Effect of Liquid Surface Tension on Small Hole Distillation Sieve Tray Pressure Drop

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Experimental work on a 229-mm-dia. air/liquid distillation simulator shows that the surface tension of a given liquid can affect the total tray pressure drop, which normally consists of the sum of dry tray pressure drop, clear liquid head, and residual pressure drop. Both the dry tray pressure drop and clear liquid head values establish correlations in the literature for their prediction. The residual pressure drop, however, has been regarded as a constant value. This is not the case and the residual pressure drop is a dynamic variable. Three different surface-tension liquids (water, benzyl alcohol, and n-Propanol) are used to isolate this effect. Results presented correlate the residual pressure drop in terms of the gas F-factor, the clear liquid head, and the traditional residual head loss definition.

Introduction

The pressure drop across distillation sieve trays is very important in setting energy targets in distillation plants. Generally, the pressure drop per tray is correlated as the sum of resistances to the vapor flow up the column. These are:

- The orifice resistance to the gas passing through the perforations on the tray
- The resistance offered to the gas by the aerated mass of liquid on the tray itself.

In this article, the terms gas and vapor are used interchangeably to denote the less dense phase rising through a column. The definition of tray pressure drop can be expressed mathematically as (in terms of liquid head losses on the tray):

$$h_{tot} = h_{dry} + h_{froth}.$$

Many authors have used this type of expression to define the tray pressure drop (Hunt et al., 1955; Lockett, 1986; Kister, 1992; Davy and Haselden, 1975; and Bekassy-Molnar and Mustafa, 1991a). The orifice resistance to the gas passing through the perforations in the tray can be determined by passing gas through the tray with no liquid on it and measuring the pressure drop. Several correlations have been derived for this and will be discussed later. The pressure drop through the froth is nominally made up from two parts:

1. The resistance to the gas having to pass through the liquid on the tray.
2. The pressure needed to create bubbles at each orifice and other liquid/vapor effects.

Using this definition the term h_{froth} can be split into:

$$h_{froth} = h_{cl} + h_r$$

with the terms as defined earlier. Over many years, workers have developed correlations for the head loss due to liquid on the tray; these will also be discussed later. However, little has been offered in terms of the residual head term, h_r. This still remains a problem for designers to predict, with some simply adding a constant, estimated amount for each tray.

This work looks more closely at the idea of tray residual pressure drop and at how its perfection can be improved by isolating the surface-tension effect using different surface-tension liquids.

Experimental

A static distillation simulator rig was constructed especially for this study in the Chemical Engineering Laboratories at the University of Nottingham. The rig is shown in Figure 1. Air from the main is fed to the rig at 6.9 bar. The flow of air into the rig is controlled by a Saunders valve. A pressure relief valve on the downside of this flow control valve acts as a safety measure against excessive flow and pressure. Air-flow

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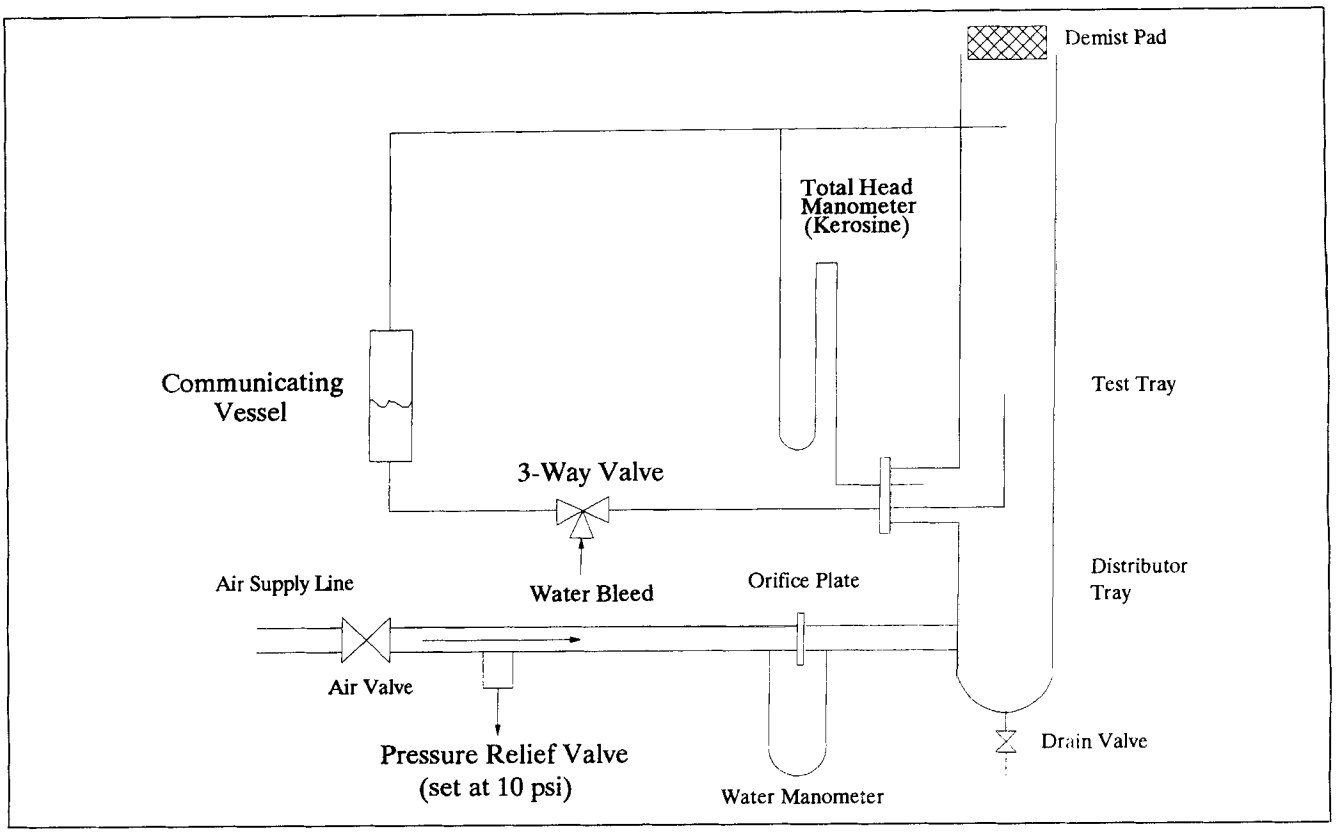


