

# Downcomer Froth Density at High Pressures

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Prepared for Presentation at the  
AIChE 2002 Annual Meeting  
November 3-8, Indianapolis, Indiana  
Distillation Honors Session for M. J. Lockett  
Paper No. 101c

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November 2002  
Unpublished

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## ABSTRACT

Downcomer froth density is a key parameter in downcomer design and sizing. Experimental data for downcomer froth density at high pressures are rarely found in literature. This study experimentally determined the downcomer froth density for the isobutane/normal butane system at pressures from 115 to 500 psia in a 4-foot diameter high-pressure distillation column. Four different downcomers covering wide design variations from straight to sloped downcomers were used. These downcomers were constructed of transparent materials and positioned so that the two-phase flow action in the downcomer were observable from outside the windowed column. The downcomer froth density was determined from the measured downcomer liquid holdup and froth height. It was found that the average froth density measured is generally above 0.6, which is substantially higher than previously reported and common literature beliefs. A sufficient height of clarified liquid was seen in the bottom of the downcomer for most of the operating conditions. Based on the measured froth density and experimental observations, it can be concluded that the decrease in tray efficiency at high pressures is not caused by vapor entrainment through the downcomer.

## INTRODUCTION

When the difference in liquid and vapor density decreases as the operating pressure of distillation column increases, the driving forces for separation of two-phase mixtures in downcomers become very small. The resulting low separation capability of two-phase mixtures in downcomer may limit the column capacity due to downcomer flooding and reduce the mass transfer efficiency due to the vapor entrainment through the downcomer.

The purposes of the downcomer in a tray column are to separate the gas phase from the liquid phase and to deliver the liquid phase to the next tray below. Obviously, failure of the downcomer to achieve the latter purpose will not allow the column to operate at the required rate without flooding. Although failure of the downcomer to achieve the former purpose will in most cases allow the column to operate, the vapor entrained or recycled back through the downcomer may lower the apparent tray efficiency of the column. Recycled vapor also has other effects such as raising the tray pressure drop and increasing the tray spray height.

The phase separation processes taking place in an ideally operating downcomer may be divided into three general regions as shown in Case A of **Figure 1**. Each of the regions has a specific function in the overall separation process. The vapor disengagement zone occupies the uppermost portions of the downcomer. The actual separation of the vapor from the liquid phase takes place here. The vapor separates from the frothy mixture as it is falling from the tray to the downcomer. The second zone in the downcomer is the region of stabilized froth. This zone absorbs the impact energy of the frothy mixture when falling into the downcomer. The third zone in the downcomer is the clarified liquid zone. This region contains almost completely clarified

liquid except for a few vapor bubbles that occasionally enter due to turbulent effects. The clarified liquid zone serves essentially as a buffer zone above the downcomer exit lip.

A poorly designed downcomer may fail to satisfy either or both of its basic purposes for a variety of reasons. If the downcomer is too small, insufficient cross-sectional area at the top of the downcomer for a straight downcomer or at somewhere in the downcomer for a sloped downcomer may not provide sufficient area for vapor disengagement. This always leads to entrainment of vapor. Obviously, the clarified liquid zone will no longer exist as shown in Case B of **Figure 1**. In many cases the lack of vapor disengagement in the downcomer leaves the liquid in the downcomer in such a highly aerated state that the downcomer no longer has enough height to provide sufficient liquid head to overcome the flow resistances. This leads to overflow of the downcomer and flooding of the column.

If the downcomer is too big and the resistance to flow through the downcomer is too small, there may be insufficient liquid head in the downcomer so that the height of the clarified liquid zone goes essentially to zero as shown in Case C of **Figure 1**. The loss of the clarified liquid zone inevitably results in vapor being carried down through the downcomer.

The performance of downcomer is characterized by three main parameters, downcomer froth height, clear liquid height or downcomer backup, and downcomer froth liquid volume fraction or froth density. The froth density varies at different locations in downcomer. It usually has the highest value at the downcomer bottom and decreases towards the top of the two-phase mixture. Its mean value is defined as the ratio of downcomer clear liquid height to the downcomer froth height. Experimental values for the downcomer froth density under distillation conditions are rarely found in literature. Lockett (1986) documented a few data points from two sources. **Figure 2** shows the mean downcomer froth density as a function of the difference in liquid and vapor density for multiple downcomer (MD) trays reported by Union Carbide (1970) and cited by Lockett (1986). **Figure 3** gives the mean downcomer froth density estimated by Hoek & Zuideweg (1982) from measured tray efficiency. The results shown in **Figure 3** are for the IC4/NC4 system at 165, 300, and 400 psia. They are calculated based on assumptions that the decrease in tray efficiency for the butane system from 165 psia to 400 psia is caused by the vapor entrainment through the downcomer. The assumption is rather speculative in nature. Lockett and Gharani (1979) do not expect the vapor entrainment to have a noticeable effect on tray efficiency at high pressures. Thus, it is essential to have experimental data to support the analysis presented by Hoek & Zuideweg (1982).

The purpose of this paper is to present experimental data measured in distillation column for the butane system at different pressures up to 500 psia and to verify literature findings and analysis.

## **EXPERIMENTAL SETUPS**

When this study was initiated, it was apparent that a good solution to the problem would require experiments for which the dynamics of flow and separation in the downcomer could be reliably determined. Experience had shown that measurements of liquid head in the downcomer by the use of bubblers become less reliable as operating pressures are increased. There is also the problem of the interpretation of these measurements. It was therefore decided to utilize transparent downcomers which could be viewed from the four existing windows in the F.R.I. high pressure column. The transparent downcomer provided excellent conditions for the viewing and filming of the dynamics of flow and separation.

