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# STEAM-WATER SEPARATION

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**Abstract.** A review is presented of the selection, design and operation of steam-water separation equipment. The criteria for choosing a separation system are first discussed and typical applications are described. Then, each of the major types of separator (gravity separators, drop inertia separators and cyclone separators) are reviewed in detail and the principal problems in design and operation for each respective type presented. Finally, procedures for testing separators are reviewed and overall conclusions drawn.

## 1. INTRODUCTORY MATERIAL

### 1.1 *Importance*

Steam and water mixtures are found in many pieces of process equipment such as boilers, heaters, extraction lines, turbines and superheaters. Depending on the use to which the steam is put, this moisture can cause problems. For this reason separators are an important part of these steam systems. Let us list some of these problems that arise as a result of carryover.

In the superheater section of boilers, the silica carried over with the moisture will be deposited on the tube walls. This causes sufficient scale so that the superheater tubes overheat and fail. When steam is expanded in a turbine, moisture forms. This moisture, usually in the form of drops, erodes the turbine blade downstream. In low-carbon steel extraction lines or, in the crossover piping which leads to the feedwater heaters or reheaters, the film of water on the walls dissolves the oxide causing additional corrosion. Impacting drops can fatigue the oxide also causing additional corrosion. These processes both accelerate the corrosion-erosion of the steel (or as it is often called, the flow assisted corrosion). One way of eliminating all these problems is to separate the moisture from the steam.

Carryunder is a problem too. When a jet of water enters a pool, air or steam can be entrained and carried down. This is called carryunder and it degrades the performance of natural circulation systems and can cause pump cavitation. This can also be estimated from the information provided later in this article.

### 1.2 *Organisation and scope*

We shall start by surveying the drop sizes typical of different kinds of systems. We shall then describe the characteristics of various kinds of separators so that an informed selection of an appropriate separator can be made. Several examples of separator systems will then be given illustrating how the advantages of one kind of separator can be used to complement those of another. Each type of separator will then be described including how it works and how it fails. The operating limits will be delineated. We shall continue by providing design information for each kind and typical performance data for them. Finally we will conclude with a discussion on how to scale experiments on separators.

### 1.3 *Drop and particle sizes and behavior*

Before going on to describe the various kinds of separators, it is necessary to say something about the average drop sizes, the drop size spectra and the drop behavior as found in steam-water systems. Though steam-water separator systems are designed to operate over the whole range of qualities, most deal with a high quality flow in the dispersed or annular flow regime. To design a separator system is necessary then to have an idea of what drop sizes are likely to be found and how these drops behave.

Table 1 which originated from Lapple (1961) (though later reproduced in many other publications, e.g. Hetsroni, (1982)) gives a useful overview of drop and particle behavior. The entire range of drop sizes that might be found in steam separators is included. All the information on drop behavior is given as a function of drop size. Particles of many kinds are shown too. This table deserves some study.

To help get oriented, the drops found in nature are also included. Also shown in this table are typical settling velocities for particles and drops as a function of their size along with their Reynolds numbers. These settling velocities are calculated for a drop or particle specific gravity of 2 however. This is not an important departure for a steam and water system considering the range of the log-log scale used in Table 1. The separators appropriate for the different drop size ranges are also included. As this is a very useful chart, it will be referred to repeatedly later in this chapter.

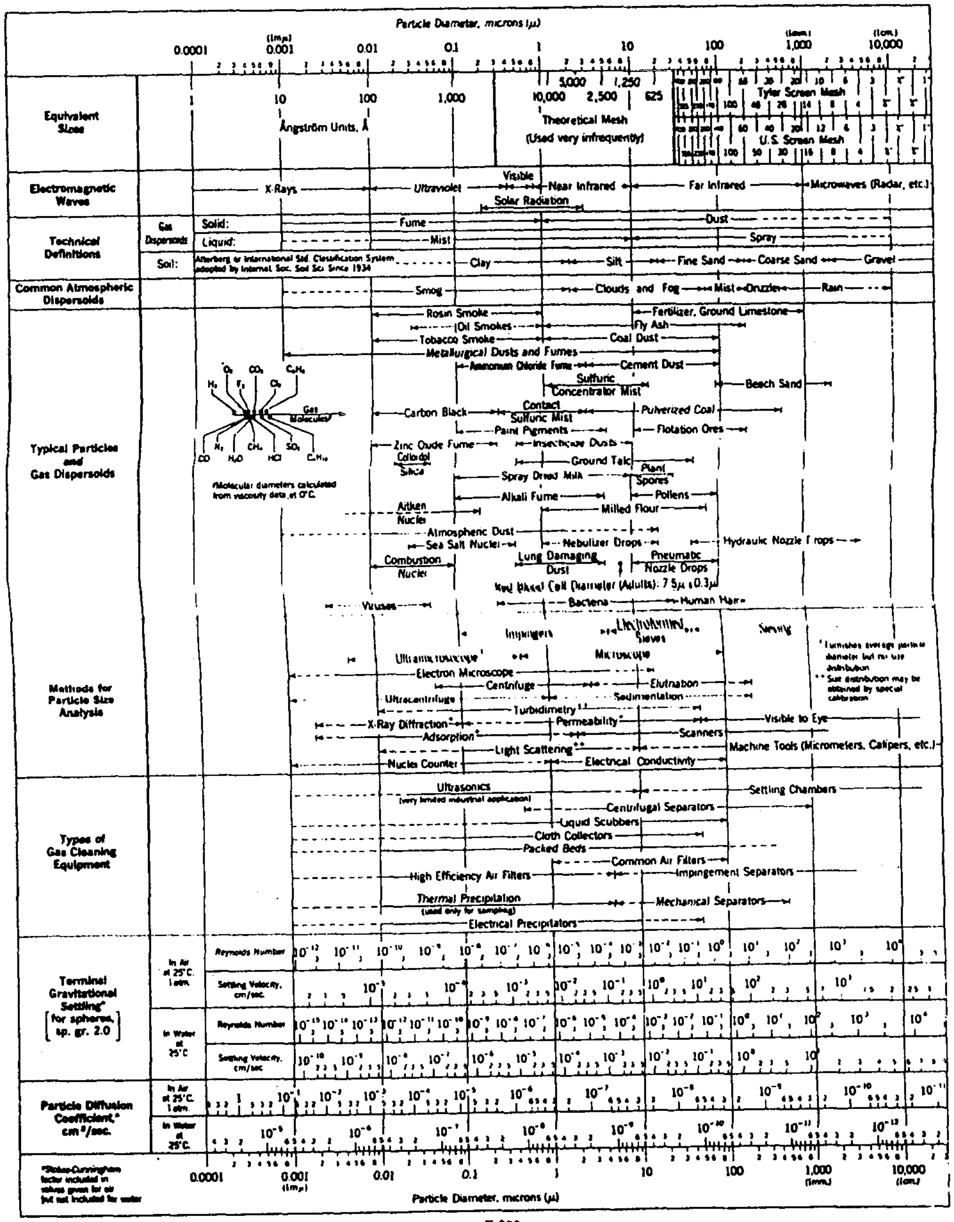
The most recent and complete work on drop sizes is that of Azzopardi and Hewitt (1997) which surveys a wide range of drop size literature. In order to make this a free-standing work, a short section on drop sizes and size distributions is given below. If this information is insufficient, it is recommended that the above reference be consulted.

The most important variable determining the drop size in a flowing system is the Weber Number. It is defined as

$$\mathrm{We} \doteq \frac{\rho_g V^2 D_d}{\sigma} \tag{1.1}$$

The $V$ in equation (1.1) is the relative velocity between the drop and the surrounding vapor. For a freely falling drop or accelerating drop, the critical Weber number is, Katoaka et al. (1981):

**Table 1** Characteristics of particles and particle dispersoids




C. E. Lapple, Stanford Research Institute Journal, Vol. 5, p.95 (Third Quarter, 1961)

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$$8 < \mathrm{We}_{\mathrm{crit}} < 22 \tag{1.2}$$

This means that when the Weber number for a drop exceeds this value, the drop breaks up. When the relative velocity between the drop and the gas is attained gradually the higher value is appropriate. When it is attained suddenly, the lower value should be used.

The value of the drop diameter calculated from equation (1.2) represents the largest drop which one might expect to find. Smaller drops are almost certainly present, too.

The data sets correlated by Kataoka et al. (1981) are largely for annular flows of air and water at about one atmosphere of pressure. The dimensionless groups used in that work, however, make the extension to steam-water flows reasonably simple. The fact that these drops were formed from an annular flow, however, needs some discussion.

The drops formed in a boiler tube would usually be formed from an annular flow, so the correlation of Kataoka as it is, is probably appropriate for them. The drops formed in a turbine or in a nozzle however are probably formed by homogeneous condensation in the expanding flow and are very small, typically less than one micron in diameter. They will, however, often agglomerate and be thrown to the wall, where they agglomerate further to form an annular film. By the time the flow makes it to a separator or bleed line, most of the liquid flow will occur either in the annular film on the wall or in the form of re-entrained drops. The drops will certainly be much larger than they were when they were first formed. The results of Kataoka are also recommended, therefore, even if the drops are formed downstream of nozzles or in turbine extraction piping.

For many order-of-magnitude calculations a mean drop size is useful for getting oriented. Kataoka et al. (1981) recommended the following equations for the volume (or mass) average diameter. In the middle range for the data shown on Figure 1.

$$D_{vm} = 0.0099 \frac{\sigma}{\rho_g j_g^2} \mathrm{Re}_g^{2/3} \left( \frac{\rho_g}{\rho_f} \right)^{-\frac{1}{3}} \left( \frac{\mu_g}{\mu_f} \right)^{\frac{2}{3}} \tag{1.3}$$

$$D_{\max} = 0.031 \frac{\sigma}{\rho_g j_g^2} \mathrm{Re}_g^{2/3} \left( \frac{\rho_g}{\rho_f} \right)^{-\frac{1}{3}} \left( \frac{\mu_g}{\mu_f} \right)^{\frac{2}{3}} \tag{1.4}$$

so the maximum sized drop is about three times larger than the average. The volume mean diameter in this equation is that diameter for which half of the volume of entrained liquid is in the drops larger than $D_{vm}$ and half is in drops that are smaller. Figure 1 shows how $D_{vm}$ compares to the data and Figure 2 gives the entire distribution over all sizes. Because of the pronounced banding of the data, it is obvious there is some systematic error in these equations. Probably some unrecognized geometric differences in the experiments are responsible for the wide scatter band.

Figure 3 (Snyder, 1959) gives the measured drop counts for three velocities of a steam water flow for the conditions indicated in the caption. The calculated $D_{vm}$ is also given. It is smaller than the value calculated from Figure 1. This is due to the fact that this data is for a heated tube where the drops were accelerated, while the data of Figures 1 and 2 is for a fully developed air-water flow. Both the spectrum shape and the

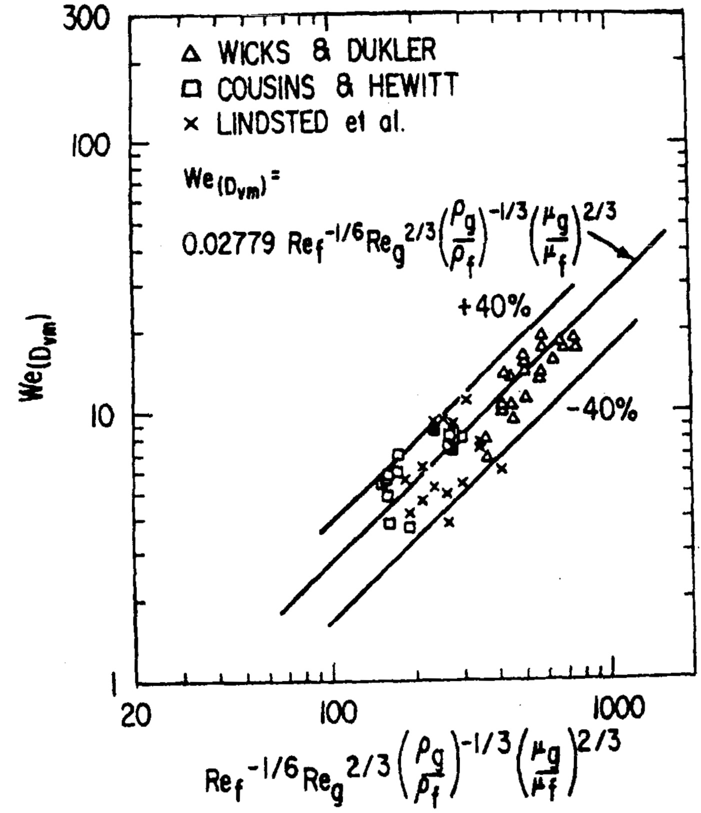


**Figure 1** Mean droplet sizes, Kataoka, et al. (1981) showing the effect of liquid flow rate in addition to the other variables

magnitude are typical of the values one might expect to find in a steam-water two-phase flow. One of the most important characteristics of this spectrum is that a few large drops account for most of the mass while a huge number of very small drops at the small end of the spectrum account for very little.

Another important source of liquid entrainment in a two phase flow is that which arises from a pool on the surface of which bubbles are breaking. Bubbles rise to the surface, break and the liquid rushes in forming a jet which projects one or more drops into the vapor. Garner et al. (1954) collected some typical drop size spectra for these conditions which are reproduced here as Figure 4. Though the largest number of drops is in the size range of 10 or 20 $\mu$m, the most important are those in the 500 $\mu$m range. When the diameters of the small drops are cubed in order to obtain the volume or mass, the importance of the small drops is greatly diminished. Figure 4 gives examples of the drop size spectra found in a flow leaving a pool (Garner, et al. 1954).

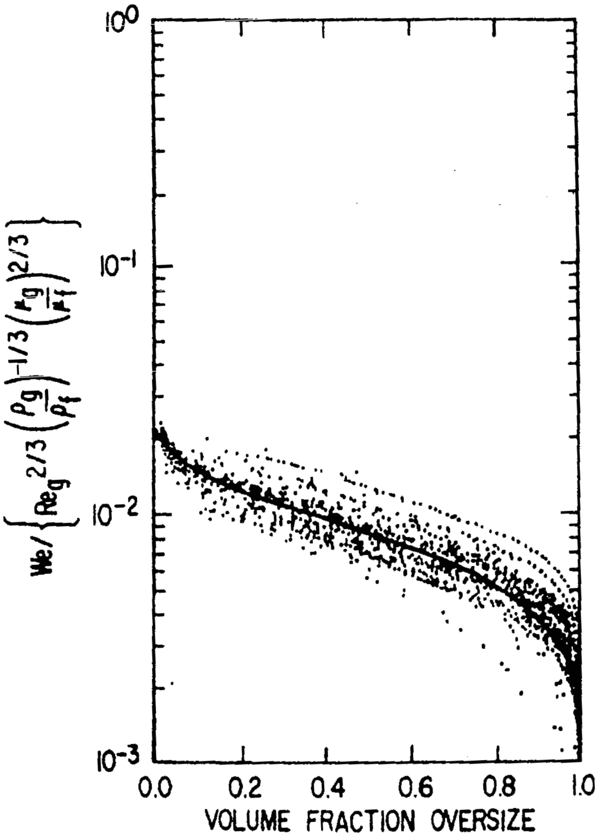


**Figure 2** Droplet size distributions, Kataoka, et al. (1981)

With this brief introduction to the drop sizes and spectra that might be found entering steam separation equipment, let us turn now to the main purpose of this work, helping to select, design and predict the performance of steam-water separation systems.