Figure 1. 229-mm-dia. distillation simulator.

measurement is by a calibrated orifice plate across which a 1,500-mm water manometer is connected. The distillation simulator is fabricated from three 229-mm-dia. sections of QVF glass. The air enters the base of the column and passes through a sieve tray whose purpose is to even out the air distribution. The sieve tray is a piece of punched aluminum (7.9% open area, 1.8-mm holes on a 6.1-mm triangular pitch) typical of that used in air-separation columns. The gas passes through a 457-mm-long flow-unification section to the base of the test tray. The test tray for these experiments was of the same material as the distributor tray. Above the test tray, a 609-mm length of QVF was placed, into which the liquid was poured for the distillation tests. A circular pad of knitmesh demister sat on the top of this glass to prevent any droplets of liquid from being carried over. The whole rig was housed in a fume cupboard so liquids with different surface tensions (usually different organic liquids) could be used without risk of fire or intoxication.

The test tray was fitted with five clear liquid head tappings (see Figure 2). These tappings take liquid from the tray and produce a column of clear liquid equivalent in height to the height of liquid on the tray. PVC tubing was used to connect these tappings from the tray to a communicating vessel (Bekassy-Molnar and Mustafa, 1991b). The clear liquid head tappings were placed at different radii from the center of the tray. By connecting these to the communicating vessel, an average clear liquid height over the whole of the tray could be read. An added advantage of the communicating vessel is that local fluctuations in head that are normally experienced with small tube manometers are suppressed, yielding a steady average value. The communicating vessel has a diameter of 51 mm and a length of 330 mm. Total tray pressure drop was measured using a kerosene manometer connected across the tray and froth. Both this and the communicating vessel are connected to the vapor space above the froth to ensure that the correct pressure difference was being recorded.

Initially, the dry tray characteristic of the sieve tray was measured. Different values of superficial air flow over the range 0.3–2.5 m/s (F-factors 0.33–2.74) were set through the column and the total head drop across the tray measured. F-factor is defined in this article as the product of superficial gas velocity and square root of vapor density. It was assumed that this characteristic would not change for the wet tray.

Three liquids were used in the pressure drop study, water, benzyl alcohol (BeOH), and n-propanol (PrOH). Their physical properties are shown in Table 1. The liquids used vary in density and viscosity as well as in the surface tension. Haq (1982) performed a study that considers the effects of these physical properties on tray parameters in which he concluded that the clear liquid height is independent of the physical properties of the solutions used, and that total pressure drop across the tray is almost proportional to the surface tension of the liquids used, but is independent of both the density and the viscosity. With this in mind, the variations of density and viscosity between the liquids being used will not affect the results significantly.

To begin the experimental tests, the air was turned on to a low flow; this was to prevent the liquid dumping through the

