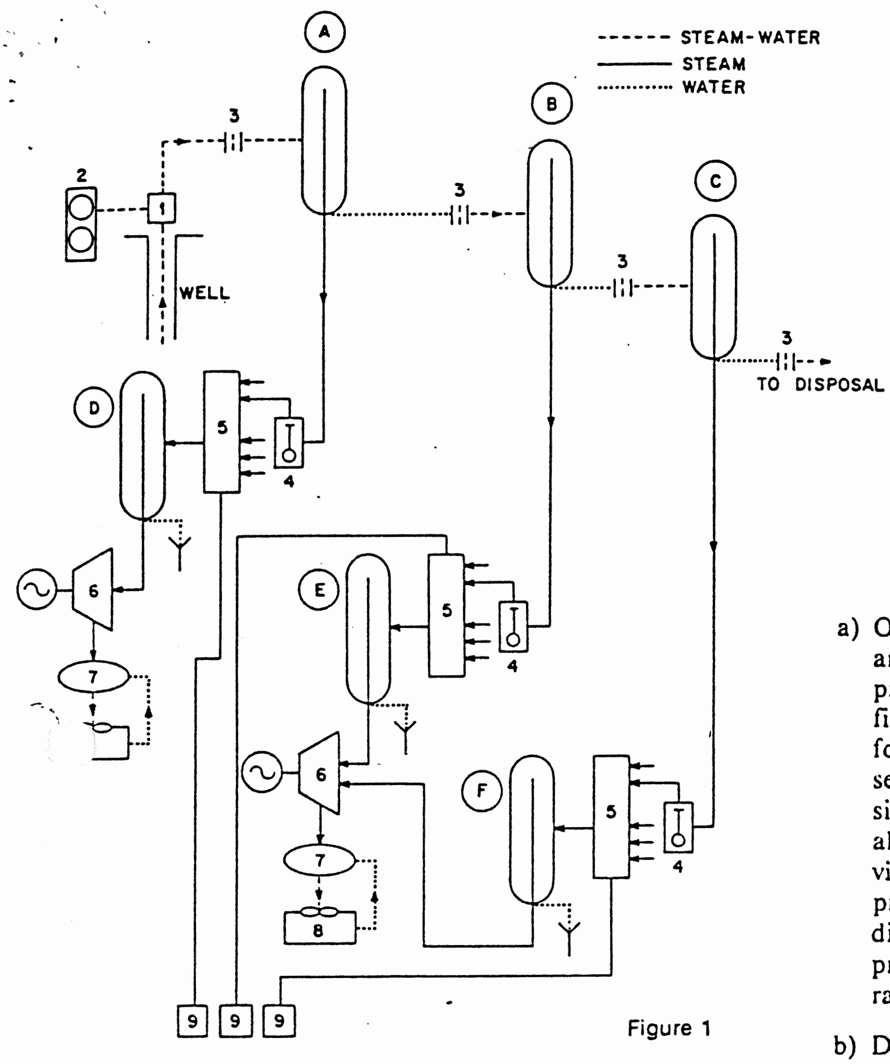

Figure 1

FIGURE 1. SCHEMATIC DIAGRAM OF TRIPLE-FLASH PLANT.

1. Wellhead Valves Tree
2. Wellhead Silencer
3. Flashing Orifices
4. Ball Float Valve (Check Valve)
5. Steam Headers
6. Turbines
7. Condenser
8. Cooling Tower
9. Steam Silencers

A. Primary Separator
B. Secondary Separator
C. Tertiary Separator
D. Primary Dryer
E. Secondary Dryer
F. Tertiary Dryer

This paper deals only with Webre-type separators and dryers because:

- They are extremely simple (no moving parts that can be corroded or eroded). In the Webre cyclone, the steam first moves to the top and then changes direction through 180° to go down and out the bottom outlet. Since both the steam and the water outlets are at the bottom of the cyclone, piping layouts are very simple.
- Their simplicity of operation has been proved in many liquid-dominated geothermal fields.
- This type of separator and dryer is very easy to clean. This is a fundamental item because the geothermal brine contains silica, among other chemicals, which is mainly responsible for scaling. It is recommended to schedule at least one general maintenance per year for well-head separators.
- The outlet steam quality and the efficiency are very high. The reported outlet steam quality (dryness) has an average of 99.95 percent (McDowell, 1976) at Wairakei field, New Zealand, and higher than 99.99 percent at Cerro Prieto, Mexico.

