PREDICTION OF THE EFFICIENCY OF SIEVE TRAY USING AIR-WATER SYSTEM

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ABSTRACT

This investigation deals with the effect of weir height, liquid and gas flow rate on tray efficiency. The tests were carried out on a single pass cross flow tray of air-water system of 0.3 m diameter for clear liquid height over sieve tray with weir height 3, 4 and 5 cm.

Point efficiency values were found to be in the same range for different weir height, but it improves slightly with weir height. And the average values of point efficiency were 83 % for 3 cm weir height, 85 % for 4 cm weir height and 89 % for 5 cm weir height. While, point efficiency of 90 % was obtained for 5 cm weir height and liquid flow rate ranging between 5.8 to 7.32 m^3/s.

In the range of clear liquid height over hole diameter (h_L/d_H) between 2 to 10, increasing the Reynolds number ranging between $2.0*10^5$ to $1.6*10^6$ for gas phase increases point efficiency.

Prediction of Murphree (Tray) efficiency using Lopez and Castells (1999) equation shows that the ratio of E_{MV}/Ep is equal to 1, due to low value of calculated Peclet number (degree of liquid mixing), which ranged between 0.07 to 1.5.

الخلاصة

درس هذا البحث تاثير تغير كل من إرتفاع السد و جريان السائل و الغاز على إرتفاع السائل فوق الصينية المنخلية و كفائتها لنظام هواء-ماء.

يزداد ارتفاع السائل فوق صينية اختبار واحدة ذات قطر 0.3 متر وعدد فتحات 213 فتحة و ارتفاع سد3 و4 و5 سم بزيادة جريان السائل بين 0.12 الى 0.58 متر مكعب \ساعة ويقل مع زيادة جريان الغاز من 35 الى 100 متر مكعب \ ساعة.

كانت قيم الكفاء ة النقطية متقاربة لكنها تتحسن قليلا مع زيادة ارتفاع السد . وكانت معدلاتها مع ارتفاع السد هي 83% لارتفاع سد3 سم و85% لارتفاع سد 4 سم و 89% لارتفاع سد 5 سم . في حين اعلى قيمة للكفاءة النقطية كانت 90% لارتفاع سد 5 سم و جريان ماء بين 8.5 و 7.32 م^3/ ثا .

كذلك زيادة عدد رينولدز للطور الغازي يزيد من الكفاءة النقطية للصواني المنخلية في حالة كون نسبة إرتفاع السائل إلى قطر ثقب الصينية تتراوح بين 2 إلى 10.
تم تخمين كفاءة ميرفري للصينية باستخدام معادلة لوبيز و كاستلز (1999) والتي اشارت إلى إن نسبة كفاءة ميرفري إلى الكفاءة النقطية كانت تساوي واحد بسبب إنخفاض قيم عدد بكلت للسائل والتي تراوحت بين 0.07 و 1.5.

KEYWORDS
Sieve tray, Tray efficiency, Point efficiency, Murphree plate efficiency

INTRODUCTION

The tray efficiency governs the number of actual trays needed to achieve the desired product purity specifications. With highly efficient trays one can install a lower number of these highly efficient trays to achieve the separation desired.

Several tray efficiency definitions in use. Three different efficiencies are useful, in particular (Wijn, 2003).

- The overall efficiency (*Eo*), the socalled: Fenske efficiency.
- The average tray efficiency, first defined by Murphree (E_{MV}).
- The local (or point) efficiency (*Ep*).

For nonreactive systems, several methods are available for estimating the Murphree tray efficiency from point efficiency estimates made either from laboratory-scale measurements, such as using an Oldershaw column, or from published correlations (Dribika and Biddulph, 1986; Bennett and Grimm, 1991; AIChE, 1958). Klemola 1998 lists references for more than a dozen tray efficiency correlations. For each of these methods, the conversion of point efficiency to tray efficiency relies on the choice of the mixing model to be used.

The liquid mixing on the tray has been modeled using several approaches. Lewis (1936) analyzed the ideal case of plug flow across the tray, which may be approached for large diameter columns. Gautreaux and O'Connell (1955) treated the flow as a series of perfectly mixed pools across the tray. The primary difficulty in the utility of their method is incorrectly estimating the number of mixed pools on the tray. The AIChE (1958) study used a more rigorous mixing model based on eddy diffusivity for diffusive backmixing based on the dimensionless Peclet number AIChE, (1958). Foss et al. (1958) developed a method for relating the Peclet number to the number of perfectly mixed pools across the tray. More recent work has included mixing models of increasing complexity Prado and Fair, (1990); Garcia and Fair, (2000).