## 2. THE CHOICE OF A SEPARATOR

### 2.1 *Considerations in the choice of a separator*

A variety of concerns govern the choice of a separator. These include the following:

#### 2.1.1 *Separation efficiency*

Some applications like superheaters require clean steam. High separation efficiency is very important for this application. Separation efficiencies in excess of 99% are

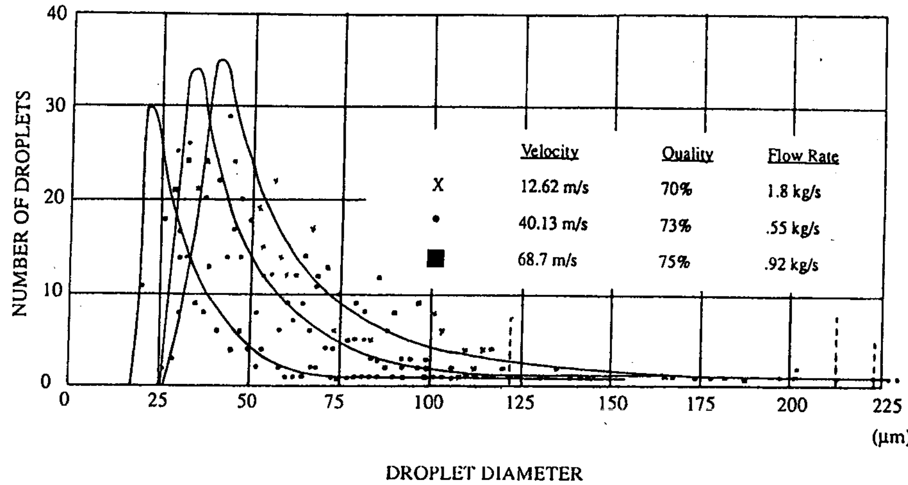


**Figure 3** Droplet diameter for several different flow rates for an atmospheric pressure steam-water flow in a heated tube 5 mm in diameter (Synder, 1959). The calculated $D_{vm}$ for the .55 x $10^{-4}$ kg/s flow rate is 500 $\mu m$. This is less than one would calculate for these conditions using the recommended methods but within the scatter shown in Figure 2

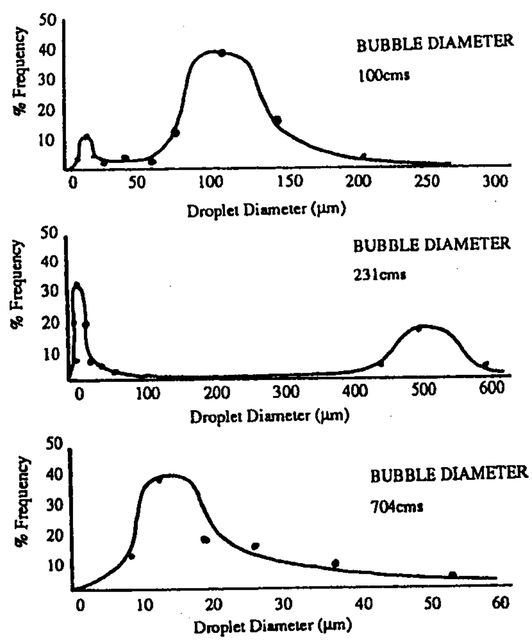


**Figure 4** Examples of drop size spectra resulting from bubbles of different sizes breaking at a water surface (Garner et al. 1954)

essential. Any carry-over includes silica which is ultimately deposited on the superheater tubes causing overheating. Other applications like moisture separator-reheaters can tolerate rather low efficiency because the liquid condensate is so clean to start with that scale buildup is not a problem. Poor separation efficiency, therefore, is tolerable in these devices. Similarly, 80% separation efficiency is acceptable for the extraction line from a turbine because the erosion is greatly reduced if most of the moisture is removed while both the space for these separators and the allowable pressure drop are limited.

### 2.1.2 *Pressure drop*

Pressure drop is one of the most important considerations primarily because we rely on the gravity pressure difference in the drains in order to make the separator work. When the pressure drop is too large, the separator fails to work. Cyclone separators typically return the separated liquid to a pool through a drain line the end of which is submerged in the pool. When the separator pressure drop is too large, liquid backs up this tube ultimately degrading the separator performance to the point where it can be said that the separator has failed.

### 2.1.3 *Space availability*

Space is valuable in pressure vessels like steam drums, or moisture separator reheaters or in the upper plenum of a nucleate reactor. Depending on the application, the volume occupied by the separator can be an important consideration when trying to decide what type of separator to select. Gravity separators require the largest volume for a given flow rate while impingement separators require less and cyclone separators the least of all. A good measure of separator size is the characteristic velocity. Table II gives this for several types. Low characteristic velocities mean large separators.

### 2.1.4 *Availability of performance data*

While it is certainly possible to design a separator from the information that is available in these notes, it is unlikely that the information give in this article is sufficiently complete so that a really high performance separator could be designed. The design can be done with the information given here but the actual performance would have to be obtained from an experiment. Ordinary separators could be designed and used without further testing.

### 2.1.5 *Inlet quality*

Very wet steam-water mixtures can be in the bubbly, slug or churn-turbulent flow regimes. Only gravity or cyclone separators are able to handle steam-water mixtures as wet as those characteristic of these flow regimes. High quality steam-water flows such as those exiting a steam drum of a once-through boiler or those found in the extraction lines of turbines are usually in the dispersed or annular-dispersed flow regime. For these, wire mesh, chevron, or other type of impingement separator is often appropriate. Table II summarizes these characteristics.

✓ Carry-under

**Table II** Types of separators and their characteristics. Adapted from Monat et al. (1986). McNulty et al. (1986), Smith (1986), Mauro et al. (1990)

| Type | Approximate Droplet Size Range $\mu m$ | Separation System Flow Regime | Typical $F_s$ $\frac{1}{s}\left(\frac{kg}{m}\right)^{1/2}$ | Typical $\Delta P$ Pa | Two Phase Flow Regime |
|---|---|---|---|---|---|
| Gravity Separator | >10.0 | Laminar or Turbulent | .25-15 | negligible ~1 velocity head | Any quality but best for low quality slug or annular dispersed flow |
| Droplet Diffusion | >10.0 | Turbulent | 2.5-5 | About 1 velocity head | Highly dispersed droplet flow |
| Knitted Wire Mesh | >3.0 | Turbulent | .8-1.6 | 25-500 | Highly dispersed droplet flow |
| Chevron or Impingement Separator | >6.0 | Turbulent | .8-3.7 | 250-500 | Highly dispersed droplet flow |
| Cyclone Separator | 10.0 and up | Turbulent | 2.5-1.7 | 750-7500 | Any quality or flow regime |

In which the characteristic velocity is

$$F_s \triangleq V_g \sqrt{\rho_g} \tag{2.1}$$

## 2.2 *Types of separators*

These types of separators and their characteristics are listed in Table II. This table will help in designing a system suitable for the application in question.

Even for very wet steam, the volume of liquid flowing is usually smaller than the volume of vapor. For this reason, one can look at the characteristic velocity which is to be calculated from $F_s$ and Table II and the accompanying equations. It is the velocity of the mixture into the separator. The larger this velocity, the smaller the separator. For impact type separators, like the fiber filter, the knitted wire mesh or a chevron separator, the characteristic velocity is the approach velocity. For gravity separators, it is the superficial velocity of the vapor at the free surface of the liquid. For cyclone separators, it is the velocity at the entrance to the cylindrical chamber where the separation occurs.

For cycle separators, which are the only separators which are appropriate for all qualities, the inlet velocity to the cyclone is the characteristic velocity.

### 2.2.1 *PWR Steam Generator*

The first example is a steam separator installation which is shown in Figure 5. It is installed in a Westinghouse pressurized water reactor steam generator in the bulbous section at the top of the steam generator pressure vessel. A two phase mixture enters the swirl vane separators and dry steam exists at the top of the vessel. The details of the flow through the drying section are best illustrated by turning to Figure 6 where the flow through a model of a *W* steam generator is illustrated.

Wet steam enters the vertical pipe in the center of the dome. It then passes through the swirl vanes. Liquid is deposited on the walls and drains back to the pool above the "U" tubes in the steam generator. The steam and some water continues up where some

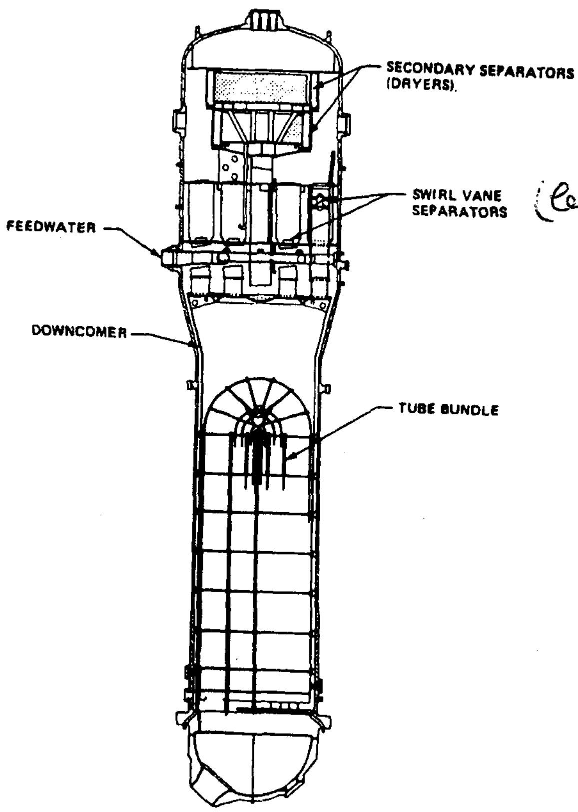


**Figure 5** A Westinghouse Model F steam generator showing the separator section in the bulbous part of the generator at the top of the drawing. Young et al. (1984)

**Figure 6**
Young et a

moisture
remaining
of the rer
describing

**Table III**

| |
|---|
| Pressure |
| Temperatu |
| Steam qua |
| Steam qua |
| Steam flov |
| Drying sec |
| Drying sec |

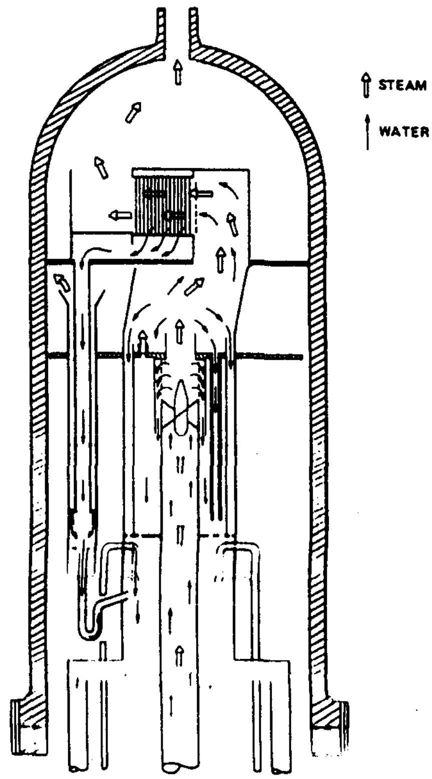


**Figure 6** A detail of the MB-2 steam separator section showing the steam and water flow paths. Young et al. (1984)

moisture drops out on the deck plate and drains back to the pool. The steam and remaining water passed through the chevron separator at the top of Figure 6 where most of the remaining water is separated while the steam passes out the top. The statistics describing this separator are given in Table III.

**Table III** Operating parameters for the Westinghouse PWR steam separator section

| | | |
|---|---|---|
| Pressure | 7.37 mPa | (1,070 psia.) |
| Temperature | 343°C | (650°F) |
| Steam quality in | about 20% | |
| Steam quality out | 99.75% | |
| Steam flow | $4.09 \times 10^6$ kg/hr | ($8.99 \times 10^6$ lb/hr.) |
| Drying section ID | 6.08m | (20 ft.) |
| Drying section height | 9.12m | (30 ft.) |

These values of the approximate dimensions from Table III and figures 5 and 6 can be used to estimate the volumes and flow areas needed to separate moisture in a large system for typical steam rising conditions. It should be noted that this drying section really has three stages of separation. All three are needed to have both good separation efficiency and high steam flow rates.

### 2.2.2 *Moisture-separator reheaters (MSR)*

These devices are needed to remove the moisture from partially expanded steam before it is returned to the low pressure turbines for further expansion. Figure 7 is a schematic of an MSR. The wet steam enters at the right, passes through the chevrons in a horizontal direction and then goes up, over the reheater tubes and out the top. Separated moisture is drained out the bottom of these units. These devices often use screen separators too. They are standard equipment in both BWR and PWR plants.

These too are high performance devices. The operating conditions are given in Table IV.

### 2.2.3 *Steam drum separator section*

Figure 8 illustrates the separator section in a steam drum. A steam-water mixture enters from the tubes in the boiler in the bottom half of the steam drum. The mixture passes circumferentially into the annular gap between the drum and baffle up to the cyclone separators. It enters these tangentially. The water then exits through the bottom while steam with a little carryover exits from the top.

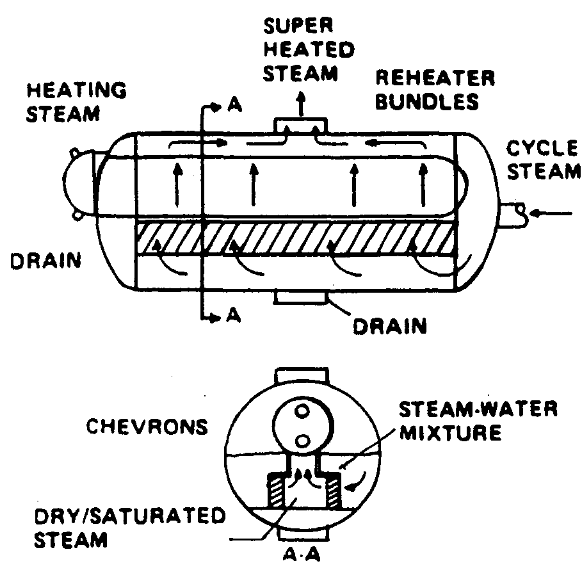


**Figure 7** Schematic of a moisture separator reheater. Moore & Sieverding (1976)

**Table IV** Operating conditions for a typical MSR separation section, Moore & Sieverding (1976)

| | | |
|---|---|---|
| Pressure | 1.309 kPa | (190 psia) |
| Temperature | 335°C | (350°F) |
| Steam quality in | 93% | |

Because of the low moisture content in, there is no need for an initial cyclone separator to remove the bulk of the inlet moisture.

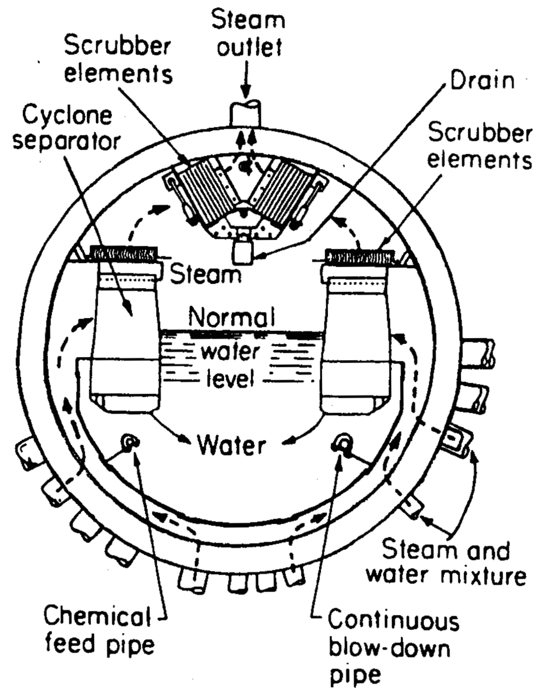


**Figure 8** Steam drum separator section typical of modern drum type natural circulation boilers. Avallone, et al. (1987)

The steam typically passes through one or two scrubbers before going out to the turbine or superheater unit. These stages of separation are very much like those found in the top of the PWR steam generator. These three examples show how the flow rate and pressure drop characteristics of different kinds of separators have been combined to produce dry steam economically.

Carryunder can be a problem too. It can separate in the downcomers and degrade the circulation. It too must be avoided. Later in this work, when cyclone separators are discussed, carryunder will be considered.

We will now give a description of each separator type and how it operates. We shall then define the operating limits for each type and outline how a separator would be designed to conform to these limits. Any special properties of that separator type will then be mentioned.

## 3. GRAVITY SEPARATORS

Gravity separators are most commonly found in the oil and gas industry rather than the power industry. They are so easy to build, however, that they are often used and some guidelines on their construction are useful. They can be installed for general service or put in for temporary service if required.

They consist of either a spherical tank or, a horizontally or vertically oriented cylindrical tank. The liquid level is maintained near the maximum flow area of the tank by the level control on the trap through which the separated liquid is removed. The steam water mixture enters under the water level and the phases separate due, primarily, to gravity. A good rule-of-thumb is that the superficial velocity of steam at the interface which should be less than .3 m/s. Gas or vapor is withdrawn at the top of the vessel while the liquid exits through the trap at the bottom. The two phase mixture can also enter above the water level where it impinges on a baffle. The vapor velocity must be maintained low enough so that the drops from surface waves do not result in re-entrainment and small drops can fall out of suspension. Table I gives an idea of how rapidly drops fall as a function of size. In any case, re-entrainment from the pool is the problem so that is what one must design for. Entrainment from the pool takes place by several mechanisms. If a bubble makes it to a free surface and breaks, a wave on the free surface propagates both away from and towards the center of the ring that defined the edge of the bubble before it broke. When the wave propagating in meets itself in the center, a jet is formed that rises straight up and breaks up into one or more drops that are projected with a velocity of a meter per second or so. This mechanism for entrainment is most important at low steam superficial velocities, 0.3 m/s or less, Garner et al. (1954).

Another mechanism of droplet entrainment is the breakup of foam on the surface. The bubbles which constitute the foam break and the slight overpressure in the bubble projects the ligaments and sheets of liquid away from the free surface. These subsequently break up and the drops which are small enough are carried out by the vapor. The double humped drop spectra evident on figure 4 is due to this dual source of drops.

### 3.1 *Entrainment from a free surface*

The most complete study of entrainment at a free surface is that due to Kataoka et al. (1981). Most of what follows is drawn from that work.

