The Effect of Open Area on Sieve Tray Performance

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ABSTRACT

The studies described in this paper were made to understand the effect of open area on sieve tray mass transfer and hydraulic performance. Tests were conducted in the 1.22 m diameter column of Fractionation Research, Inc. (FRI) experimental distillation unit. The sieve trays were tested over a wide range of open areas from 5 to 20 percent. Three different hydrocarbon systems, cyclo-hexane/n-heptane, iso-butane/n-butane, and o/p-xylene, were used at pressures of 20 mm Hg to 11.38 bar. Experimental results, including tray capacity, efficiency, pressure drop and entrainment, are presented and discussed. The performance of sieve trays with different open area was determined and compared. Explanations of the test results are given based on the fundamental analysis.

Key Words: Distillation, open area, sieve tray, efficiency, capacity, pressure drop, entrainment

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INTRODUCTION

Sieve trays are perforated trays with downcomers, and have been widely used in petrochemical industries for many years. Properly designed sieve trays have capacity and efficiency equivalent to other type of trays. They can be used in either clean or services with moderate fouling tendencies. Due to the low cost of the sieve tray and ease of maintenance, they replaced the expensive bubble cap trays in petroleum industries. Sieve trays in turn have been replaced by valve trays that have much higher turndown ratio. The market share of sieve trays is about 25% of the trayed columns (1), but it is in continuous decline due to advances in proprietary and valve trays. The early sieve tray designs had hole diameters of 2-4 mm(2), causing the perforation plugging in dirty services. Larger hole diameter trays, typically 10-25 mm, are more common in the industry. Since the design of a sieve tray is non-proprietary, it is an excellent basis of comparison with vendor suggested design of proprietary trays or valve trays.

The literature contains a large amount of experimental data for various type of trays used in distillation columns. Most of these data are obtained from simulator or small columns using air-water system at atmospheric pressure. Using such data to develop correlations and models for sieve tray designs, may result in unexpected results when are used in commercial columns with systems other than air-water and pressures other than atmospheric pressure.

This paper intends to present experimental data measured in a commercial size column using a range of systems and pressures. The purpose of this work is not to compare the experimental data to those predicted by the current correlations available in the open literature. It is hoped that having accurate experimental data from a commercial scale unit, would enable the developers to improve the existing models for the sieve tray designs. **Figure 1** is a photograph of a typical sieve tray tested by FRI.

EXPERIMENTAL EQUIPMENT

Plant Description

Figure 2 shows the FRI experimental unit that consists of two commercial size distillation columns and their support systems. For most operation modes only one column is used. The 1.22 m inside diameter high-pressure column is 8.4 m tall from bottom head seam to the top flange and rated for pressures up to 37 bar. The low- pressure column is rated from deep vacuum to 11.4 bar and consists of two sections. The lower section is essentially identical to the high-pressure column but is topped with a 3.66 m tall transition zone. The upper section has a 2.44 m inside diameter and is 6.7 m tall. Each column has a flanged head and clean inner wall design, which allows installation of hardware at any location in the column. Sight windows are strategically located to provide visual observation points inside the column. Couplings are available every 152 mm along the shell, which permits temperatures and pressures to be measured and samples to be withdrawn. The description of the FRI experimental unit, the procedure for obtaining and analyzing these data have been detailed previously(3)(4)(5). The low-pressure column was used for this study.

Tray Design

Figure 3 is a schematic drawing of the test tray, with 13% nominal size downcomer and 14% hole area, as was installed in the column. Two sets of trays with straight segmental downcomers were used for these tests, one set with 5% and the second with 13% nominal downcomer size. The 5% downcomer size was used for high vacuum system for o/p-xylene at 20 mmHg, while the second set of trays were used for isobutene/n-butane (iC_4-nC_4) system at 11.38 bar and cyclohexane/n-heptane (C_6-C_7) system at 0.276, 0.35 and 1.65 bar.

The trays with 5% downcomer had a bubbling area of 90% of the column area. The percent nominal hole areas were, 11%, 14%, and 20% of the bubbling area. The hole diameter was 12.7 mm on equilateral triangular centers. The downcomer was a segmental type with a sealed area of nominal 5%. The outlet weir length of 762 mm and outlet weir heights of 0, 50.8, and 101.6 mm were used. The sharp side of holes was facing the vapor in this set of the trays. The detail dimensions of this set of tray are shown in **Table I.**

Table II displays the detail dimensions of the set of trays with 13% nominal downcomer size. The bubbling area for this set of trays was 74% of the column area, with percent nominal hole areas of 5%, 8%, 14%, and 20% of bubbling area. As the first set of trays, the hole diameter was 12.7 mm on equilateral triangular centers. The outlet weir length was 940 mm with heights of 0, 25.4, 50.8, and 152.4 mm. In contrast to the first set, there were few runs with the smooth side of the holes were facing the vapor flow.

Four to ten trays with tray spacing of 610 or 915 mm were used in these experiments. For entrainment studies, the top tray was employed as an entrainment collection tray. The entrainment collection tray was similar to the other trays, except there was no downcomer or incoming liquid flow. Liquid from the entrainment collection tray was recycled to the reflux accumulator by gravity flow after it was metered. To measure mass transfer efficiency and the internal conditions, liquid samples were withdrawn from bottom of each downcomer as the outlet sample of the tray attached to the downcomer.

TEST MIXTURES AND TEST PROCEDURES

Systems

The results for three different test systems are discussed in this paper. The pressure range was from high vacuum with o/p-xylene system at approximately 20 mm Hg absolute to high pressure iC_4-nC_4 at 11.38 bar pressure. The third system used in these tests is cyclohexane/n-heptane (C_6-C_7) at 0.276, 0.35 and 1.65 bar. The average approximate physical properties for the systems tested at the indicated pressures are given in **Table III**, which is based on the FRI physical properties database.

Capacity

Except for the high vacuum runs, the capacity runs were made at total reflux and several constant liquid rate loads. The maximum attainable rates under stable conditions, defined as incipient flood by FRI, were determined for sieve trays by procedure previously described(3).

Efficiency

All efficiency studies were conducted using the total reflux mode of operation. To calculate the efficiency, liquid samples were withdrawn from the bottom of each downcomer. The analyzed liquid samples were the liquid composition at the outlet of the tray connected to the downcomer. The compositions were obtained using vapor phase chromatography for o/p-xylene and iC_4-nC_4 mixtures, and by refractive index for the C_6-C_7 mixture. The analysis were within

1% band width accuracy. The composition profiles for the trays were plotted in terms of log[x/(1-x)] versus the tray location. The overall tray efficiencies were calculated, after dropping the outlier points and smoothing the profiles. The Fenske-Underwood$^{(6)}$equation was used to obtain the total reflux efficiency from

$$N_t = \frac{\log\left[\frac{x_T(1-x_B)}{x_B(1-x_T)}\right]}{\log\alpha}$$

And

$$E_o = N_t / N_a$$

Pressure Drop

Total reflux pressure drop were measured for single trays, as well as multiple trays in sections of the column. The sections included all the trays, top half, and the bottom half. The reported pressure drops, are measurements averaged per tray basis.

Entrainment

The entrainment rates were measured at total reflux and several constant liquid rates. The following standard procedure was followed to obtain the constant liquid load entrainment measurement:

1. For the specified liquid load, the vapor rate was increased incrementally till a high entrainment rate was observed.
2. The conditions in the column were held steady until equilibrium was reached, after which all the measurements and flow rates were recorded.
3. The procedure was repeated by decreasing the vapor rate in stepwise manner, obtaining the entrainment for each vapor rate with a fixed liquid load.

The intervals were selected in such a way to obtain three to five entrainment rates for a specified liquid load.

RESULTS FOR 5% DOWNCOMER

Efficiency

The effect of percent hole area on overall tray efficiency, for o/p-xylene at approximate 20 mm Hg absolute pressure, is shown in **Figure 4**. The 20 percent hole area shows a lower overall tray efficiency than the 11 and 14 percent hole area tray tested by FRI.

Pressure Drop

Figure 5 shows the effect of percent hole area on total reflux pressure drop of o/p-xylene at 20 mm Hg. At a specified capacity factor, the 11% hole area has the highest pressure drop per tray, while the 14% and 20% hole area tray have a successively lower pressure drop at corresponding capacity factors, Cs.

Entrainment

The percent hole area effect on the entrainment for 12.7 mm hole diameter, 14% and 20% hole area, at approximately 20 mm Hg absolute pressure for o/p-xylene system is shown in **Figure 6.** The entrainment data were obtained at constant liquid loads of 18 and 25 m^3/h/m of the outlet weir length. It should be noted the 14% hole area entrainment rates were obtained with a weir height of 102 mm. It can be seen that the effect of liquid load for a given percent hole area is minimal, while there is an apparent effect of percent hole area on entrainment. The effect may be attributed to the percent hole area difference, because no weir height effect on entrainment was observed comparing 0 mm weir height data to those of 102 mm weir height.

RESULTS FOR 13% DOWNCOMER

Capacity

The effect of percent hole area on capacity of iC_4-nC_4 system at 11.38 bar for a sieve tray with 12.7 mm hole diameter and 38.1 mm downcomer clearance height for the 5% and 8%, and 108 mm for the 14% and 20% hole area sieve tray is shown in **Figure 7**. There was no outlet weir for the 20% hole area tray, while the other three tray designs had a 51 mm outlet weir height. There are two mechanism of flooding that can be attributed to the flooding of high pressure systems. The first is associated with the vapor handling limitations of the tray panel, and is called jet flooding; and the second is due to the liquid handling capacity of the downcomer, and is known as the downcomer flood. The solid symbols in **Figure 7** indicate the total reflux floods. At liquid loads below the total reflux flood, the capacity is limited by the panel design; while with high liquid loads, capacity of this system is downcomer size limited. The difference in flooding capacity of total reflux runs and the runs with $L/V < 1$ is very small, indicating the low dependence of the capacity on percent hole area for 8%, 14%, and 20% hole area trays. The 5% hole area tray had much lower capacity of the other three trays, which is indication of the effect of high pressure drop contribution to the downcomer flood. The slight increase in capacity of the 20% hole area tray may be associated to the elimination of the outlet weir, resulting in a lower liquid height on the tray, allowing higher vapor handling capacity.