For nonreactive systems with cross-flow trays, the concentration varies across the tray as a result of nonideal mixing. In the limit of perfect liquid mixing on the tray, the concentration is constant across the tray and the point efficiency and tray efficiency are the same. For nonideal mixing, concentration gradients develop across the tray that lead to differences in the tray and point efficiencies. In the extreme limit of plug flow across the tray, the concentration gradient is maximized and the difference is also at a maximum.

Bennett et al. (2000) used the recent correlation reported by Bennett et al. (1997), they address point efficiency, entrainment, mixing within the froth, weeping, and cross-flow and parallel-flow tray types. Their correlation for point efficiency is:

$$E = 1 - \exp\left[\frac{-0.0029}{1 + m \dfrac{\rho_{MV}}{\rho_{ML}} \sqrt{\dfrac{D_V (1-\varphi_e)}{D_L \left(\dfrac{A_H}{A_B} \right)}}} (\mathrm{Re})^{0.4236} \left(\frac{h_L}{d_H} \right)^{0.6074} \left(\frac{A_H}{A_B} \right)^{0.3195} \right] \qquad (1)$$

There are no generalized correlations that apply to all types of tray deck designs. So, this approach will use the broadly based correlations developed for sieve trays to develop some optimization rules and then to discuss the implications of using other types of trays on these rules. The optimization goals are:

1. Maximizing theoretical stages per section or column height,
2. Minimizing pressure drop per theoretical stage, and
3. Maximizing the operational range, turn-down, or turn-up.

MURPHREE AND POINT EFFICIENCIES

The Murphree vapor efficiency for a tray is defined as the ratio of the actual change in vapor mole fraction for a component divided by the change in mole fraction that would be experienced if the vapor leaving the tray were in equilibrium with liquid leaving the tray.

$$E_{MV} = \left(\frac{\bar{y}_{n+1} - \bar{y}_n}{y_{n+1} - y_n^*} \right)_{Tray} \qquad (2)$$

When E_{MV} is Murphree vapor efficiency, $\overline{y}_{n+1}$ is average mole fraction in the vapor entering the tray, $\overline{y}_n$ is average mole fraction in the vapor leaving the tray, and y^*_n is the mole fraction that would be in equilibrium with liquid leaving the tray.

The point efficiency Ep is defined similarly, but applies to a particular point on the tray, with a particular liquid-phase composition.

$$Ep = \left(\frac{y_{n+1} - y_n}{y_{n+1} - y_n^*} \right)_{point} \tag{3}$$

The point efficiency follows from application of the two-film-mass-transfer model for point of vapor as it travels up-ward through the liquid phase and engages in mass-transfer exchange with the liquid. The liquid composition is assumed to be constant in the vertical direction.

The key point in introducing the above equations is to realize that difference between point efficiency and Murphree vapor efficiency arises as a result of the variation in y^* that occurs across the tray as liquid phase composition changes. These changes result from mass balance consideration (as components are absorbed or desorbed) for no reactive system, and from both mass balance and chemical reactive consideration for reactive system. Thus, it is necessary to perform some type of integration across the tray, that is to invoke a mixing model, to account for these changes. In addition, for fast reactions where local mass-transfer coefficients are enhanced depending on the local concentration of reactants, the resulting gradient in mass-transfer enhancement factor must also be accounted for (Fisher and Rochelle, 2002).

EFFECT OF MIXING AND SIGNIFICANCE OF LIQUID PECLET NUMBER (*PE*) ON E_{MV}/ *EP* RELATIONSHIP

The assumption of Lewis (1936) concerning lack of liquid mixing (backmixing) on the gas-liquid contacting tray (although mathematically expedient at the time) is in reality not true; just as total liquid mixing equally not true in traditional industrial-size columns (diameter equal to or grater than one meter). In fact, a degree of liquid backmixing always exists in the liquid as it traverses the tray of such columns. The degree of liquid mixing is characterized by the Peclet number (*Pe*).

$$Pe = \frac{Q_L Z_o^2}{A_a h_L De} \tag{4}$$

A small Peclet number indicates a high degree of mixing and vice versa. According to (Lo'pez and Castells, 1999), if *Pe* is less than 0.2 the liquid is considered well-mixed such that E_{MV} can be considered equal to *Ep*. On the other hand a *Pe* value of about 39 indicates condition approaching liquid plug flow on the tray (Dribika and Biddulph, 1986). Hence a *Pe* value of 50 and higher indicates definite liquid plug flow condition. In such a case the tray efficiency will be larger than point efficiency; the difference between them increasing as *Pe* increases.