Imagine a free surface with steam bubbling through it. Three regimes of carryover can be identified (Figure 9). Near the surface the drops have sufficient velocity so that

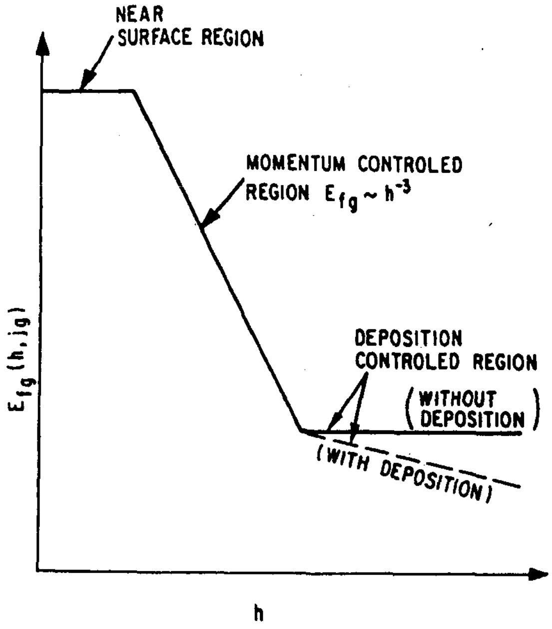


**Figure 9** The effect of height above a pool on carryover or entrainment. Kataoka, et al. (1981)

they are rising at almost their formation velocity. Above that region the drops lose velocity, due to gravity and drag, so the amount of liquid crossing a horizontal plane (while traveling up) decreases. Still further up, the only drops left are those that are so small that they cannot fall back against the rising vapor. They can, however, be deposited on any surfaces that are present, drain back and thus be removed. They are not large enough to fall back on their own, however.

Referring to Figure 9, correlations for the carryover at the surface, the depletion of the droplet flow with height and the asymptotic droplet flux are all needed. These are determined as follows.

Starting at the pool surface, the notion of entrainment looses its validity when the superficial gas velocity is so great that there is no distinct water level. This occurs at about the point where:

$$E_{fg} = 5.0 \tag{3.1}$$

where

$$E_{fg} \doteq \frac{\rho_f \, j_{fe}}{\rho_g \, j_g} \tag{3.2}$$

This can be viewed as the criterion for the transition from the churn-turbulent to the annular or annular-dispersed flow regime within the pool.

The reduction in the entrainment carried up with elevation can be calculated by means of Figure 10. Starting at the upper right one proceeds down and to the left until the level for which the carry over desired is attained. The symbols appearing on Figure 10 are defined below.

$$j_{ge}^{*} \hat{=} j_g \Big/ \left( \frac{\sigma g \Delta\rho}{\rho_g^2} \right)^{1/4} \tag{3.3}$$

$$h^{*} \hat{=} h \Big/ \left( \frac{\sigma}{g\Delta\rho} \right)^{1/4} \tag{3.4}$$

$$N_{\mu g} \hat{=} \mu_g \Big/ \left( \rho_g \sigma \sqrt{\sigma / g\Delta\rho} \right)^{1/2} \tag{3.5}$$

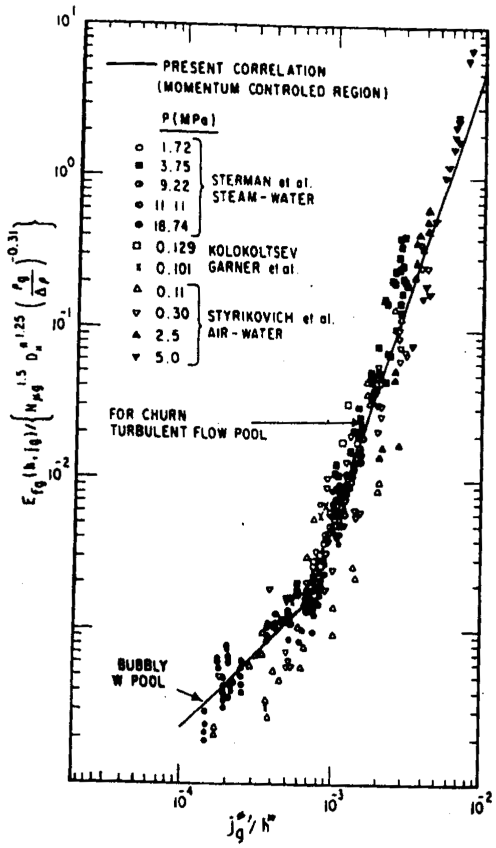


**Figure 10** Reduction in entrainment with height above the pool. Kataoka et al. (1981)

$$D_H^* \hat{=} D_H \Big/ \sqrt{\frac{\sigma}{g\Delta\rho}} \qquad (3.6)$$

Figure 10, in essence, is to be used to give the flow rate of drops which are small enough to be carried up at the given superficial velocity of vapor. Figure 10 and equations (3.1) to (3.6) really apply to a chamber of uniform flow cross sectional area. When the flow area is changing, as in a spherical or horizontally oriented cylindrical tank for instance, the change in area is reflected as change in $j^*_g$. If one imagines the flow approaching the exit port at the top of a spherical tank, there will be an elevation above which the superficial velocity of vapor will be sufficiently large so that everything will be carried out. This elevation can be determined by plotting $E_{fg}$ from Figure 10 as a function elevation (accounting for the effect of area change on $j^*_g$) and identifying the elevation at which the velocity is high enough so everything is carried up.

Above this elevation, drops are carried up and often deposited on the vessel and pipe walls from whence they either flow back into the pool or are carried up as an annular film. These processes will be explored later in this work, in the section on drop diffusion separators.

The core of this section is contained in Figure 10. A considerable range of data is included on this plot with both steam-water and air-water well represented. The parameter ranges included are shown in Table V. Above a superficial velocity of 2 m/s there is no distinct liquid level so carryover cannot be defined.

**Table V** Data ranges for pool entrainment

| | |
|---|---|
| Fluids | Air-water and steam-water |
| Pressure | 0.1 to 18 MPa |
| Pool surface superficial velocity | 0 to 2.0 m/s |
| Height above the pool | 0 to .85 m |

### 3.2 *Pressure drop*

For a gravity separator, in which the two phase mixture is in the form of bubbles in a pool, the separator pressure drop is essentially the hydrostatic pressure difference between the inlet and the free surface. For the rest of the separator the pressure drop is negligible because the velocities are so low.

## 4. DROP INERTIA SEPARATORS

A variety of separators such as straight tubes, screens, chevrons and several others all rely on inertia to cause the drop to be deposited or a wall, from which the liquid drains away. This section will discuss three of these designs in some detail.

### 4.1 *Droplet deposition from a turbulent flow*

This is about the simplest design for a separator that one can imagine. It is a straight vertical tube in which the turbulent-fluctuations in the vapor cause entrained drops to be deposited on the wall. Gravity then causes the liquid to drain down out the bottom. For this kind of separator to work, the flow regime must be dispersed so the quality is always quite high. The separated liquid is removed from the inlet plenum while the steam exits from the top of the tube. There are several criteria to which separators of this kind must be designed if they are to operate properly. These are listed and then discussed below.

1. The flow should be up.
2. The flow must be turbulent.
3. The velocity must be below the flooding velocity at both the entrance and the central section of the tube.
4. The tube must be long enough to allow droplet deposition to proceed as far as is desired.

Let us now discuss each of these criteria.

#### 4.1.1 *Flow direction*

Up flow is better than down flow largely because gravity tends to increase the transit time for the drops in the tube and allow more of them to be deposited for a given tube length. It is also easier to imagine designing a system for removing liquid from the inlet plenum, without re-entraining it, than it is for the exit plenum in which the drops might leave the lip of the tube as spray.

On reflection it would appear that an inclined, rather than vertical, up flow tube would probably be better than either vertical up or vertical down flow. This is true for several reasons. Gravity would help to deposit the drops on the bottom of the tube. This would augment the drop deposition rate. Inclined tubes have a higher flooding velocity than vertical tubes of the same design. Properly designed entrances to these tubes could probably effect a cleaner separation of the phases than could be accomplished in the inlet plenum of a vertical tube. The only penalty for an inclined tube array as it would probably use more space than a vertical tube array that did the same job.

#### 4.1.2 *Choice of velocity*

Turbulent flow is assured by choosing a Reynolds number for the vapor flowing alone in the tube which is greater than the critical Reynolds number. That is:

$$\frac{j_g D \rho_g}{\mu_g} > 5000 \tag{4.1}$$

The contribution of the liquid, to the superficial mixture velocity for the liquid fractions characteristic of dispersed flow is quite negligible so the above equation is entirely adequate for selecting the minimum vapor velocity.

Any velocity above this will work effectively to remove the drops. However, with increasing steam velocities, the film on the wall will first stall and then reverse. Figure 11 shows the flow regimes that will be observed. Figure 12 shows how the pressure drop will vary in the region where the film reverses, Hewitt et al. (1965). For most of the counterflow region, the pressure gradient is very much smaller than the hydrostatic pressure gradient for pure liquid.

### 4.1.3 *Flooding*

When the film is stalled we speak of the tube as being flooded. The flooding velocity has been studied and for vertical tubes is best calculated using the flooding correlation of Wallis (1969) or Bankoff and Lee (1985), Figure 13. The variables $j^*_f$ and $j^*_g$ are defined as:

$$j_g^* \triangleq \frac{j_g\, \rho_g^{1/2}}{[g\, D(\rho_f - \rho_g)]^{1/2}} \tag{4.2}$$

$$j_f^* \triangleq \frac{j_f\, \rho_f^{1/2}}{[g\, D(\rho_f - \rho_g)]^{1/2}} \tag{4.3}$$

The flooding correlation using these variables is of the form:

$$j_f^{*1/2} + j_g^{*1/2} = C \tag{4.4}$$

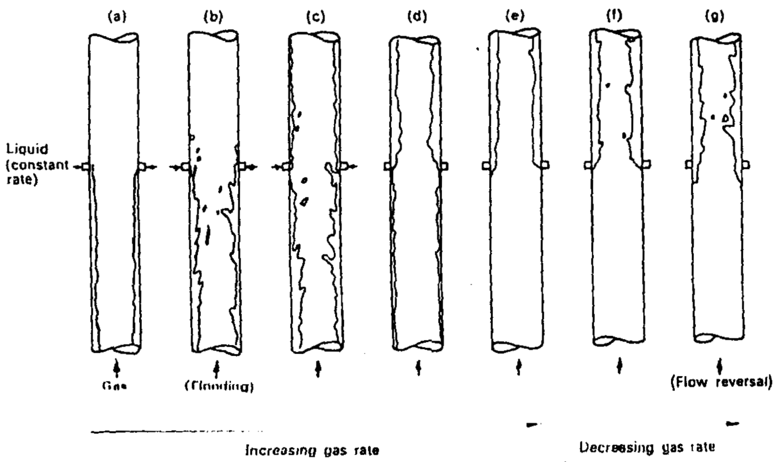


**Figure 11** Film behavior in a vertical tube with upflowing gas. Hewitt et al. (1965)

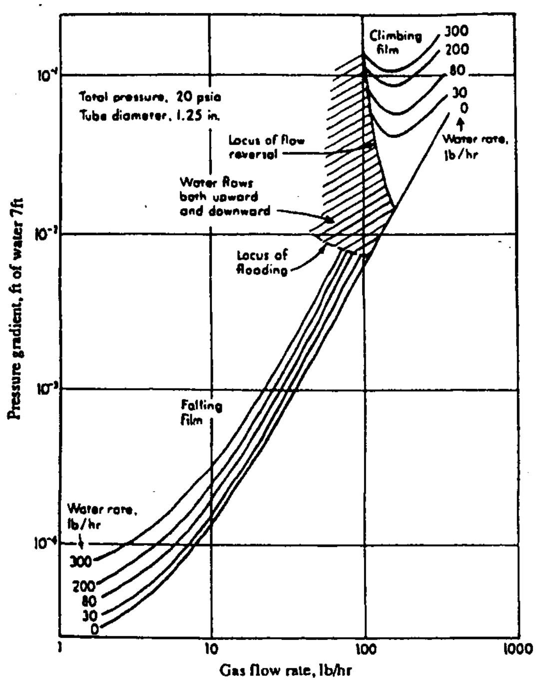


**Figure 12** Pressure drop characteristics near the boundary between counter current and cocurrent flow. Hewitt et al. (1965)

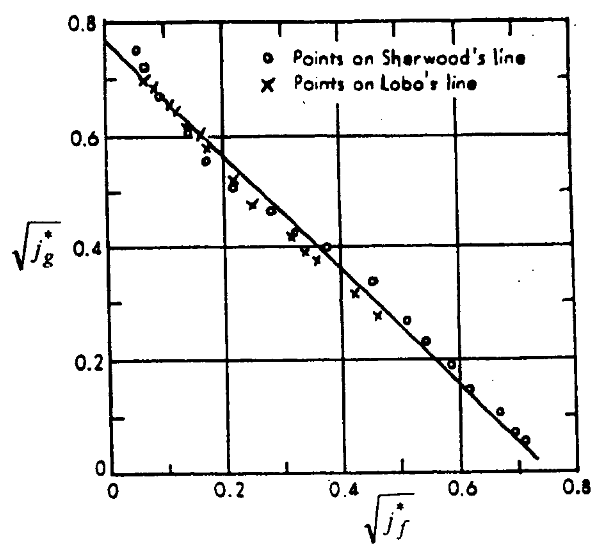


**Figure 13** Flooding correlation for a vertical tube. Wallis (1969)

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4.1.4 *Dro*

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where the constant is a function of the end conditions. The constant on the right is as follows:

for a sharp edge entrance to the tube

$$C = 0.725 \tag{4.5}$$

When the entrance or edge effects are minimized

$$0.88 < C < 1 \tag{4.6}$$

and flooding can occur in the middle of the tube.

The range of conditions covered in a separator receiving a dispersed flow is very small. Operation is virtually confined to the $j_f = 0$ intercept of figure 13. This is because the flow rate for the liquid flowing down cannot be larger than the flow rate of drops which are carried into the pipe. That liquid flow rate is, however, very small because of the flow regime we are in, dispersed-annular, and because of the velocity. This kind of separator must always operate below the flooding velocity for the film. The recommendations for determining the flooding velocity for such a separator is as follows:

> Assume the liquid rate is negligible and use the $j_f = 0$ intercept on Figure 13 to determine the flooding velocity. Always operate below that velocity. Check that the droplet flow rate is not so large that, if it were all in the form of a falling film, it would alter this value significantly.

cocurrent

Flooding in vertical tubes can, in general, occur at the bottom, in the middle, or at the top. For this application flooding at the top is impossible because most of the liquid in the flow will have been removed before the mixture gets there. Flooding somewhere in the middle of the tube cannot be ruled out. Flooding at the entrance is quite likely, however. If the entrance to the tube is cut on a bias, say 30° from the vertical, flooding at the entrance can be eliminated, Perry (1984). Otherwise flooding is most likely to occur at the entrance. When the entrance to the tube is cut on a bias, a value of $C$ within the range given by equation (4.6) should be used. The range represented in equation (4.6) is a result of hysteresis in the flooding data. Increasing flows flood at a higher velocity than a decreasing flow unfloods.

#### 4.1.4 *Droplet deposition rates*

Let us now turn to the deposition rate of drops from a turbulent flow. Liu & Agarwal (1974), Liu & Ilori (1975), Farmer (1969) and McCoy & Hanratty (1977) describe the processes and present models that can be used to calculate the rate at which the concentration of drops in a two phase flow are depleted by deposition on the walls.

A simple answer is appropriate to start with. According to Farmer (1969) and Lopes & Dukler (1986) about half the entrained droplets are deposited every 3 to 7 L/D's. This, of course, is not a law of nature but a rule-of-thumb that applies to typical drop size in gas flows at ordinary velocities. In addition, the references just cited all indicate that some additional drop deposition occurs in the entrance region of the tube. This is probably because the incoming flow has some swirl and the drops are centrifuged out to the wall. Once the swirl has decayed sufficiently, turbulent diffusion governs. Before presenting the turbulent droplet deposition rate one should be reminded of the chart, reproduced here as Table I, which shows how large drops are and how they compare to the drops in nature that are familiar to all of us. Table I also shows us what to expect in terms of droplet behavior as a function of drop size while section 1.3 gives us an idea of what drop sizes we should expect for a given system. Let us now turn to turbulent deposition of droplets.

A grand correlation of droplet deposition data is reported by McCoy & Hanratty (1977) and is reproduced here as Figure 14. Three regions are evident. For very small $\tau^*$ (that is small drops like smoke), Brownian notion governs and a constant Sherwood number is appropriate for calculating the droplet deposition rate. These drops are much smaller than the ones we are concerned with here.

For the range when

$$0.1 < \tau^* < 20 \tag{4.7}$$

the mass transfer coefficient is a strong function of $\tau^*$. These drops are probably too small to worry about too.