Figures 8 and **9**, display the effect of the percent hole area on the flooding capacity of sieve tray with C_6-C_7 at 0.276 and 1.65 bar pressures respectively. In both figures the 5% hole area tray has substantially lower capacity than the 8% and 14% hole area trays. Both of these figures indicate that at low liquid rates, the capacity increases with percent hole area. At high liquid rates the effect of hole area diminishes, and basically in this region the measurements are within the experimental error band.

Efficiency

In **Figure 10**, the overall tray efficiencies of the four tray designs with iC_4-nC_4 at 11.38 bar are compared. The efficiency of the 8% sieve tray is consistently higher than that of 14%

sieve tray, which in turn is higher than that of 20% sieve tray. The efficiency of the 5% sieve tray up to a capacity factor of 0.022 m/s is higher than of the 8% hole area sieve tray, inline with the behavior of the other trays. However, the 5% sieve efficiencies drop to below that of the 8% sieve tray. This may be attributed to several factors including but not limited to the anomalies in data measurements, composition effects, or the high pressure drop of the 5% sieve tray.

Figures 11 and **12**, show the overall tray efficiencies for C_6-C_7 system at 0.276 and 1.65 bar respectively. The trend for the effect of hole area on efficiency is very similar to that of *i*C_4-nC_4 at 11.38 bar. Due to excessive weeping, there was no efficiency measurements for C_6-C_7 system at 0.276 bar below 50% of total reflux flood. There was no test of C_6-C_7 system at deep vacuum with the 20% hole area sieve.

Pressure Drop

The effect of hole area on total reflux pressure drop measurements are shown in **Figure 13** for *i*C_4-nC_4 system at 11.38 bar, C_6-C_7 system at 0.276 bar in **Figure 14** and for 1.65 bar in **Figure 15**. All these figures indicate, the tray with lowest hole area has the highest pressure drop; the hole area effect diminishes when the hole area is increased from 14% to 20%. The effect is more pronounced when the 5% hole is compared to the other three trays with higher hole area.

Entrainment

The entrainment studies for each system included the entrainment measurement for each system at several constant liquid loads. There are not sufficient reliable entrainment measurements, at different hole open areas, for *i*C_4-nC_4 system at 11.38 bar to make concrete conclusion for the effect of hole area on entrainment for high-pressure systems. Only 8% and 14% hole area sieve trays with C_6-C_7 system at 0.35 and 1.65 bar have enough data points to show the effect of hole area on entrainment. To get a clear picture of the effect of hole area on entrainment(7), one must study the effect of liquid rate, vapor rate, and system properties on entrainment.

Effect of Liquid Load on Entrainment

There are conflicting views on the effect of liquid load on entrainment in the literature. Various researchers have found that increasing the liquid load either increases entrainment(8, 9) , decreases entrainment(10), or both(11, 12). **Figures 16** and **17** are the liquid load effect on entrainment for C_6-C_7 system at 0.35 bar for 8% and 14% hole area respectively. **Figures 18** and **19**, are graphs for the same system at 1.65 bar. These graphs along with other systems tested by FRI, shown for several entrainment levels, dramatically display the complex nature of the liquid load effect on entrainment. These figures indicate that, depending on the magnitude of the liquid load, all the reported conclusions for the effect of liquid load on entrainment in the literature may be correct. One may stipulate that at very low liquid rates, due to low liquid level on the tray, there is a very low resistance to the vapor flow that results in high entrainment rate. As the liquid load increases, the liquid level on the tray increases, resulting in high resistance to the vapor flow and consequent reduction in the amount of vapor energy for creating entrained liquid droplet reducing the entrainment rate. Further increases in liquid load continue to decrease the entrainment rate, while increasing the liquid height on the tray. As the liquid height on the tray increases, the distance that the drop needs to travel to reach the tray above decreases. There is a balancing point, where further increase in the liquid rate causes an increase in the entrainment rate.

Effect of Vapor Rate on Entrainment

A typical set of measured entrainment rates as a function of vapor rate and several constant liquid loads is shown for 8% hole area sieve with C_6-C_7 system at 1.65 bar in **Figure 20**, and for C_6-C_7 system at 0.35 bar with a 14% hole area sieve in **Figure 21**. These figures indicate the strong dependence of entrainment on the vapor rate. At some conditions, a ten percent change in vapor rate may result in a ten-fold change in entrainment. This has made the prediction of entrainment with any degree of accuracy very difficult.

Effect of Hole Area on Entrainment

Figure 22 is a comparison of the entrainment rate for C_6-C_7 system at 0.35 bar with an 8% and a 14% hole area sieve tray. Both trays show similar behavior and trend; however, for constant entrainment level of 0.5 kg/(s.m) and up the liquid load of 5 L/(s.m), the 14% hole area tray requires about 10% more vapor rate to generate the same amount of entrainment as the 8% tray. This is an indication that the 14% hole area tray, at low liquid loads, generate less entrainment than the 8% tray. **Figure 23** is similar to **Figure 22**, and shows the effect of open hole area on entrainment rate of C_6-C_7 system at 1.65 bar, it can be seen the hole area effect on entrainment is more drastic at this pressure. Increasing the hole area from 8% to 14% has resulted in more reduction in the entrainment rate of the sieve tray that was observed at 0.35 bar pressure.

CONCLUSIONS

Performance characteristics of a sieve tray with 12.7 mm holes, hole areas ranging from 5% to 20%, two downcomer designs with a nominal size of 5% and 13% of the column area, with systems that cover a wide range of properties have been obtained in a large scale commercial installation. Although the results from these studies are not typical of all sieve tray designs, certain findings such as the effect of system properties, liquid loadings, and percent hole areas on capacity, efficiency, pressure drop, and entrainment can be important to hardware design and optimum operating conditions.

It was observed the efficiency of the 20% hole area tray was lower than the efficiency of 11% and 14% hole area trays for o/p-xylene at 20 mm Hg absolute pressure with the 5% downcomer size. The pressure drop and entrainment were lower for the higher hole area tray at comparable rates.

For the 13% nominal size downcomer trays, no difference in capacity was obtained on the butane system when the 8%, 14%, and 20% trays were compared; however, the 5% hole area tray had much smaller capacity than the other trays. Similar observation was made for C_6-C_7 system at 0.276 and 1.65 bar with 5%, 8%, and 14% hole area trays. The efficiency suffered slightly as the percent hole area increased. As for the 5% nominal size downcomer, the pressure drop and entrainment were lower for the higher hole area tray at comparable rates for trays with 13% nominal size downcomer.

The results from these controlled experimental tests of an industrial size column and trays are useful when compared to the existing design technology as well as the development of new sieve tray design methods.

Nomenclature

C_s = superficial capacity factor based on column cross-sectional area, (m/s)
E_o = overall tray efficiency
N_a = actual number of trays
N_t = theoretical number of trays
x = mole fraction of more volatile component in liquid phase
x_B = mole fraction of more volatile component in liquid phase at bottom of section of trays
x_T = mole fraction of more volatile component in liquid phase at top of section of trays

Greek Letters
α = relative volatility

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Table I. Tray Design Detail with 5% Downcomer

Column Diameter, mm	1213
Tray Spacing, mm	610, 915
Perforated Sheet, Material	316 SS
Perforated Sheet, Thickness, mm	1.59
Outlet Weir, Height x Length, mm x mm	25.4, 102 x 762
Edge of Hole Facing Vapor Flow	Sharp
Clearance under Downcomer, mm	19.1
Effective Bubbling Area, m^2	1.041
Nominal Downcomer Area, %	5
Hole Diameter and Spacing, mm x mm	12.7 x 33.3, 30.2, 25.4
Nominal Hole Area, % Bubbling Area	11, 14, 20
Hole Area, m^2	0.110, 0.135, 0.181

Table II. Tray Design Detail with 13% Downcomer

Column Diameter, mm	1213
Tray Spacing, mm	610
Perforated Sheet, Material	316 SS
Perforated Sheet, Thickness, mm	1.59
Outlet Weir, Height x Length, mm x mm	0, 25.4, 50.8, 152.4 x 940
Edge of Hole Facing Vapor Flow	Sharp, Smooth
Clearance under Downcomer, mm	22.2, 38.1, 50.8, 57.2, 108
Effective Bubbling Area, m^2	0.859
Nominal Downcomer Area, %	13
Hole Diameter and Spacing, mm x mm	12.7 x 50.8, 38.1, 30.2, 25.4
Nominal Hole Area, % Bubbling Area	5, 8, 14, 20
Hole Area, m^2	0.043, 0.072, 0.118, 0.167

Table III. Average Physical Properties of the Test Systems under Operating Conditions

System						
	Unit	Cyclohexane/n-Heptane			o/p-xylene	Isobutane/n-Butane
Pressure	bar	0.276	0.35	1.65		11.38
	mm Hg				16 - 20	
Vapor Density	kg/m^3	1.210	1.128	5.032	0.124	28.27
Liquid Density	kg/m^3	707.9	705.6	659.1	845.6	493.4
Liquid Viscosity	mPa/s	0.43	0.41	.25	.52	0.091
Surface Tension	mN/m	19.44	19.1	14.2	26.43	5.27
Relative Volatility		1.82	1.81	1.57	1.285	1.236

