Heat Transfer Performance of Large Structured Packing

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Prepared for presentation at AICHE Spring National Meeting
Houston, Texas
March, 1999

High Capacity, HI Efficiency Trays and Packings for the New Millenium

UNPUBLISHED

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Abstract

Results are presented on the heat transfer performance of a short bed of a large sheet metal structured packing, Intalox 4T, in a 1.2 m (4 foot) diameter distillation column. Heat transfer studies were made at total reflux and L/V >1 with a totally condensing system, cyclohexane/n-heptane (C_6/C_7), at 1.65 bar (24 psia) and a partially condensing system, cyclohexane/n-heptane with methane gas at 3.03 bar (44 psia). The first test was made with no packing in the column, followed by test with 1.07 m (3.5 foot) bed of structured packing. Single wide-angle spray nozzles were employed as liquid distributors for both empty column and short bed tests. A high quality orifice pan liquid distributor was also used for the short bed test. The overall result is that for a totally condensing system with a well atomized spray, virtually all of the heat transfer occurred within about 305 mm (12 inches) from the nozzle outlet. The test confirmed that spray nozzles are an effective direct contact heat transfer device. With non-condensing gas injection, the heat transfer rate was slowed down but very little or no additional heat transfer took place in the bed. Consequently, no meaningful heat transfer coefficient could be determined in the packed bed.

Introduction

Direct contact heat transfer is an important method of heat exchange between two countercurrent process streams within a column, such as pump-around zones in refinery columns, de-superheating sections of catalytic cracking fractionators, and ethylene quenchers. Direct contacting devices may be classified roughly as sprays, trays, grids, random packings, and structured packings. Previous studies (Ognisty, 1990, Ognisty & Kao, 1988) have primarily emphasized trays and random packings. The mass transfer performance of structured packings under distillation and absorption that has been reported fairly widely (Fitz, Kunesh & Shariat, 1999, Rocha, Fair & Bravo, 1993, Spigel & Meier, 1987). However, few studies have been done on their heat transfer performance, particularly in the way of commercial-scale experimental studies. Spiegel etc. (1995) presented results of direct heat transfer in structured packing with a non-condensing system. This paper presents experimental heat transfer data obtained by Fractionation Research, Inc. (F.R.I.) in the 1.2 m (4 ft) diameter low pressure distillation column. Norton Intalox^{TM} Size 4T has been tested with a total condensing system, cyclohexane/n-heptane (C_6/C_7), at 1.65 bar (24 psia) and a partially condensing system, cyclohexane/n-heptane with methane gas at 3.3 bar (44 psia). Three single wide angle spray nozzles were utilized as liquid distributors for both empty column and short bed tests. A high quality orifice pan distributor was also used for the short bed test.

Experimental Equipment

Packing

As shown in **Figure 1**, Intalox 4T is a large size structured packing made from corrugated stainless steel sheets placed side by side with opposing inclinations of the crimps. The surface of the sheet metal is textured and perforated. The packing has a specific surface area of 133 m^2/m^3 (40.5 ft^2/ft^3) with crimp channel height of 18.4 mm (0.72 inches). For the short bed tests there were four layers with each layer consisting of 8 blocks. The height of each layer is 273 mm (10.75 inches).

Liquid Distributors

Single wide-angle spray nozzles were employed as liquid distributors for both empty column and short bed tests. The nozzle is a full cone spray nozzle. Maximum Free Passage (MP) fouling-resistance nozzles manufactured by the Bete Fog Nozzle Company were selected for these tests. The nozzles were water flow tested at both the factory and F.R.I. before they were installed in the column. Three different nozzles were used for different flow rate ranges in order to have nozzle pressure drops between 0.34 and 1.65 bar (5 and 24 psi). As a result the small, medium and large nozzles designated 1125W, 1500W, 2000W were chosen. The nozzle outlet diameters are 28.6 mm (1.125 inches), 38.1 mm (1.50 inches) and 50.8 mm (2 .0 inches), respectively. To avoid the cost and time involved in shutting down and entering the column for each nozzle change, a three nozzle feed line movable header was devised. The 1125W and 1500W nozzles were attached to two outer 63.5 mm nozzle feed lines, while the 2000W nozzle was connected to the central 76.2 mm feed line. The three nozzle feed lines, nominal height 1.2 m to the nozzle inlet, were linked to a single 76.2 mm I.D. header pipe, height 2.25 m, centered on a pivot near the top of the 1.22 m column section. The appropriate nozzle was swung into the centerline position using pre-marked levers and turned on and off using double universal joint gate valves when in operation. To minimize thermal conduction effects, the main fed pipe was insulated with a 102 mm I.D. jacket that was continuously purged with nitrogen. **Figure 2** shows the lower section of the nozzle header setup and these three nozzles used in the tests.