For

$$\tau^* > 20 \tag{4.8}$$

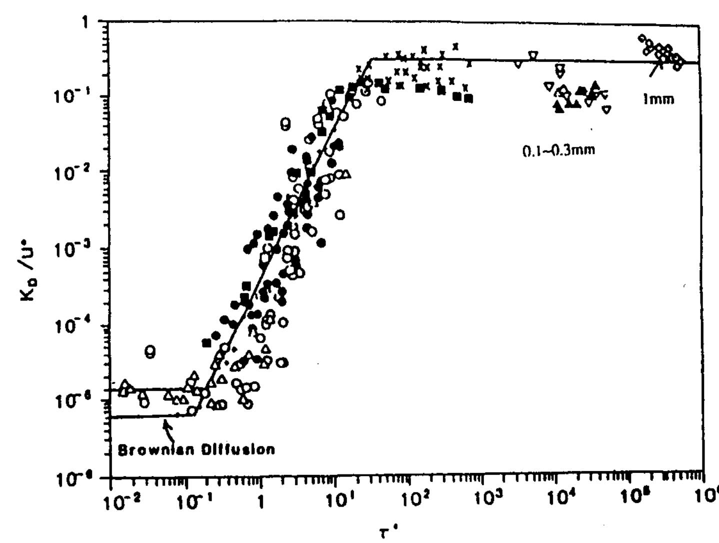


**Figure 14** Deposition rates for drops in a turbulent flow. McCoy & Hanratty (1977), Lopes & Dukler (1986)

the mass transfer coefficient is independent of $\tau^*$. This is the most important region. For this region,

$$\frac{K_D}{u^*} = 0.20\,. \tag{4.9}$$

The mass flux at the wall is then calculated from equation (4.10)

$$\frac{\dot{m}}{A} = K_D C_D \tag{4.10}$$

This region typically covers drops larger than 10 microns or, in other words, the drops which contain most of the mass in the two phase flows which we are concerned with (see Table I and figures 1 through 4). It is recommended that equation (4.10) above be used for all drop sizes to calculate the deposition rate on the pipe wall.

Before proceeding, the terms appearing in equations (4.7) through (4.10) should be explained. $\tau^*$ is the dimensionless particle relaxation time or stopping time. It is defined in equation (4.11):

$$\tau^* \doteq \frac{1}{18}\frac{\rho_f}{\rho_g}\left(\frac{\rho_g u^* D_d}{\mu_g}\right)^2 \tag{4.11}$$

$u^*$ is the friction velocity as defined in equation (4.12)

$$u^* \doteq \left(\frac{\tau_i}{\rho_g}\right)^{1/2} \tag{4.12}$$

The $\tau_i$ in equation (4.12) should be calculated using an appropriate two-phase pressure drop correlation such as the homogeneous or Martinelli, Hetsroni (1982), and the relation between wall shear stress and the pressure gradient in a pipe.

This regime has drops deposited by turbulent fluctuations in the flow. The drops acquire a turbulent velocity component in the core and are then carried through the boundary layer, by their inertia, to the wall where they stick. There is a stopping time which, for small drops, is so short that the drop cannot make it to the wall before it is stopped. Spray, therefore, would be deposited on the walls while smoke probably would not be. The smoke particles do not usually have enough inertia to be carried through the boundary layer.

In equation (4.10)

$\dot{m}/A$ is the mass transfer rate to the wall (mass/unit area/time)

$K_D$ is the mass transfer coefficient (length/time)

$C_D$ is the liquid concentration in the flow (mass/unit volume)

$CD$ is calculated assuming the liquid is dispersed as small drops moving at the vapor velocity. Equation 4.10 also assumes the drops and vapor are both moving at the same velocity which, an examination of Table I will show is approximately true for most of the drop sizes of interest. Though for very small drops the deposition rate drops off, it is suggested that the right hand asymptote of Figure 14 always be used.

### 4.1.5 *Pressure drop*

Let us now turn to the question of pressure drop. Two phase pressure drop can be estimated in the approach piping from any established two-phase pressure drop correlations. For the separator itself, the range of operating velocities is quite constrained so that the resulting pressure drop is quite small. An idea of how small it is can be obtained by looking again at the pressure drop curves of figure 12. If we consider a gas flow rate of 70 lb/hr and a water flow rate of 30 lb/hr we would have a quality of 70%. If the gas phase were steam, it would be very wet steam. However, from Figure 12 the pressure drop is only very slightly more than it would be for that tube at that gas flow rate. This is a very low value. Under the circumstances it is recommended that, to calculate the pressure drop, assume a dry vapor is flowing at the vapor velocity. Neglect the effect of both the wall film and the entrained drops. Both factors increase the pressure drop slightly but the effect is probably too small to bother with. There is no established correlation for a dispersed, annular, counter flow in which the net liquid flow is almost zero as it would be in this regime so this recommendation will have to suffice. This completes analysis of droplet deposition steam separators.

## 4.2 *Impingement separators*

These include filter, screen and chevron type separators. They all rely on the inertia of a drop to cause it to hit a surface while the conveying steam flow turns to avoid it. They also, all rely on gravity to remove the separated liquid. In proceeding from fibers through screens to chevrons one is proceeding from devices that can remove very small drops but have a high pressure drop to ones that are less effective on small drops but experience smaller pressure losses. Table II shows the ranges of drops size where good separation is to be expected in these separators. Because of their pressure drop characteristics, the devices with large pressure losses tend to be operated at lower velocity levels but there is a wide range of drop sizes and velocity levels for which any of these devices will perform satisfactorily.

### 4.2.1 *Screen separators*

Moore & Sieverding (1976) gives a complete review of screen performance. Their findings will be used freely in this work. Other recent publications of interest in this context are those of Pederson (1988) and Capps (1994).

Screen behavior is characterized by a separation efficiency. Let us start by considering a single wire in cross flow and ask what fraction of the drops for which their projection in the approach flow intersects the projection of the wires is trapped. If 100% of the drops whose projections intersect that of the wire are trapped, then we speak of the separation efficiency as being 100%. In fact very small drops will tend to follow the flow as it passes over the wires while large drops will continue forward virtually undeflected. The separation efficiency for a single wire then should be a function of drop size too, being better for large drops. In any case, the competing effects are a function of a dimensionless group called the Stokes number which is defined as

$$\mathrm{St} \doteq 2\left(\frac{L}{D_d}\right) = \qquad (4.13)$$

where $L$ is the stopping distance. It can be computed from Stokes law ($\mathrm{Re}_d < 1$) but for a fuller range of drop sizes, Figure 15 should be used.

The theoretical (dotted) line of Figure 15 is derived from potential flow for the wire. For cross flow Reynolds numbers which are sufficiently large, an additional parameter is needed to describe the droplet hydrodynamics too. Moore & Sieverding (1976) provides the details.

### 4.2.2 *Screen separation*

A single wire theory is not enough. A real screen is composed of woven wires with a voidage of $\varepsilon$. These screens, in turn, are stacked to make a pile. The theoretical prediction assumes the same percentage of the approaching drops is removed at each

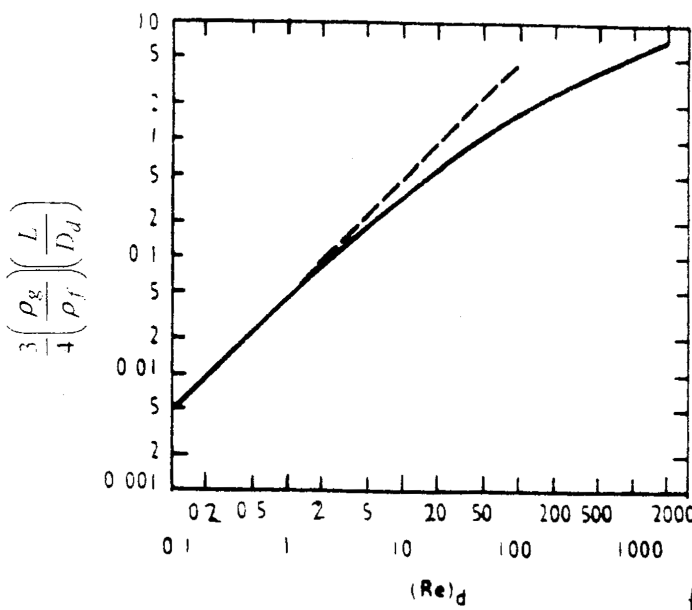


**Figure 15** Stopping distance for a drop. Moore & Sieverding (1976)

St = 10

$\frac{\rho_v D_d U \rho_e}{\mu_v \rho_e}$

screen. An expression for the efficiency of the array can be defined as is given below as equation (4.14):

$$\eta_k = 1 - \exp\left[ -\frac{8}{3} \frac{(1-\varepsilon)\eta_w H_k}{\pi D_w} \right] \tag{4.14}$$

In equation (4.14),

$\eta_w$ = Single wire separation efficiency see figure 16a

$D_w$ = Wire diameter

$H_k$ = Total depth of the screens

This equation for stacks of screens is compared to the data of several investigators in Figure 16b. The prediction is quite satisfactory.

4.2.3 *The velocity limit for screens*

The screens fail to separate properly when the velocity level is too high. For vertical up flow, the large drops that result when the trapped moisture agglomerates, are unable to fall back before being re-entrained. This is a phenomenon similar to flooding even though the steam is not necessarily flowing vertically up. Figure 17 shows that there is

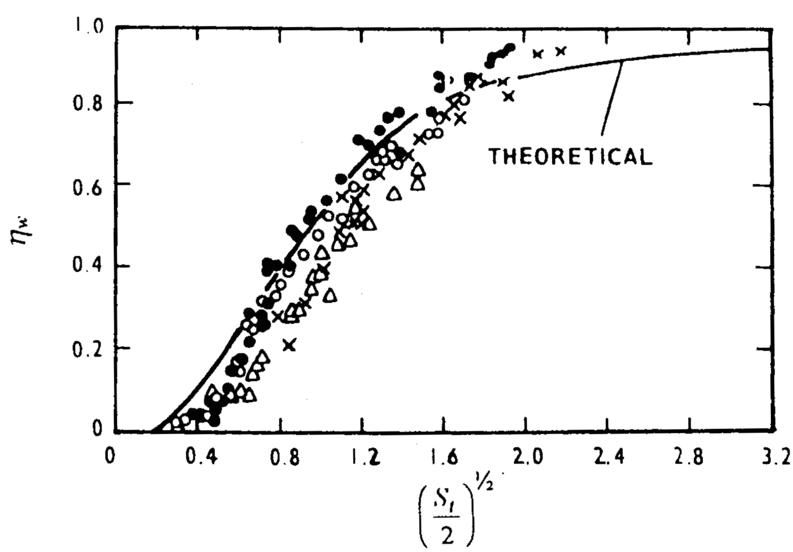


**Figure 16a** Efficiency of separation for a single wire as a function of the Stokes number. The flow is normal to the wire. Moore and Sieverding (1976)

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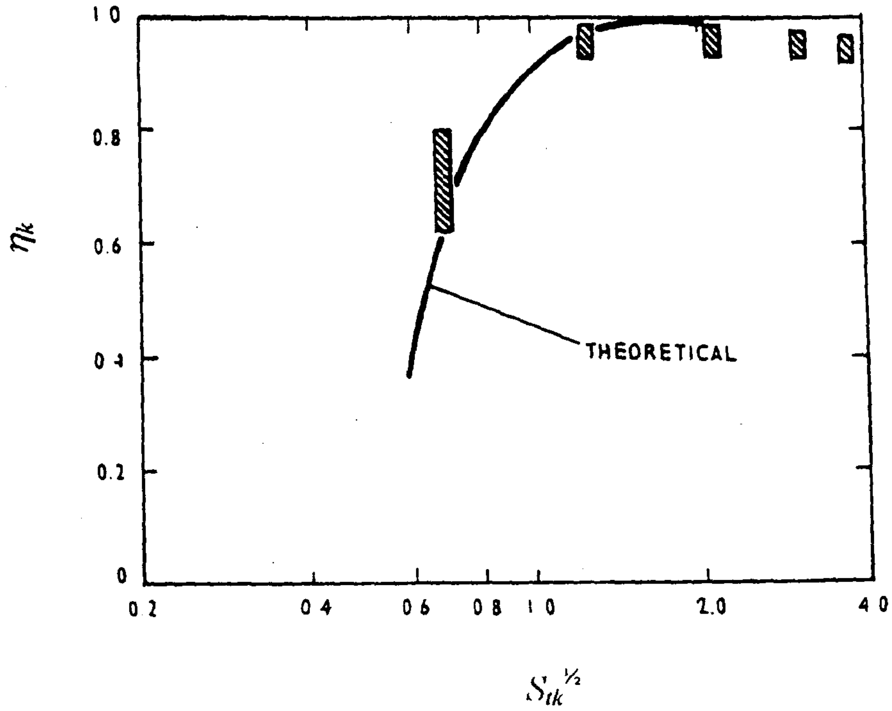



**Figure 16b** Efficiency of separation for a wire mesh as a function of the Stokes number. Up to a drop Reynolds number of 1, the drops follow Stokes law. Moore & Sieverding (1976)

an optimum flow angle for which the flow rate through a vertical screen is maximized before this occurs. This occurs with the approach flow inclined about 45 degrees from the horizontal.

A single set of screen flooding data is cited in Moore & Sieverding (1976) which is reproduced here as Figure 18.

The coordinates of Figure 18 involve the Kutataladze number which has a characteristic dimension based on gravity and surface tension. The Kutataladze number is defined as:

$$\mathrm{Ku} \triangleq \frac{\rho_g^{1/2} V_g}{(g\sigma(\rho_f - \rho_g))^{1/4}} \tag{4.15}$$

where $V_g$ is the approach velocity to the screen.

The dimensional group which is the abcissa is given as

$$\frac{g(\rho_f - \rho_g)}{\sigma} \tag{4.16}$$

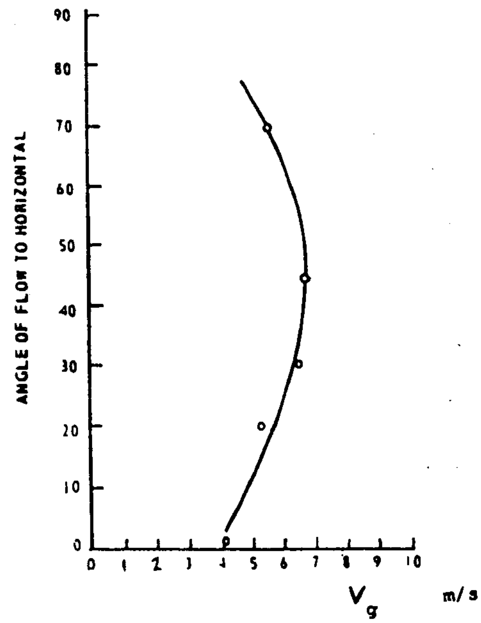



**Figure 17** The optimum angle of approach when a drop laden flow approaches a screen. Moore & Sieverding (1976)

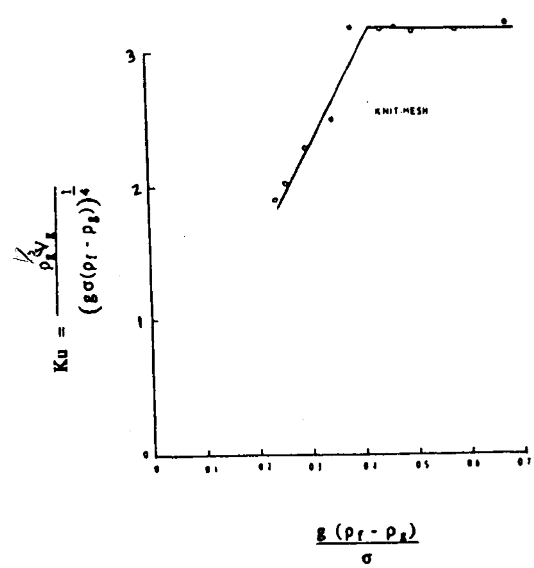



**Figure 18** Flooding velocities for knit mesh screens in vertical up flow. Moore & Sieverding (1976)

and has units of reciprocal (mm)$^2$. This quantity should probably be nondimensionalized by a characteristic dimension of the screens but this has not been done yet.

#### 4.2.4 *Pressure drop in screens*

The procedure for determining the pressure drop for two phase flow through wet screens has not yet been established. The recommendation is to use appropriate screen pressure drop formula such as given in Idelchik 91986) to calculate the pressure drop for the gas flowing alone in a single dry screen. This pressure drop should be multiplied by the number $m$ of screens. In order to account for the presence of water in the flow this pressure drop should also be multiplied by a factor accounting for the additional mass due to the water. As we are in the dispersed flow regime, the volume flow rate of liquid is very small and a homogeneous model should be adequate. That is:

$$\Delta p = \Delta p_1 \, n \left( \frac{1}{x} \right) \tag{4.17}$$

where $x$ is the quality of the approach flow. This formula would tend to give a conservative answer on one hand because much of the liquid will be separated out of the first few screens so multiplying the overall screen pressure drop by $1/x$ is probably excessive. On the other hand, if the screen is wet, the flow area for the air will be reduced. This will tend to increase the pressure drop. A precise answer would have to be obtained from an experiment. In equation (4.17) $\Delta p_1$ is the pressure drop due to the first screen.