The performance of steam-water cyclones is governed by two types of variables.

a) Operating variables, relating to properties, rates and states of the phases. Generally speaking, the pressure (and temperature) of the separator is fixed by the inlet pressure of the turbine; therefore, the farther the well is from it, the greater the separation pressure. The mixture can be considered inside the separator at equilibrium, then all properties (pressure, temperature, density, viscosity, etc.) are fixed. Each well has a different pressure-flow curve; consequently, each well has different flow of mixture (for the same operating pressure) with a different inlet steam-water mass ratio.

b) Design variables, relating to type and dimensions of cyclones. In a geothermal field, one can find wells with great production of mixture having a very high steam-water mass ratio and small production with low steam-water mass ratio; therefore the designer should stand up to the problem of standardizing the size of the well-head separator or designing two or three different sizes. From the design, performance and cost points of view, we recommend to have two or three sizes, assuming that the maintenance cost is kept low.

The outlet steam quality and the pressure drop are the main criteria for designing separators and dryers, and there are very few papers in the literature concerning their design. Since 1961, the base for designing geothermal separators has been the method given by Bangma (1961); however, this method is an empirical one which has no way to predict the outlet steam quality that will produce a particular separator under different conditions. Pollak and Work (1942) suggest an equation for the prediction of liquid entrainment in Webre-type separators, but it has been of little utility due to the lack of reliability. It can be said that there is no method that can be used for designing separation equipment which is also capable of predicting its behavior under several operating conditions.

Theory

In this part of the paper we will discuss the theory of separation for steam-water mixtures in a Webre-type cyclone regardless of the application (separator or dryer). There are two different terms that, in spite of this, are very often taken indistinctly:

- The efficiency of separation (η_{ef}), defined as the mass ratio of separated liquid to inlet liquid.
- The outlet steam quality (χ_o), defined as the mass ratio of outlet steam to outlet steam-water.

Figure 2 shows a flow diagram of the separation stage. By definition:

$$\eta_{ef} = \frac{W_L - W_A}{W_L} \quad (1)$$

$$X_o = \frac{W_V}{W_V + W_A} \quad (2)$$

Substituting equation (1) into equation (2), outlet steam quality is related to efficiency by

$$X_o = \frac{W_V/W_L}{1 - \eta_{ef} + W_V/W_L} \quad (3)$$

i) If $\eta_{ef} = 0$ then X_o is the inlet steam quality

ii) If $\eta_{ef} = 1$ then $X_o = \eta_{ef} = 1$ (this is the only case where $X_o = \eta_{ef}$

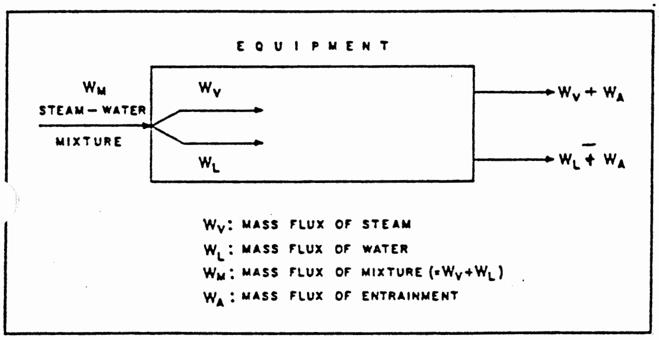

FIGURE 2. Schematic Flow Diagram of the Separation Stage

Figure 3 (IEE, 1980) and Table 1 (Bangma, 1961), show that the outlet steam quality is low when the inlet steam velocity and the upward steam velocity (annular steam velocity inside of the separator) are low. When both steam velocities increase, the outlet steam quality goes up to a point (breakdown point) where the outlet steam quality breaks down drastically. For modeling, it is assumed that there are two independent phenomena with influence on the efficiency of separation as follows:

$$\eta_{ef} = \eta_m \cdot \eta_A \quad (4)$$

η_m = Centrifugal efficiency

η_A = Entrainment efficiency

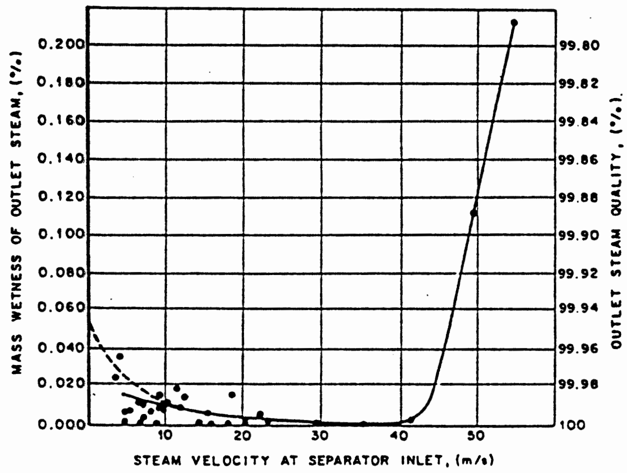

FIGURE 3. Separator performance measured by outlet steam quality (%) and mass wetness of outlet steam (%) against steam velocity at separator inlet (m/s).