Of the above models, the AlChE study (1958) seems to be still the most popular (Lo'pez and Castells, 1999) and is as follows:

$$\frac{E_{MV}}{E_P} = \frac{1-e^{-(\eta+Pe)}}{(\eta+Pe)\left(1+\frac{\eta+Pe}{\eta}\right)} + \frac{e^{\eta}-1}{\eta\left(1+\frac{\eta}{\eta+Pe}\right)} \quad (5)$$

Where

$$\eta = \frac{Pe}{2}\left[\sqrt{\left(1+\frac{4\lambda_o E}{Pe}\right)}-1\right] \quad (6)$$

Eddy diffusivity (*De*)

As pointed out in the previous section, one of the parameters affecting the liquid Peclet number value (and consequently the degree of liquid mixing as it traverses the tray) is the eddy diffusivity (*De*). Usually specific eddy diffusivity is measured experimentally (Chan and Fair, 1984),

To develop a simple relationship and to approximately account for eddy diffusion and the liquid continuous region , droplet mass exchange was assumed to occur over the entire two-phase layer height $h_{2\Phi}$,. Hence, Bennett and Grimm (1991) correlation was:

$$De = 0.02366\left(g h_{2\Phi}^{3}\right)^{1/2} \quad (7)$$

Where for the correlation (equation (7)):

$$h_{2\Phi} = h_{Fe} + \left[\frac{0.794 K_s^2}{(A_h/A_a)\Phi_e}\right] \quad (8)$$

$$h_{Fe} = C'\left[\frac{Q_L}{\Phi_e}\right]^{2/3} + h_w \quad (9)$$

$$\Phi_e = \exp\left(-12.55 K_s^{0.91}\right) \quad (10)$$

$$C' = 0.501 + 0.439\exp(-137.8h_w) \qquad (11)$$

The correlation (equation (7)) was modified later by Bennett et al. (1997) taking also into consideration diffusion resulting from turbulence in the liquid continuous region. This modified correlation was given by Lo'pez and Castells (1999) as follows:

$$De = (4)(0.024)\left(gh_{2\Phi}^3\right)^{1/2} \qquad (12)$$

Where for this correlation

$$h_{2\Phi} = h_{Fe}\left[1 + \left(1 + 6.9\left(\frac{h_L}{d_H}\right)^{-1.85}\right)\frac{Fr_G}{2}\right] \qquad (13) \qquad Fr_G = \frac{V_{ej}^2}{gh_{Fe}}$$

(14)

$$Ve_j = 3K_s\sqrt{\frac{\sqrt{3}}{(A_h/A_a)\Phi_e}} \qquad (15)$$

EXPERIMENTAL WORK

Equipment

The experimental laboratory apparatus used is shown in Fig. 1 and consisted of the following:

i. Glass column. (QVF)
ii. Liquid storage tank.
iii. Blower.
iv. Centrifugal pump.
v. Connecting piping.
vi. Measuring instruments

Geometrical parameters

The following specifications were used which were concluded from Coulson (1985), Treybal (1981) and Ludwig (1979).The plate used is shown in **Fig. (2)**

Material of construction of sieve plate	aluminum alloy A-1050 (99.5 % by wt. Al)
Column diameter	30 cm
Hole diameter	5 mm
Plate thickness	5 mm
Weir height	3 cm, 4 cm, 5 cm
Weir length	22 cm

Length of liquid path	22 cm
Total no. of holes	213
% Free area	7.7
Active or bubbling area	0.05372 m^2
Vapor density (air) standard	1.1982 kg/m^3
Liquid density (water) standard	997.94 kg/m^3
Hole pitch	13.5 mm triangular
Hole area /Active area	13.16 %
Active area /Column area	76.1 %
Outlet calming zone width	18 mm