### 4.3 *Chevron separators*

Moore & Sieverding (1976), Monat et al. (1986) and McNulty et al. (1986) contain most of the information that is needed to design or select a Chevron separator. Much of what appears below is gleaned from these references. These separators are characterized by a lower pressure drop but also a lesser effectiveness than the screens that are used for removing the small drops. In common with screens, these separators are used in the dispersed flow regime where the liquid loading is usually small.

The plates can be arranged so that the flow is either up, or horizontal with the liquid draining down due to gravity for either orientation. Re-entrainment, in any case is what limits their performance. Re-entrainment is really a consequence of flooding for up flow and is a function of the same variables. Let us begin by considering the chevron separators that work in up flow.

#### 4.3.1 *Performance*

Monat et al. (1986) and McNulty et al. (1986) give the best description of how these work. Figure 19 (McNulty et al. 1986) illustrates how the plates in these separators are configured. Sheet metal or plastic is formed into corrugations which are oriented so that the grooves make an angle of 45° with the horizontal. The corrugations in the adjoining

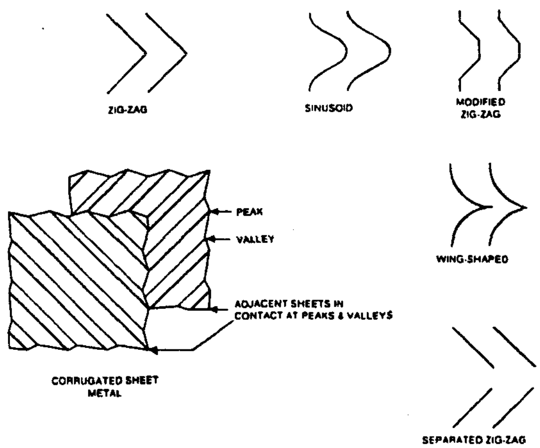



**Figure 19** Various chevron geometries. McNulty et al. (1986)

corrugated strips are oriented in opposite directions so that only the peaks or valleys in the corrugations touch. The separated liquid drains as it will.

Table VI from McNulty et al. (1986) describes eighteen different types of chevron separators. A typical droplet removal efficiency as a function of drop size is shown in Figure 20. It is clear that the removal efficiency is quite good for the drop sizes for which most of the mass is contained. The removal efficiency tends to increase with velocity for all drop sizes until the point where re-entrainment (or flooding) occurs. Even 10 $\mu$m drops can be removed effectively with the best chevron geometries.

Let us now turn our attention to the chevron separators in which the flow is horizontal. Figure 21 from Moore & Sieverding (1976) shows a typical chevron separator in plane view. Flow enters at the left and flows horizontally in a zig-zag course between the plates depositing the drops as it goes. The separated liquid runs down the plates in the form of a ribbon in front of the scoops which are at the crests of the corrugation. The water, surprisingly, does not actually enter the scoop because a vortex which is trapped in the scoop prevents it. For any separator of this kind the water runs down the plate into a pool at the bottom where it is drained away.

Representative values of the maximum allowable gas and liquid flow rate are shown in Figure 22 where the decrease in the allowable gas flow rate with increasing liquid flow rate (decreasing quality) is evident. These experiments were performed with air and water at one atmosphere pressure. The degradation in performance is much like flooding and probably can be extrapolated to steam conditions using the flooding parameters. The performance of short plates is apparently also degraded by an entrance effect.

### 4.3.2 *Pressure drop*

Pressure drop is one of the important considerations when selecting a chevron geometry for a particular application. The pressure drop characteristics for the 18 geometries described in Table VI are shown in Figure 23. This figure can be used to

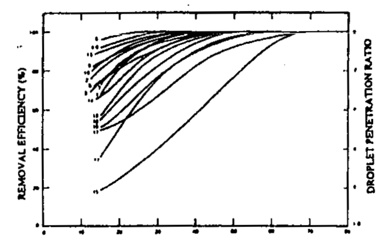
**Table VI** Description of various chevron separator geometries. McNulty et al. (1987)

| Chevron Number | Description |
|---|---|
| 1. | 4-pass sinusoid with hooks. $1\frac{1}{4}$ in. spacing, plastic |
| 2. | 3-pass modified zig-zag. 1 in. spacing, 45° angle to flow, plastic |
| 3. | 4-pass sinusoid with hooks. $1^1/_8$ in. spacing, plastic |
| 4. | 4-pass zig-zag with hooks. 2 in. spacing, 45° angle to flow, stainless steel (SS) |
| 5. | 4-pass zig-zag, no hooks, 2 in. spacing, 45° angle to flow, SS |
| 6. | Corrugated sheet metal packing, ½ in. corrugation height, 12 in. thick, 45° angle to flow |
| 7. | Corrugated sheet metal packing, 1 in. corrugation, ht. 12 in. thick. 30° angle to flow |
| 8. | Corrugated sheet metal packing, 1 in. corrugation, ht. 12 in. thick. 45° angle to flow |
| 9. | Corrugated sheet metal packing, ½ in. corrugation, ht. 6 in. thick. 45° angle to flow |
| 10. | 3-pass modified zig-zag, 1.5 in. spacing, 45° angle to flow, plastic |
| 11 | 3-pass modified zig-zag, 1 in. spacing, 45° angle to flow. SS |
| 12 | 2-pass modified zig-zag, 0.75 in. spacing, SS |
| 13. | 3-pass zig-zag with hooks, 2 in. spacing, 45° angle to flow, SS |
| 14. | 3-pass zig-zag, no hooks, 2 in. spacing, 45° angle to flow, plastic |
| 15. | 2-pass separated zig-zag, $1^1/_8$ in. spacing, 30° angle to flow, SS |
| 16. | 2-pass modified zig-zag, 0.75 in. spacing, plastic |
| 17. | 2-pass wing-shaped blade. $3\frac{1}{4}$ in. spacing, plastic |
| 18. | 3-pass zig-zag, no hooks, 2 in. spacing, 45° angle to flow, SS |

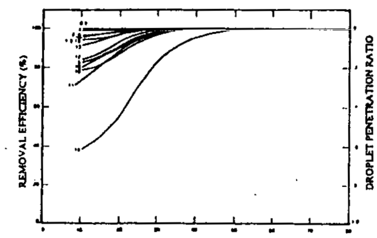
Angle to flow signifies the angle between the principal gas flow direction and the Chevron blade. For corrugated sheet metal, it is the angle between the ridges (or grooves) and the principal flow direction.
SI Conversion: mm = in x 25.4

estimate the pressure drop for a variety of conditions. The Euler number shown in Table VII is, in fact, the number of velocity leads lost in that particular separator based on the approach velocity for the dry gas.

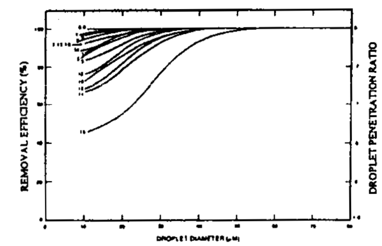
The pressure drop for a wet gas is somewhat higher primarily because the draining liquid occupies some of the flow area. The quantity $R$ shown in Table VII is the ratio of the wet pressure drop to the dry for the same gas velocity. The addition of liquid can increase the pressure drop by as much as 50%.




*Droplet removal efficiency at 1.6 m/s.*




*Droplet removal efficiency at 3.6 m/s.*




*Droplet removal efficiency at 3.1 m/s.*

**Figure 20** Droplet removal efficiency versus air velocity for several drop sizes using the chevron shapes listed in Table VI

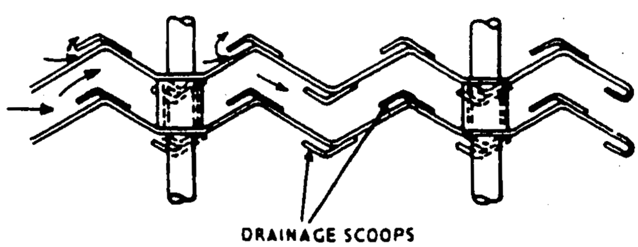



**Figure 21** The cross section of a chevron separator with scoops showing the path of the air. Moore & Sieverding (1976)

## 5. CYCLONE SEPARATORS - INTRODUCTION

Cyclone separators are both the most versatile and the most common type used in steam systems and so deserve a detailed description. By far the most useful reference describing them and their operation is that of Carson et al. (1980). This reference presents the results of an extensive industry sponsored project to evaluate and upgrade the steam separators used in the nuclear industry. Designs are described, performance data presented, design limits evaluated and suggestions for further work given. This report is an incomparable source of information for the most important class of steam separators. Information on other types of separators is given too but in sketchier form. Before proceeding to the body of this section on cyclone separators it is appropriate here to describe carryunder.

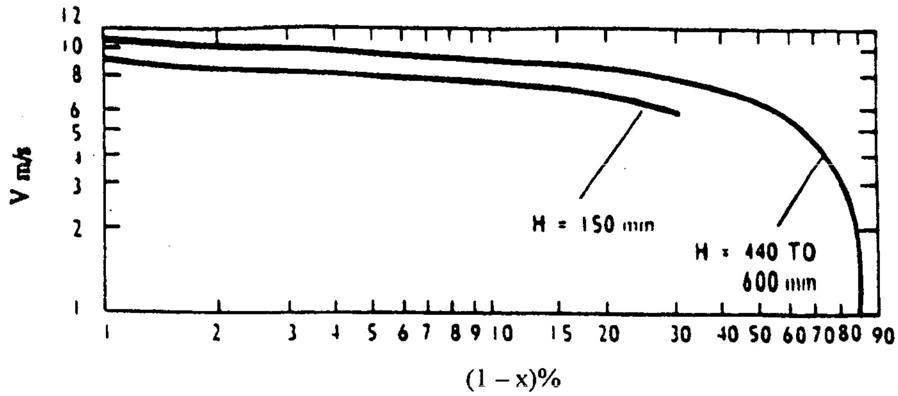



**Figure 22** The critical velocity at which performance deteriorates in a vertical chevron separator with horizontal flow similar to that illustrated in Figure 21. Moore & Sieverding (1976)

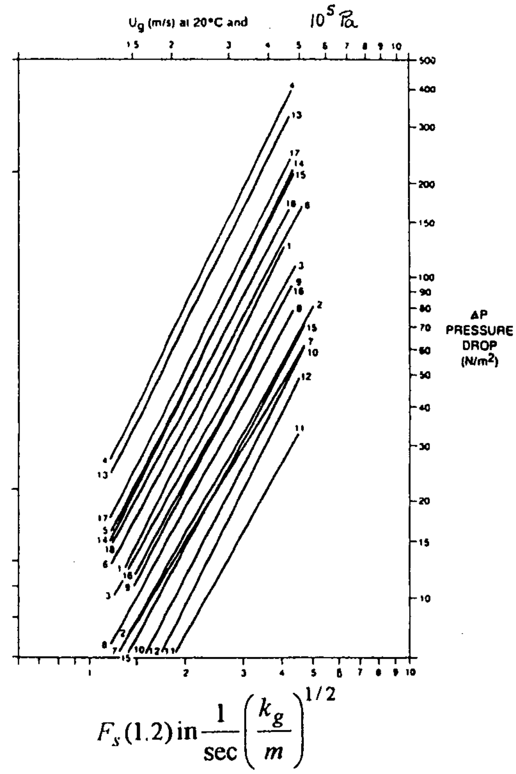



**Figure 23** Pressure drop characteristics of the 18 chevron separators flowing air as described in Table VI. McNulty et al. (1986)

**Table VII** Pressure drop for various chevron separator geometrics. McNulty et al. (1987). The chevron numbers are the same as in Table VI

| | Inlet | Loading = 0.3 gpm/ft$^2$ | | Inlet | Loading = 2.5 gpm/ft$^2$ | | |
|---|---|---|---|---|---|---|---|
| Chevron Number | $(F_1)$* | $\Delta P$ in $H_2O$ | $R$** | $(F)$* | $\Delta P$ in $H_2O$ | $R$** | Euler Number† |
| 1 | 3.93 | 1.10 | 1.21 | 3.60 | 1.10 | 1.43 | 11.7 |
| 2 | 3.29 | 0.43 | 1.08 | 3.09 | 0.43 | 1.23 | 5.89 |
| 3 | 2.97 | 0.40 | 1.0 | 2.77 | 0.40 | 1.21 | 9.63 |
| 4 | 3.10 | 1.10 | 1.09 | 3.00 | 1.10 | 1.14 | 32.6 |
| 5 | 3.00 | 0.57 | 1.0 | 2.80 | 0.57 | 1.0 | 17.8 |
| 6 | 4.10 | 1.40 | 1.0 | 3.60 | 1.40 | 1.28 | 13.1 |
| 7 | 4.30 | 1.50 | 1.18 | 3.91 | 1.50 | 1.51 | 5.35 |
| 8 | 3.70 | 0.53 | 1.05 | 3.35 | 0.53 | 1.11 | 7.12 |
| 9 | 3.20 | 0.70 | 1.07 | 2.80 | 0.70 | 1.29 | 8.51 |
| 10 | 3.39 | 0.27 | 1.05 | 3.15 | 0.27 | 1.41 | 4.47 |
| 11 | 4.00 | 0.20 | 1.17 | 3.70 | 0.20 | 1.47 | 2.89 |
| 12 | 4.40 | 0.51 | 1.11 | 3.90 | 0.51 | 1.26 | 3.75 |
| 13 | 3.20 | 0.94 | 1.05 | 3.05 | 0.94 | 1.08 | 28.4 |
| 14 | 3.00 | 0.57 | 1.04 | 2.50 | 0.39 | 1.07 | 17.7 |
| 15 | 3.60 | 0.23 | 1.0 | 3.30 | 0.23 | 1.0 | 5.41 |
| 16 | 3.80 | 1.00 | 1.0 | 3.50 | 1.00 | 1.09 | 8.56 |
| 17 | 2.30 | 0.40 | 1.18 | 1.80 | 0.30 | 1.33 | 20.5 |
| 18 | 3.20 | 0.51 | 1.0 | 2.85 | 0.51 | 1.05 | 15.3 |

$= V_g\sqrt{\rho_g}$ where $K_g$ is in ft/sec and $\rho_g$ is in lbm/ft$^3$

*Critical $F$, above which reentrainment occurs in ft/s (lbm/ft$^3$)

**$R$ is the ratio of wet to dry pressure drop below the $F$, at which loading begins

†Eu = $2\Delta P_{gc}/\rho_g U^2_g$ where $\Delta P$ is in lbf/ft$^2$ rather than in $H_2O$.

SI Conversion: m$^3$/m$^2$ x h – gpm/ft$^2$ x 2.445; m/s = ft/s (lbm/ft$^2$) x 1.113; N/m$^2$ = in. $H_2O$ (x 249).

## 5.1 *Carryunder*

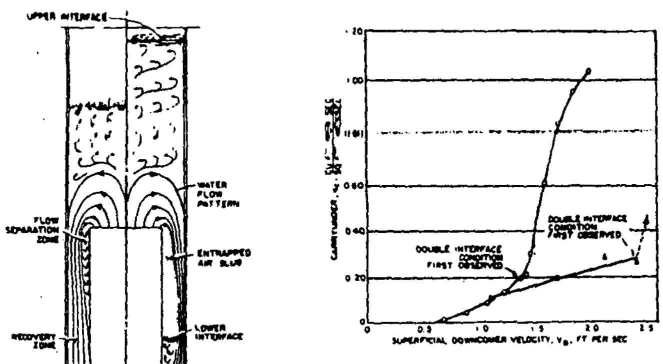
Carryunder is a form of performance degradation peculiar to cyclone separators. When the separated liquid returns by flowing down to the pool from whence it came, it entrains some steam with it. The more rapidly the returning water flows down, the more steam is entrained and the more effectively the entrained stream is carried down with the return flow. Carryunder is undesirable because the pressure recovery in the downcomers of natural circulation systems is reduced.

The further the separated liquid falls before it rejoins the pool, the more rapidly it moves so that carryunder tends to decrease as the liquid level in the downcomer rises. This is evident from the performance data for several of the separators described in this section.

Carryunder is also affected by the geometry in ways that are not entirely predictable. A downflowing two-phase flow can assume several configurations. The configuration depends on the flow rate, the geometry and the history. When the upflowing separated liquid makes a sharp 180 degree turn; for instance, at the top of the separator, hydrodynamic separation can occur, and a stationary bubble of steam will form in the separated region. This causes both more carryunder and a reduction in the pressure recovery.

Any time the downflowing liquid moves down more rapidly than an entrained bubble can rise, a bubble can be trapped. Once a bubble is trapped, a substantial reduction in downflow velocity is needed to free it. The worst case is a velocity that just holds a large bubble stationary such as illustrated in Figure 24a from Marshall (1964). Figure 24b also shows that for the same velocity in the downcomer, two different carryunder flow rates are possible depending on whether a stationary bubble is present or not.