For the short bed tests, a high quality orifice pan liquid distributor with a design operating flow range of 12.95 to 38.38 m^3/h (57 to 169 gpm) was also used as the liquid distributor. The pan consists of 121 orifices of diameter 7.13 mm (0.281 inches), 28 rectangular vapor risers, of inside dimensions 61.0 x 139 mm (2.40 x 5.47 inches), and a pre-distributor sparge pipe with 6 downpipes and liquid momentum breakers. The distributor pan height is 749 mm (29.5 inches). **Figure 3** shows the picture of the liquid distributor.

Temperature Measuring Devices

A total of 21 Type-T thermocouples were used in the heat transfer measurement: 11 for liquid temperature measurements and 10 for vapor temperature measurements. **Figures 4 and 5** are photographs of the temperature probes used for this study. The topside of each device (**Figure 4**) had liquid temperature measurement capture well(s). The thermocouple probe in each well was insulated to minimize conduction of heat to the copper pipe. Coarse wire mesh was used to cover each well to prevent liquid splashing both into and out of the well and help trap sufficient liquid to completely submerge the probe tip for an accurate measurement. The underside of each device (**Figure 5**) had vapor temperature measurement probes located out of the line with respect to the liquid temperature probes to avoid interference. Each probe was located in an insulated elongated capture well. The well was designed to guide vapor flow towards and past the probe tip and escape through the non-insulated section of copper pipe via side holes small enough to prevent liquid leaking into the capture well. Two bayonet thermowells had four temperature measurement sites. One had three sites for liquid and one for vapor. The other had three vapor sites only. Also shown in **Figures 4-5** is a bayonet liquid sampler (bottom of the photographs) with a thermocouple, which measured both liquid temperature and composition at the same column location.

Gas Injection

For heat transfer studies with methane injection, natural gas was injected into the reboiler vapor. The gas flowed through the overhead system and exited via a knock back condenser to minimize test fluid loss. Temporary piping then routed the gas through an additional knock-out drum prior to venting via a ground flare.

Column Configuration

Figure 6 shows the column configuration of empty column tests with nozzle installation, locating the vapor distribution/liquid collector bubble cap tray, the support grid, thermocouples, samplers and pressure cells. The bubble cap tray was positioned 457 mm (18 inches) above the centerline of the reboiler vapor return line. The closest temperature measurement probes to the nozzle were situated 305 mm (12 inches) below the nozzle outlet.

Figure 7 shows the column configuration of short bed tests with nozzle installation. The setup was essentially same as the empty column test except installing a 4 layer totally 1.07 m (3.5 ft) short bed of Intalox 4T structured packing. The distance between the nozzle outlet and top of the bed was 381 mm (15 inches). The closest temperature measurement probe to the nozzle thermocouple was located 130 mm (5-1/8 inches) below the nozzle outlet. Additionally, for these tests, gas injection was used to determine the effect of non-condensable gas on heat transfer.

Figure 8 shows the column configuration of short bed tests with a high quality orifice pan liquid distributor. Compared to previous configurations two changes were made. The first involved replacing the nozzles with the high quality orifice pan distributor. The second involved the removal of the vane collector and demister since no measurable entrainment was obtained during the first two tests with nozzles. The liquid distributor was to be installed 203 mm (8 inches) above the top of the bed. Top thermocouples were positioned directly on top of the packing. Again gas injection was used in these tests to decide the effect of non-condensables on heat transfer.