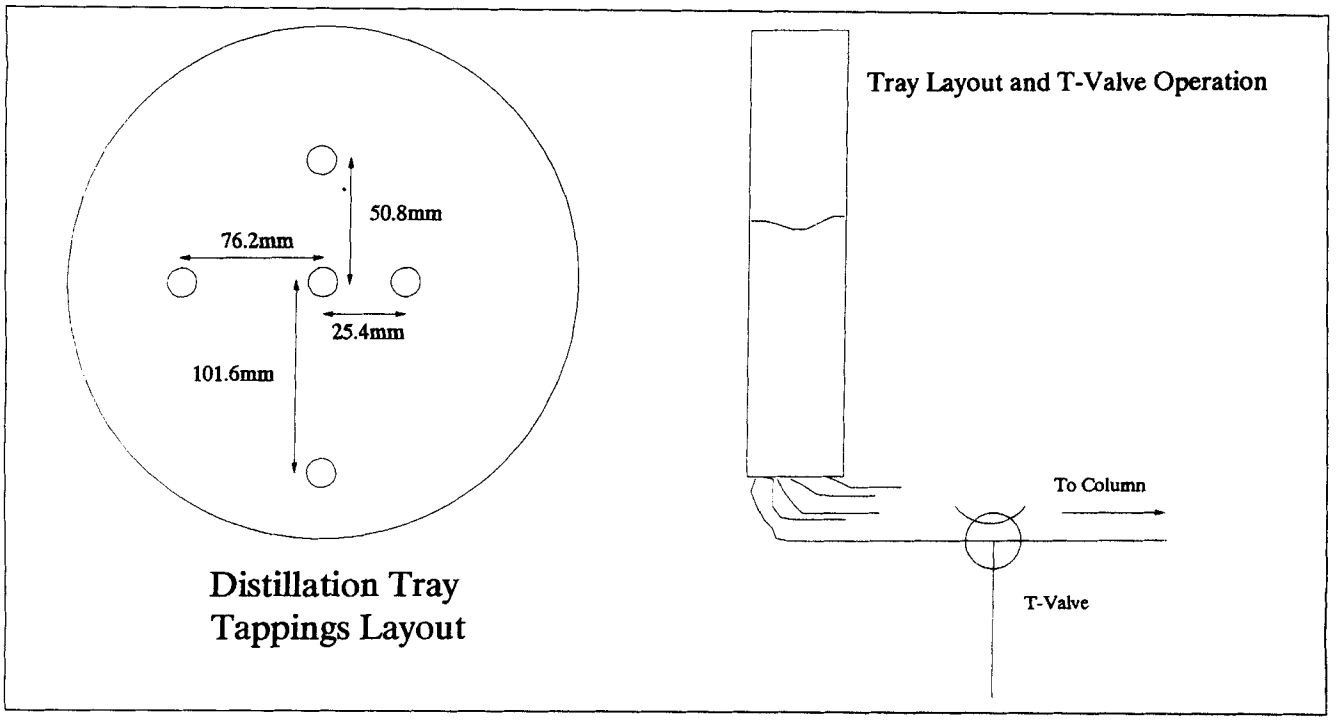


Figure 2. Test tray and valve layout.

tray as it was poured. The liquid was dribbled slowly over a metal baffle around the column wall. Increasing volumes of liquid were poured onto the tray to simulate different liquid loadings. When a froth had developed on the tray, some of the test liquid was blown through the lines connecting the communicating vessel with the tray floor using the T-valves to expel any air bubbles that may have been trapped. The air rate was increased at set increments and at each value; the total head and clear liquid head were measured. At the end of each run, the air was turned off and the final clear liquid head value was measured on the communicating vessel and confirmed by eye with the liquid height on the tray. The drain valve was opened and the liquid allowed to drain out.

Results

Dry tray pressure drop

The dry tray pressure drop of sieve trays is normally correlated as an orifice-type equation:

$$h_{\text{dry}} = \frac{\xi \rho_G}{2g\rho_L}\left(\frac{U_s^2}{\phi^2}\right).$$

Lockett (1986) makes note of the fact that there are over twenty correlations in the literature that correlate the orifice coefficient against some tray parameter. For this study, the correlation of Stichlmair and Mersmann (1978) is used. The orifice coefficient is correlated against the ratio of tray thickness to hole diameter with the hole Reynolds number as a parameter (see Figure 3). The tray type used here has a t/d_h value of 1.11; thus the orifice coefficient is constant over the whole range of hole Reynolds numbers. The orifice coefficient calculated, ξ_o, has to be corrected for fractional hole area. They proposed

Table 1. Physical Properties of Liquids

Liquid	Density (kg/m^3)	Viscosity (Ns/m^2)	Surface Tension (N/m)
Water	999.43	0.001006	0.0728
Benzyl alcohol	1,103.26	0.005744	0.0372
n-Propanol	803.40	0.002207	0.0237

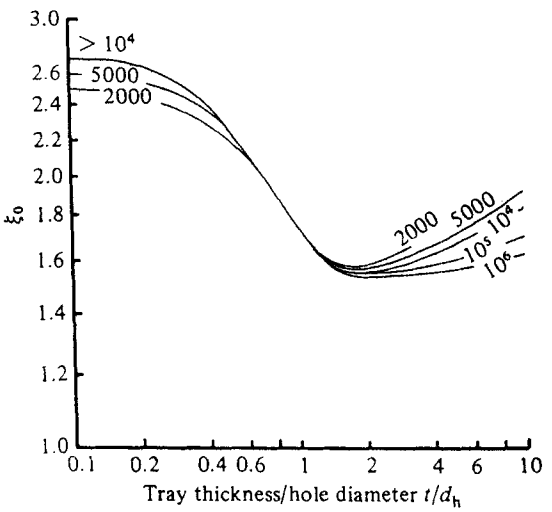


Figure 3. Correlation of Stichlmair and Mersmann (1978).

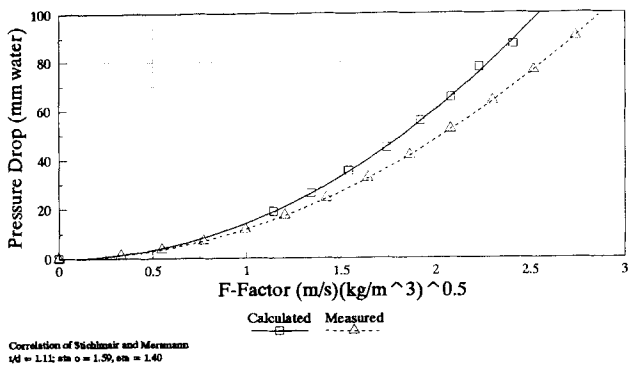


Figure 4. Dry tray pressure drop comparison.

$$\xi = \xi_o + \phi^2 - 2\phi\xi_o^{0.5} \quad \text{for } \frac{t}{d_h} < 2$$

$$\xi = \xi_o + \phi^2 - 2\phi \quad \text{for } \frac{t}{d_h} > 2.$$

For the sieve tray in this work,

$$t/d_h = 1.11.$$

Hence $\xi_o = 1.59$ (from the graph), and $\phi = 0.079$ for the sieve tray. Hence

$$\xi = 1.59 + (0.079)^2 - 2(0.079)(1.59)^{0.5}$$

$$\xi = 1.397.$$

Using this value, a predicted curve of dry tray pressure drop could be produced at different values of F-factor. This is shown in Figure 4. The mean deviation of the calculated value from the measured value is approximately 7.5%. It is also noticeable that the measured values all lie below the calculated values. This can be explained by the sieve material having punched holes rather than the drilled holes that the correlations have been produced for. The sieve material's punch side has curved surfaces allowing for a smoother entry for the gas and hence a smaller head loss. Other correlations for dry tray pressure drop follow the same shape and form as the model of Stichlmair and Mersmann.