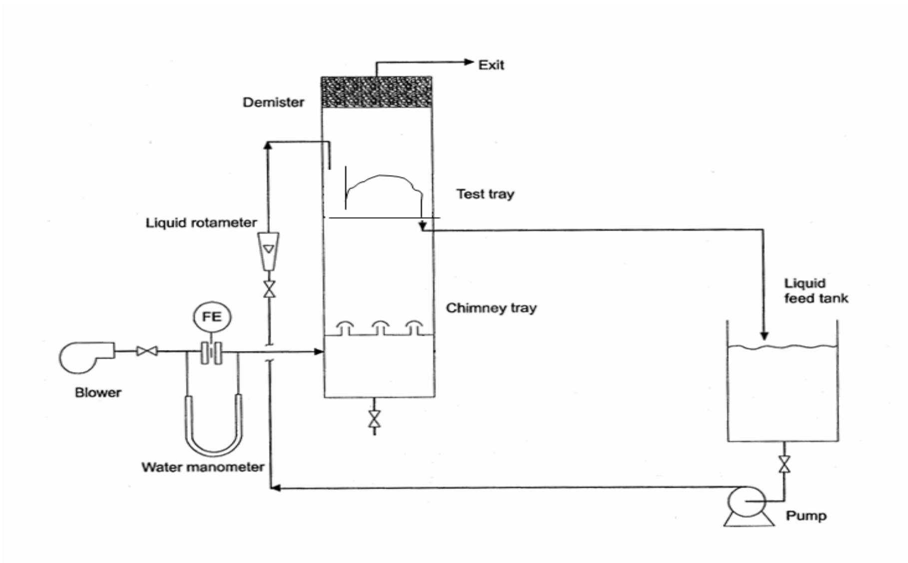


Fig. (1), Schematic diagram of the experimental rig

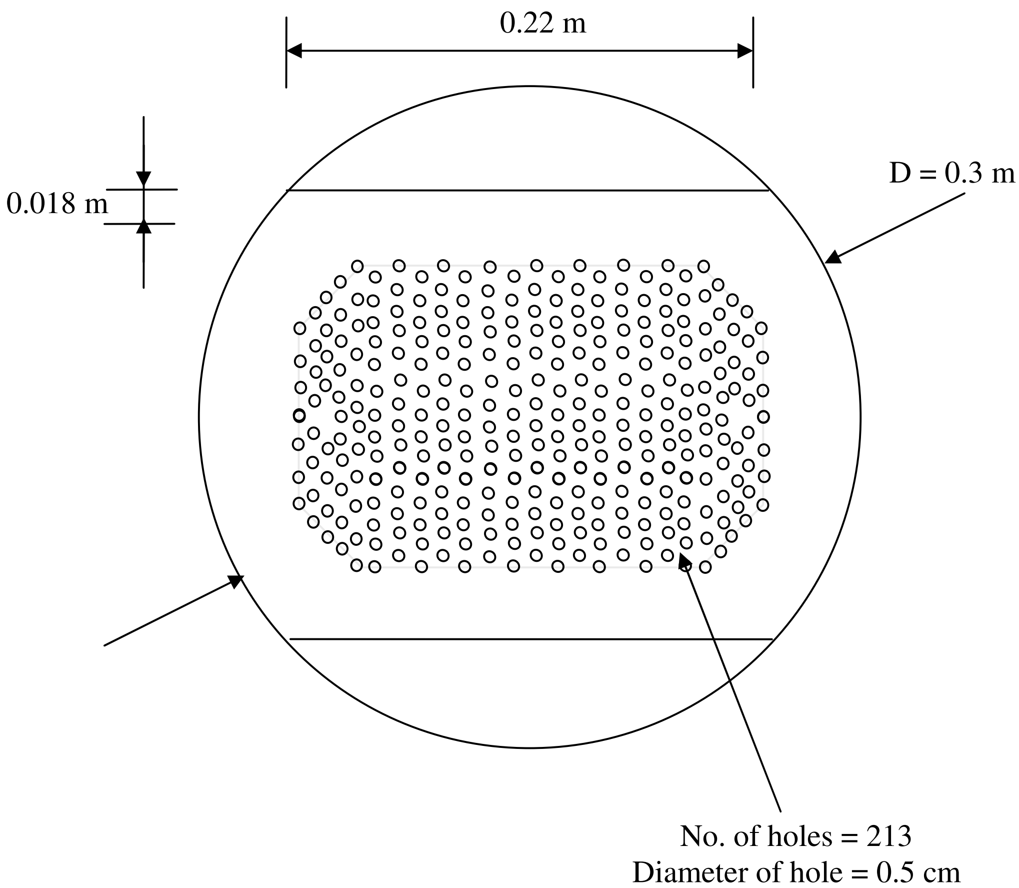


Fig. (2)., Schematic diagram of the sieve tray

Experimental procedures

The experimental program related to the laboratory rig consisted of the following particular steps employed for the operational system:

1. Initially, a sufficient quantity of the liquid to be used was prepared and introduced to the larger of the one liquid tank. This liquid quantity amounted to about $50*10^{-3}$ m^3.
2. The air blower was operated and the air flow was adjusted by a manual gate valve (placed on the 3" ND pipe) utilizing the installed calibrated orifice meter for this purpose. This value of air flow corresponded to the minimum required to avoid dumping of the liquid from the perforated test tray at its minimum adopted inlet flow rate of 0.25 m^3/h.
3. The main supply/recirculating liquid pump was then operated and the liquid flow was adjusted at 0.1 m^3/h by the globe valve upstream of the area flow meter which was utilized for this purpose. This value of liquid flow rate was practically the minimum stable rate of

flow achievable in the rig due to the variation in the reservoir tank liquid level over the duration of an experimental run.

4. The glass column was then observed to ensure that some liquid overflowed the outlet weir. If that was not the case, the air flow rate was gradually increased to achieve this overflow and subsequently fixed and recorded at this overflow occurrence. This procedure was necessary to keep away from the weep point.
5. The next step was to increase the air flow was used to values corresponding approximately to 35, 50, 60, 70, 86 and 100 m^3/h while maintaining the liquid flow are at 0.1 m^3/h. Hence, it was possible to decrease the value of the weeping fraction and/or increase the value of liquid flow over the outlet weir.
6. The procedure pointed out in points 2 and 5 above was repeated over for increasing in the liquid flow rate to the test tray; namely 0.1, 0.14, 0.18, 0.22, 0.26, 0.3, 0.34, 0.38, 0.46and 0.58 m^3/h and measuring the clear liquid height and froth height for each change.

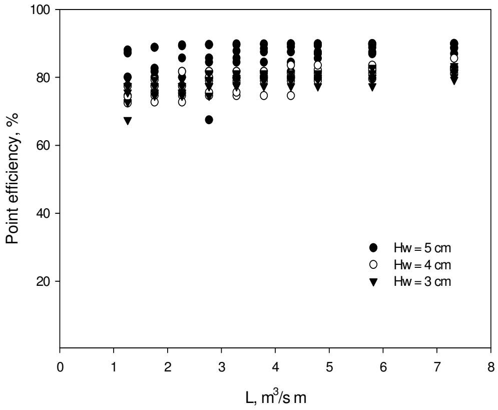
DISCUSSIONS

Effect of weir load (Q_L/L_w), clear liquid height (h_L) and weir height (h_w) on point efficiency (Ep)

Figure (3) shows the effect of changing liquid flow rate (weir load) on the point efficiency. The point efficiency appears increase with clear liquid height as shown in Figure (4), when the liquid flow rate increasing the liquid height increases over the tray deck which will increase the interfacial area and contact time and hence point efficiency.

Maximum values of point efficiency for 5 cm weir height 90 % for liquid flow rate ranging between 5.8 to 7.32 m^3/s m and clear liquid height between 3.5 to 4 cm.

Point efficiency values appear in the same range for different weir height. The average values of point efficiencies versus weir height are summarized in Table (1) and appear improve slightly with weir height. This improvement of point efficiency is due to increasing of liquid height above the tray deck.



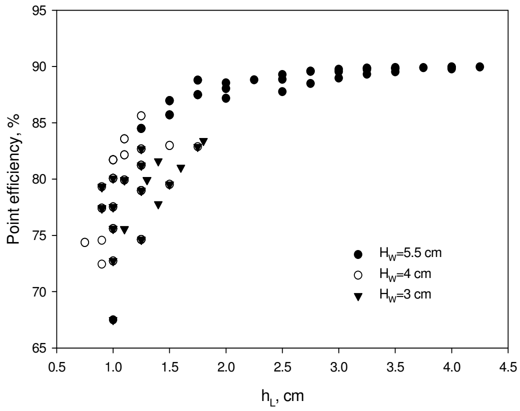


Fig. (3)., The point efficiency versus weir liquid load Fig.(4)The point efficiency versus clear liquid height

The results of point efficiency versus liquid height are compared with Porter (1992) results, who worked on air-water system with 6.35 mm hole diameter, weir height 10, 20, 50 mm and liquid weir load from 0.00125 to 0.025 m^3/m.s and Prado (1987), who worked on the same system but with weir height 25.4, 50.8, 76.2 mm and liquid weir load from 0.0015 to 0.0028 m^3/m.s as shown in Figure (5) Comparison between the results obtained from Porter (1992), Prado (1987) and the present work shows good agreement.