Figure 1. 14% Hole Area Commercial Sieve Tray

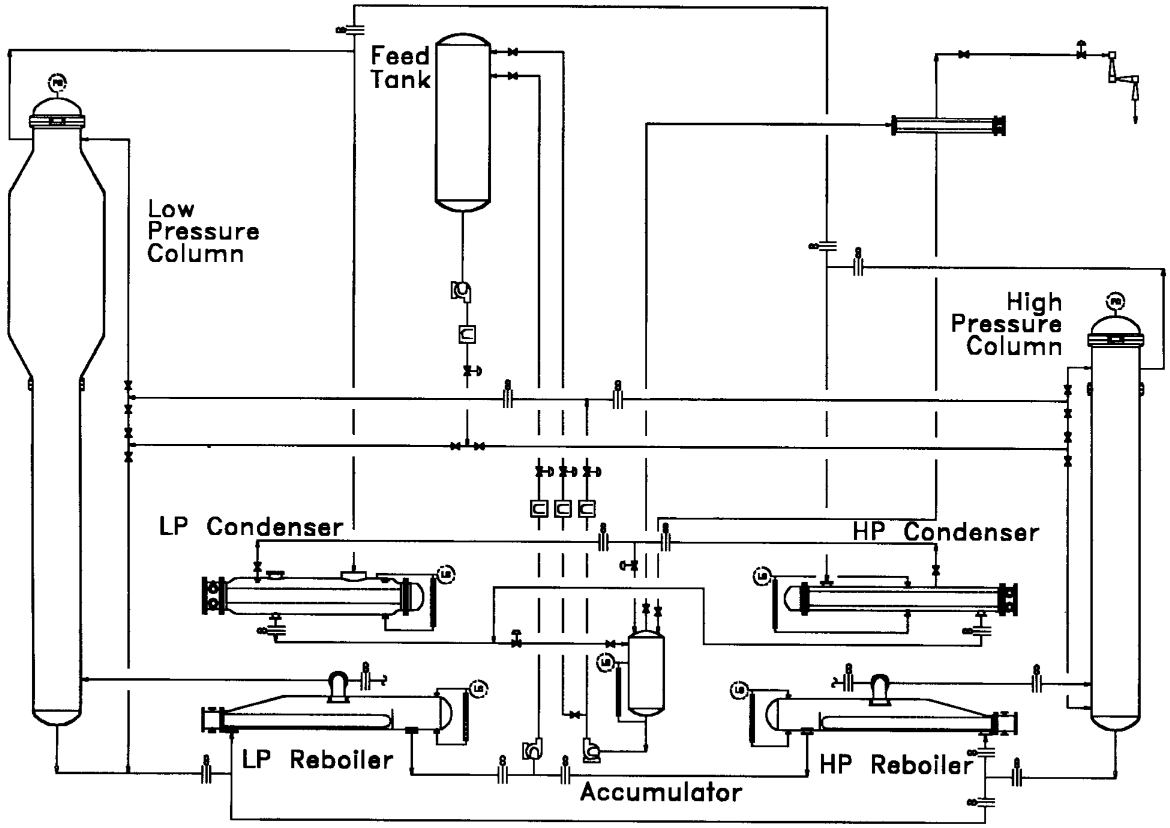

Figure 2. FRI Experimental Unit

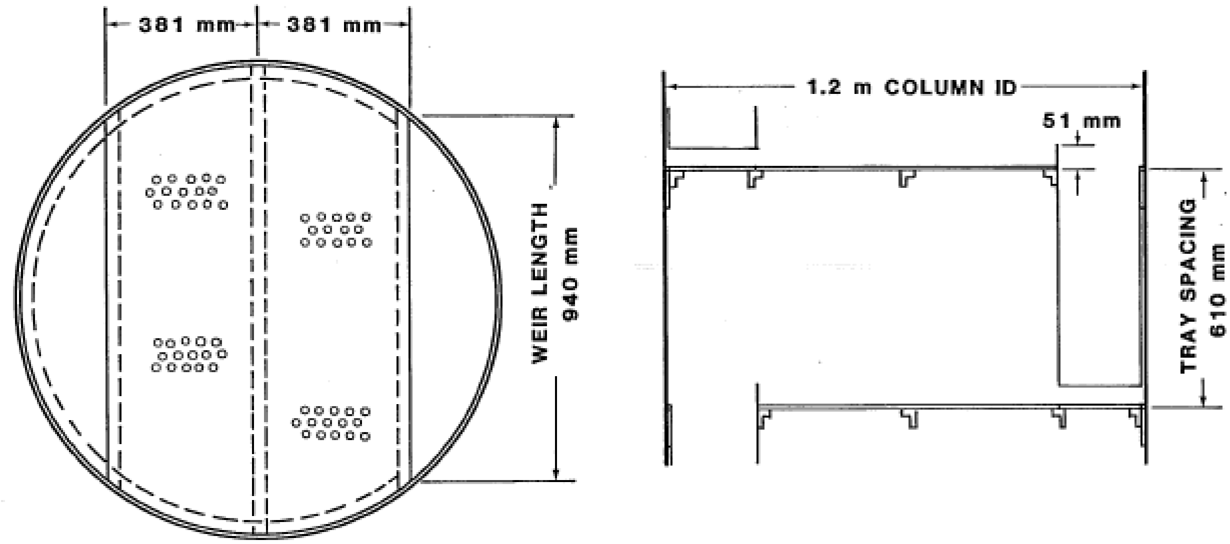

Figure 3. Diagram of Test tray with 13% Downcomer

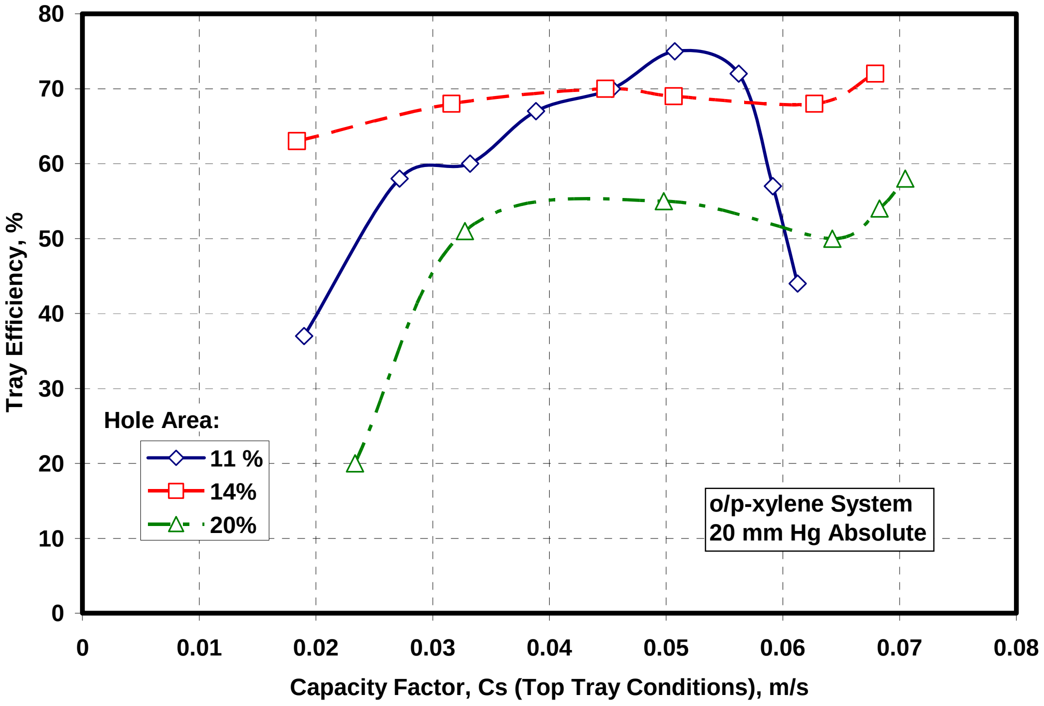

Figure 4. Effect of Hole Area on Efficiency for 5% Downcomer Tray

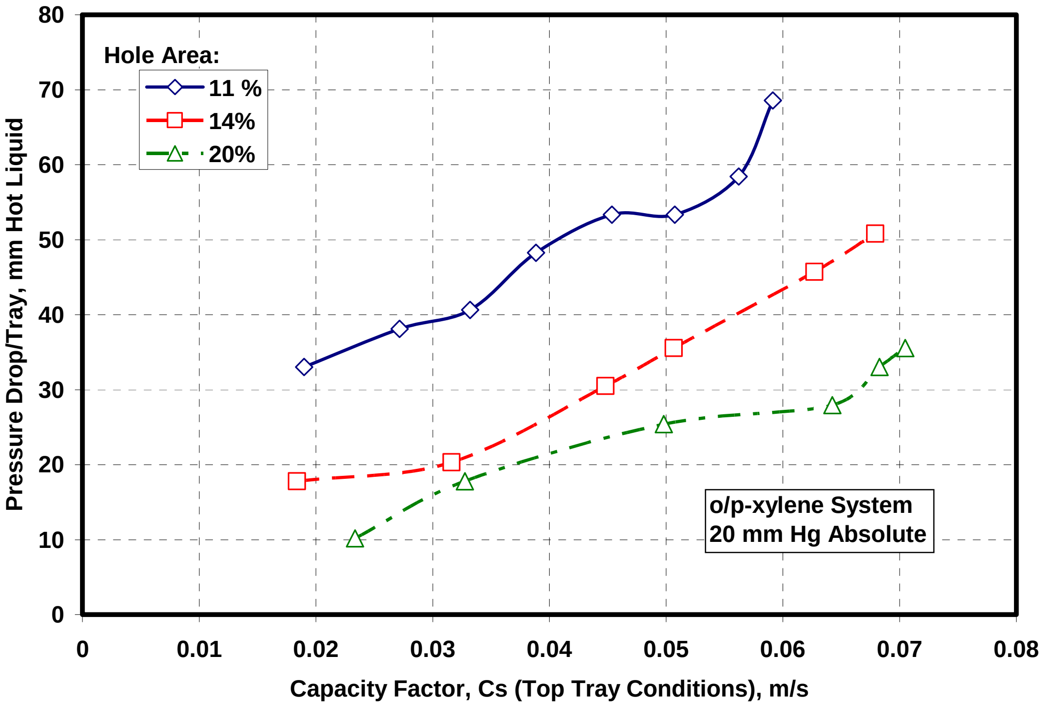