The centrifugal efficiency increases when the inlet steam velocity goes up ($\eta m \to 1$ as $V_T \to \infty$), and the entrainment efficiency goes up when the upward annular steam velocity goes down ($\eta_A \to 1$ as $V_{AN} \to 0$).

CENTRIFUGAL EFFICIENCY (ηm)

Using the same approach of Leith and Licht (1972), the centrifugal efficiency is given by equation (5)

$$\eta_m = 1 - \mathrm{EXP}\left[-2\,(\psi C)^{\frac{1}{2n+2}}\right] \quad (5)$$

$$n_1 = 0.6689 \quad D^{0.14} \quad (6)$$

$$\frac{1 - n_1}{1 - n} = \left(\frac{294.3}{T + 273.2}\right)^{0.3} \quad (7)$$

$$\psi = \frac{\rho_w \, d_w^2 \, (n+1)\, u}{18 \, \mu_v \cdot D} \quad (8)$$

$$u = \frac{Q_{VS}}{A_o} \quad (9)$$

The parameter ψ is a centrifugal inertial impactation parameter, reflecting operating conditions within the cyclone. Equation (8) shows that ψ is very sensitive to d_w, therefore, reliable estimates of d_w are necessary to obtain accurate results for ψ. The estimation of d_w will be discussed later.

Figure 4 shows the nomenclature used throughout this article and it should be pointed out that this nomenclature is the same for the separator or dryer—with the difference that the separator has spirial inlet with a change in cross - section from cylindrical to rectangular shape at the entrance when the dryer has a tangential inlet with constant cross-area. The dryer has no water outlet nozzle (only a drain), being tangential-type for the separator.

$$C = \frac{8 \, K_c \, D^2}{A_o} \quad (10)$$

FIELD (COUNTRY)	WELL (SEPARATOR)	INLET MASS FLUX MIXTURE (Kg/s)	SEPARATION PRESSURE (KPa ABS)	SEPARATOR DIAMETER (m)	INLET STEAM VELOCITY (m/s)	OUTLET STEAM QUALITY (%)	REFERENCE
WAIRAKEI (NEW ZEALAND)	44 PRIMARY SEPARATOR	87	1550	0.76	72	99.500	Bangma, 1961
OTAKE (JAPAN)	SECUNDARY SEPARATOR (MODEL)	22	—	—	55	99.925	Aikawa and Soda, 1976
CERRO PRIETO (MEXICO)	M-50 PRIMARY SEPARATOR	72	853	1.37	37	99.991	Laxalde and others, 1982
CERRO PRIETO (MEXICO)	U-5 TERCIARY SEPARATOR	367	255	2.14	24	99.997	"
CERRO PRIETO (MEXICO)	U-5 SECONDARY SEPARATOR	377	441	2.14	16	99.999	"
CERRO PRIETO (MEXICO)	U-5 TERCIARY SEPARATOR	146	245	2.14	8	99.986	"

ABLE 1. Outlet steam quality (%) against inlet steam velocity (m/s) for several Webre separators at different geothermal fields.

The parameter C is a cyclone design number, reflecting the physical shape of the cyclone.