Systematic measurements of carryunder are not available nor are there general downflow, flow regime maps. Typically deterioration is possible for superficial downflow liquid velocities greater than 0.3 m/s and is likely for downflow velocities greater than 1 m/s. Within the range given above, whether the deterioration due to a trapped bubble or carryunder depends on the geometric details and the operating history of the system.




(b)

| | | | Vessel ID | | Specific Air Flow $\left(\frac{\text{Volume}}{\text{Time \& Area}}\right)$ | | Interface Height | |
|---|---|---|---|---|---|---|---|---|
| (a) | Symbol | AD/AV | in | m | ft/s | m/s | in | m |
| | O | 0.65 | 5.1 | .12 | 1.3 | .40 | 19 | .48 |
| | Δ | 0.62 | 0. | .44 | 1.3-1.5 | .40-.46 | 20-32 | .51-.81 |

**Figure 24** The effect of geometry and history on carryunder as determined by Marshall (1960) in an air-water experiment.
(a) The apparatus showing the two possible flow regimes and how a trapped bubble can form.
(b) Data showing the effect of the trapped bubble on the carryunder

### 5.2 *Types of cyclone separators, their design and performance*

In this section a quick review of the types of cyclone separators will be given, then one type will be chosen to discuss in considerable detail. This example will serve both as a demonstration of how these separators work and as a source of typical performance data. References to other works on cyclone separators will be made as appropriate though the details on all the separators mentioned in Carson et al. (1980) are cited at the end of each section in that report.

A great variety of cyclone separator designs exist. They all appear to work satisfactorily or they would have been eliminated if they did not. Paik et al. (1987) reports on separation experiments, using air and water, performed on small scale, transparent models of several of the types of separators cited by Carson et al. (1980) and mentioned here. Exact models of these separators were not constructed, only approximate replicas were constructed based on the undimensioned figures appearing in various papers and reports. In spite of this, all the cyclone separators tested in that program work satisfactorily and displayed, as far as could be seen, the same kind of behavior that the full-sized separators from which they were modeled.

There is ongoing interest in more detailed modelling of cyclone-type separators. Analytical models are described, for instance, by Betts et al. (1994) and Arpandi et al. (1995). Significant progress is also being made in modelling such systems using computational fluid dynamics (CFD); typical studies in this category are those of Kitamura et al. (1993), Erdal et al. (1996) and Motta et al. (1997). The reader interested in such detailed models is referred to these cited papers.

#### 5.2.1 *Curtis-Wright separator*

The first type of separator is illustrated in Figures 25a and b in two views. The steam water mixture enters the device flowing in a vertical, up direction and passes through the swirl passages mounted at the top of the riser. The water is thrown out onto the downcomer walls and the steam exits between the swirl tubes into the next stage of separations. Figure 25c gives some full scale performance data.

#### 5.2.2 *Westinghouse separator*

The second type of separator is illustrated in Figure 26a and b. An upflowing steam water mixture passes through a swirler which throws the liquid to the inner wall of the annulus where most of the water is removed. Almost dry the steam passes up through the hole in the center of the top plate into the next stage of the drying section while the separated water is removed through a slot near the top of the outer wall. Performance information for this type of separator is provided in Table VIII.

#### 5.2.3 *General Electric cyclone separator*

This separator is illustrated in Figures 27a, b and c. A series of spinners and skimmers removes separated liquid as the steam and any remaining water proceeds up the center of the device. Key dimensions are also provided. Performance is provided on Figure 27d

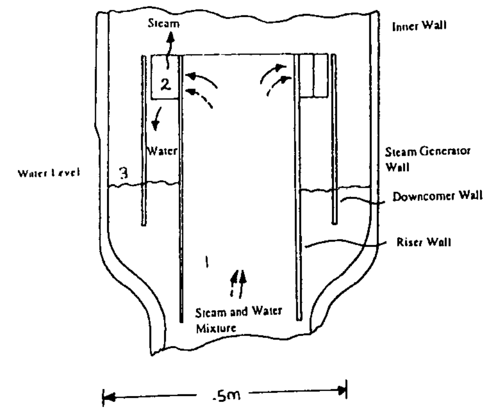



**Figure 25** Curtis-Wright steam separator. Carson & Williams (1980).
(a) Elevation, showing the overall dimensions

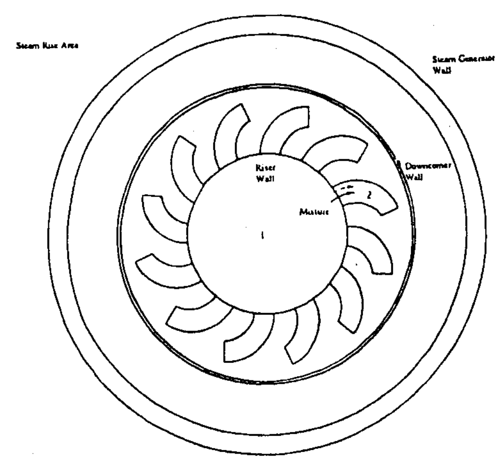



**Figure 25** (b) Plan of the top of the separator

and e. This type of separator shows deterioration in performance for low steam flows and low liquid flow rates unlike most of the others.

5.2.4 *KWU separator*

This is illustrated in Figure 28a. The mixture enters at the bottom and flows up through a torturous path losing water in several stages. There are so many unique

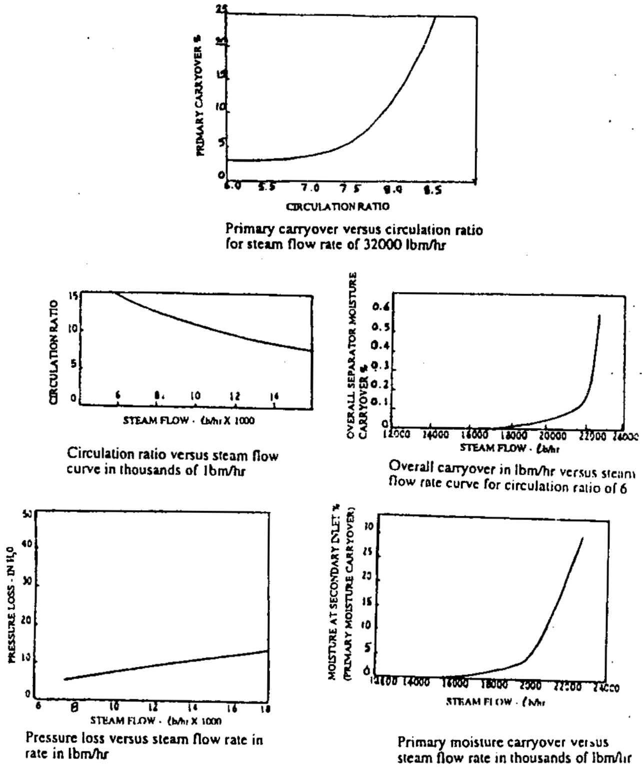



**Figure 25 (c)** Typical performance. Conversion factors: 2.2 lbm/s = 1kg/s, 1 in water = 249 Pa

features that a rational design for this device is difficult to imagine. Experiments are essential. Figures 28b and c give the performance.

### 5.2.5 *Combustion Engineering separator*

This is shown in Figure 29a and b. Spin is imparted to the two phase mixture after which the separated water flows out the holes in the sides of the inner cylinder. Performance data is including carryunder shown on Figure 29c and d.

### 5.3 *Discussion*

In all these examples, the carryover is of two kinds. Within the design envelope for the device, some water is re-entrained from the surfaces that define the device. The details of how this happens are often difficult to foresee partly because liquid deposition is unpredictable and partly because secondary flows in complex shapes are very unpredictable. Only a visual experiment will indicate where this kind of re-entrainment occurs and suggest how the design can be changed so it is minimized or eliminated.

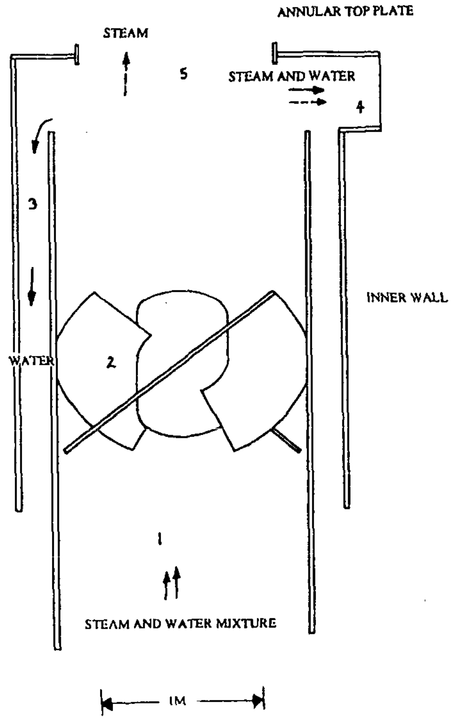



**Figure 26 (a)** Elevation. Westinghouse steam separator. Table VIII gives typical performance information. Carson & Williams (1980)

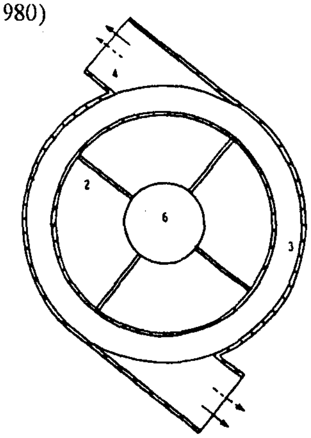



**Figure 26 (b)** Top view

The other kind of carryover occurs when the device is obliged, in some way, to operate outside its design envelope. This is usually due to high water, but can result from too high or too low flow rates too. The amount of this kind of carryover increases very rapidly as the water level (or pressure the difference across the separator) increases. Configuring the separator so that this kind of carryover is avoided is the most challenging task for the designer. The five separators shown in this section are examples of ones that work. The performance information and key dimensions provide a measure

**Table VIII** Calculated performance of a Westinghouse separator

Nominal separator conditions

Saturation Pressure – 781 psi (5.41 MPa)

Steam Flow per Separator – 1,167,000 Lbm/hr (530,454 kg/hr)

Water Flow per Separator – 2,916,670 Lbm/hr (1,325,759 kg/hr)

Water Level – 43" (1.09m) below top of separator

Calculated performance

| Circulation Ratio | Efficiency | Exit Quality |
|---|---|---|
| 2.5 | .743 | 34.0% |
| 3.5 | .753 | 61.8% |
| 4.5 | .763 | 70.2% |

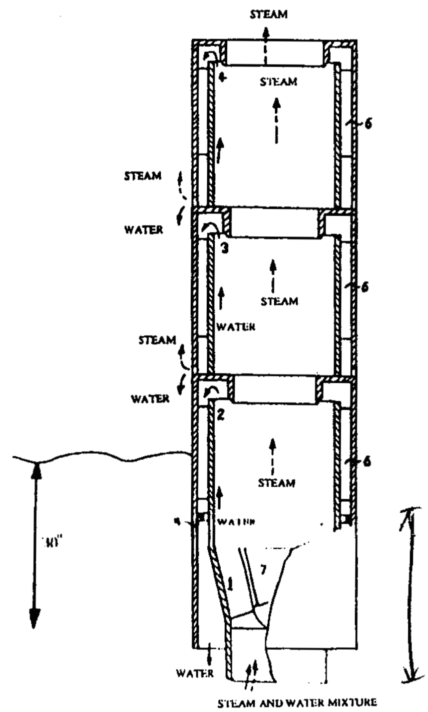
Effect of steam flow on the calculated performance

| Water Flow Lbm/hr (Kg/hr) | Steam Flow Lbm/hr (Kg/hr) | Efficiency | Exit Quality |
|---|---|---|---|
| 2916600 (132,572) | 583300 (265,136) | .60 | 34.0% |
| 291660 (132,572) | 1167000 (530,454) | .75 | 61.8% |
| 291660 (132,572) | 1750000 (759,454) | .75 | 70.2% |

Effect of water level on the calculated performance

| Circulation Ratio | Height | Efficiency | Exit Quality |
|---|---|---|---|
| 3.5 | 30"(.76m) below reference evaluation (low water level) | 0.753 | 61.8% |
| 3.5 | 15"(.38m) below reference evaluation (high water level) | 0.623 | 51.5% |

of how well separators perform and the space they occupy. Any one could be viewed as a model that could be built or, if necessary, improved. In the remainder of this section a generic centrifugal separator will be described and the performance discussed in some detail. This example should be treated as a study of the concerns that must be addressed if any centrifugal separator is to be successful. However, before going to this example we should digress a little because the way we are handling centrifugal separators is different from the way we are handling the others.




$\Delta P_{swirl} = \Delta P_{gh}$

**Figure 27** General electric steam separator. Carson & Williams (1980) **(a)** Elevation

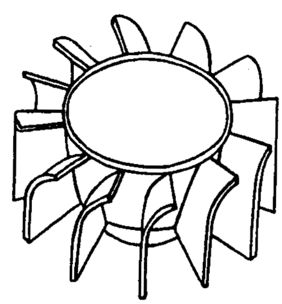


**Figure 27 (b)** Axial vanes

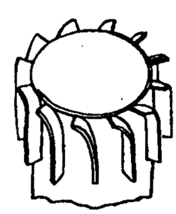


**Figure 27 (c)** Straightening vanes

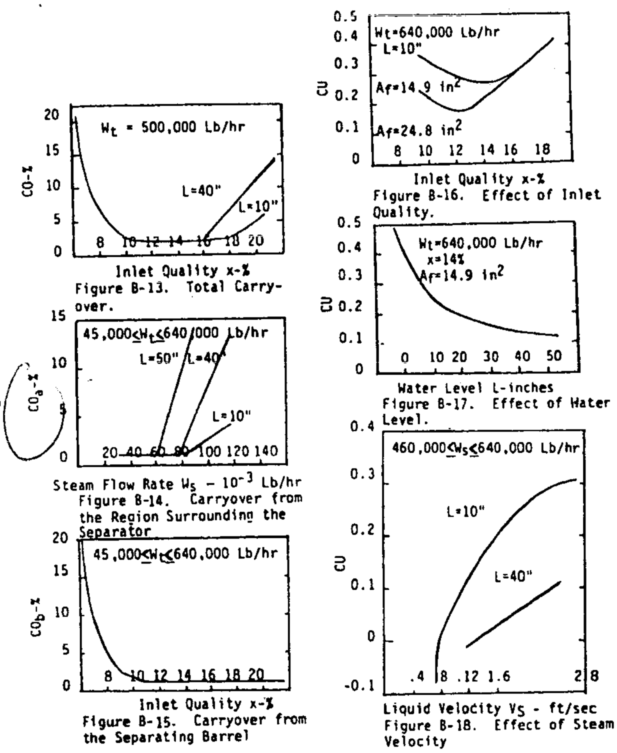



**Figure 27 (d)** Performance

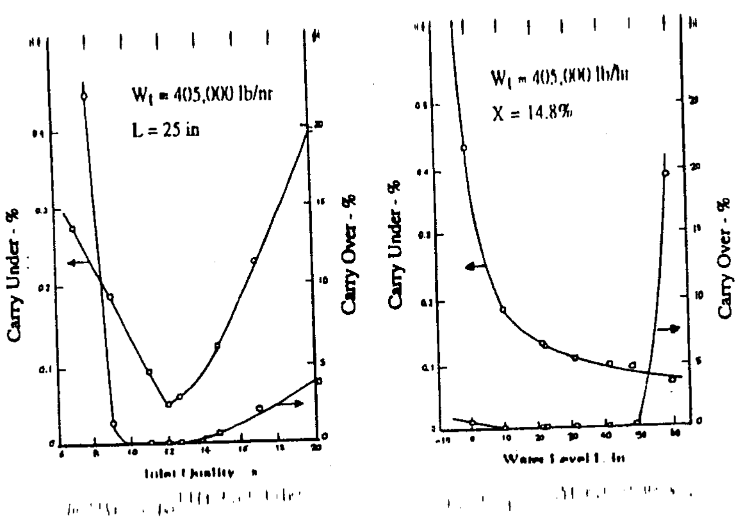



Figure 27 (e) Effect of quality and level on carry under and carry over

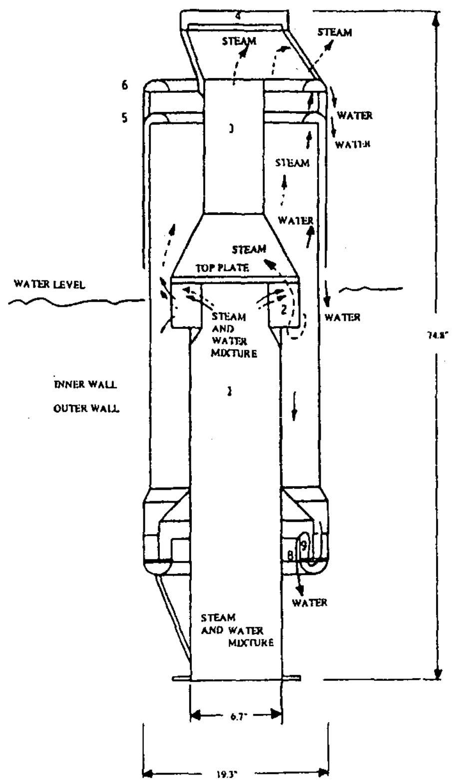



**Figure 28** Kraftwork Union (KWU) steam separator. (Carson & Williams (1980) **(a)** Elevation showing scale

Given the power of computers, why is it that separators are not designed the way other fluid machinery is – that is by constructing an analytical model and trying possible designs on the computer. Why not write down the equations of fluid mechanics for the geometry in question and predict how the device will work. There are several reasons.