Clear liquid height

This work measured clear liquid height using the communicating vessel described previously. As there is no crossflow effect on the test tray, the clear liquid height varies only slightly throughout a run. A problem with this is that the correlations in the literature cannot be used, as there is no weir loading without crossflow. It is, however, possible to deduce values of equivalent weir loadings for the situations in the tray. These data would show the range of operating conditions on the tray.

Most of the correlations for clear liquid height use a Francis-type equation for estimating the height of a liquid crest over a weir (Lockett, 1986). The height of liquid above the weir is estimated using

$$h_{ow} = \frac{1.04}{C_d^{0.67} g^{0.33}} \left(\frac{Q_L}{(1-\epsilon_w)W} \right)^{0.67}$$

A problem with this type of equation is that it assumes that the liquid flowing over the weir is completely deaerated, which is far from the case. This has been corrected for by the inclusion of the term $(1-\epsilon_w)$. However, ϵ_w is difficult to predict, as the liquid over the weir has less gas in it than does the body of the froth. As a result, setting $\epsilon_w = \epsilon$ introduces a small error, but facilitates easier calculation.

Correlations for clear liquid height include those of Colwell (1981), Chan and Fair (1982) and Bennett et al. (1983), all of which are based on the Francis-type equation; and Bekassy-Molnar and Mustafa (1991b), which was derived on a more empirical basis. Colwell (1981) has been adopted for the work in this study. The correlation has an iterative solution where an initial estimate of the clear liquid height is made. Thus, assume $h_{cl} = 50$ mm (say), whence

$$\frac{\epsilon}{1-\epsilon} = 12.6 \left[\frac{U_s^2}{g h_{cl}} \cdot \frac{\rho_g}{\rho_l - \rho_g} \right]^{0.4} \phi^{-0.25}$$

$$h_f = \frac{h_{cl}}{1-\epsilon}$$

$$h_{ow} = h_f - h_w.$$

Calculate the discharge coefficient C_d from:

$$\text{for } \frac{h_{ow}}{h_w} \le 8.14 \quad C_d = 0.61 + 0.08 \frac{h_{ow}}{h_w}$$

$$\text{for } \frac{h_{ow}}{h_w} > 8.14 \quad C_d = 1.06 \left[1 + \frac{h_w}{h_{ow}} \right]^{1.5}.$$

Thus calculate the value of the clear liquid height:

$$h_{cl} = (1-\epsilon) \left[h_w + \frac{0.730}{C_d^{0.67}} \left(\frac{W_l}{1-\epsilon} \right)^{0.67} \right].$$

Adjust the h_{cl} value and repeat the process until the value converges. Experience has shown that convergence is achieved after a small number of iterations.

A useful aside at this point is the choice of correlation. It is important when choosing a correlation that the right one for the flow regime in which the tray is operating is used. The reason for this is that the mechanism of liquid holdup changes from regime to regime. Chen (1987) questioned Colwell's screening of his data to separate those of the froth and the spray regimes. It was concluded that the reason for this was the use of an inappropriate correlation for the froth-spray transition, namely that of Porter and Wong (1969).

Bennett et al. (1983) proposed a similar type of expression to that of Colwell, but it did not require the use of an iterative procedure. More recently, Bekassy-Molnar and Mustafa (1991b) have applied a more empirical correlation for most of the data available in the literature. They based their correlation on the most up-to-date data of the available correlations for the froth-mixed and mixed-spray transitions (Chen, 1987).

They proposed:

$$\text{Froth Regime} \quad h_{cl} = 0.084\phi^{-0.36}h_w^{0.64}d_h^{-0.19}\psi^{0.35}$$

$$\text{Mixed Regime} \quad h_{cl} = 0.091\phi^{-0.70}h_w^{0.63}\psi^{0.33}$$

$$\text{Spray Regime} \quad h_{cl} = 0.015\phi^{-1.61}h_w^{0.50}d_h^{0.33}$$

$$\psi = \frac{W_l}{U_s}\sqrt{\frac{\rho_l}{\rho_g}}.$$

These correlations cover the whole range of distillation tray operation and have good parity with the experimental results.

The results obtained in this study were generated using a static flow system—a charge of liquid being poured onto the tray and the changes in the clear liquid head being measured over a range of gas flows. Despite the clear liquid height changing only slightly over the rang of F-factors covered, it is possible, using the correlations noted, to predict an equivalent weir loading from these results. Lockett (1986) reviewed the correlations available and recommends the use of Colwell's correlation, and subsequently with the comments of Chen (1987) being taken into account. For each combination of U_s and h_{cl}, a weir loading can be deduced. The height of the weir used was 12.5 mm, a value that is not untypical in air separation plant use. The results are shown in Figures 5a and 5b for the correlations. Most of the weir loadings lie in the range 0–100 cm^3/cm·s, with some more remote points at around 250–300 cm^3/cm·s. The higher weir loads are those of the largest charges of liquid to the column. Most of the data generated in this study were in the froth regime. The froth-spray transition was calculated for each run using the correlation of Chen (1987):

$$\text{Froth-Mixed} \quad \frac{h_{cl}}{d_h} = 3.79\left(\frac{U_s}{\phi}\right)\sqrt{\frac{\rho_g}{\rho_l}}$$

$$\text{Mixed-Spray} \quad \frac{h_{cl}}{d_h} = 1.89\left(\frac{U_s}{\phi}\right)\sqrt{\frac{\rho_g}{\rho_l}}.$$

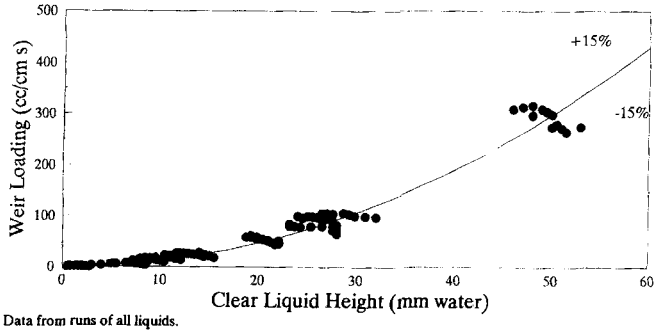
The results of this screening are shown in Figure 6. The results that fall into the mixed or spray regime were deleted because only results in the froth regime are applicable for the correlation used.