Table (1)., Average values of point efficiency versus weir height

Weir height, cm	Average point efficiency, %
3	83
4	85
5	89

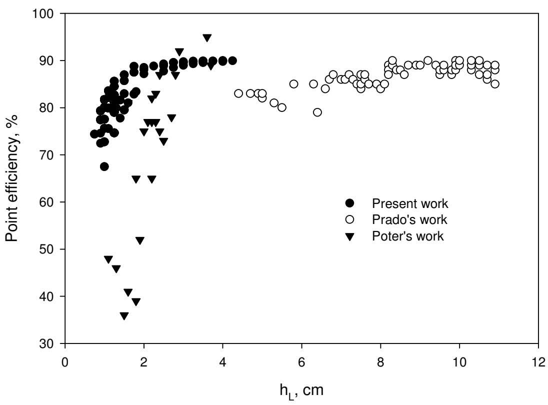
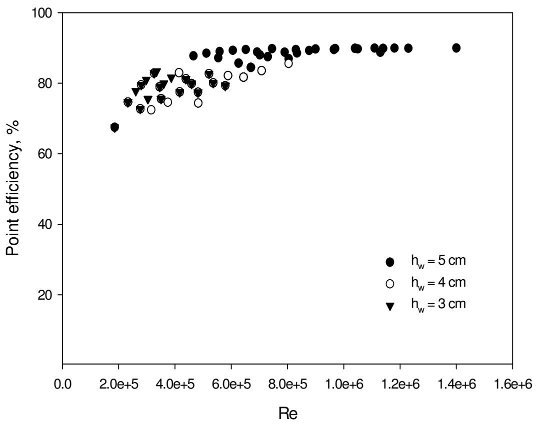


Fig. (5). Comparison of various air-water systems and present work

Effect of F-factor on tray point efficiency (*Ep*)

Bennett et al. (1997) correlation (equation (1)) was used to calculate the point efficiency which is shown that point efficiency increases with gas velocity (Reynolds number Re) as shown in Figure (6).

Large values of gas velocity through the perforation (large *Re*) yield higher interfacial area. As expected the ratio of h_L/d_H plays a significant role and the efficiency increases with h_L/d_H which is ranging between 2 to about 10, as shown in Figure (7).



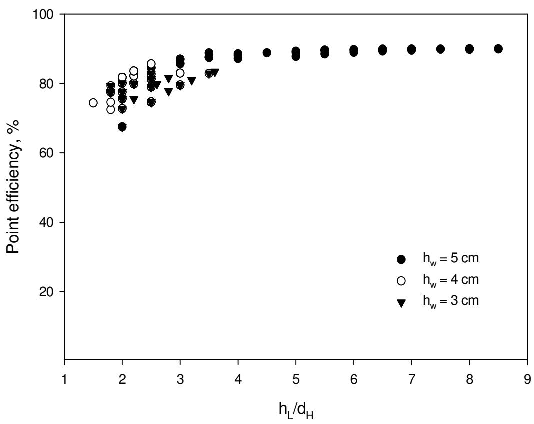


Fig. (6)., The point efficiency versus Reynolds number **Fig. (7)**, the point efficiency versus h_L/d_H

The above results (effect of weir load and gas velocity on point efficiency) are in good agreement with Bennett et al. (2000).

Bennett et al. (2000) reported that the denominator of the term within the major bracket is the correction required when liquid phase resistance is important. No significant effect of changing the diffusivities of CO_2 and NH_3. This gives good evidence that the liquid phase resistance is not important.

Predicted Murphree tray efficiency (E_{MV})

The prediction of Murphree tray efficiency is done by using recently equation of Lopez and Castells (1999). This equation predicts the ratio of Murphree tray efficiency over point efficiency as function of Peclet's number (*Pe*). *Pe* for experimental data are calculated and ranged between 0.07 to 1.5.