**Figure 4** shows the basic arrangement of components that was used for all of the transparent downcomer variations tested. Tray 3, a bubble cap tray, was provided to preheat the cold reflux. Tray 2 consisted of the test tray, which was a sieve tray in all cases, and the transparent downcomer. The essential purpose of Tray 1 was to provide a seal for the transparent downcomer and to separate the vapor-liquid traffic. Tray 1 did not have any of the usual provisions for flow of vapor through the tray such as holes, caps, etc. The transparent downcomer was moved approximately a foot away from the column wall to provide greater visibility of the back of the downcomer through the two column window ports shown on the left side of the column in **Figure 4**. The void space, created by moving the downcomer away from the column wall, was equipped with an inert gas purge line so that when visibility was hampered by mist or fog created by the test system the void space could be purged to clarify the atmosphere. The front apron of the downcomer was made of translucent glass so that the light from the photo-flood lamps placed outside the two window ports on the opposite side of the column would be evenly dispersed for motion pictures taken through the window ports behind the downcomer.

The transparent downcomer was utilized in four methodical variations for the present study. The first transparent downcomer tested was a non-sloped (vertical front apron) version occupying a nominal 13% of the column area. The 13% downcomer was known to be too small for optimum capacity in the F.R.I. column with the IC4/NC4 system at 500 psia. But, since it was the objective of this study to determine the optimum downcomer size required, a logical starting point was with a downcomer that could easily be flooded.

The second downcomer variation that was tested occupied a nominal 40% of the tower cross-sectional area at the top of the downcomer. Because of the large downcomer area at the top, the downcomer was sloped to a smaller area (nominal 9% of the tower area) at the bottom to provide adequate bubbling area on the tray below.

The third downcomer variation tested was a downcomer that occupied a nominal 25% of the tower area at the top and was sloped to approximately 9% at the bottom. Since the construction of the 25% downcomer is similar to that of the 40% downcomer. The same perforated tray was used for the 25% downcomer as was used for the 40% downcomer, and a blank section was added to occupy the extra space left by the smaller downcomer. The downcomer clearance for the above three designs is 1.5". The fourth downcomer design is the same as the third design except for with a 0.5" downcomer clearance. The details of the four variations in downcomer design are shown in **Table 1**.

Instrumentation of the transparent downcomer, in addition to the visual observations and motion pictures, consisted of bubblers and hot liquid manometers. Four separate bubblers, used to measure liquid head in the downcomer, were located within each of the transparent downcomers tested. The bubblers were located at 0, 6, 12 and 18 inch elevations, respectively, from the bottom of the downcomer. Three hot liquid manometers were also used with each downcomer to perform a function identical to that of the bubblers. The three manometers each consisted of a glass tube connected from the downcomer to the sieve tray area above. The manometers were connected to the transparent downcomers at 0 inch, 6 inches and 12 inches elevation from the bottom of the downcomer.

## EXPERIMENTAL PROCEDURE

Prior to this study, there were no known visual observations of the flow mechanics inside of an operating downcomer at high pressures. Because of this, it was decided to run an exhaustive series of tests on each of the transparent downcomers.

A 50/50 mixture of isobutane and normal butane (IC4/NC4) was used for the large portion of the tests conducted. The physical properties of the IC4/NC4 system were varied over a considerable range by adjusting the operating pressure to 115, 165, 200, 300, 400, and 500 psia. The approximate physical properties of the IC4/NC4 system at pressures used in tests are given in **Table 2**. The basic plan for each downcomer configuration tested was to run a complete matrix of liquid and vapor loadings for each test system selected. The liquid rates were varied from very low to very high rates and the vapor rates were varied from rates corresponding to flood conditions to rates that gave excessive weeping.

The reason for varying the liquid rate is obvious; as the liquid rate is increased, the superficial liquid velocity in the downcomer must eventually reach a value such that vapor will be carried through the downcomer. The vapor rate was varied since it is reasonable to expect that increased vapor rates can result in a more aerated froth being delivered from the tray to the downcomer. The vapor rate variation also changes the level of liquid backed up in the downcomer by pressure drop.

The downcomer exit clearance was adjusted to two variations for the 25% x 9% sloped downcomer. The variations in the exit clearance altered the resistance to flow through the downcomers, and thereby increased the possibilities of observing the maximum liquid rates at which ideal operation could be obtained with the given downcomer cross-sectional areas.

Downcomer liquid head measurements were taken for each test run. The liquid manometers were tapped directly into the side of the downcomer at 0 inch, 6 inches and 12 inches elevation and observed from outside the column through the window ports. Also, bubblers purged with inert gas were inserted directly into the downcomers at 0, 6, 12, and 18 inches elevation to measure the liquid head.

## RESULTS AND DISCUSSION

Although a lot of experimental data were collected in this study, this paper focuses on the amount of vapor entrainment through the downcomer and presents the froth density determined for the bottom 6" of the downcomer. The froth density of the bottom 6" of the downcomer is calculated by the ratio of liquid holdup for the bottom 6" of the downcomer to 6" of height. The liquid holdup for the bottom 6" of the downcomer is the holdup difference measured from the bubblers position at 0" and 6".