Residual pressure drop

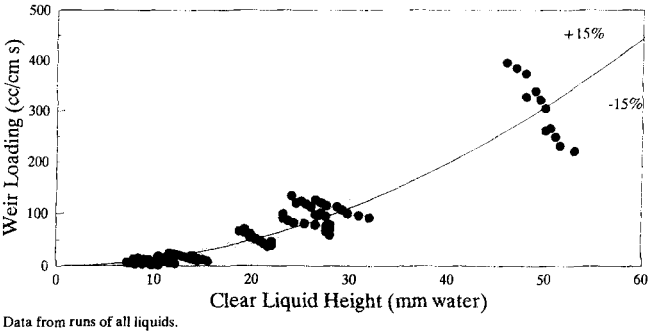
The residual pressure drop term forms the final component in the tray pressure drop equation. The residual pressure drop is defined as *that value of pressure drop that is required to provide equality between the total head loss and the sum of dry tray and clear liquid head losses*. It has been traditionally related to the pressure required to overcome the surface-tension forces when forming a bubble at a submerged orifice (Fair, 1963). Mathematically, this is expressed as

$$h_\sigma = \frac{4\sigma}{\rho_l g d_h}.$$

More recently it has been related to the way bubbles form at



(a)



(b)

Figure 5. Correlation of clear liquid height with weir loading: (a) Colwell; (b) Bennett.

tray holes in terms of the excess pressure inside the bubble during formation. Bennett et al. (1983) looked at the pressure inside the bubble at each bubble diameter and related this to a mean value, $D_{B\max}$. The mean value $D_{B\max}$ is found by resolving a vertical force balance on the bubble at departure (Figure 7):

$$\text{Buoyancy} = \frac{\pi}{6}D_{B\max}^3(\rho_l - \rho_g)g$$

$$\text{ST force} = \pi d_h(\sigma \sin\theta).$$

Equating these expressions at the departure point from the hole gives

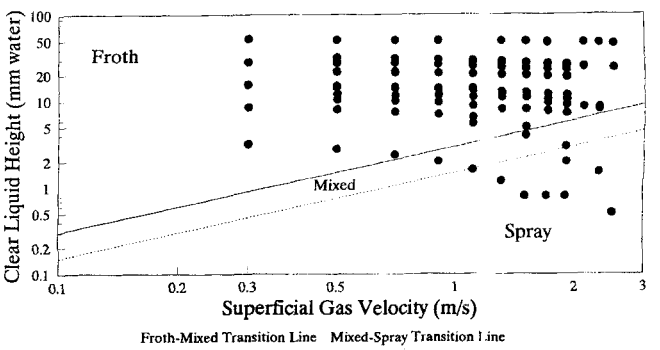


Figure 6. Froth-mixed-spray transition.

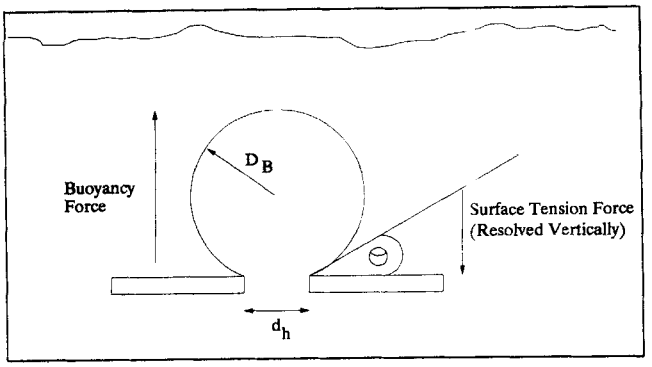


Figure 7. Bubble formation model.

$$D_{B\max} = (6\sin\theta)^{1/3}\left[\frac{d_h\sigma}{(\rho_l - \rho_g)g}\right]^{1/3}.$$

This value of bubble departure diameter is then substituted into an expression developed by Pavlov (1964) based on the energy expended in forming the bubble

$$h_r = \frac{6\sigma}{\rho_l g D_{B\max}}.$$

For water, the value of θ is about 20°. This is a commendable method of predicting the residual pressure drop, as it is the first to employ a method for looking at bubble formation, which is, at best, a complex process. However, using a static balance in the dynamic system introduces errors. Again, for a given liquid, the residual head remains constant and does not change with operating parameters.

From this study, splitting the total tray pressure drop into its components has revealed that the residual head loss increases with F-factor. This is illustrated in Figures 8a–8c. The residual pressure drop was calculated by subtracting the dry tray and clear liquid heights from the total tray pressure drop as defined previously.