Referring to equation (4); namely:

$$Pe = \frac{Q_L Z_o^2}{A_a h_L De} \qquad (4)$$

It is apparent that h_L and *De* must be evaluated in order to establish the value of *Pe*. Clear liquid height was used in equation 2.13 was determined experimentally for three weirs height (3, 4, and 5 cm), while the *De* correlation given by Bennett et al. (1997), being most recent in the literature was used in this study. Accordingly *De* values shown in appendix were obtained.

According to Lopez and Castells (1999) equation E_{MV} is equal to *Ep* obtained from the experimental data as shown in Figure (8).

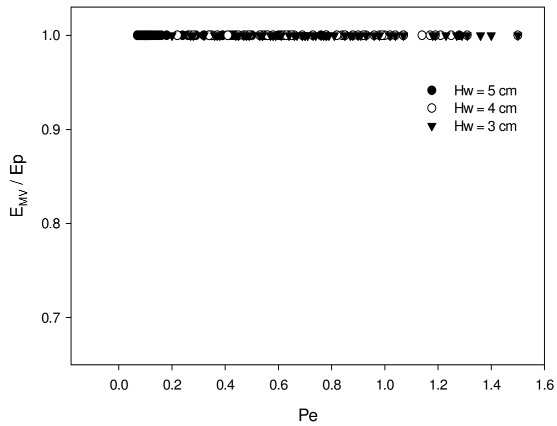


Fig. (8)., Murphree tray efficiency per point Efficiency versus Peclet number

CONCLUSIONS

The following conclusions can be drawn from the results obtained:

1. Maximum calculated value of point efficiency for 5 cm weir height is 90 % for liquid flow rate ranging between 5.8 to 7.32 m^3/s and clear liquid height between 3.5 to 4 cm.
2. Point efficiency values are in the same range for different weir height, but it improves slightly with weir height and the average values of point efficiency are 83 % for 3 cm weir height, 85 % for 4 cm weir height and 89 % for 5 cm weir height.
3. At large values of Reynolds number for gas phase, the point efficiency increases with h_L/d_H in the range 2 to 10 to about 90 %.
4. Evaluation of liquid Peclet number by equation of Lopez and Castells (1999), shows that *Pe* ranged between 0.07 to 1.5.
5. Prediction of Murphree efficiency by using Lopez and Castells (1999) equation shows that the ratio of E_{MV}/Ep is equal to 1 for all experimental data due to low value of liquid Peclet number.

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NOMENCLATURE

Symbol	Description	Units
A_a	Active area	m^2
A_h	Hole area	m^2
C'	Constant defined by equation 11	
d_H	Hole diameter	m
De	Eddy diffusivity for liquid mixing	m^2/s
D_L	Liquid molecular diffusivity	m^2/s
D_V	Vapor molecular diffusivity	m^2/s
E_{MV}	Murphree gas-phase tray efficiency	-
E or E_p	Point efficiency	-
E_o	Overall column efficiency	-
F	F factor $=V_{gh}\sqrt{\rho_g}$	m/s
Fr_G	Gas Froude number defined in equation 14	-
g	Gravity acceleration	m/s^2
$h_{2\Phi}$	Two-phase layer height on the tray (sum of liquid continuous region + gas continuous region)	m
h_{Fe}	Effective froth height	m
h_L	Clear liquid height in the two phase layer on the tray	m
h_w	Outlet weir height	m
K_S	Density corrected superficial gas velocity over active area ($=V_{ga}[\rho_g/($	m/s

	$\rho_L - \rho_g)^{1/2}]$)	
L_w	Weir length	m
m	Slope of equilibrium line	
Pe	Liquid Peclet number	-
Q_g	Volumetric gas flow rate	m^3/s
Q_L	Volumetric liquid flow rate	m^3/s
Re	Reynolds number	-
V_{ej}	Gas velocity defined by equation 15	m/s
y	Gas concentration (mole fraction)	
y^*_n	Mole fraction that would be in the equilibrium with liquid leaving the tray	
$\bar{y}_n$	Average mole fraction in the vapor leaving the tray	
$\bar{y}_{n+1}$	Average mole fraction in the vapor entering the tray	
Z_o	Liquid flow path length	m

Greek Letters

η	Defined by equation 6
Φ_e	Effective relative froth density as defined in equation 10

Subscripts

0	Evaluate at z = 0
1	Evaluate at z = 1
g	Gas
h	Hole
hor	Horizontal
L	Liquid
w	Weir

Superscripts

—	Mean value
*	Equilibrium value if used with x or y