$$A_o = A_e \cdot B_e \qquad \text{(separator)} \tag{11}$$

$$A_o = \frac{\pi (D_T)^2}{4} \qquad \text{(dryer)} \tag{11'}$$

$$K_c = \frac{t_r \; Q_{VS}}{D^3} \tag{12}$$

$$t_r = t_{mi} + t_{ma}/2 \tag{13}$$

$$t_{mi} = \frac{VO_S}{Q_{VS}} \tag{14}$$

$$VO_S = \frac{\pi}{4} \left(D^2 - D_e^2 \right) z \tag{15}$$

$$t_{ma} = \frac{VO_H}{Q_{VS}} \tag{16}$$

$$VO_H \cong VO_1 + VO_2 - VO_3 \tag{17}$$

$$VO_1 = \frac{\pi D^2}{4} \alpha \tag{18}$$

Assuming ASME flanged and dished head

$$VO_2 = 0.081 \; D^3 \tag{19}$$

$$VO_3 = \frac{\pi D_e^2}{4} (\alpha + 0.169 \; D) \tag{20}$$

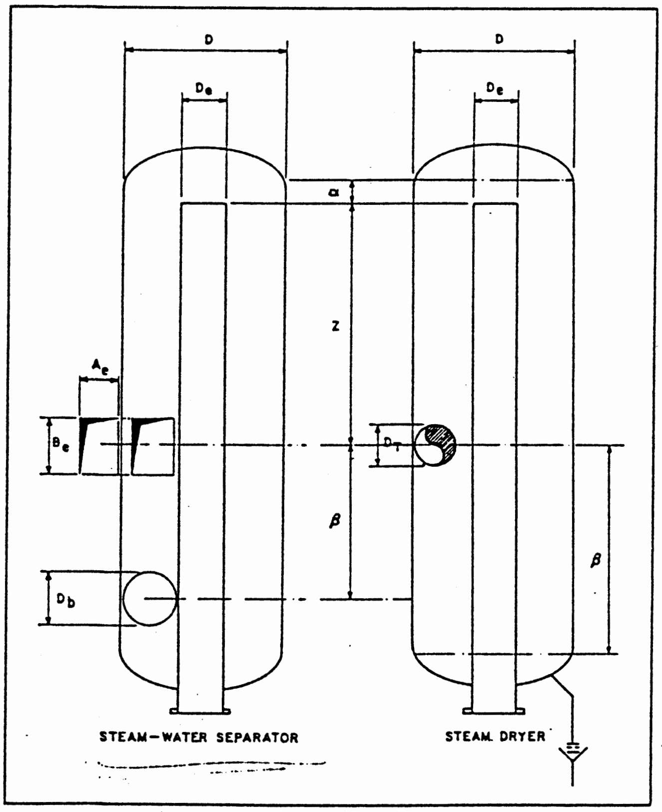

FIGURE 4. Schematic diagram of Webre-type steam-water separator and steam dryer.

Drop Diameter (d_w)

The parameter ψ is given by equation (8) where the drop diameter (d_w) and the tangential velocity of drop at cyclone wall (u) are the most important parameters. For simplicity, it is assumed that u can be taken satisfactorily as equal to the average velocity of steam at the entrance; but for the estimation of d_w, there is not a simple solution. The diameter d_w should be taken as the effective average drop diameter inside the cyclone.

It is well known that the efficiency of a cyclone is reduced when the drop diameter decreases; therefore, one should understand the causes and reasons for an increase or a reduction of the drop diameter. We believe that the drop size inside the cyclone is governed by the drop diameter in the pipe upstream of the cyclone. The latter is determined by the balance between the inertia and the surface forces, as well as by the equilibrium between drops leaving and arriving at the wall, the pressure drop, and the type of two-phase flow pattern, pipe line configuration, etc. Among the numerous correlations consulted (Delale, 1980; Hinze, 1955; Azzopardi and others, 1980; Nukiyami and Tanasawa, 1938), we tested several of them obtaining unfavorable results. The Nukiyama-Tanasawa equation (Nukiyami and Tanasawa, 1938) gives the trend of results—probably due to the fact that the mechanism of breakup of venturi throats are similar to the mechanism of breakup of a vapor-liquid-system in a pipe. Taking this equation as the basic relation for drop-size evaluation, we proceed to modify it by adding different terms in the following way: Taking from the data bank, obtained from actual well-head separators, the data with 100 percent or 99.99 percent outlet steam quality ($\eta_A = 1$) and the equations (3) to (20) knowing everything except d_w we got equation (21).

$$d_w = \frac{A}{V_T^a} \sqrt{\frac{\sigma_L}{\rho_L}} + BK \left[\frac{\mu_L^2}{\sigma_L \; \rho_L} \right]^b \left(\frac{Q_L}{Q_{VS}} \right)^c V_T^e \tag{21}$$

Where:

$$V_T = \frac{4Q_{VS}}{\pi D_T^2}$$

$A = 66.2898$

$K = 1357.35$

$b = 0.2250$

$c = 0.5507$

The variables a, e, B are dependent on the type of two-phase flow pattern according to Baker's method (Lawrence, 1952) and are given in Table 2. Equation (21) is not a general equation and it is not dimensionally consistent; therefore, it should be used with the following dimensions: ρ_L in g/cm,^{3} V_T in m/s, σ_L in dyne/cm, μ_L in poises and Q_L and Q_{VS} in m^3/s, resulting d_w in microns. All variables should be evaluated at separator's pressure.