Figure 5. Effect of Hole Area on Pressure Drop for 5% Downcomer Tray

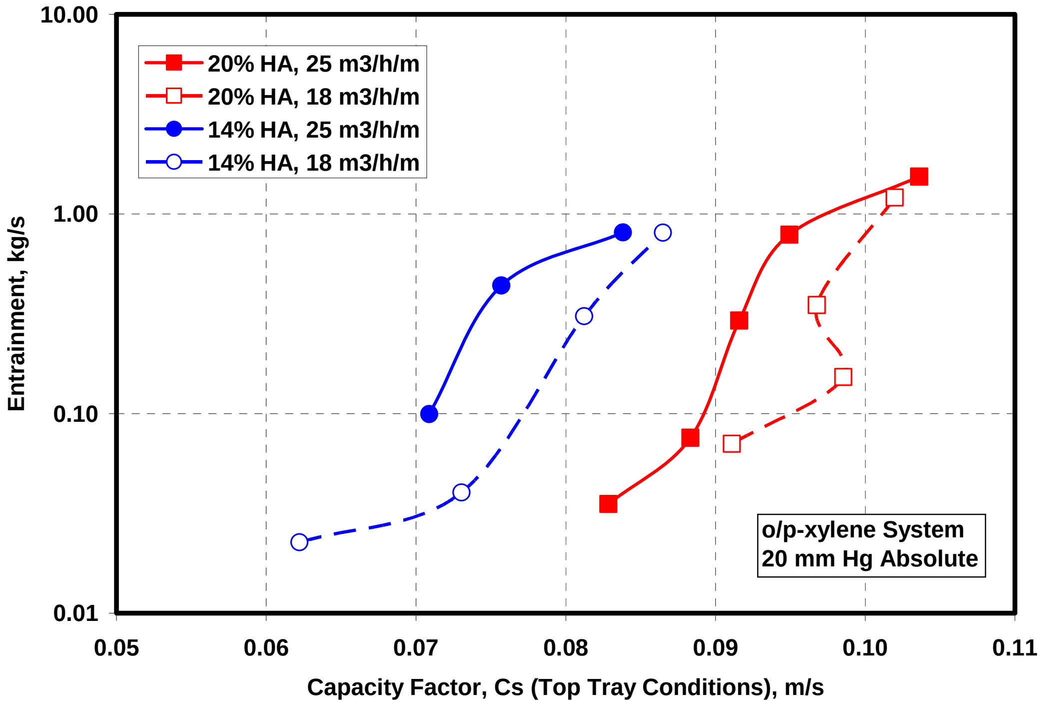

Figure 6. Hole Area Effect on Entrainment with 5% Downcomer

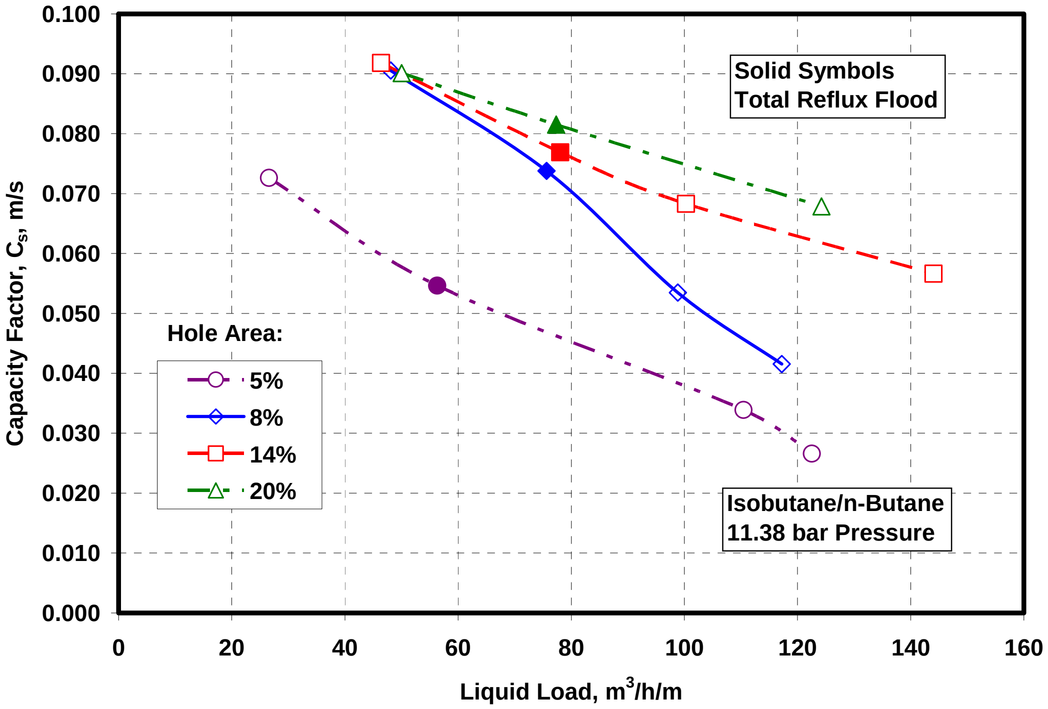

Figure 7. Hole Area Effect on Capacity of 13% Downcomer

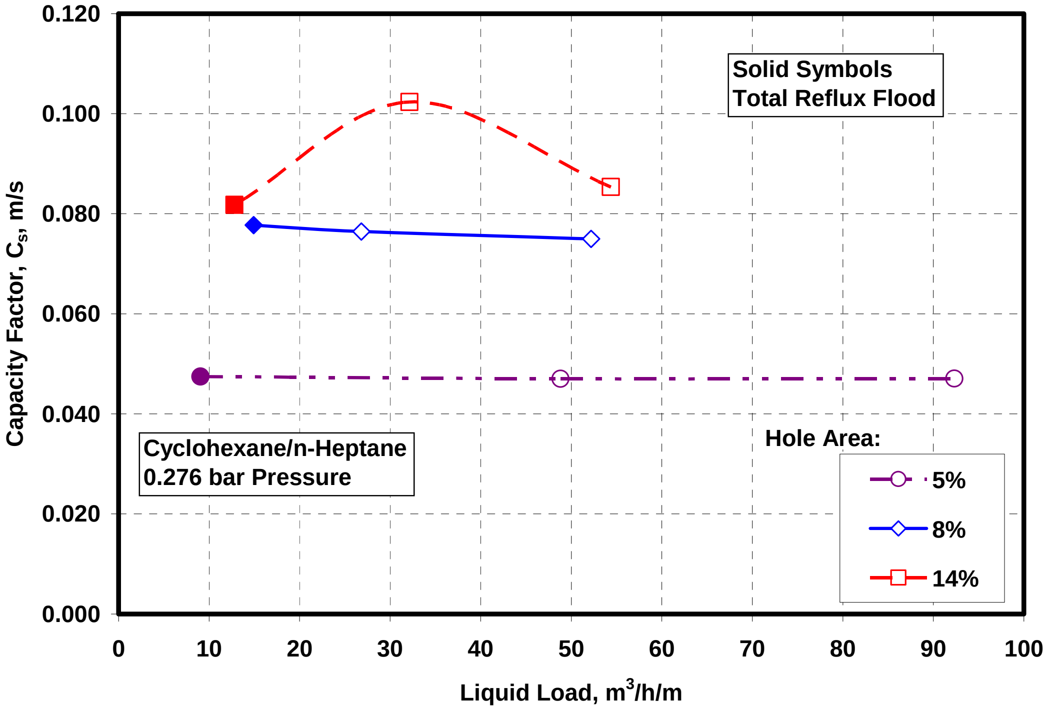

Figure 8. Hole Area Effect on Capacity with 13% Downcomer Tray

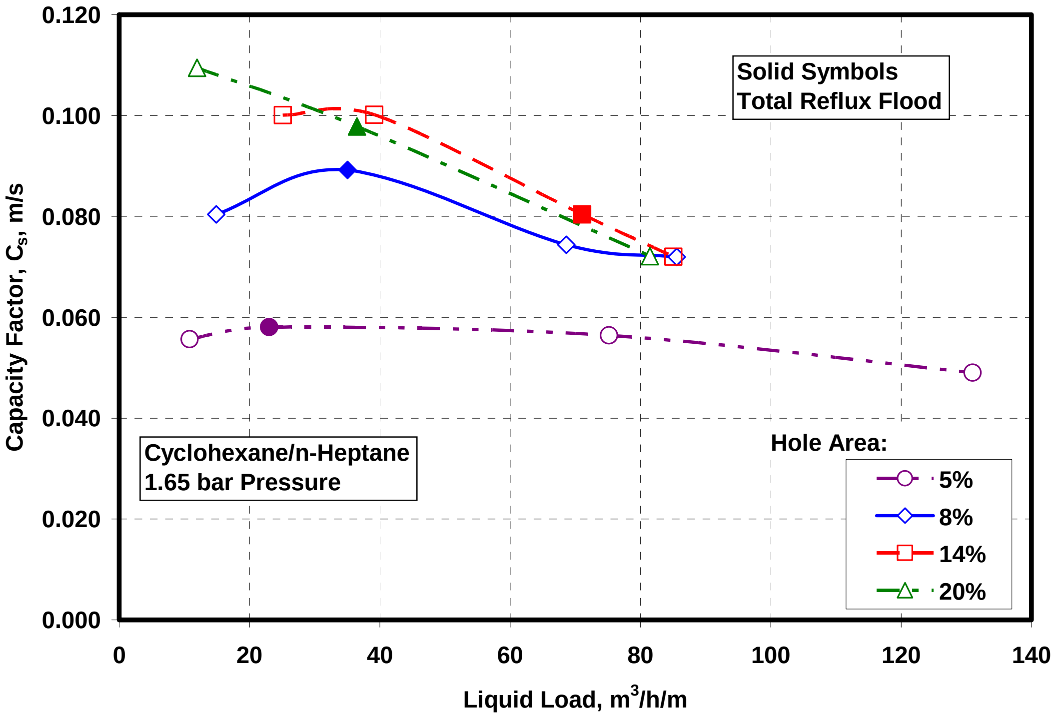