Important visual observations were made for all test runs concerning the amounts of clarified liquid in the bottom of the downcomer and possible vapor entrainment. It was observed that when the total froth height in the downcomer was low, it frequently occurred that the froth falling into the downcomer fell almost exclusively along the glass windows of the downcomer, resulting in froth being forced down into the downcomer next to the window. It was seen that the liquid frequently tends to clarify just in the lower corners of the downcomer. The liquid flow

becomes more or less stagnant in the corners of a segmental downcomer and should therefore clarify quite easily in those locations. It was also frequently found that clarified liquid exists in the bottom of the downcomer only part of the time. The oscillatory appearance of clarified liquid appears to be due to flow fluctuations and turbulence. It frequently occurred that a sufficient height of clarified liquid was obtained in the bottom of the downcomer and an occasional bit of large scale turbulence would cause a few single bubbles to be injected into the clarified liquid region. It could be observed whether the single bubbles would recover and overcome the downward liquid velocity, or whether the liquid velocity was so high that bubbles are carried completely through the downcomer and out onto the next tray below.

In addition to the visual observation, all bubbler and manometer readings are recorded and analyzed. The froth density of the bottom 6" of the downcomer is obtained based on bubbler readings. The obtained results are shown in **Figures 5 to 8** for the four designs tested, respectively. The closed solid symbol in these figures represents the froth density of 1 achieved at the bottom 6" of the downcomer or no vapor entrainment. The open symbol indicates the froth density of less than 1 at the bottom 6" of the downcomer or some vapor entrainment.

**Figure 5** shows the results obtained for downcomer design 1 for the IC4/NC4 system at 115, 165, 200, 300, 400, and 500 psia. It can be seen that clear liquid was obtained at the bottom of the downcomer or there was no vapor entrainment at 165 psia or below. Downcomer operation under these operating conditions should correspond to Case A in **Figure 1**. Vapor entrainment might exist at low rates at 200 psia corresponding to downcomer operation shown in Case C in **Figure 1**. At 400 psia and above, vapor entrainment exists at high rates. These results indicate that the 13% downcomer is too small under these operating conditions. Case B in **Figure 1** shows the possible downcomer operation in that situation.

**Figure 6** gives the results for downcomer design 2 under various pressures. No vapor entrainment was observed for all runs at various pressures up to 500 psia. These results show that the 40% x 9% sloped downcomer had very good two-phase separation capability up to and including the IC4/NC4 system at 500 psia.

The results for downcomer design 3 are shown in **Figure 7**. It can be found that the 25% x 9% sloped downcomer had good two-phase separation capability at 300 psia. However, at 400 and 500 psia, its capability is not as good as that of 40% x 9% downcomer. The froth is not clarified at the bottom of the downcomer at low rates. For downcomer design 4 with 0.5" downcomer clearance, clear liquid exists at the bottom of the downcomer for all runs at 300, 400, and 500 psia. These results are presented in **Figure 8**.

From bubbler readings positioned at 4 different elevations, the mean downcomer froth density can be determined for each run. **Figure 9** shows the mean downcomer froth density averaged from all runs for downcomer design 1 of the 13% straight downcomer as functions of density difference and the system pressure. It can be seen that the mean downcomer froth density decreases as the system pressure increases. The calculated mean froth density from tray efficiency losses by Hoek and Zuiderweg (1982) are also shown in the figure for comparison. From these results, it can be concluded that the assumptions made by Hoek and Zuiderweg (1982) in

calculating the mean froth density is not valid. The decrease in tray efficiency as the operating pressure increases for the IC4/NC4 system is not due to the vapor entrainment through the downcomer. Experimental data show that there is little or no vapor entrainment through the downcomer for most of the normal operating conditions. The measured mean downcomer froth density for the butane system is much higher than that reported in literature.

## **CONCLUSIONS**

Mean downcomer froth density for the bottom 6" of the downcomer and for the whole downcomer was determined from bubbler readings for the IC4/NC4 system at various pressures up to 500 psia in a 4-ft distillation column. Four different downcomer designs including both straight and sloped downcomers were employed in this study. Experimental results show that there is little or no vapor entrainment through the downcomer for most of the normal operating conditions. It was found that the mean downcomer froth density determined in this study is generally above 0.6, which is significantly higher than that reported in literature and common beliefs. It can be concluded that little vapor entrainment through the downcomer for most operating conditions has little or no effect on the tray efficiency. The decrease in tray efficiency as pressure increases (Sakata and Yanagi, 1979) is not due to the vapor entrainment.

## **REFERENCE**

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Lockett, M.J. and Gharani, A.A.W., "Downcomer Hydraulics at High Liquid Rates," I. Chem. E. Symp. Ser., No. 56, P. 2.3/43 (1979).

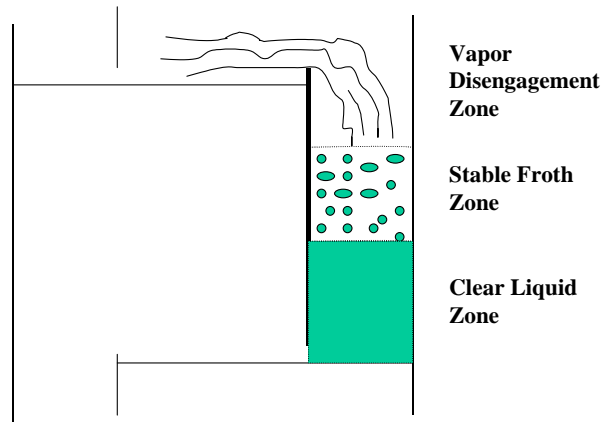
Hoek, P.J. and Zuiderweg, F.J., "Influence of vapor entrainment on distillation tray efficiency at high pressures," AIChE J. 28, (4), 535 (1982).