From the brief descriptions of the five types of separators shown here and the detail that is evident even in the schematic drawings included, it is clear that modeling even a single phase flow through one of these devices would be a challenge. Added to this, however, are the complications characteristic of any two phase-flow problem plus our ignorance of the actual inlet conditions. Let us discuss each of these difficulties in more detail.

At some point in every one of the separator designs mentioned in this section there is an annular film. We do not, at this time, have a generally established method for relating the liquid film properties like the flow rate, thickness, roughness, entrainment rate, and so forth and the core flow properties or any of these characteristics to an interfacial shear stress. Similarly, we do not have a way of determining how much steam is entrained in the liquid or how much liquid is entrained in the vapor. In a word we do not have either the constitutive relations or the phasic equations so that a computer solution is even

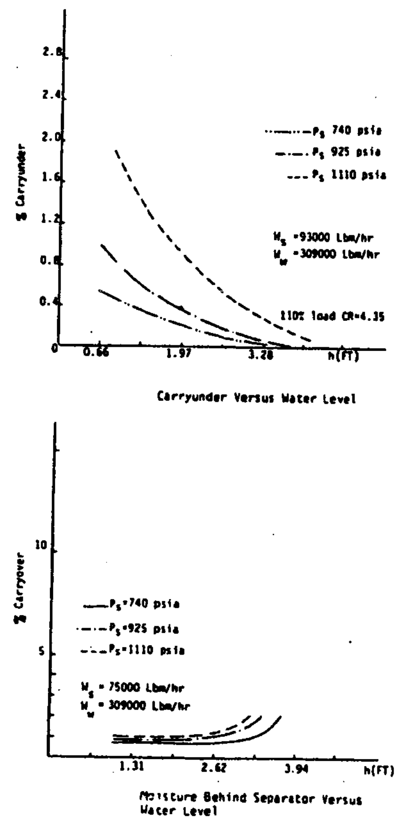



**Figure 28 (b)** Performance

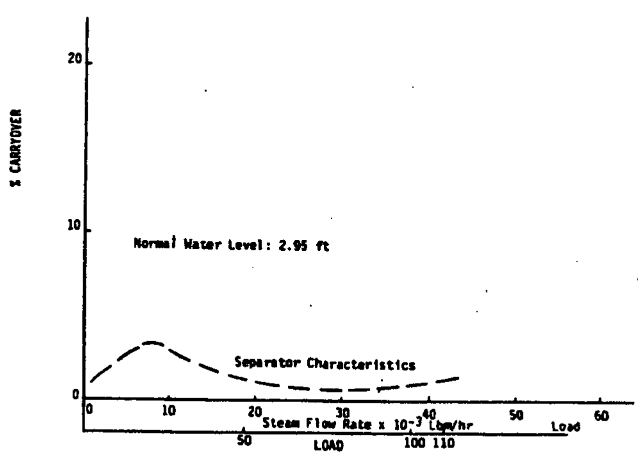



**Figure 28 (c)** Performance of the combined separator dryer system

**Figure 2**
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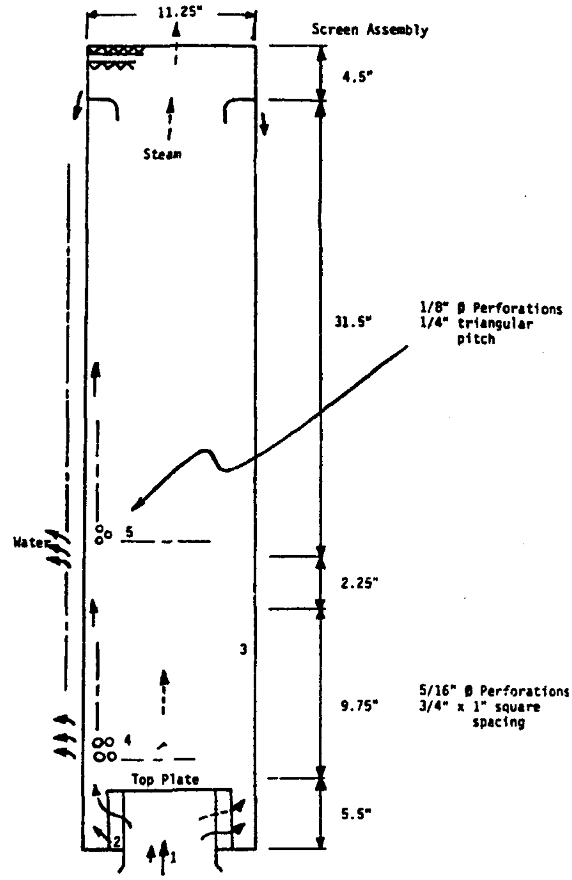


**Figure 29** Combustion engineering steam separator. This separator shows very good performance until a critical water level is reached at which point a rapid deterioration occurs. Carson & Williams (1980) **(a)** Elevation

possible. While we can relate film thickness to roughness, and friction factor, we are not sure that these equations are able to describe the annular film in a separator because these equations are derived from pipe flow experiments.

We also have problems with the boundary conditions. The available data on the drop size spectra is really very limited. The drop sizes and numbers are a function of the flow conditions and what has happened upstream. The measurements of these quantities for the geometries, flow rates and steam conditions of interest simply do not exist. We would not know how to start our calculations even if we had the knowledge and tools to write and solve the two fluid equations in the separator. For this reason separators are still designed experimentally by cutting, trying and backing up the observations with simple calculations.

Carson et al. (1980) includes full scale steam-water performance data for many of the quantities of interest. There is also much separator data in the literature for small scale experiments using air and water. At the end of this section some general guidelines of

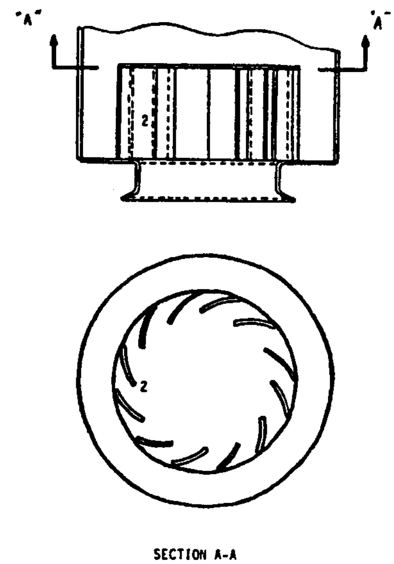


**Figure 29 (b)** Swirler details

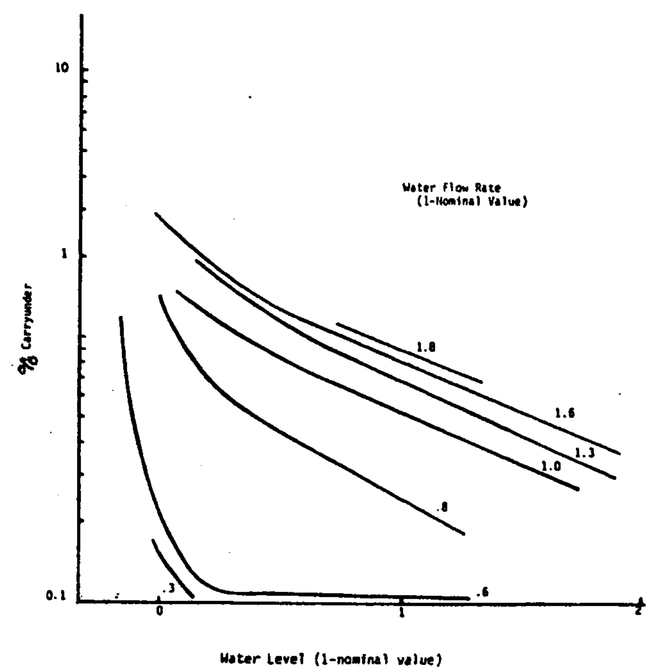


**Figure 29 (c)** Carryunder performance

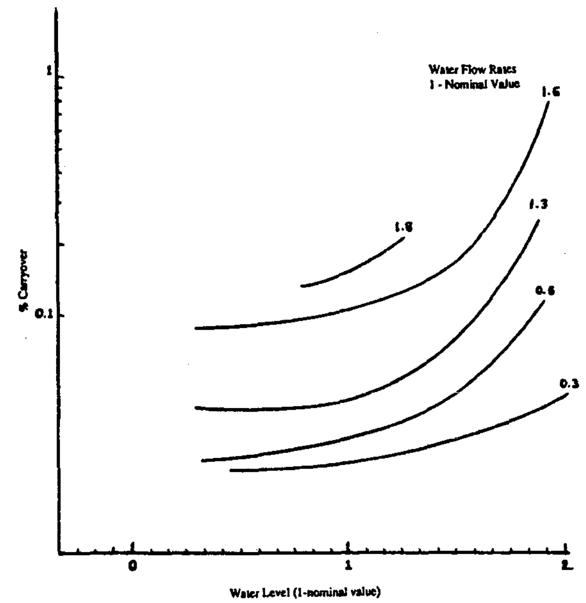


**Figure 29 (d)** Carry over performance

testing will be given to allow one to relate small scale air-water data of these experiments to the steam-water conditions of interest. For the present, however, we will use the air-water experiments of Paik et al. (1986) for the example of how a cyclone separator operates.

## 5.4 *Model separator behavior*

The separator illustrated in Figures 30a and b is an approximate model of a Westinghouse steam generator separator system. It was constructed by scaling the dimensions from a drawing in Young et al. (1984) but, altering them so that only standard sizes of plastic were used in the model. It was made largely of plastic so that its operation could be observed. Both normal and degraded operation were tested. During normal operation, the velocity vectors for the two phases are illustrated in Figure 30b. Submergence is measured from the bottom of the downcomer shown on Figure 30b to the collapsed liquid level. Because the interface is so disturbed and some air is entrained and carried down (carryunder), no distinct water level could be observed in the downcomer. The general velocity level is low enough, however, so that the gravity term in the pressure drop equation governs and the collapsed liquid level in the downcomer must be very close to that which is seen in the pool outside the separator.

The primary measurement is the carryover. Typical of the extensive data collected is that shown on Figure 31. Over the useful range of operation, 95% of the water would be removed in the centrifugal or first stage of the separator system. From observing how the device operated, it was clear that some liquid was deposited on the streamlined object in

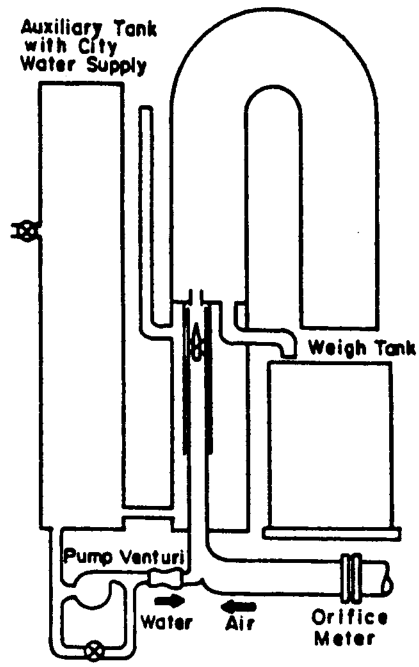


**Figure 30** Schematic of the separator system used in the experiments of Paik et al. (1987) **(a)** Schematic of the air-water testing

the center of the swirler and also on the blades from which it was re-entrained and carried up into the gravity separation chamber. Some liquid is also re-entrained from the lip of the skimmer. When the water flow rate and pool level is high enough, entrainment from the pool surface also occurs and the carryover increases very rapidly.

The reason for this deterioration is first the increasing water level causes a pressure increase on the outside of the porous riser and the flow out near the bottom ceases or actually reverses. That is, the water flows into the riser from the downcomer. Clearly this flow will soon cause the carryover to increase.

Increasing either the two phase flow rate or the liquid flow rate increases the water level in the downcomer which ultimately causes the performance to deteriorate. As the flow rate increases, the two phase pressure drop across the spinner increases and the liquid in the downcomer is, in a sense "sucked" up. At some point this undesirable pressure drop also causes the liquid to flow in the wrong direction through the holes in the riser, causing the carryover increase very rapidly. For this particular design this occurs at a level (measured from the bottom of the downcomer) of about 1 m for a great variety of liquid and gas flow rates. Overloading the separator does not, in itself, cause failure. Failure occurs because the liquid level is too high in the downcomer and re-entrainment occurs. Any combination of conditions which lead to the water level (measured from the pool) of this separator being greater than 1 m caused high carryover.

We can now go back through the five types of separators mentioned earlier in this section and identify the most likely condition which leads to a rapid increase in the

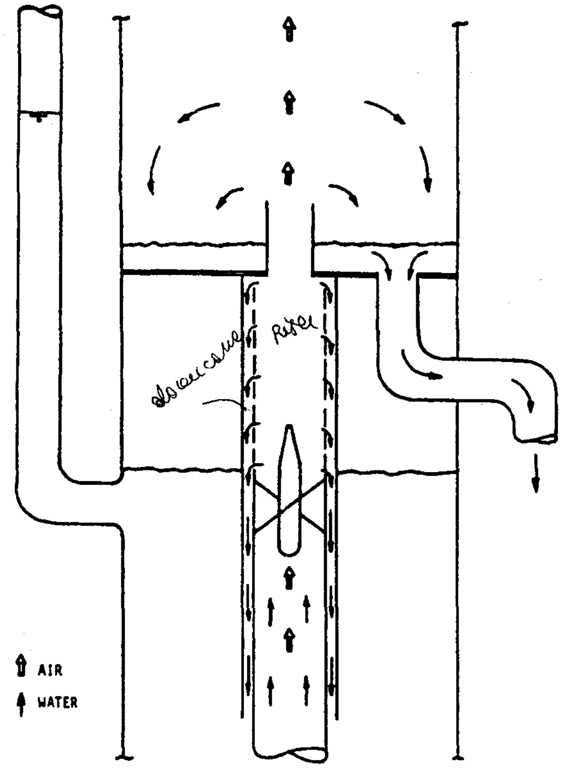


**Figure 30 (b)** Details of the air-water flow in the separator section

carryover. The key to designing a successful centrifugal separator is identifying the failure mechanism due to high water level and then proportioning the device so that though flow is maximized without causing deterioration in the performance due to high water level to occur.

For the Curtis-Wright separator Figure 25a and b the water level will rise on the outside until the pool flows back through the bottom of the arms illustrated in plan view. A similar failure will occur in the Westinghouse design Figure 26a and b. The pool in the downcomer will overflow the weir at the inner wall and recycle the water.

For the General Electric design, Figures 27a, b and c failure will occur when the pool rises far enough so that the water flow from the bottom stage will be reduced. This will cause additional water to be carried up to the second stage and the performance for the entire separator will be degraded. A similar failure will occur in KWU design Figure 28.

In the Combustion Engineering design Figure 29 a sufficiently high water level will cause water to flow in instead of out of the lowest holes and overload the whole device. The flow occurring in this type of separator also leads to the peculiar characteristic that its performance improves with increasing liquid flow because of an increased radial pressure gradient. More liquid flow in gives a greater radial pressure difference and more liquid flows out the lowest row of holes.

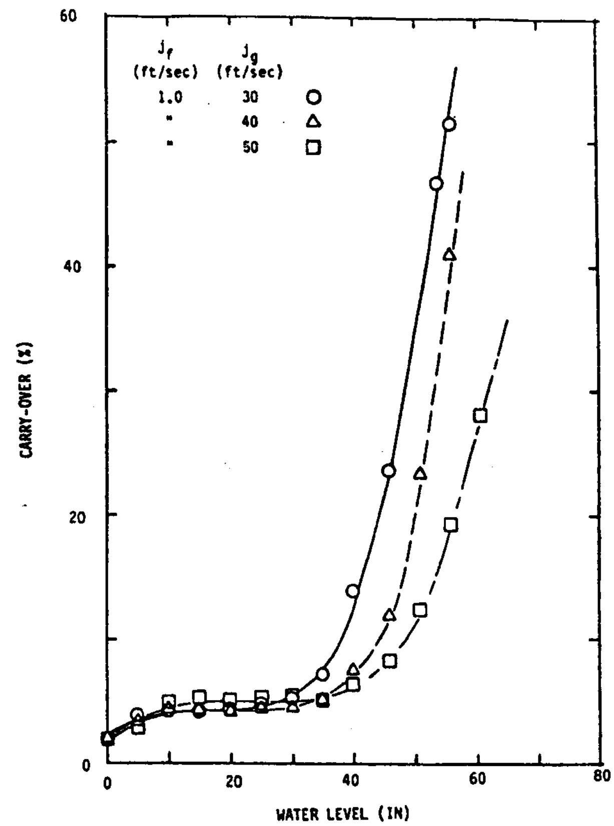


**Figure 31** Carryover from the separator of Figure 29. For this separator there is a sharp deterioration in performance at a water level of 1 m (measured from the bottom of the downcomer)

Each separator design, in fact, has some unexpected or counter-intuitive aspect to its behavior which can only be understood if the visual observations are made to see what the two phase flow is actually doing. Visual observations are as essential as the overall carryover measurements because some of the detailed behavior is so counter-intuitive. The possible secondary flow configurations for a two phase flow in a complex shape is just about beyond imagining. The visual observations show how the separator works, why it fails and suggests changes that might improve its performance. This kind of testing must be done before the device is built.