Experimental Procedure

Empty Column Test

An initial series of runs were conducted with no packing in the column to assess the heat transfer performance of the spray nozzle only. It was hoped that this test would make it possible to isolate the packing heat transfer performance. The test was made at total reflux and top feed (L/V >1) with a totally condensing system, cyclohexane/n-heptane (C_6/C_7), at 1.65 bar (24 psia). In the top feed series, feed was directed to the top of the column.

Short Bed Tests

Based on the empty column operating experience, heat transfer studies were made with the C_6/C_7 condensing system at 1.65 bar (24 psia) and with natural gas injection up to 3.03 bar (44 psia). After tests with spray nozzles as liquid distributors, the high quality orifice pan distributor was installed approximately 203 mm (8 inches) above the bed. In all tests, total reflux and top feed (L/V > 1) runs were carried out.

Data Analysis of Direct Heat Transfer of Condensing Systems

Figure 9 is a simplified sketch of the heat transfer measurement zone locating the support plate (Position 2) as the staring point and the liquid distributor level (Position 1) as the terminating point.

The over-all heat transfer Q_T is

$$Q_T = L_1(H_{L2} - H_{L1}) + \Delta V(H_{L2} - H_L^*) \tag{1}$$

Where H_L^* is the liquid enthalpy at mean condensation temperature.

$$Q_T = Q_G + Q_C = Q_G + \Delta V.\lambda \tag{2}$$

$$Q_T = UA(T_G - T_L)_{AV} \tag{3}$$

$$Q_T = \alpha h_{ga}(T_G - T_i)_{AV} + \Delta V.\lambda \tag{4}$$

$$Q_T = h_{la}(T_i - T_L)_{AV} \tag{5}$$

$$Q_G = \alpha h_{ga}(T_G - T_i)_{AV} \tag{6}$$

Where,

Q_T = Total heat duty of a heat transfer process
Q_G = Vapor sensible heat duty
Q_C = Condensation heat duty
ΔV = Rate of mass transferred between phases
λ = Latent heat at mean condensation temperature
UA = Over-all heat transfer coefficient
h_{ga} = Gas phase sensible heat transfer coefficient
h_{la} = Liquid phase sensible heat transfer coefficient
α = Ackerman correction factor
T_L = Liquid temperature
T_G = Vapor temperature
T_i = Interface temperature

Due to the vapor condensation, the movement of the mixed vapor toward the cold surface carries each component more rapidly than if the heat transfer were solely by diffusion. Similarly, diffusion of each component carries heat more rapidly than by simple heat transfer through a non-condensing film. The Ackerman factor α accounts for the effect of mass transfer on the rate of sensible heat transfer, which can be calculated by the following equation (Sherwood & Pigford, 1956),

$$\alpha = \frac{\Delta V C_P / h_{ga}}{1 - \exp(-\Delta V C_p / h_{ga})} \tag{7}$$

Where C_p is the heat capacity of transferred mass.

Combining Equations 3, 4 and 5, the over-all heat transfer coefficient can be expressed as:

$$\frac{1}{UA} = \frac{1}{h_{la}} + \frac{Q_G}{\alpha h_{ga} Q_T} \tag{8}$$

If the liquid phase coefficient is assumed to be very large, the over-all heat transfer coefficient is represented by:

$$UA = \alpha h_{ga} \frac{Q_T}{Q_G} = \frac{Q_T}{(T_G - T_L)_{AV}} \tag{9}$$

From Equations 6 and 7, the gas phase sensible heat transfer coefficient can be calculated by,

$$h_{ga} = \frac{\Delta V C_p}{Ln\left[\dfrac{1}{1 - \dfrac{\Delta V C_p \Delta T_{AV}}{Q_G}}\right]} \tag{10}$$