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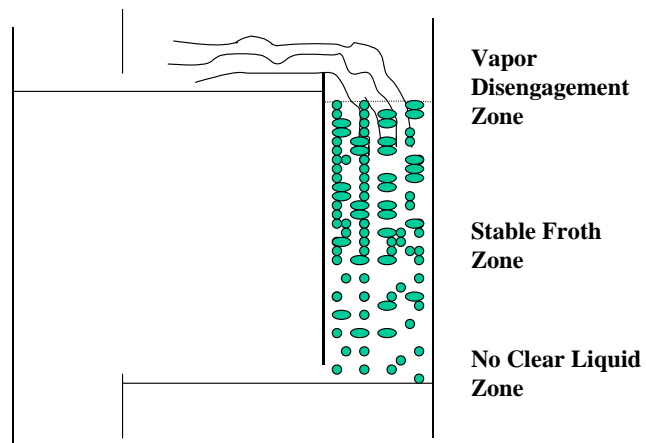
Union Carbide Corp, "MD-Tray Design Manual, Union Carbide Corp.," Tonawanda, New York (1970).

Figure 1: Two Phase Mixtures in Downcomer

Case A: No Vapor Entrainment



Case B: Vapor Entrainment Due to High Two Phase Velocity



Case C: Vapor Entrainment Due to Low Downcomer Backup

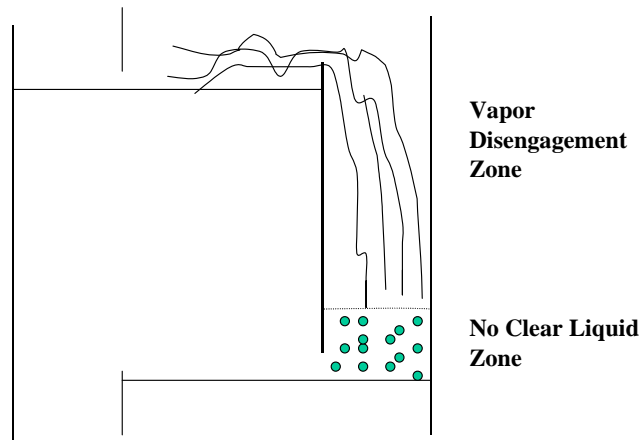


Figure 2: Mean Liquid Fraction in DC For Non-foaming System for MD Tray  
(Union Carbide 1970, Cited by Lockett 1986, Page 101)

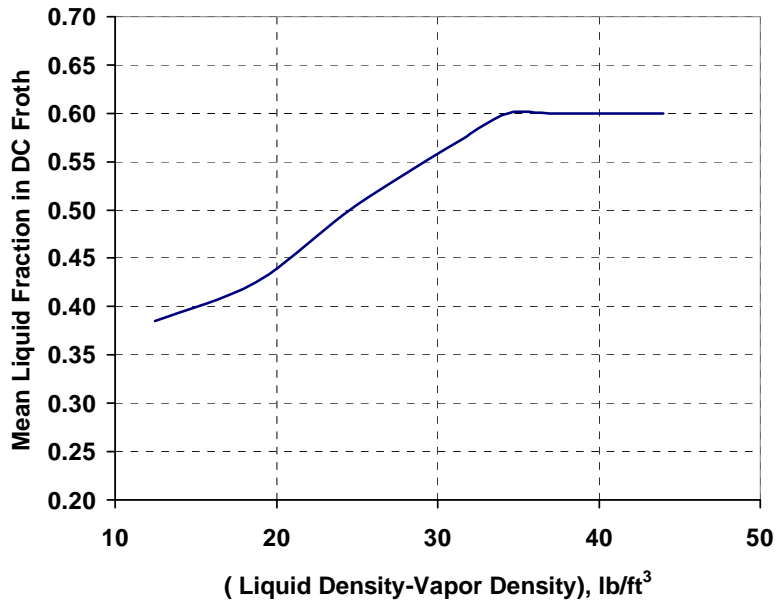


Figure 3: Mean Liquid Fraction in DC for IC4/NC4 System at 165, 300, and 400 psia  
(Calculated by Hoek & Zuiderweg 1982, Cited by Lockett 1986, Page 101)