Figure 9. Hole Area Effect on Capacity with 13% Downcomer Tray

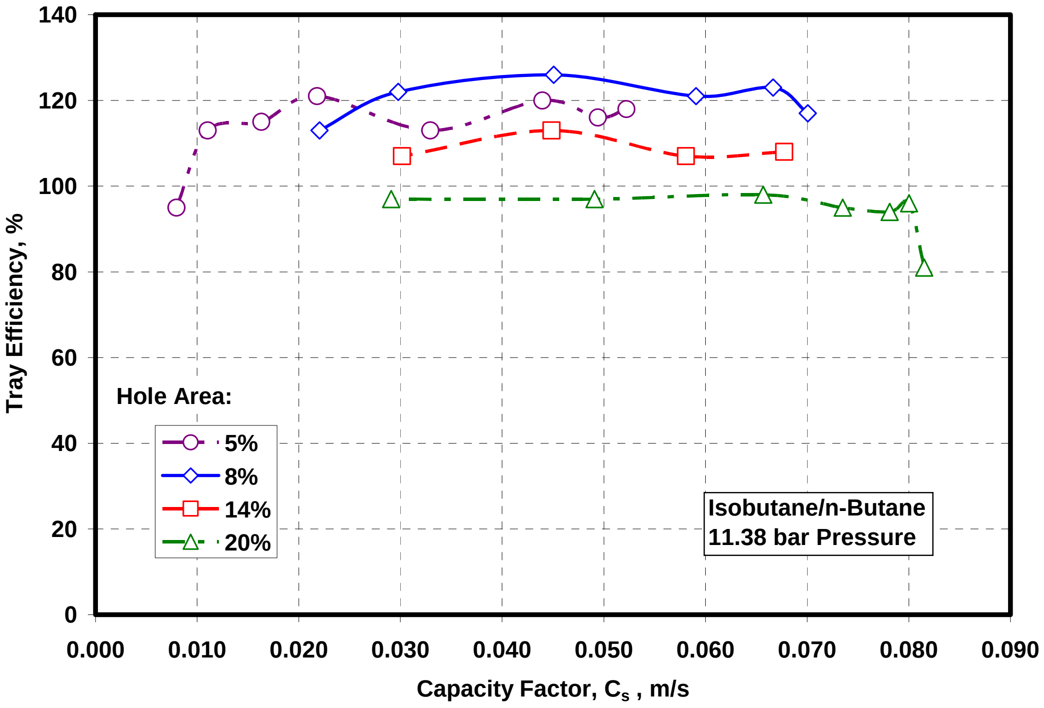

Figure 10. Effect of Hole Area on Efficiency for 13% Downcomer Tray

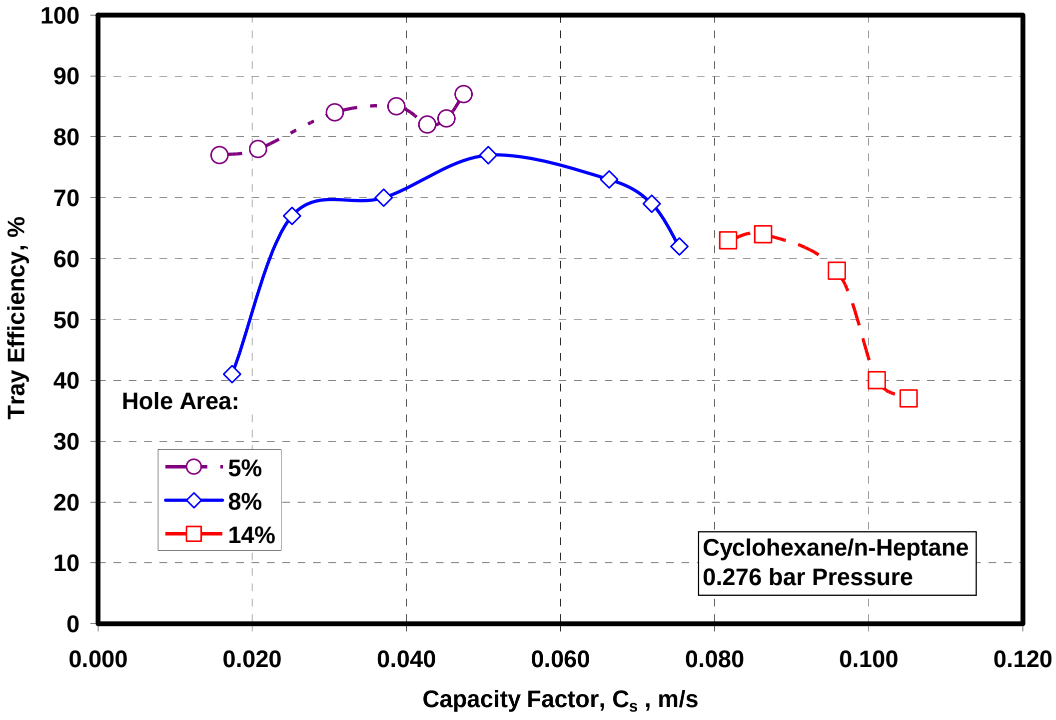

Figure 11. Effect of Hole Area on Efficiency for 13% Downcomer Tray

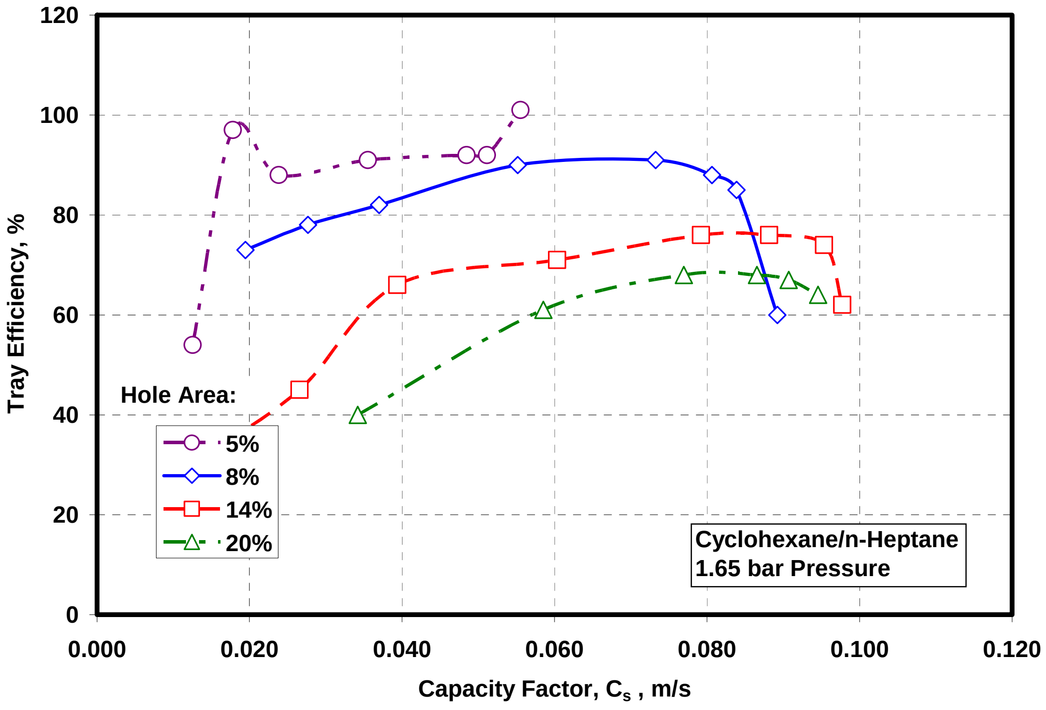

Figure 12. Effect of Hole Area on Efficiency for 13% Downcomer Tray