ENTRAINMENT EFFICIENCY

The centrifugal efficiency term, by itself, was not able to predict the outlet steam quality due to the fact that η_m always increases as u (or V_T) increases; however, it is known that at a given point, the entrainment goes up drastically with high velocities. The term which takes this into account is the entrainment efficiency (η_A), arrived at from data reduction and given as equation (23).

$$\eta_A = 10^{\,j} \tag{23}$$

$$j = -3.384 \quad (10^{-14}) \, (V_{AN})^{13.9241} \tag{24}$$

$$V_{AN} = \frac{4Q_{VS}}{\pi (D^2 - D_e^2)} \tag{25}$$

$$0 \leqslant \eta_A \leqslant 1 \tag{26}$$

The method given here was developed with a data bank taken from well-head separators (D = 1.4 m, 4.5 ft.) at Cerro Prieto geothermal field. The method has been tested against data experimentally obtained in secondary and terciary Webre separators of 2.1 m (7 ft.) and dryers of 2.6 m (8.5 ft.) with very good results. The absolute difference between the outlet steam quality experimentally measured and the one predicted by this model averages 0.005 percent. It should be noted that this method has not been tested exhaustively; therefore, it should be taken only as a good procedure before it is compared with new data.

Design Parameters

GENERAL RECOMMENDATIONS

For separators, the inlet should be of the rectangular spiral-type, and the floor of the spiral should have a slight fall (say 4°) just as it enters the cyclone to encourage the water to flow downwards more rapidly (Bangma, 1961). For dryers, the inlet should be of the circular tangential-type because pressure drop is reduced with this arrangement.

TYPE OF TWO-PHASE FLOW PATTERN	a	B	e
STRATIFIED AND WAVY	0.5436	$94.9042\ (XS)^{-0.4538}$	0.0253
ANNULAR	0.8069	$198.7749\ (XS)^{0.2628}$	-0.2188
DISPERSED AND BUBBLE	0.8069	$140.8346\ (XS)^{0.5747}$	-0.2188
PLUG AND SLUG	0.5436	$37.3618\ (XS)^{-6.88 \times 10^{-5}}$	0 0253

TABLE 2. Variables a, e, B to be used with equation (21)

The steam outlet pipe should be as large as possible, even inside of the top head of the equipment. The only limitation is that the area between the end of this pipe (lip) and the wall of the top head should be at least equal to the cross-area to this pipe. We recommend 1.25 times the cross-area. This is a common practice in Mexico (developed by the staff of Cerro Prieto) which has given exceptional results because the residence time is increased and the possibility of water going directly to the steam outlet pipe (short circuit) is diminished. Aside from this, the chances of water running upward along the steam-outlet pipe and contaminating the steam at the rim are reduced. The diameter of this pipe (De) should be equal to the inlet mixture pipe diameter (D_t).

The outlet water pipe diameter (Db) should be equal to the inlet mixture pipe diameter (D_t).

The separator should consider a water drum which can be either integrated or not. This drum acts as a volume to give smooth operation and as a water-seal to avoid steam losses.

PARAMETERS

The recommended design parameters for geothermal separators and dryers are given in Table 3.

PARAMETER	SEPARATOR	DRYER
MAXIMUM STEAM VELOCITY AT INLET MIXTURE PIPE	45 m/s (150 fps)	60 m/s (195 fps)
RECOMMENDED STEAM VELOCITY RANGE AT INLET MIXTURE PIPE	25-40 m/s (80-130 fps)	35-50 m/s (115-160 fps)
MAXIMUM ANNULAR UPWARD STEAM VELOCITY INSIDE CYCLONE	4.5 m/s (14.5 fps)	6.0 m/s (20 fps)
RECOMMENDED ANNULAR UPWARD STEAM VELOCITY INSIDE CYCLONE	2.5-4.0 m/s (8-13 fps)	1.2-4.0 m/s (4-13 fps)
$R_1 = D/D_t$	3.3	3.5
$R_2 = D_e/D_t$	1.0	1.0
$R_3 = D_b/D_t$	1.0	*
$R_4 = \alpha/D_t$	-0.15 **	-0.15 **
$R_5 = \beta/D_t$	3.5	3.0
$R_6 = Z/D_t$	5.5	4.0

* It should be calculated as a drain

** This ratio is negative because of the nomenclature (inside the head)

TABLE 3. Recommended design parameters for Geothermal separators and dryers.