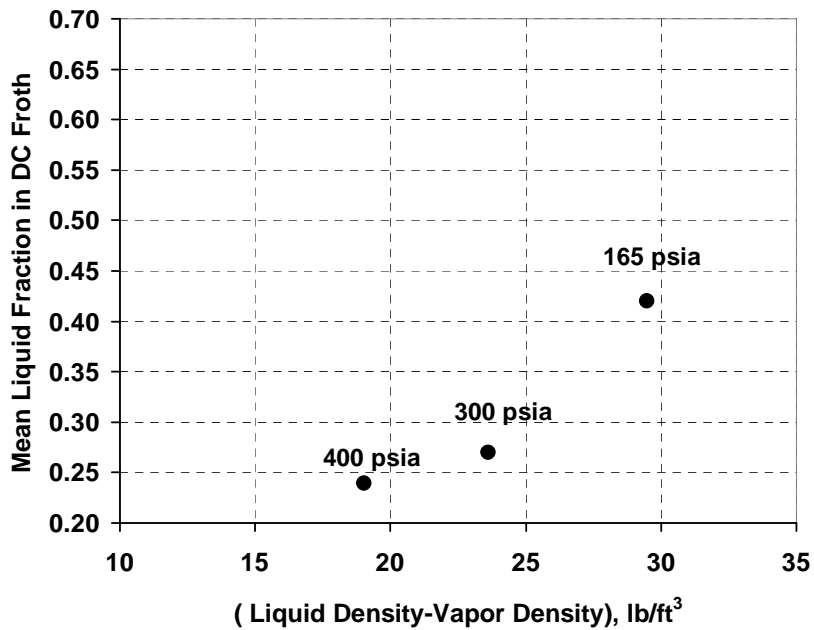


Figure 4: Experimental Setup

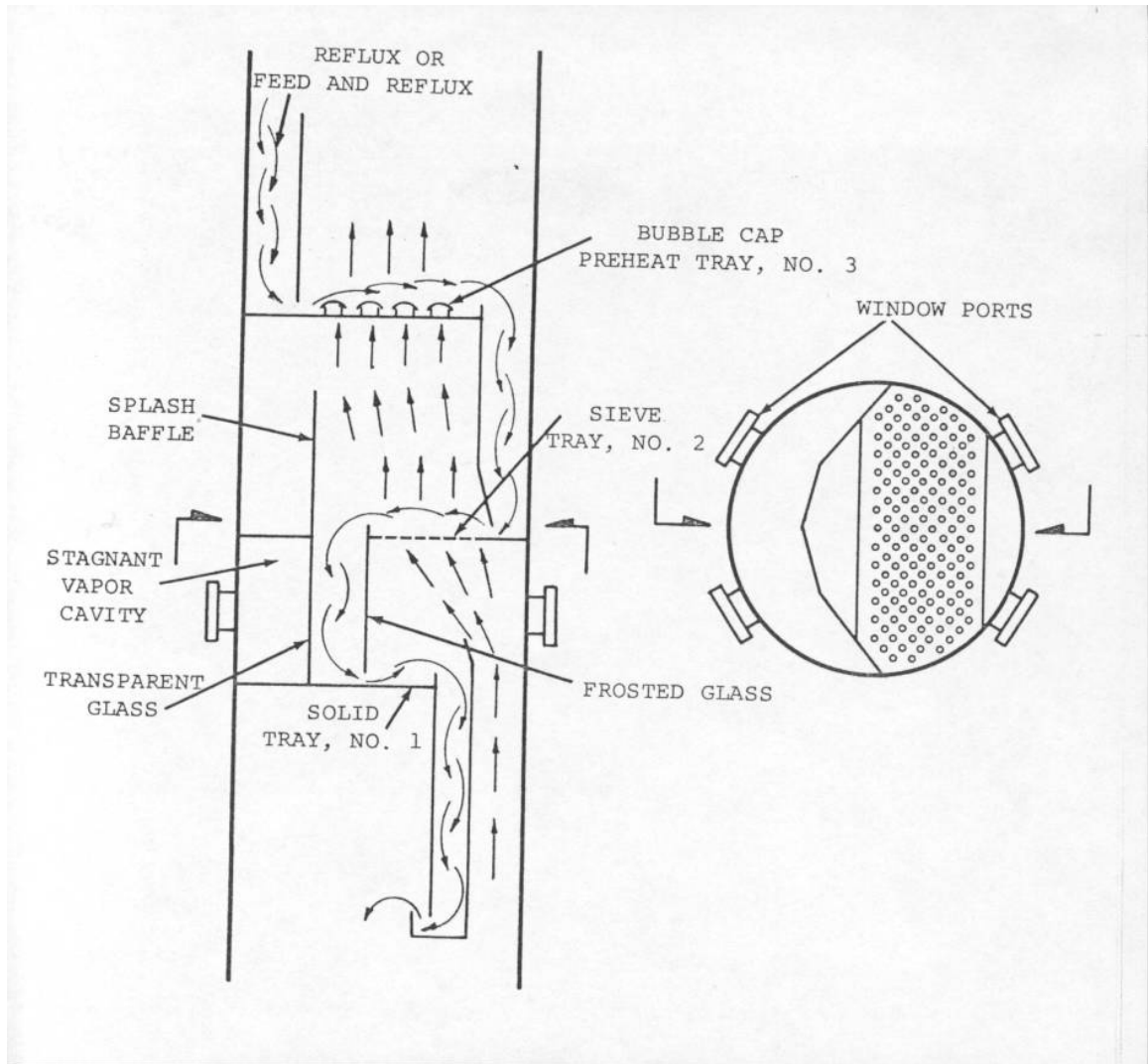


Figure 5: Liquid and Vapor Rates For Design 1  
 Solid symbol for froth density=1, Open Symbol for froth density <1