An empirical analysis of these data was performed to attempt to correlate the residual head as a function of the other tray properties. It was decided to use the following semiempirical expression as a basis for calculating the residual pressure drop:

$$h_r = n\left[\frac{\sigma}{\rho_l g d_h}\right] + \alpha F + \beta h_{cl}$$

where n, α, and β are coefficients determined from the experiments. The method of calculating each of the coefficients is outlined below:

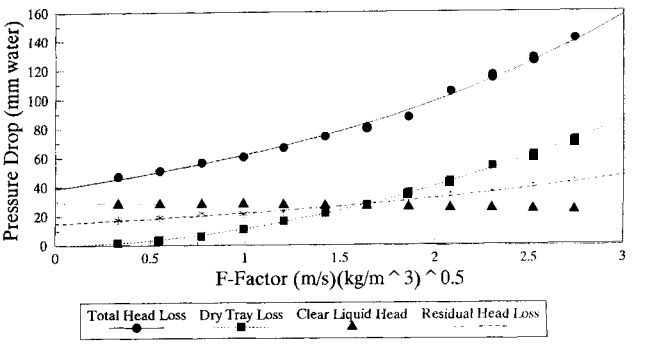
1. Plot values of h_r vs. h_{cl} at $F = 0$, obtained by extrapolation. Extrapolate this line to find the value of h_r at $F = 0$, $h_{cl} = 0$. This will yield the value of n from the intercept of the graph on the h_r axis (see Figures 9a–9c).
2. From the plot generated, find the slope of the graph. This will give the variation of the residual head loss with clear liquid height, hence β.
3. Plot $h_r - [n\sigma]/[\rho_l g d_h] - \beta h_{cl}$ against F to yield the value of the slope, α.

The values of the coefficients found by experiment are shown in Table 2. These models give a reasonable fit to the experimental values (Figure 10a–10c). The fits for all liquids are good, most points lying within a range of ±15%. Figure 10c shows three points that have markedly higher measured residual head losses than predicted. These occurred at the heaviest liquid loadings in the column and are not seen in the results obtained with the other liquids (Figure 10a and 10b).

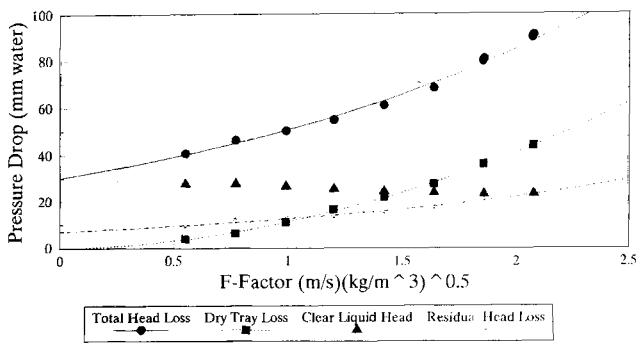
Discussion

Dry tray pressure drop

There is a difference between the calculated and measured values for all F-factors in the dry tray characteristic, which becomes more marked at high gas throughputs. The dry tray pressure drop was calculated by Stichlmair's equation:



(a)



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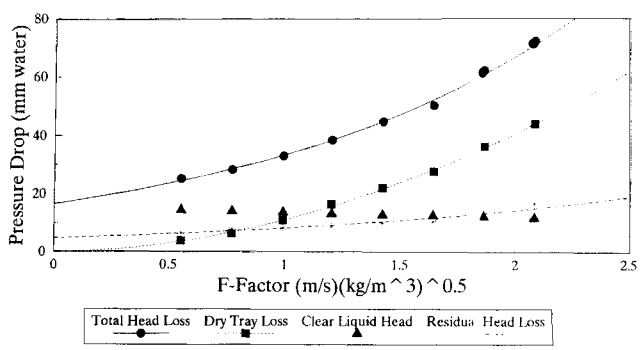
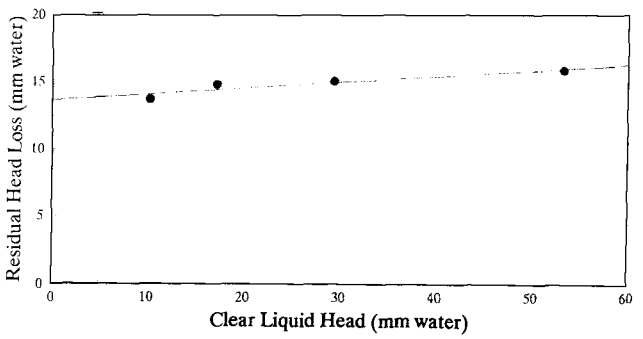
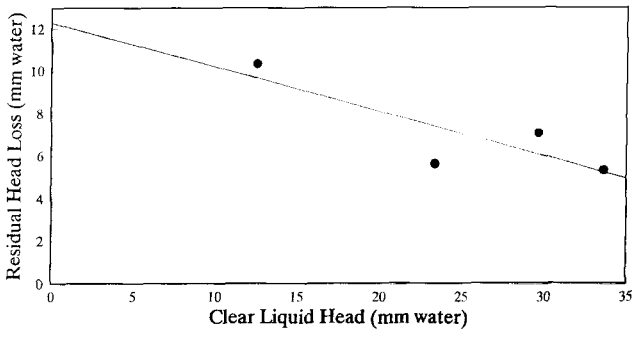


(c)

Figure 8. Tray pressure drop breakdown: (a) liquid = water; (b) liquid = BeOH; (c) liquid = PrOH.





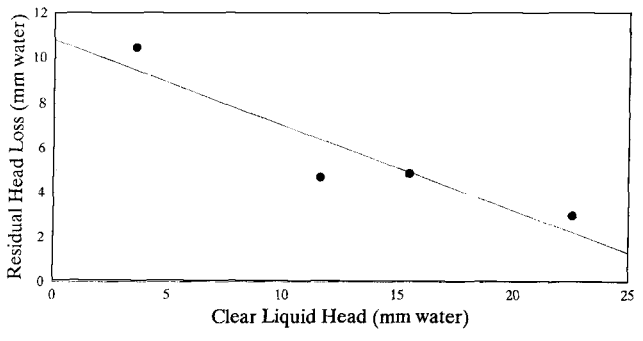


Figure 9. Extrapolation of residual head loss: (a) liquid = water; (b) liquid = BeOH; (c) liquid = PrOH.