Pressure Drop

The gas pressure drop can be expresses as (Lawrence, 1952; Ludwig; Koch and Licht, 1977; Shepherd and Lapple, 1939)

$$\Delta P = \frac{(NH)\; u^2 \rho_V}{2} \qquad (27)$$

$$NH = 16 \frac{A_e \; B_e}{D_e^2} \qquad \text{(separator)} \qquad (28)$$

$$NH = 16 \left(\frac{\pi D_T^2}{4 \; D_e^2} \right) \qquad \text{(dryer)} \qquad (28')$$

Bangma shows that the total gas pressure drop is given by

$$\Delta P = \Delta P_1 + \Delta P_2 \qquad (29)$$

where ΔP_1 is the gas pressure drop between the separator inlet and the separator body, and ΔP_2 between the separator body and the separator steam outlet.

$$\frac{\Delta P_1}{\Delta P_T} \approx 0.6 \qquad \frac{\Delta P_2}{\Delta P_T} \approx 0.4 \qquad (30)$$

CONCLUSIONS

a) From equation (3), one can say that for any given cyclone pressure, the drier the inlet mixture the greater the amount of steam flow the cyclone will handle, other things being equal.

b) The inlet steam velocity is a very important factor. At low velocities the outlet steam quality is bad and the equipment is big. Increasing the velocity, the outlet steam quality increases and pressure drop goes up, but the size of piping and equipment are reduced. Breakdown occurs at high input velocities and becomes worse as the velocity is increased.

c) The annular upward velocity inside the cyclone is also very important. At low velocities the entrainment is low and at high values the entrainment can be excessive.

d) The method is based on the steam phase; therefore, the dimension "β" has no effect on the outlet steam quality, but it is known that this dimension has influence on the performance of the cyclone. This is a disadvantage of this method that should be corrected with experimentation. The recommended valve for β is based on experience (Bangma, 1961).

e) Although the method outlined here can certainly be improved, at this time it is a good design procedure.

ILLUSTRATIVE EXAMPLE

A geothermal secondary separator should be designed to give an outlet steam quality of 99.95 percent for the following conditions:

- Mixture Enthalpy = 813.3 kJ
- Separation Pressure = 547.7 kPa
- Mixture Flux = 190346.4 kg/h
- Maximum Pressure Drop = 68.9 kPa
- Integral Water Drum

a) Preliminary Calculations

With the separation pressure and steam tables we find:

- Separation temperature (saturation) = 155.3°C
- Steam Enthalpy = 2751.5 kJ/kg
- Water Enthalpy = 654.8 kJ/kg
- Specific volume of steam = 0.3586 m^3/kg
- Specific volume of water = 0.0011 m^3/kg

With the separation temperature

- Steam viscosity = 14.67 (10^{-6}) kg/m.s.
- Liquid viscosity = 1.736 (10^{-4}) kg/m.s
- Surface tension = 0.0467 N/m
- Inlet mixture quality

$$X_i = \frac{HM - HLS}{HVS - HLS}$$

$$X_i = \frac{813.3 - 654.8}{2751.5 - 654.8}$$

$$X_i = 0.0756$$

$$Q_{VS} = \frac{W_M \cdot X_i \cdot V_{ev}}{3600}$$

$$Q_{VS} = \frac{(190346.4)\ (0.0756)\ (0.3586)}{3600}$$

$$Q_{VS} = 1.4334\ m^3/s$$

$$Q_L = \frac{W_M\ (1-X_i)\ (V_{eL})}{3600}$$

$$Q_L = \frac{(190346.4)\ (1-0.0756)\ (0.0011)}{3600}$$

$$Q_L = 0.0538\ m^3/s$$

b) Design

Inlet area and diameter of inlet pipe

$$A = \frac{Q_{VS}}{V_T}$$

Assuming an inlet steam velocity of 35 m/s (115 fps)

$$A = \frac{1.4334}{35} = 0.041\ m^2$$

$$D_T = \left[\frac{4\ A}{\pi}\right]^{0.5} = 0.2284\ m$$

The next standard diameter is 0.254 m (10", sch 40) therefore $D_t = 0.254$ m (10" sch 40).
$V_t = 28.27$ m/s