Results and Discussions

Figure 10 indicates the temperature difference for empty column total reflux operation, at nozzle level, "Top Bed", 838 mm (33 inches) above the support grid and "Bottom Bed". ("Top Bed" is the location where the top of the bed would be installed, 305 mm (12 inches) below the nozzles. "Bottom Bed" is the top of the support grid.) **Figure 11** is a similar plot for empty column top feed operation. As may be seen in these two figures, the vapor and liquid temperature pinched at the closet measuring point to the nozzle discharge outlet. Both figures show that even with temperature differences as high as 60 ^{o}C at the nozzle level, the temperature difference is less than 2.7 ^{o}C. This implies that equilibrium is being reached (pinch) and the heat transfer is limited solely by the mass flow rate. Thus results confirmed that spray nozzle is an effective direct heat transfer device for a totally condensing system, heat transfer is almost instantaneous (Kunesh, 1993).

In an attempt to reduce the heat transfer rate to the point where a heat transfer coefficient could be determined, the heat transfer tests using the short bed of Intalox 4T structured packing were conducted using natural gas injection. Temperature difference plots were generated as shown in **Figures 12-15**. **Figures 12-13** are based on the short bed tests with nozzles, while **Figures 14-15** are based on the tests with the orifice liquid distributor. For the short bed tests with nozzles, the four temperature difference locations are the same as that used for the empty column tests except that the 838 mm (33 inches) elevation was raised to 991 mm (39 inches).

As may be seen in each of the four figures, the temperatures still pinched in short bed tests. Operation with gas injection slowed down the heat transfer to the point where a consistent temperature difference could be measured at the top of the bed, but little or no additional heat transfer took place in the bed. Although some of the heat transfer occurred in the bed, the close approach of the liquid and gas temperature and the obvious non-linearity of the condensation process makes any attempt to deduce a heat transfer coefficient pointless and possibly misleading.

Despite the fact that no absolute heat transfer coefficients, UA, could be calculated with confidence, some interesting qualitative trends with respect to liquid and vapor rates can be ascertained. **Figure 16** shows the effect of liquid rate on UA for the empty column tests with spray nozzle. Results indicate that the UA increases almost linearly with entering liquid rate irrespective of the vapor rate, which means that temperature pinching occurred and the heat transfer process is liquid mass flow rate limited. **Figure 17** shows the effect of vapor rate on UA at different liquid mass flow rates for the empty column tests with spray nozzle. The plot shows that the UA is vapor rate independent. These results again confirm that temperature pinching has occurred.

Conclusions

The heat transfer coefficient of the tested large size structured packing could not be determined since very little or no additional heat transfer took place in the packed bed with a totally condensing system or non-condensing gas injection. Spray nozzles are an effective direct heat transfer device. Therefore, in a direct contact heat transfer applications where liquid is heated by condensing a dew point vapor, only a simple bank of spray nozzles and a short vapor-liquid contacting space appears to be needed.

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Figure 1. Intalox 4T Large Sheet Metal Structured Packing