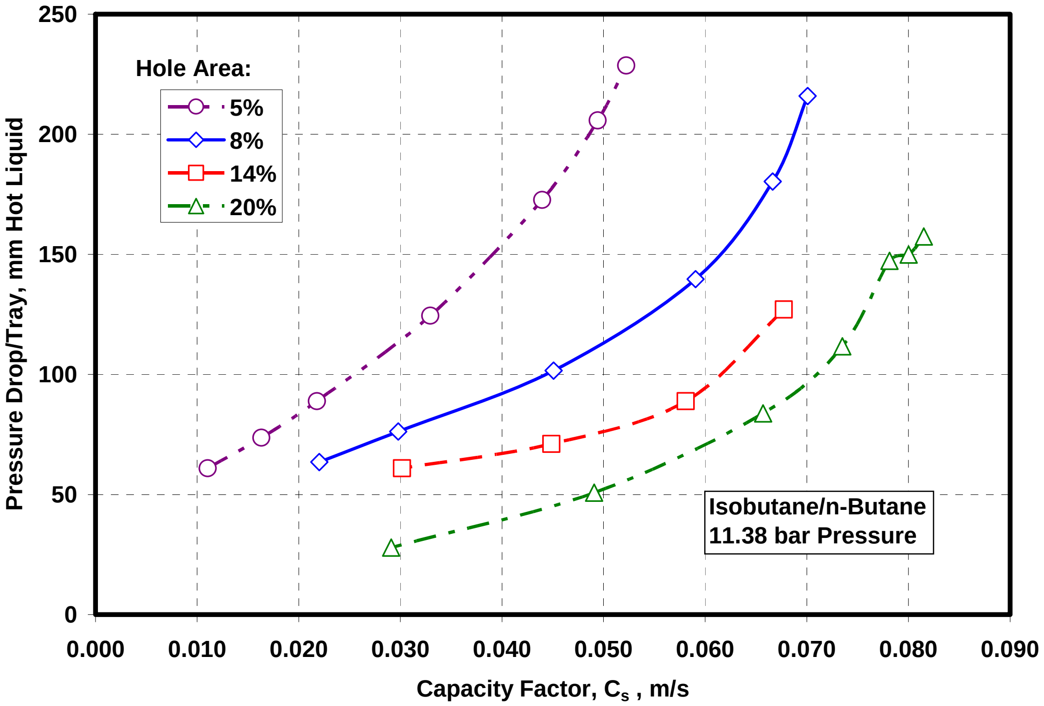

Figure 13. Effect of Hole Area on Total Reflux Pressure Drop for 13% Downcomer Tray

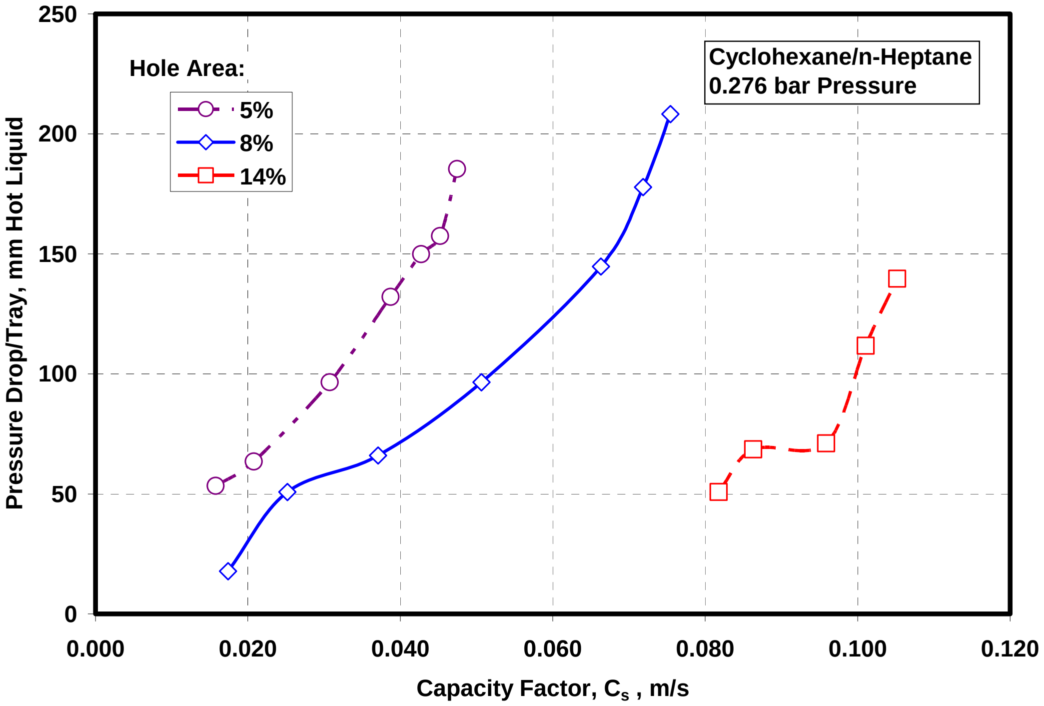

Figure 14. Effect of Hole Area on Total Reflux Pressure Drop for 13% Downcomer Tray

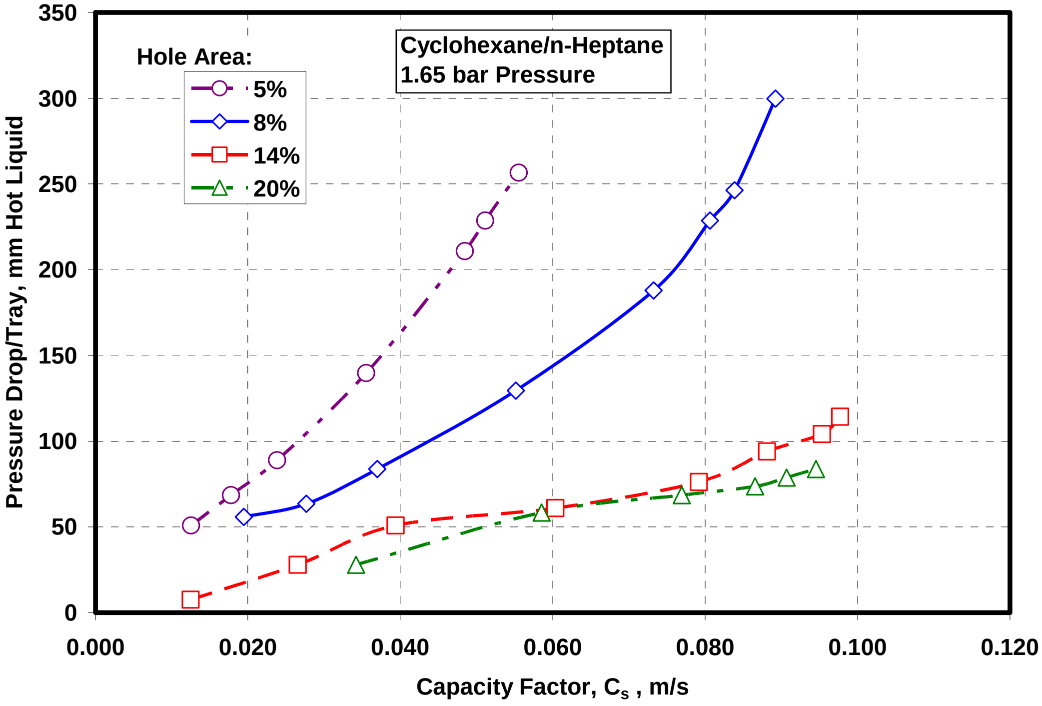

Figure 15. Effect of Hole Area on Total Reflux Pressure Drop for 13% Downcomer Tray