From Table 3

D	=	$3.3\ D_t$	=	0.84 m
D_e	=	$1\ D_t$	=	0.254 m
D_b	=	$1\ D_t$	=	0.254 m
α	=	$-0.15\ D_t$	=	-0.04 m
β	=	$3.5\ D_t$	=	0.89 m
z	=	$5.5\ D_t$	=	1.40 m

The separator has a spiral inlet with a cross-area

$$A_o = A_e \cdot B_e \approx (D_T)^2$$

$$A_o \approx 0.0645\ m^2$$

$$u = \frac{Q_{VS}}{A_o} = \frac{1.4334}{0.0645}$$

$$u = 22.22\ m/s$$

- Integral water drum

It is a common practice to take the same diameter of the separator with a length equal to

$$L_{WD} = \frac{\beta + z}{3}$$

$$L_{WD} = 0.76\ m$$

c) Centrifugal Efficiency

$$n_1 = 0.06689\ (0.84)^{0.14}$$

$$n_1 = 0.6528$$

$$\frac{1 - 0.6528}{1 - n} = \left[\frac{294}{155.3 + 273.2}\right]^{0.3}$$

$$n = 0.6114$$

$$VO_S = \frac{\pi}{4}\ (0.7056 - 0.0645)\ (1.4)$$

$$VO_S = 0.7049\ m^3$$

$$t_{mi} = \frac{VO_S}{Q_{VS}} = 0.49\ s$$

$$VO_1 = \frac{\pi D^2}{4}\ \alpha$$

$$VO_1 = \frac{\pi (0.84)^2}{4}\ (-0.04)$$

$$VO_1 = -0.022\ m^3$$

$$VO_2 = 0.081\ D^3$$

$$VO_2 = 0.048\ m^3$$

$$VO_3 = \frac{(0.254)^2}{4}\left[-0.04 + 0.169\ (0.84)\right]$$

$$VO_3 = 0.006\ m^3$$

$$VO_H = VO_1 + VO_2 - VO_3$$

$$VO_H = 0.02\ m^3$$

$$t_{ma} = \frac{VO_H}{Q_{VS}} = 0.014$$

$$t_r = t_{mi} + t_{ma}/2$$

$$t_r = 0.49 + 0.014/2$$

$$t_r = 0.5\ s$$

$$K_c = \frac{t_r\ Q_{VS}}{D^3}$$

$$K_c = \frac{(0.5)\ (1.4334)}{(0.84)^3}$$

$$K_c = 1.21$$

$$C = \frac{8\,K_c\,D^2}{\lambda_o}$$

$$C = \frac{8(1.21)\;(0.84)^2}{0.0645}$$

$$C = 106$$

- Drop particle

Flow pattern (Baker's method) (Lawrence, 1952)

$B_x = 16.5$ $\qquad$ $B_y = 3711.7$

Therefore the two-phase flow pattern is "dispersed." Using Table 2 and equation 2

$$d_w = \frac{A}{V_T^a}\sqrt{\frac{\sigma_L}{\rho_L}} + BK\left[\frac{\mu_L^2}{\sigma_L\,\rho_L}\right]^b\left(\frac{Q_L}{Q_{VS}}\right)^c V_T^e$$

$A = 66.2898$		$V_t = 28.27$ m/s	
$B = 31.9298$		$\sigma_L = 46.7025$ dynes/cm	
$K = 1357.3460$		$\rho_L = 0.9117$ g/cm^3	
$a = 0.8069$		$\mu_L = 1.736\ (10^{-3})$ poise	
$b = 0.2250$		$Q_L = 0.0538$ m^3/s	
$c = 0.5507$		$Q_{VS} = 1.4334$ m^3/s	

$$e = -0.2188$$

$$d_w = 116 \text{ microns}$$

- Parameters ψ

$$\psi = \frac{\rho_W\;d_w^2\;(n+1)\;u}{18\;\mu_V\;D}$$

$$\psi = \frac{(909.1)\;(116\cdot 10^{-6})^2\;(1.6114)\;(22.22)}{(18)\;(14.67\cdot 10^{-6})\;(0.84)}$$