$$h_{\text{dry}} = \frac{\xi \rho_g U_s^2}{2g\rho_l \phi^2}$$

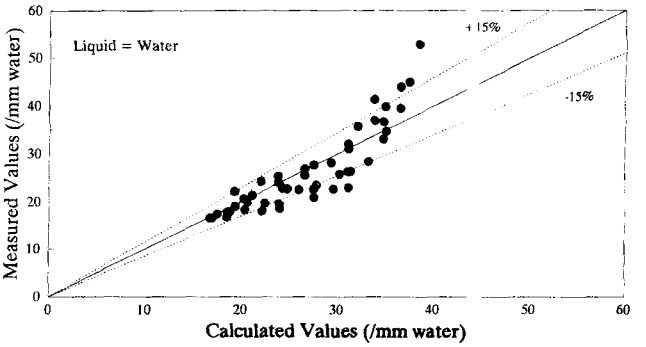
It is noticeable that in all cases, the equation gave values consistently higher than those measured. This could be due to the small hole sizes used in this study compared with standard sieve holes that are of the order 5–15 mm. A plot of log h_{dry} vs. log U_s gave a straight-line plot that was not entirely unexpected. What was interesting about these data was the fact that the slope of the line (the exponent on the U_s term) was found to be 1.83 rather than 2. This difference has been reported previously by workers in the field of structured packings (Spiegel and Meier, 1987). This points to the possible development of a new, improved correlation for dry tray pressure drop based on an exponent nearer 1.8 than 2.0. The correlation of Stichlmair and Mersmann overpredicts the value of dry tray head loss. This is better than an underprediction; however, in these days of energy conservation a more accurate prediction would be desirable. In addition to these

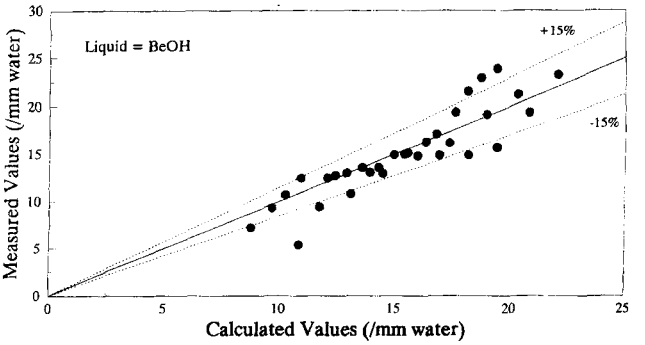
Table 2. Values of Coefficients Found by Experiment*

Liquid	n	α	β
Water	3,350	8.34	0.04
Benzyl alcohol	5,570	5.74	−0.21
n-Propanol	8,280	2.79	−0.38

*In which

$$h_r\ (\text{mm water}) = n\left[\frac{\sigma}{\rho_l g d_h}\right] + \alpha F + \beta h_{\text{cl}}\ (\text{mm water}).$$





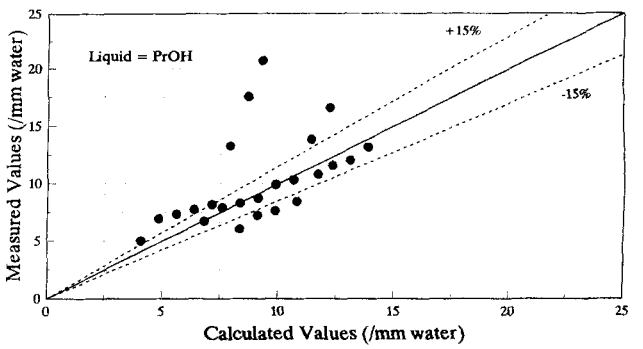


Figure 10. Measured vs. calculated values of residual head loss: (a) liquid = water; (b) liquid = BeOH; (c) liquid = PrOH.

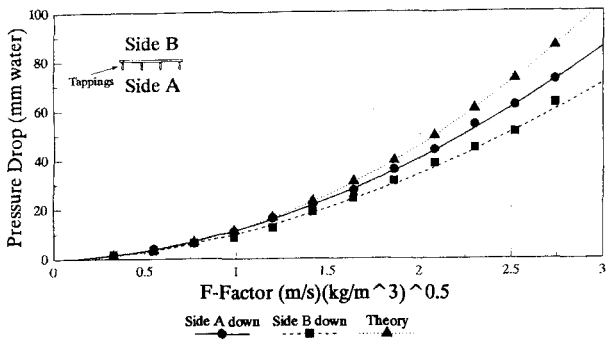


Figure 11. Sieve tray dry tray pressure drop: theory vs. rough/smooth sides.

findings, the dry tray pressure drop tests were repeated, but on this occasion the tray was turned over, that is, the head tappings were pointing upward rather than down. The side facing the air flow originally was designated side A, from where these tests had side B facing the air. The results are shown in Figure 11. It is noticeable that both sets of experimental data fall below that of the theory. The results also indicated that the wet tests performed previously used the "rough" or unpunched side down, yielding a higher contribution for dry tray pressure drop. The smooth lips formed by the punch allow for a smoother passage of air through the orifice, thus lowering the orifice coefficient. The exponents were 1.83 and 1.78 for sides A and B, respectfully.

Clear liquid head

The clear liquid head is an important variable in the tray pressure drop calculation. If the vapor were to cease rising through the column and no weeping occurred from the trays, then the height of liquid on each tray would be the clear liquid height. Correlations for the prediction of clear liquid height have been discussed earlier; however, it is interesting to note that the values of weir loadings implied by the correlations used for the tray lie within the ranges of those expected industrially for the assumed height of the weir (Kister, 1990). The correlations of Colwell (1981) and Bennett et al. (1983) show good agreement in interpreting the static system as a flow system. This analysis was carried out because of the need for interpretation; designers generally have a greater perception of tray behavior in terms of weir loadings than simply quoted values of clear liquid head. It is also interesting to note that the gas momentum correction factor (described by Bekassy-Molnar and Mustafa, 1991a) was not needed to correct for the clear liquid head. Visual observations showed little change between the actual measured value of clear liquid height and that found using the communicating vessel. By placing a known volume of liquid on the tray, and knowing the height/volume variation in the column, a direct comparison was made and little change was noted.