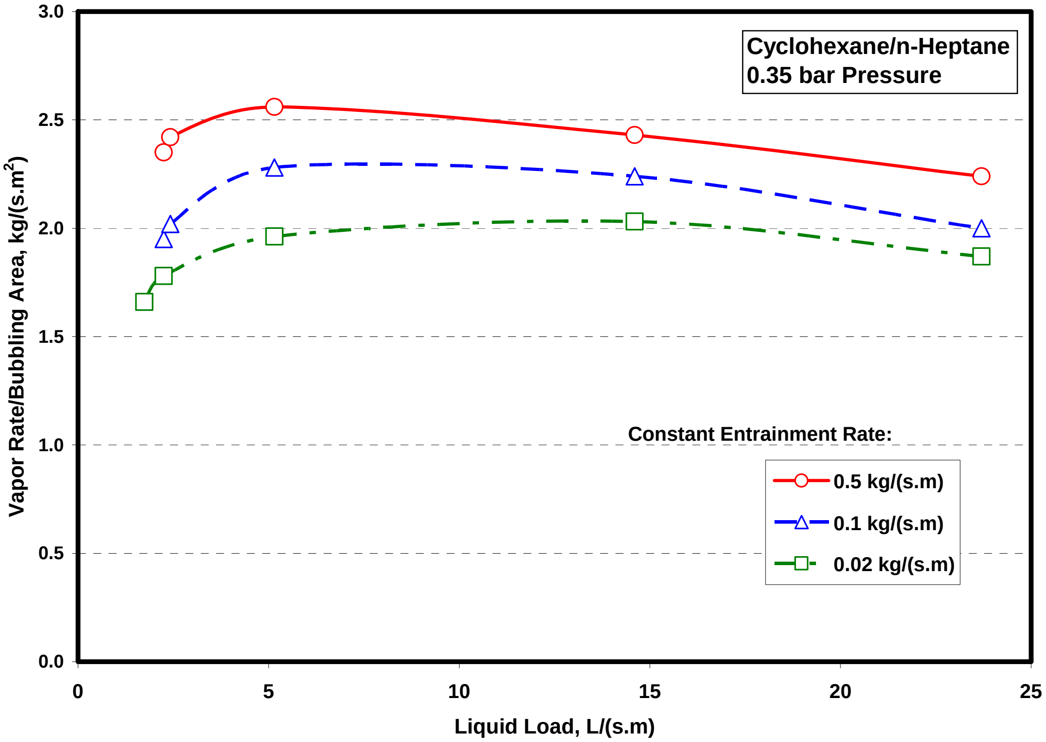

Figure 16. Liquid Load Effect on Entrainment of 8% Hole Area Sieve Tray

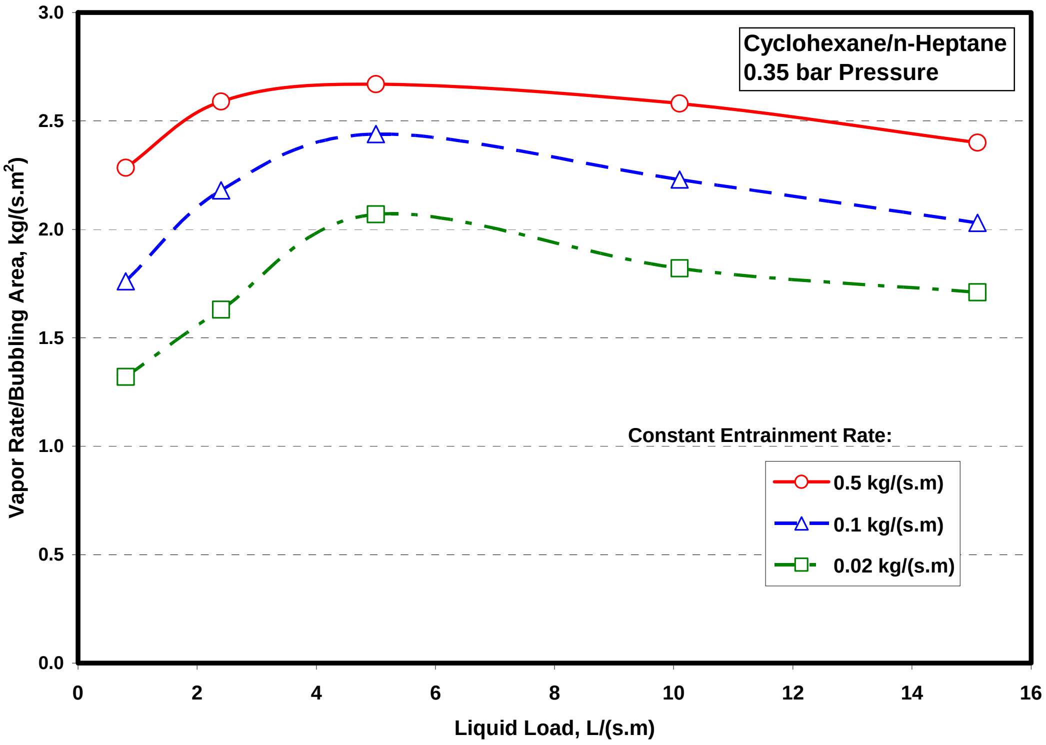

Figure 17. Liquid Load Effect on Entrainment of 14% Hole Area Sieve Tray

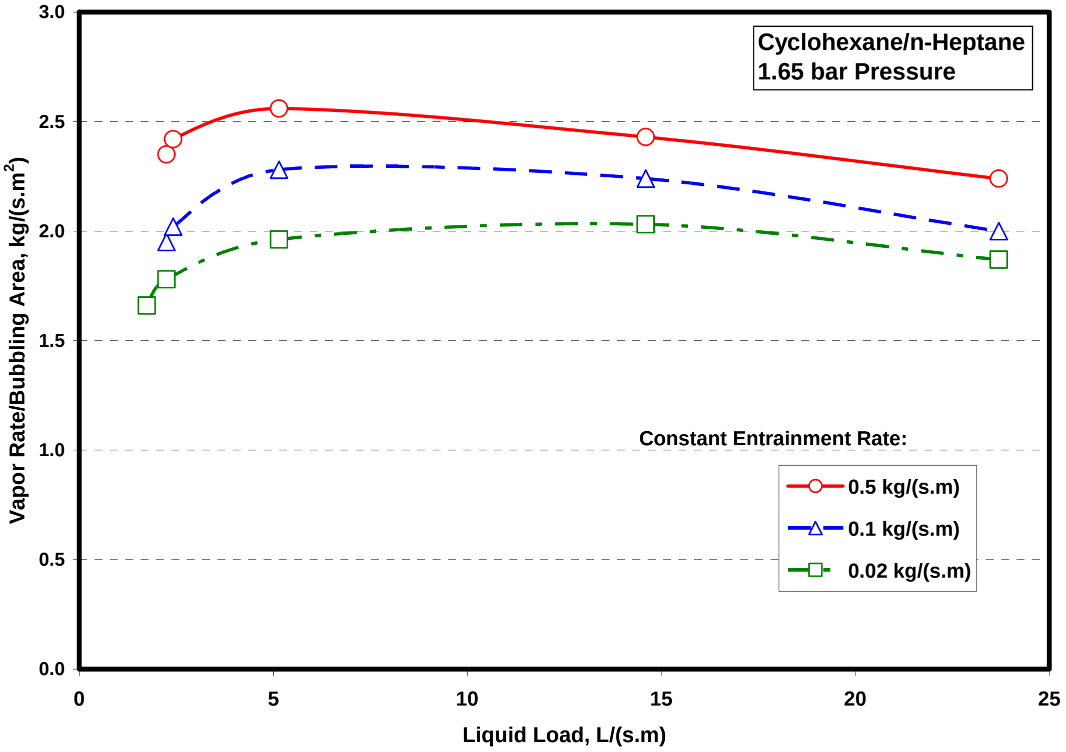

Figure 18. Liquid Load Effect on Entrainment of 8% Hole Area Sieve Tray

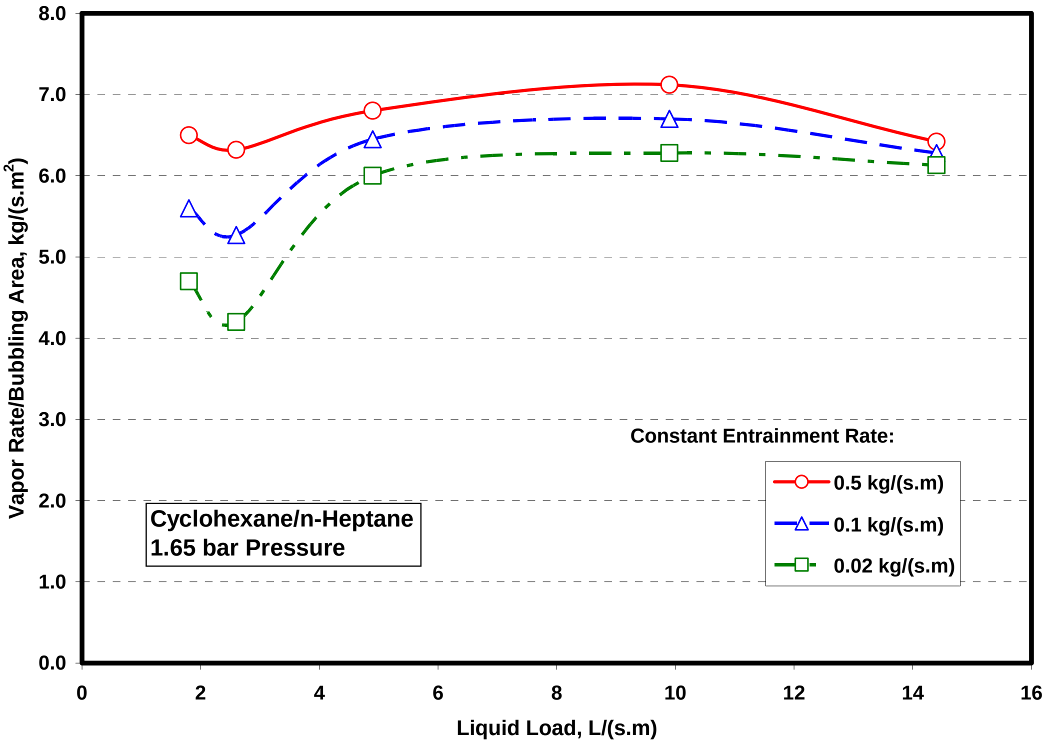

Figure 19. Liquid Load Effect on Entrainment of 14% Hole Area Sieve Tray