$$\psi = 1.9748$$

$$\eta_m = 1 - \text{EXP}\left[-2\quad(C\,\psi)^{1/2n+2}\right]$$

$$\eta_m = 1 - \text{EXP}\left[-2\;(1.9748\cdot 106)^{1/2(1.6114)}\right]$$

$$\eta_m = 99.9973\quad(10^{-2})$$

d) Entrainment Efficiency

$$V_{AN} = \frac{4Q_{VS}}{\pi\,(D^2 - D_e^2)} = 2.85 \text{ m/s}$$

$$j = -3.384\quad(10^{-14})(V_{AN})^{13.9241}$$

$$j = -7.288\quad(10^{-8})$$

$$\eta_A = 10^j$$

$$\eta_A = 99.9999\;(10^{-2})$$

e) Efficiency

$$\eta_{ef} = \eta_m\cdot\eta_A$$

$$\eta_{ef} = 99.9972\quad(10^{-2})$$

f) Outlet steam quality

$$W_V = W_M\cdot X_i/3600$$

$$W_V = 190346.4\;(0.0756)/3600$$

$$W_V = 3.9973 \text{ kg/s}$$

$$W_L = W_M\;(1 - X_i)/3600$$

$$W_L = 190346.4\;(0.9244)/3600$$

$$W_L = 48.8767 \text{ kg/s}$$

$$X_o = \frac{W_V/W_L}{1 - \eta_{ef} + W_V/W_L}$$

$$\frac{W_V}{W_L} = 0.08178 \quad ; \quad (1 - \eta_{ef}) = 2.8\;(10^{-5})$$

$$X_o = \frac{0.08178}{0.08178 + 2.8\cdot 10^{-5}}$$

$$X_o = 99.966\ \%$$

g) Pressure Drop

$$NH = 16\;\frac{\lambda_e\;B_e}{D_e^2}$$

$$NH = 16$$

$$\Delta P = \frac{NH\;u^2\;\rho_V}{2}$$

$$\Delta P = \frac{(16)\,(22.22)^2(2.7886)}{2}$$

$$\Delta P = 11\text{ k }P_a$$

Since X_o is higher than 99.95 percent and ΔP lower than 68 kPa, the designed separator can achieve the task.

ACKNOWLEDGEMENTS

The author is grateful to Mr. Eduardo Buendía for helpful suggestions on computer programming and during development of the paper.

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NOMENCLATURE

A_o = inlet area at cyclone wall, m^2

A_e = inlet width, m

B_e = inlet height, m

Bx = Baker's parameter (Ref. 13), dimensionless

By = Baker's parameter (Ref. 13), dimensionless

C = parameter defined by equation (10), dimensionless

D = diameter of cyclone, m

D_b = water outlet pipe diameter, m

D_e = steam outlet pipe diameter, m

D_T = inlet pipe diameter, m

d_w = drop diameter, m

HM = mixture enthalpy, kJ

HLS = water enthalpy, kJ/kg

HVS = steam enthalpy, kJ/kg

j = parameter defined by equation (24), dimensionless

K_c = parameter defined by equation (12), dimensionless

L_{WD} = length of the integral water drum, m

n = free vortex law coefficient, dimensionless

n_1 = parameter defined by equation (6), dimensionless

Q_L = volumetric water flow , m^3/s

Q_{VS} = volumetric steam flow , m^3/s

T = temperature, °C

t_{ma} = maximum additional time of steam in cyclone, s

t_{mi} = average minimum residence time of steam in cyclone, s

t_r = residence time, s

u = inlet tangencial velocity of drop at cyclone wall, m/s

V_{AN} = upward annular steam velocity, m/s

V_{eL} = specific volume of water, m^3/kJ

V_{eV} = specific volume of steam, m^3/kJ

VO_H = volume defined by equation (17), m^3

VO_S = volume defined by equation (15), m^3

VO_1 = volume defined by equation (18), m^3

VO_2 = volume defined by equation (19), m^3

VO_3 = volume defined by equation (20), m^3

W_A = mass flux of entrainment, kg/s

W_L = mass flux of water, kg/s

W_M = mass flux of inlet mixture, kg/s

W_V = mass flux of steam, kg/s

X_i = inlet mixture quality, dimensionless

X_o = outlet steam quality, dimensionless

z = define by Fig. 4, m

Greek Letters

α = define by Fig. 4, m

β = define by Fig. 4, m

η_A = entrainment efficiency, dimensionless

η_{ef} = efficiency of separation, dimensionless

η_m = centrifugal efficiency, dimensionless

μ_L = water viscosity, kg/m·s

μ_V = steam viscosity, kg/m·s

ρ_V = steam density, kg/m^3

ρ_W = water density, kg/m^3

σ_L = surface tension, N/m

ψ = parameter defined by equation (8), dimensionless

ΔP = pressure drop, N/m^2