Residual pressure drop

The form of the model used to predict the residual head loss was chosen on a semiempirical basis: pertinent tray variables that would be considered to have an effect on the bubble formation process were chosen. When bubbles form under a liquid, a pressure is exerted within the bubble to overcome the surface tension of the liquid. The rate at which this force is exerted is a function of the bubble formation frequency and hence the gas flow rate. For this reason, the F-factor term was included in the model. When formed, the bubble has to then move through the liquid head above the orifice by a buoyancy process. A large hydrostatic head would mean greater pressure against bubble formation. Although a number of bubbling holes would create a mean density less than that of the liquid alone, the clear liquid head term was included in the model. Single-bubble studies from sieve holes have shown maximum bubble formation frequencies of 25 bubbles/s.

The results show the following trends:

1. The value of n increases as surface tension decreases.
2. The value of α decreases as the surface tension decreases.
3. The value of β decreases as the surface tension decreases.

Traditionally, the effect of surface tension head loss has been taken as a constant (the Fair, 1963, definition). Therefore, it is not unreasonable to see the inverse proportionality relationship between the surface tension and coefficient n. Indeed the $n\sigma$ product for each liquid varies only $\pm 12\%$ from the mean value of 216.29. This is well within the tolerances of the experimental model of $\pm 15\%$. The model also predicts the effect of F-factor, which becomes less as surface tension becomes less. This could be attributed to the comparative ease with which bubbles are formed in lower-surface-tension liquids compared with higher-surface-tension liquids. Burton (1992) showed that the minimum hole gas flows for bubbling were 5.57 m/s for water and 3.27 m/s for n-PrOH. This would mean that the effect of F-factor becomes less important at lower surface tensions. The effect of clear liquid height also decreases with surface tension, this being attributed to the ease at which bubbles are formed under depths of lower-surface-tension liquids. The model seems to mirror what would be expected in each case.

This model has used the dry tray pressure drop as the orifice loss. This is not strictly justified, as has been pointed out by several authors (Lockett, 1986; Davy and Haselden, 1975; Bekassy-Molnar and Mustafa, 1991a; Burton, 1992), who have shown that the dry tray contribution to the orifice loss under wet conditions is greater than that of the dry tray. The cause of this is seepage of the liquid onto the inside of the orifice, forming an annulus and thus reducing the area for gas flow. This annulus increases the hole velocity and hence the head loss. Since the orifice head loss is a function of the square of gas velocity, the increase is marked. The result of this is that the orifice head loss curve under wet conditions increases more steeply than that of the dry tray pressure drop curve. This means that if we base residual head loss on that required for equality with total tray head loss, subtracting the greater orifice head loss results in a smaller residual head loss.

This is different from the model presented in this article. While single-hole studies are important and predict a sharp fall in residual head loss with gas rate (Burton, 1992), the chaotic behavior and rheology of the biphase around a bubbling orifice on a sieve plate bears little resemblance to the clear-liquid-type experiments carried out for single-bubble

studies. It is also intuitive that the residual head loss should decrease as gas rate is increased; residual head loss has been attributed, in part, to the bubbling process on the tray. Indeed, this bubbling process appears to be the most significant part of the makeup of residual head loss. As the gas rate is increased, a transition occurs. For a given volume of liquid on the tray, as the gas rate is increased, a point is reached where liquid-phase continuous operation (froth regime) ceases and gas-phase continuous operation begins (spray regime). This change between operating regimes results in the bubbling action ending as liquid entrainment is more prominent in the spray regime. The cessation of bubbling implies that the bubbling contribution to residual head loss should approach zero. This contribution is a significant one. This would explain the findings of other workers who have published data in the field.

This model is intended to aid the designer using *measurable* tray variables. As a result of this, the residual head loss is an "effective" head loss rather than that established by a more theoretical route, but nonetheless an aid to the designer in making a more accurate prediction of this uncertain tray variable.

Conclusions

A model is presented that can predict the residual head loss as a function of pertinent tray variables that affect bubble formation. It has been illustrated that the variation between calculated and measured values over a wide F-factor range is reasonably acceptable within limits of $\pm 15\%$ at implied weir loadings of around 0–125 $cm^3/cm \cdot s$.

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Notation

C_d = discharge coefficient for the weir equation
$D_{B\,max}$ = maximum bubble diameter on forming (m)
d_h = hole diameter (m)
F = gas F-factor $(m/s)(kg/m^3)^{1/2}$
g = acceleration due to gravity (m/s^2)
h_{cl} = clear liquid head (m)
h_f = froth height (m)
h_{froth} = head loss through the froth (m)
h_{ow} = height of liquid above the weir (m)
h_{tot} = total head loss (m)
h_w = weir height (m)
Q_L = liquid loading (m^3/s)
t = tray thickness (m)
U_s = superficial gas velocity (m/s)
W = weir length (m)
W_l = weir loading $(cm^3/cm \cdot s)$

Greek letters

ϵ = fraction of vapor in the biphase
ϵ_w = vapor fraction in biphase over the weir
ξ = orifice coefficient
ξ_o = uncorrected orifice coefficient
ρ_g = gas/vapor density (kg/m^3)
ρ_l = liquid density (kg/m^3)
σ = surface tension (N/m)
ϕ = fraction free area
ψ = flow parameter

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