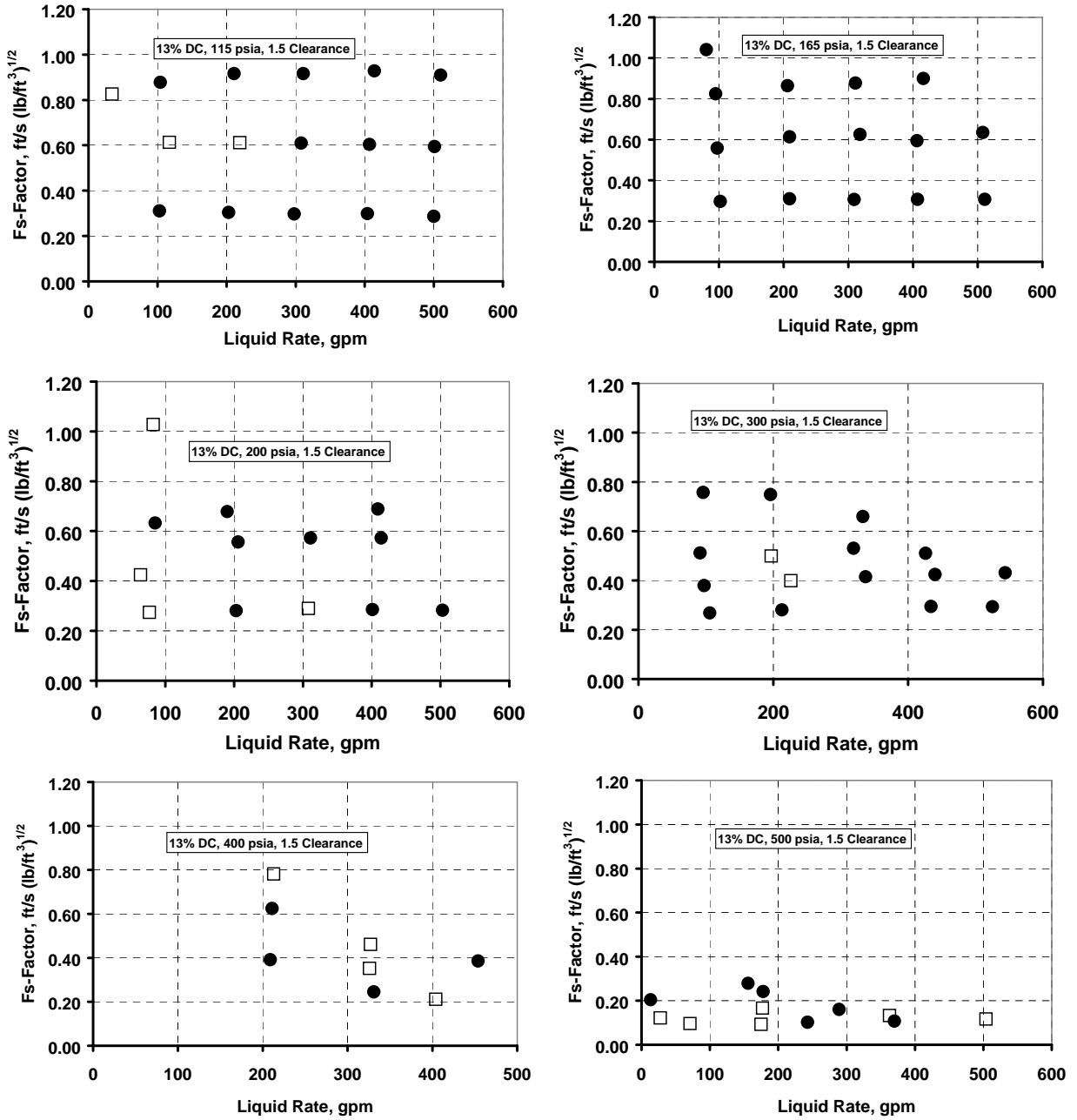


Figure 6: Liquid and Vapor Rates For Design 2  
 Solid symbol for froth density=1, Open Symbol for froth density<1