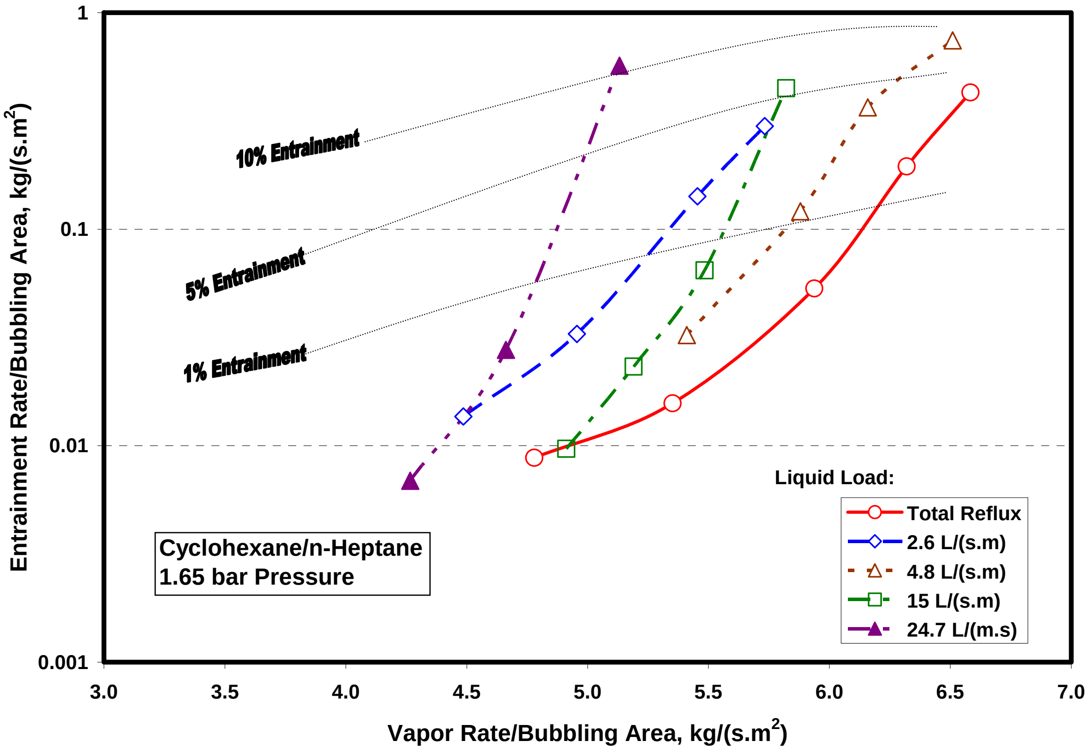

Figure 20. Vapor Rate Effect on Entrainment, 8% Hole Area Sieve Tray

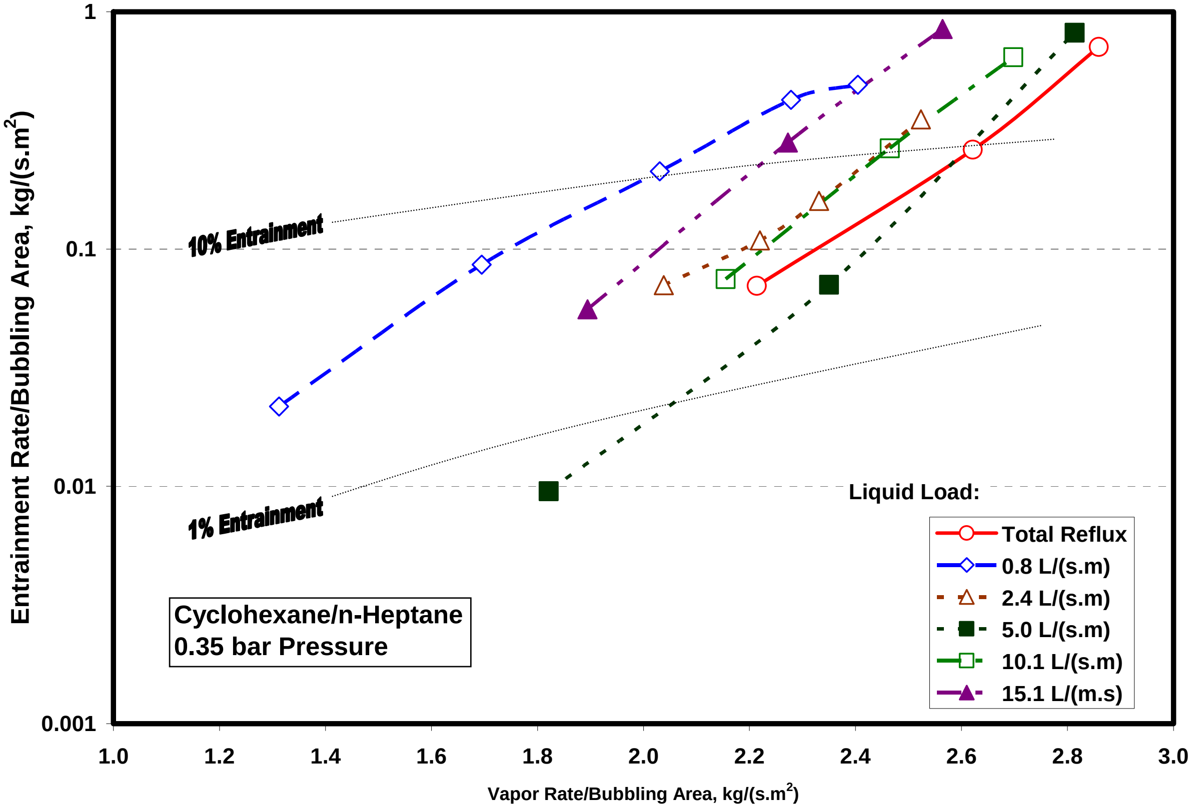

Figure 21. Vapor Rate Effect on Entrainment, 14% Hole Area Sieve Tray

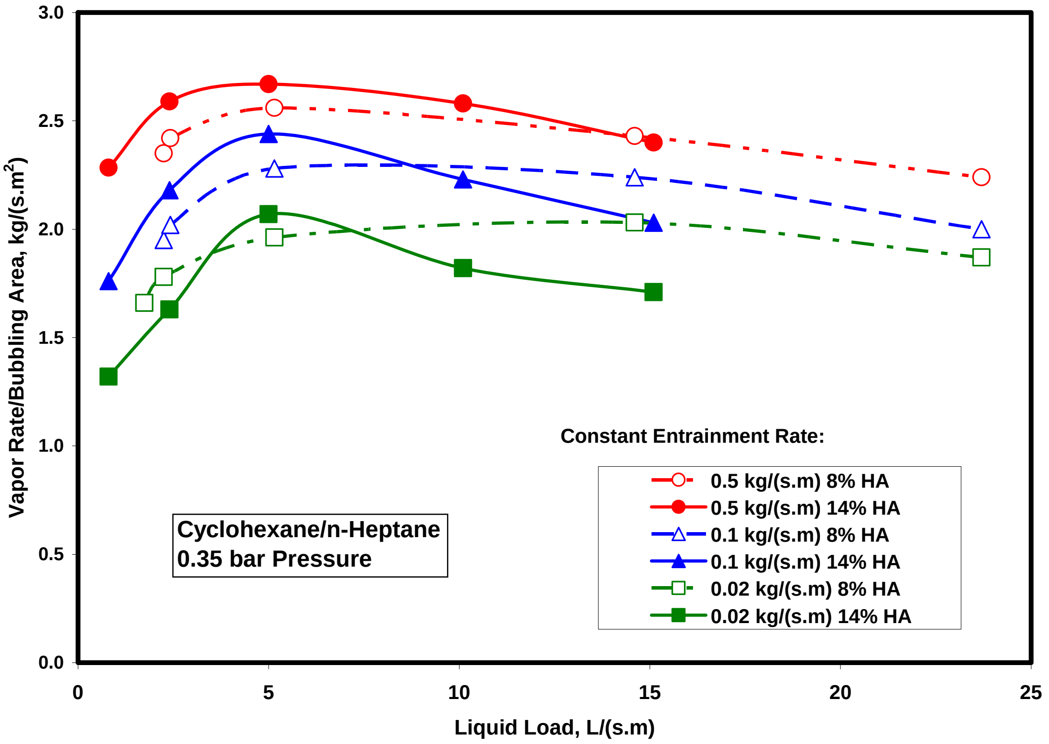

Figure 22. Effect of Hole Area on the Entrainment Characteristics

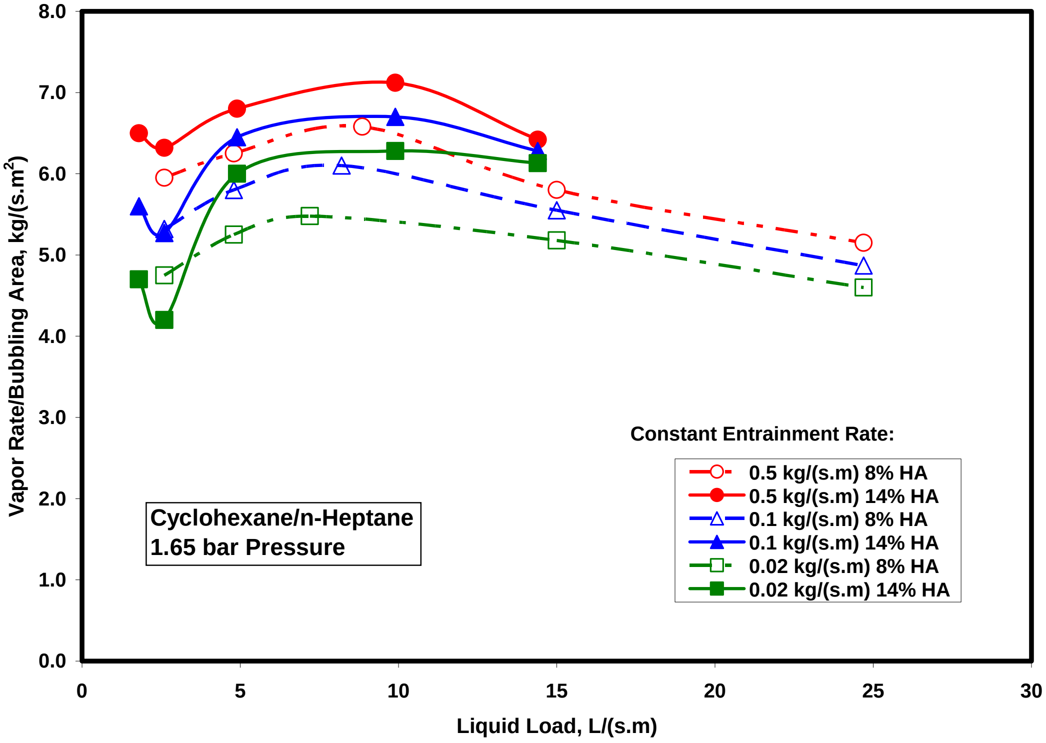

Figure 23. Effect of Hole Area on the Entrainment Characteristics