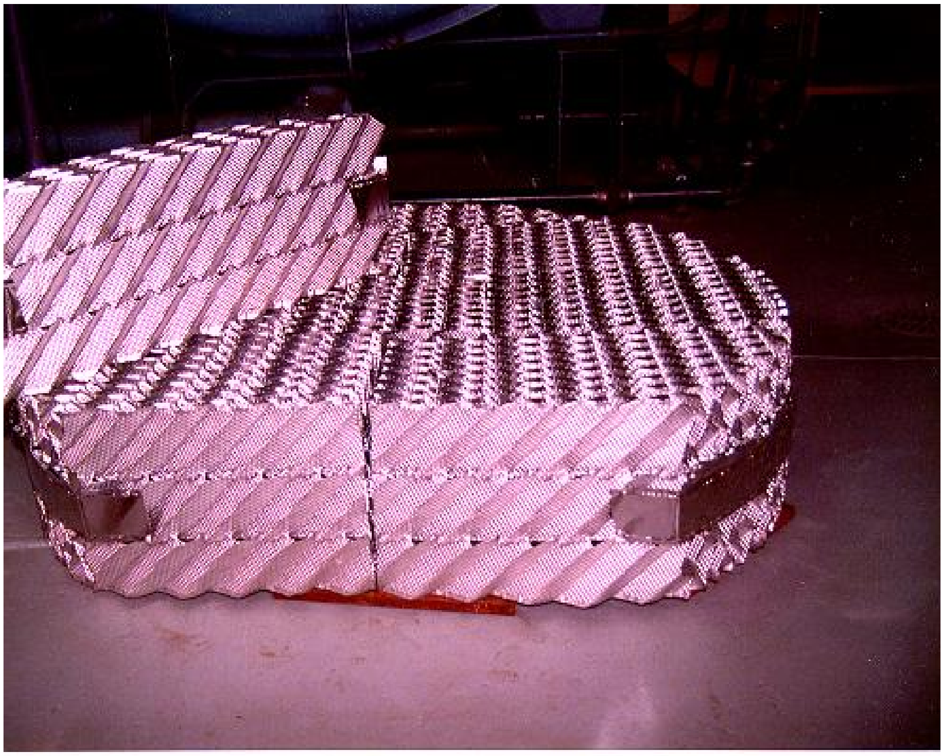


Figure 2. Three Nozzles and Movable Header Manifold Used in Tests

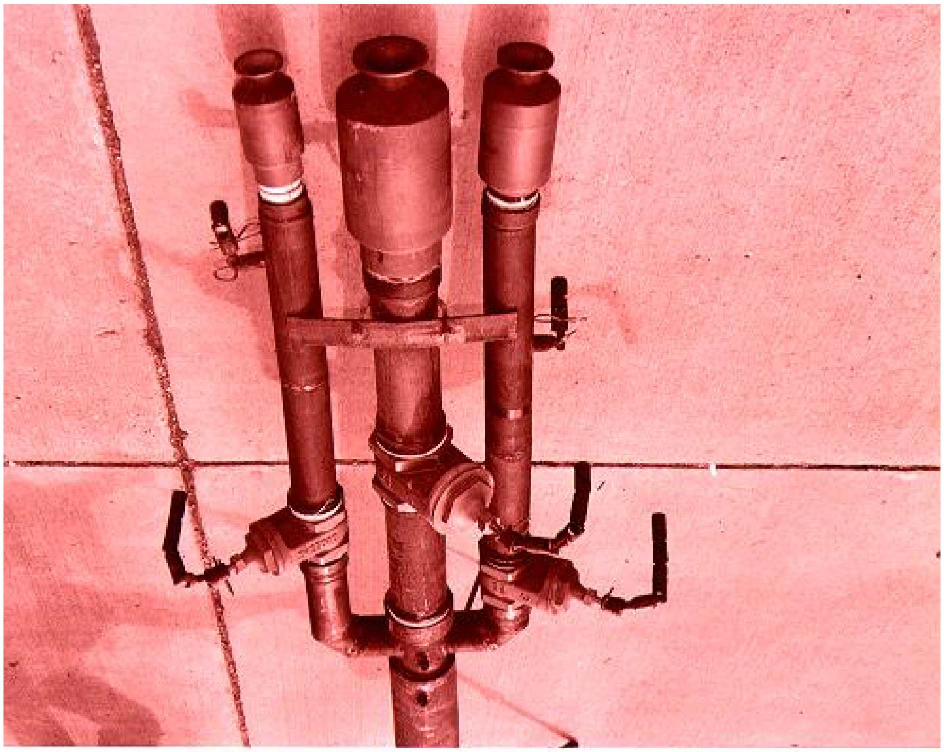