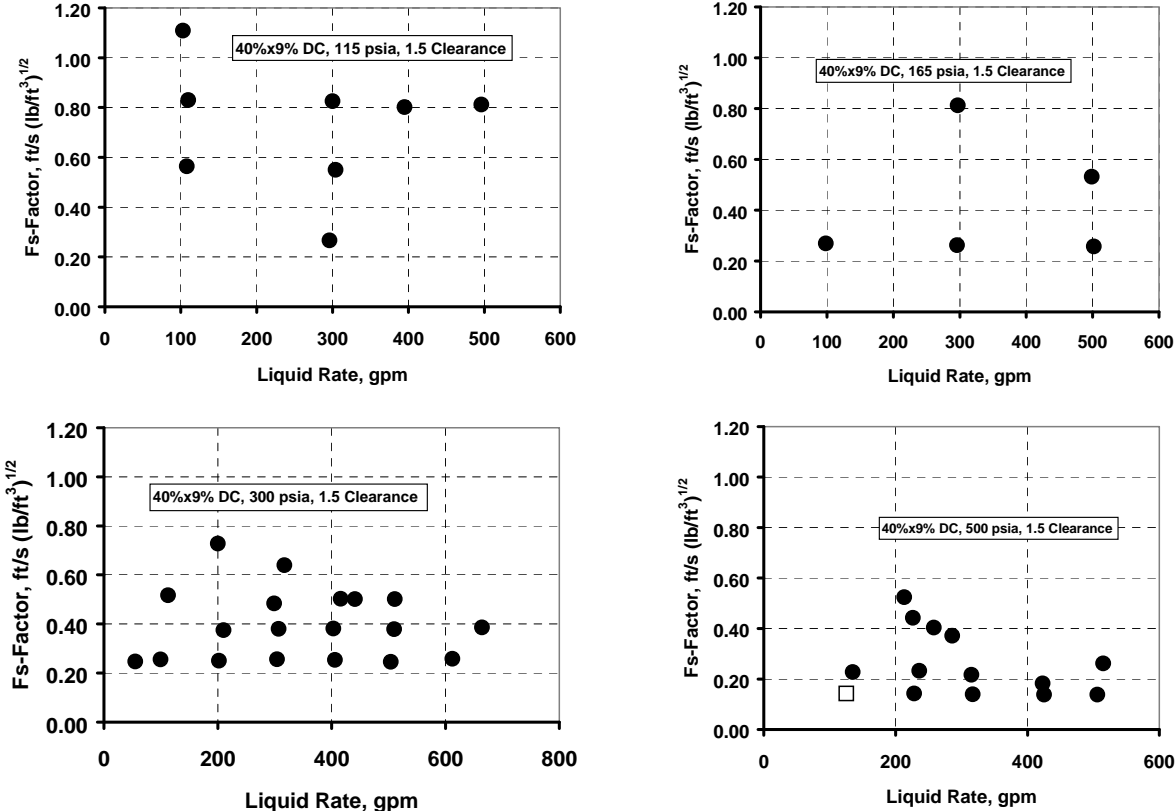


Figure 7: Liquid and Vapor Rates For Design 3  
 Solid symbol for froth density=1, Open Symbol for froth density <1

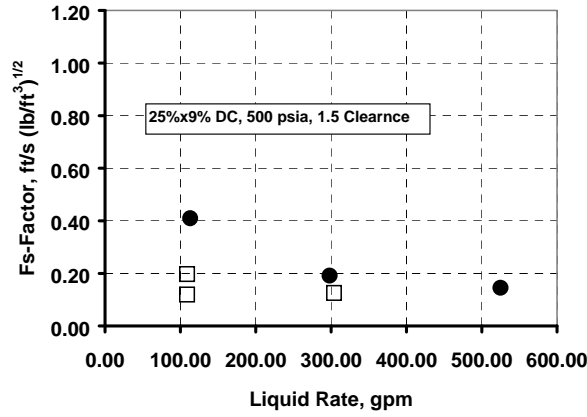
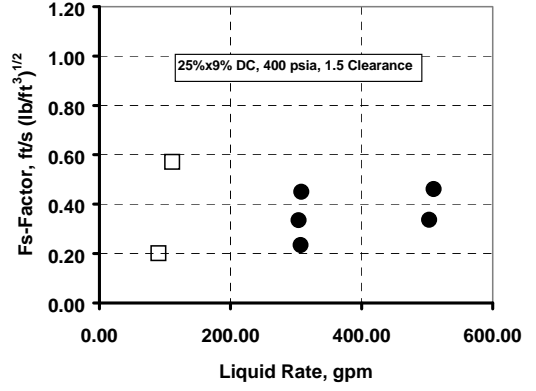
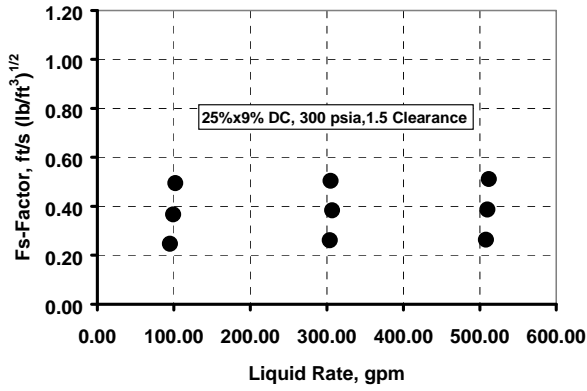


Figure 8: Liquid and Vapor Rates For Design 4  
 Solid symbol for froth density=1, Open Symbol for froth density <1

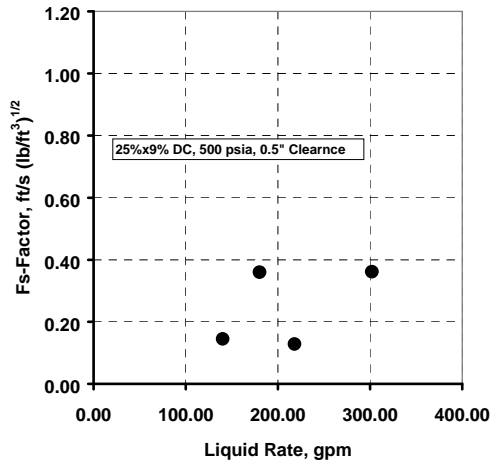
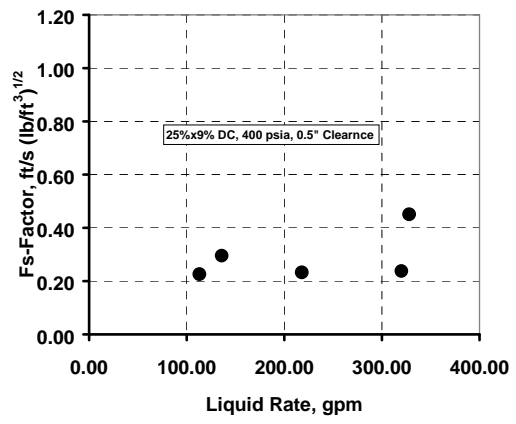
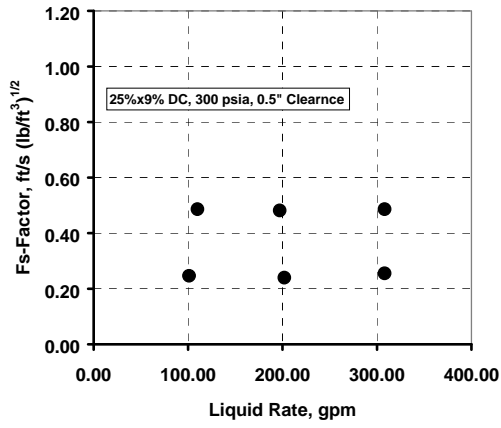