Along this line, it is particularly important to check visually any clever little features that are added to control the two phase flow in the separator. Separated regions containing recirculation bubbles can drive films on the walls in unexpected ways and have a dominant effect on the carryover even when operating within the design envelope. Most of the re-entrainment occurs as a result of secondary flows in regions where the flow is not one dimensional nor, to us, well behaved.

### 5.5 *Pressure drop*

The range of pressure drops in cyclone separators is just as varied as the range of designs. It is, however, bounded by the system into which it is installed. This range is important because these bounds define the limits of operation. Looking at Figure 30 for instance it is obvious that the pressure drop in the rising two phase mixture must be small enough so that the separated liquid can return by gravity to the pool. That is, the pressure drop cannot be larger than the hydrostatic head defined by the liquid level and the density difference between the riser and downcomer. A consideration similar to this is true for every example shown.

Pressure drop can also be important from a system point of view because a large pressure drop could degrade the thermodynamic performance of the entire plant.

A variety of pressure drop prediction schemes were tried by Paik et al. and the simplest was found to be the best. Looking at Figure 30, for instance, the friction pressure drop from the inlet pipe to the upper plenum can be calculated by considering each component in the path in turn. From the entrance to the swirler, friction and gravity can be calculated using an appropriate two phase model, for instance that of Thom as reported in Wallis (1969). At the swirler, the homogeneous model was found to be most appropriate for calculating the pressure drop. For this particular separator, excessive carryover occurs when the pressure drop is greater than 1 m which is the submergence of the normal downcomer. The riser pressure drop can be calculated using the homogeneous model while the downcomer really consists of two single phase regions.

The orifice (or short nozzle) at the top of the porous cylinder can also be calculated using the homogeneous model. It has a loss coefficient of about two velocity heads based on the approach velocity and density which, again is based on the homogeneous velocity heads of the flow actually in the orifice. There is also a small gravity term.

In general, the pressure drop in the downcomer which is mostly due to gravity can be estimated from the density of the liquid and vapor, and the level.

Many of the geometries illustrated in this section are too complex to analyze in this detail. Model tests must be run. In general, the more complex the geometry the simpler the treatment of the data. For a complex system an appropriately instrumented single phase experiment and the use of a homogeneous model to extrapolate to operating conditions is probably the best, simple way to handle the problem of pressure drop. To do this by calculation, the cyclone must be broken up into components and the appropriate densities and flow rates used along with loss coefficients evaluated from the single phase experiments. These calculations are not very precise.

A well designed cyclone separator should take as much of the pressure drop as possible in the spinner as that is only pressure drop that actually helps the separation process.

Paik et al. (1986) tried a single phase model test which worked satisfactorily. An air test was run and the pressure drop measured. The smallest flow area in this model was in the cyclone itself. The velocity of the air in that region was used to define a loss coefficient, thus:

$$\Delta p = K \frac{\rho_a V_g^2}{2} \tag{5.1}$$

the value obtained for $K$ was $K$ = 5.7 (single phase). The best value for $K$ when the separator was receiving a two phase mixture was found to be $K$ = 4.9 (two phase). The single and two phase loss coefficients (based on the homogeneous model) do not turn out to be very different. This similarly is why the use of the homogeneous model is recommended.

Of course a single, overall pressure drop number such as this is not useful when the proportions of a separator must be optimized. Under these circumstances an element by element pressure drop model must be constructed with the local loss coefficients as determined from a well instrumented model operating with only gas flowing through it.

## 6. TESTING SEPARATORS

Mauro et al. (1989) describes how a separator is tested. Because the percentage of carryover is usually so low; it is necessary to determine the percentage by special means. The technique usually adopted is to use a non-volatile tracer in the liquid, such as lithium hydroxide (LiOH), and determine the tracer concentration in the stream leaving the separator. Either an isokinetic probe to sample the flow or condensing everything completely and sampling the carryover-condensate mixture can be used.

A full scale, full pressure separator test requires a large scale test facility. The kind of developmental testing that is necessary to make a good separator cannot conveniently be done on a device which is this expensive to operate. Scaled experiments are essential. How should these experiments be designed?

Mauro et al. (1989) recommends scaling cyclone separator tests by doing the following three things:

1. Maintaining geometric similarity between a small, low pressure air-water apparatus and a larger, high pressure steam-water apparatus.

2. Running the experiments so that the superficial velocity of each phase entering the separator is exactly the same.

3. Maintaining the actual water level in the downcomer so it is exactly the same in both the model and the prototype. The water level, as measured from the bottom of the downcomer to the pool, should be kept the same in the prototype and the model. It is not scaled as the rest of the apparatus is. It is full depth.

When this is done, the carryover, in percent, in the model and the prototype is the same. The two phase pressure drop through the separator, model and prototype, are not however, quite the same. If one defines a dimensionless pressure drop based on the homogeneous model, the loss coefficients for the two tests differ as shown in Table X as given below.

Such a simple scaling procedure works because the flow regimes and local void fractions in both the model and prototype are about the same. The friction pressure drop is about the same because the flow is turbulent and the friction factor for any turbulent flow is almost constant. The scale of the apparatus does not affect the answer much.

**Table X** Pressure drop comparison of a small air-water system and a large steam water system of the same geometry

| | $L_{submergence}$ | $K$ |
|---|---|---|
| Air-water<br>$P = .3$ MPa | .75m | 7.3 |
| Steam-water<br>$P = 6.9$ MPa | .8m | 11.2 |

The steam-water loss coefficients appear to be a little higher.

Form losses and L/D's are the same in both the model and prototype. Riser heights are kept the same so that the water level that signals a rapid increase in carryover will occur at almost the same pressure drop. Other scaling parameters, of which there are many, contribute in only a peripheral way to the performance of the device.

Though here are good theories and extensive data for designing the gravity and impingement type separators of various kinds, the models that would allow us to design a cyclone separator from first principles do not exist. These must be designed on the basis of experiments. The two-phase flow models are simply not adequate to proportion these devices. The scaling recommendations and model tests described above allow one to design, interpret and extrapolate model tests quite easily.

## 7. CONCLUSIONS

Separators fail to operate properly not because they fail to separate but because the separated liquid is re-entrained.

For gravity separators, the liquid cannot fall back against the wind and is carried over. For impingement separators, the separated liquid is re-entrained before it drains. In chevron separators this occurs at the trailing edge before the liquid has a chance to drain into the pool. Similarly, for screens re-entrainment occurs when the separated liquid cannot drain away before it is re-entrained by the steam.

Failure occurs because of re-entrainment in cyclone separators too, but the details of re-entrainment differ from design to design. In the most common type of cyclone separators, the pressure in the main separation chamber drops as the demand for steam rises. This pressure drop causes the water level in the drain to rise, ultimately causing re-entrainment from the surface of the water swirling in the separator. Increasing the capacity of a separator depends most on optimizing the dimensions so re-entrainment is postponed as long as possible.

A considerable variety of cyclone separators have been designed and have proven to operate satisfactorily. Each one, however, has a feature which causes re-entrainment when a certain capacity is exceeded. The feature responsible for this must be identified by a visual experiment in a transparent model test if the design is to be improved.

Pressure drop for each type of separator can be estimated by use of existing methods. In general the minimum area which passes the whole flow governs the pressure drop for the whole device. Enlarging this area is an effective way of reducing the pressure drop. This can be done until the performance is compromised. Pressure drop, in some way, is always closely related to the region in which the performance degrades. Those factors that degrade separator performance are, therefore, usually the factors that increase the pressure drop.

The best separator or separator system for a given application can be selected by looking at the properties that of the different kinds as listed in Tables I and II. Cyclone separators are unique in that they operate for all inlet flow regimes. Any combination of steam and water can be separated in them. Impingement separators operate in only the dispersed flow regime for the entering flow. Gravity separators must operate at low enough velocities so that a distinct liquid level can be maintained. This means pool surface superficial velocities must always be less than about 2 m/s. Good separation in gravity separators requires velocities that are less than 0.3 m/s.

## 8. NOMENCLATURE

| | |
|---|---|
| $A$ | Area |
| $C$ | Flooding constant, Eq. (4.4) |
| $C_D$ | Concentration of drops in the core (units of density) Eq. (4.10) |
| $CR$ | Circulation ratio, mass flow of water-in divided by mass flow of steam-out |
| $D_d$ | Drop diameter |
| $D_H$ | Hydraulic diameter of the vessel |
| $D^*_H$ | Dimensionless hydraulic diameter of vessel, Eq. (3.6) |
| $D_{max}$ | Maximum drop size, Eq. (1.4) |
| $E_{fg}$ | Entrainment, Eq. (1b) |
| $F_s$ | Dimensional quantity with units of velocity over (density)$^{1/2}$ (see conversion with Table VI) |
| $g$ | Acceleration due to gravity |
| $h$ | Height |
| $h^*$ | Dimensionless height, Eq. (3.4) |
| $j_f$ | Liquid superficial velocity |
| $j_{fe}$ | Superficial velocity of liquid flowing upward as drops |
| $j_g$ | Steam superficial velocity |
| $j^*_f$ | Dimensionless liquid superficial velocity, Eq. (4.3) |
| $j^*_g$ | Dimensionless gas superficial velocity, Eq. (4.3) |
| $j^*_{ge}$ | Dimensionless gas superficial velocity, Eq. (3.3) |
| $K$ | Head loss coefficient, Eq. (5.1) |
| Ku | Kutateladze Number, Eq. (4.10) |
| $K_D$ | Mass transfer coefficient, Eq. (4.10) |
| $\dot{m}$ | Mass flow rate |
| $n$ | Number of screens in the stack |
| $\mu_g$ | Viscosity number based on gas velocity, Eq. (3.5) |
| $p$ | Pressure |

| | |
|---|---|
| $\Delta p_1$ | Pressure drop for one screen |
| $Re_f$ | Liquid Reynolds number |
| $Re_g$ | Steam Reynolds number |
| St | Stokes number, Eq. (4.13) |
| $V$ | Relative velocity between the drop and the surrounding vapor |
| $V_f$ | Downcomer superficial velocity |
| $V_g$ | Steam velocity |
| $U^*$ | Friction velocity, Eq. (4.12) |
| We | Weber number, Eq. (1.1) |
| $x$ | Quality |

*Greek*

| | |
|---|---|
| $\varepsilon$ | Voidage in the stack of screens, Eq. (4.14) |
| $\mu_f$ | Liquid viscosity |
| $\mu_g$ | Steam viscosity |
| $\rho_f$ | Liquid density |
| $\rho_g$ | Steam density |
| $\sigma$ | Surface tension |
| $\tau$ | Shear stress |
| $\tau_i$ | Interfacial shear stress |
| $\tau^*$ | Dimensionless stopping distance, Eq. (4.11) |

## 9. REFERENCES


Arpandi, I. A., Joshi, A. R., Shoham, O., Shirazi, S. and Kouba, G. E. (1995) Hydrodynamics of two-phase flow in gas-liquid cylindrical cyclone separators. *Proc. SPE Annual Technical Conference and Exhibition, 1995*, **Pi**, pp. 429-440.

Avallone, E., Baumeister III. T. editors (1987) *Marks Standard Handbook for Mechanical Engineers*, McGraw-Hill, 9th edition, pp.9-33.

Azzopardi, B. J., Hewitt, G. F. (1997) Maximum drop sizes in gas-liquid flows, *Multiphase Science and Technology*, **9**, 109-204.

Bankoff, S. G., Lee, S. C. (1985) A brief review of counter current flooding models applicable to PWR geometries, *Nuclear Safety*, **26** (2), 139-151.

Betts, C. M., Galvin, M. R., Green, J. R., Guyman, V. M., Slater, S. M. and Klein, A. C. (1994) An analytical model for the swirl vane separator for boiling water reactors. *Nuclear Technology*, **105**, 395-410. HAYDEN – JOURNALS, TK.N954

Capps, R. W. (1994) Properly specify wire mesh mist eliminators. *Chem. Eng. Prog.*, **90** (12), 49-55.

Carson, W. R., Williams, H. K. (1980) Method of reducing carry over and reducing pressure drop through steam separators, EPRI NP-1607.

Erdal, F. M., Shirazi, S. A., Shoham, O. and Konba, G. E. (1996) CFD simulation of single-phase and two-phase flow in gas-liquid cylindrical cyclone separators. *Proc. SPE Annual Conference and Exhibition, 1996*, **Pi**, 707-717.

Farmer, R. A. (1969) Liquid droplet trajectories in two-phase flow, Ph.D. Thesis in Nuclear Engineering, MIT.

Garner, F. H., Ellis, S. R. M., Lacey, J. A. (1954) The size distribution and entrainment of droplets, *Trans. Inst. Chem. Eng.*, **32**, 222.

Gardner, G. C. (1976) External water separators, A chapter in the book edited by M. Moore and C. H. Sieverding, *Two-Phase Steam Flow in Turbines and Separators,* McGraw-Hill.

Garner, F. H., Ellis, S. R. M., Lacey, J. A. (1954) The size distribution and entrainment of droplets. *Trans. Inst. Chem. Eng.*, **32**, 222

Hetsroni, G. (1982) *Handbook of Multiphase Systems,* Hemisphere Publishing Co., Hemisphere Publishing Company, 10-120.

Hewitt, G. F., Lacey, P. M. C. and Nicholls, B. (1965) Symposium on Two Phase Flow, **2**, pp. B401-B419.

Hewitt, G. F. and Hall-Taylor (1970) *Annular Two-Phase Flow*, Pergamon Press, p.14.

Idelchik, I. E. (1986) *Handbook of Hydraulic Resistance*, Hemisphere Publishing Corp., 2nd Edition, p.407.

Kataoka, I., Ishii, M., Mishima, K. (1981) Generation and size distribution of droplets in gas-liquid annular two-phase flow, ANL/RAS/LWR, 81-3

Kataoka, I., Ishii, M. (1983) Mechanistic modeling and correlations for pool entrainment phenomenon, NUREG/CR-3304.

Kataoka, I., Ishii, M. (1984) Mechanistic modeling of pool entrainment phenomenon, *Int. of Heat and Mass Transfer,* **29** (11), 1999-2014.

Kitamura, O., Yamomoto, M., Arakowa, C. and Kawata, Y. (1993) Computation of turbulent flow in a cyclone separator with a Reynolds stress turbulence model. *Trans. Japan Soc. Mech. Eng.*, **59**, 1959-1964.

Lapple, C. E. (1961), *Stanford Res. Inst. J.*,**5**, 94.

Liu, B. Y. H., Agarwal, J. K. (1974) Experimental observation of aerosol deposition in turbulent flow. *Aerosol Science,* **5**, 148-155.

Liu, B. Y. H., Agarwal, J. K. (1974) Experimental observation of aerosol deposition in turbulent flow, *Aerosol Science,* **5**, 148-155.

Liu, B. Y. B., Ilori, T. A. (1975) Aerosol deposition in turbulent pipe flow, *Environmental Science and Technology,* **8** (4), 351-355.

Lopes, J. C. B., Dukler, A. E. (1986) Droplet entrainment in vertical annular flow and its contribution to momentum transfer, NUREG/CR-4729.

McCoy, D. D., Hanratty, T. J. (1977) Rate of deposition of droplets in annular two phase flow, *International Journal of Multiphase Flow,* **3**, 319-331.

McNulty, K. J., Monat, J. P., Hansen, O. V. (1986) Performance of commercial chevron mist eliminators, *Chem. Eng. Prog.*, **83** (5), 48-55.

Marshall, R. C. (1964), Carryunder in gravity separation of air-water mixtures, *ASME 64-WA/HT-38.*

Mauro, G., Sala, M., Hetsroni, G. (1990) Improved Italian moisture separators. *Nuclear Engineering and Design* **118**, 197-192.

Monat, J. P., McNulty, K. J., Michalson, I. S., Hausen, O. V. (1986) Accurate evaluation of chevron mist eliminators, *Chem. Eng. Progress*, **82** (12), 32-37.

Moore, M. J., Sieverding, C. H. (1976) *Two-Phase Steam Flow in Turbines and Separators*, Hemisphere Publishing Corporation, Chapter 7.