Figure 3. Orifice Pan Liquid Distributor

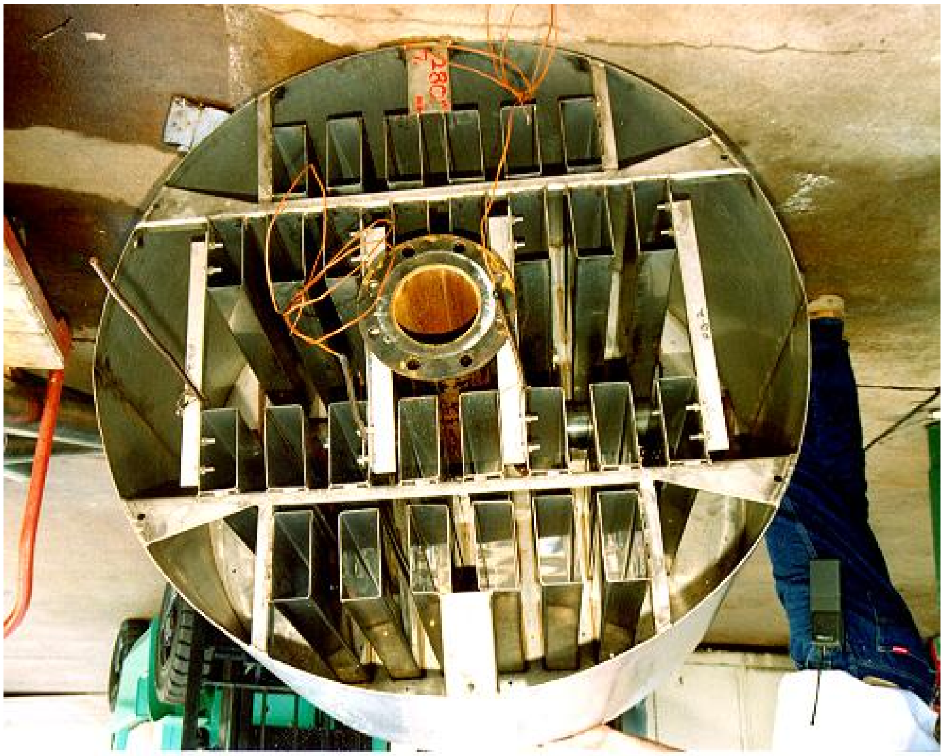


Figure 4. Temperature Measurement Devices (Top Side View)