Figure 9: Mean Downcomer Froth Density for the IC4/NC4 System  
Downcomer Design 1 for This Study

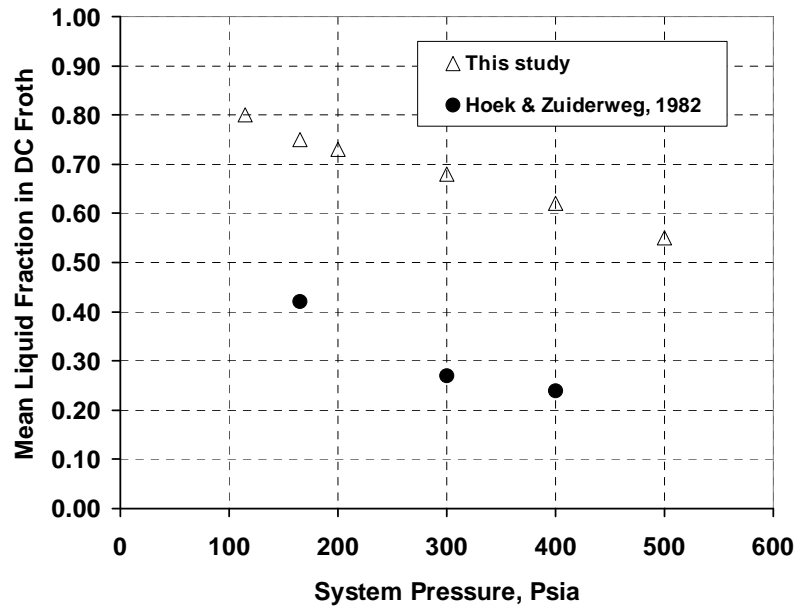
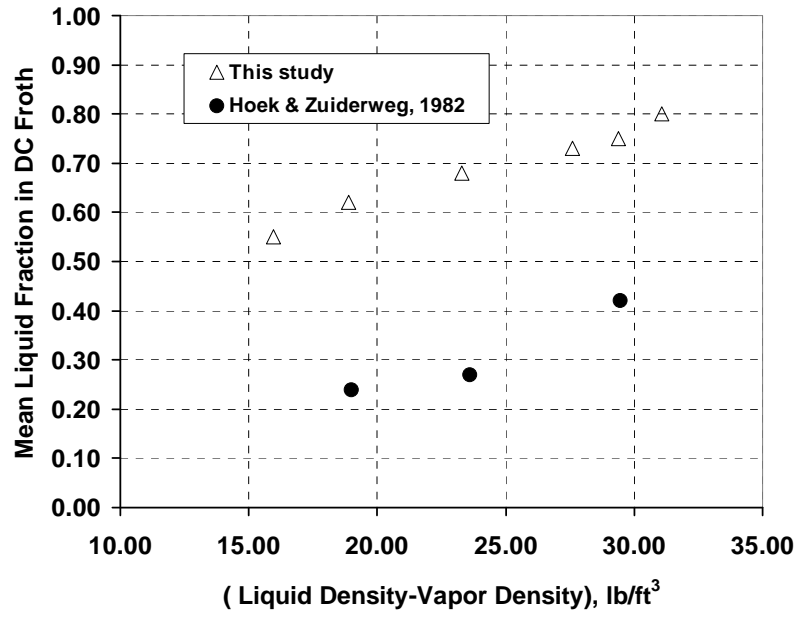


Table 1: Downcomer Dimensions

Downcomer design ID	1	2	3	4
Nominal downcomer area, %x%	13	40x9	25x9	25x9
Inside tower diameter, inch	48.0	48.0	48.0	48.0
Transparent downcomer area at top, sq. ft.	1.48	4.84	3.52	3.52
Transparent downcomer area at bottom, sq. ft.	1.48	0.78	0.78	0.78
Sieve tray hole diameter, inches	0.5	0.5	0.5	0.5
Total hole area, sq. ft.	0.73	0.58	0.58	0.58
Bubbling area, sq. ft.	6.1	1.86	2.76	2.76
Perforated tray flow path length, inches	21.4	6.9	6.9	6.9
Weir at downcomer top, inches	37x2	43x2	47x2	47x2
Downcomer exit area, sq. in.	55.5	41.3	41.3	13.8
Downcomer clearance	1.5	1.5	1.5	0.5

Table 2: Approximate Physical Properties of the IC4/NC4 System  
At Various Pressures

Pressure psia	Surface tension dyne/cm	Liquid density lb/ft <sup>3</sup>	Vapor density lb/ft <sup>3</sup>	Liquid viscosity centipoise
115	6.8	32.3	1.2	0.107
165	5.0	31	1.8	0.090
200	4.2	29.6	2.1	0.082
300	2.3	27	3.4	0.064
400	1.0	24	5.3	0.049
500	0.3	21	7.7	0.037