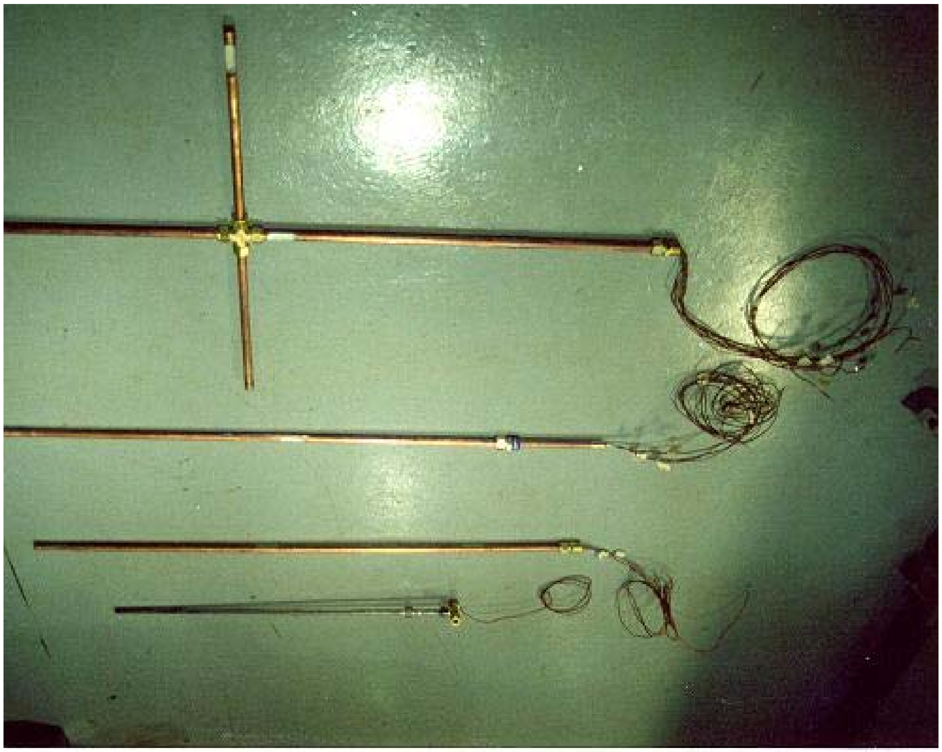
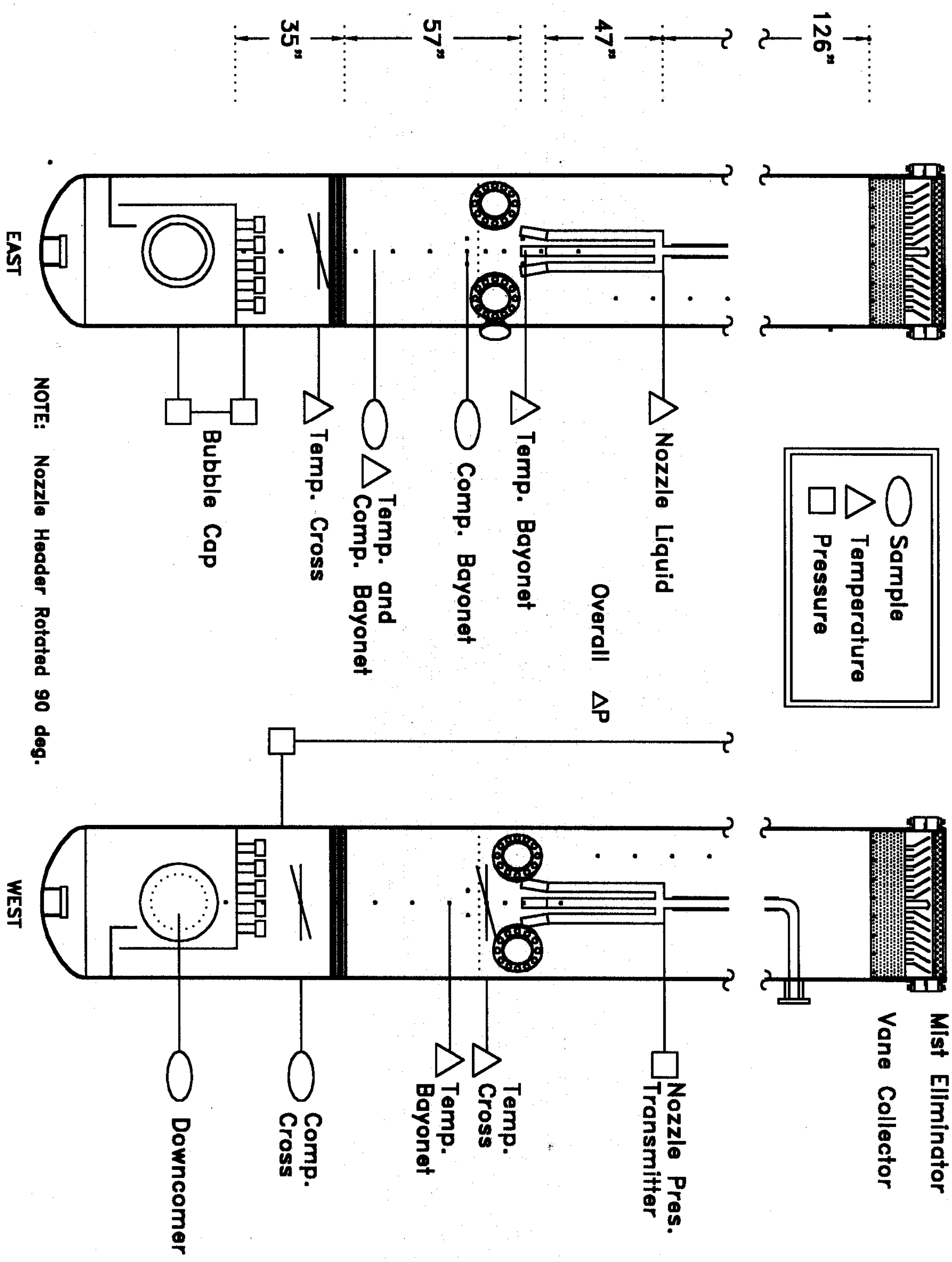


Figure 5. Temperature Measurement Devices (Bottom Side View)

Figure 6. Column Configuration for Empty Column Tests with Nozzles



NOTE: Nozzle Header Rotated 90 deg.

Figure 7. Column Configuration for Short bed Tests with Nozzles

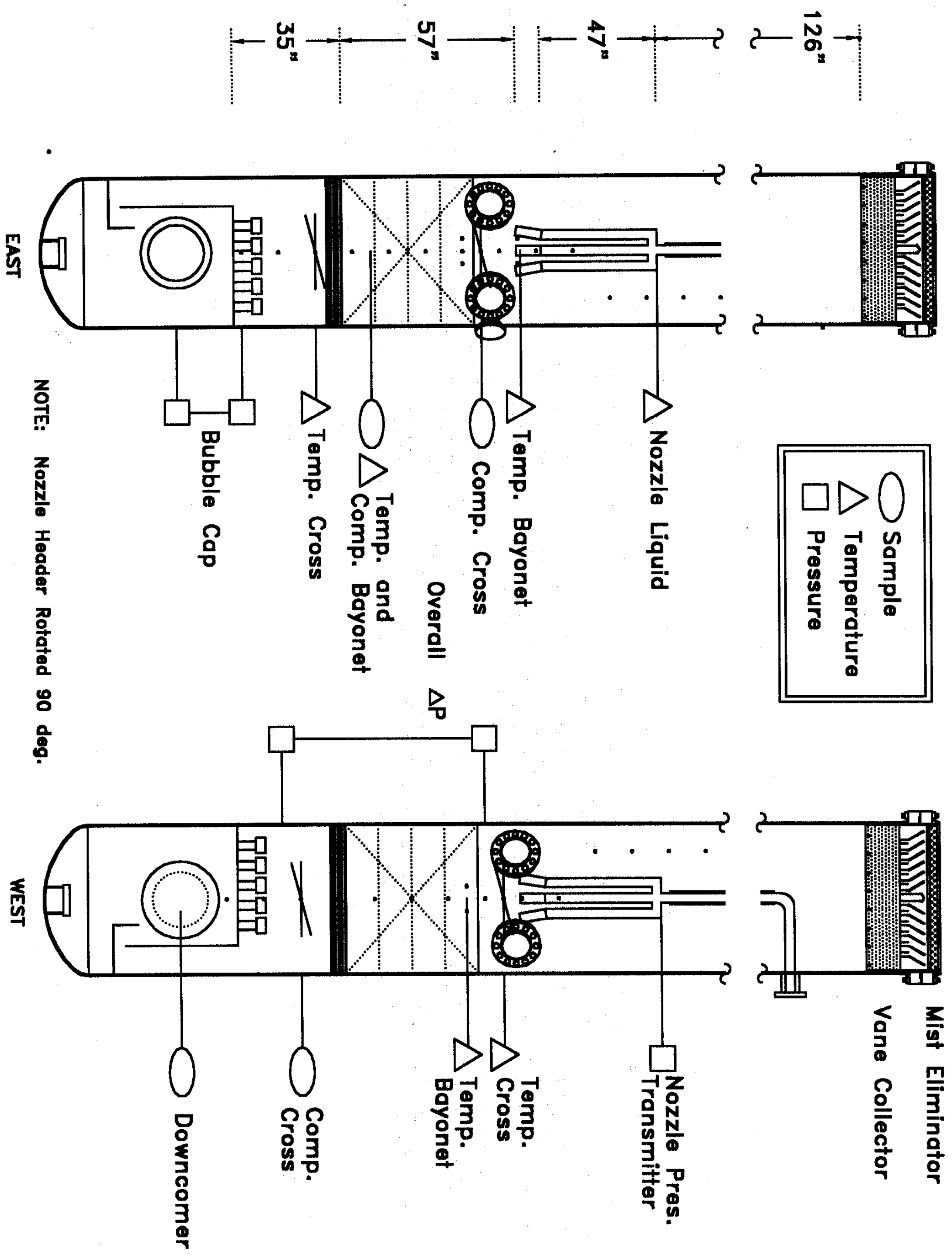


Figure 8. Column Configuration for Short Bed Tests with Orifice Pan Liquid Distributor

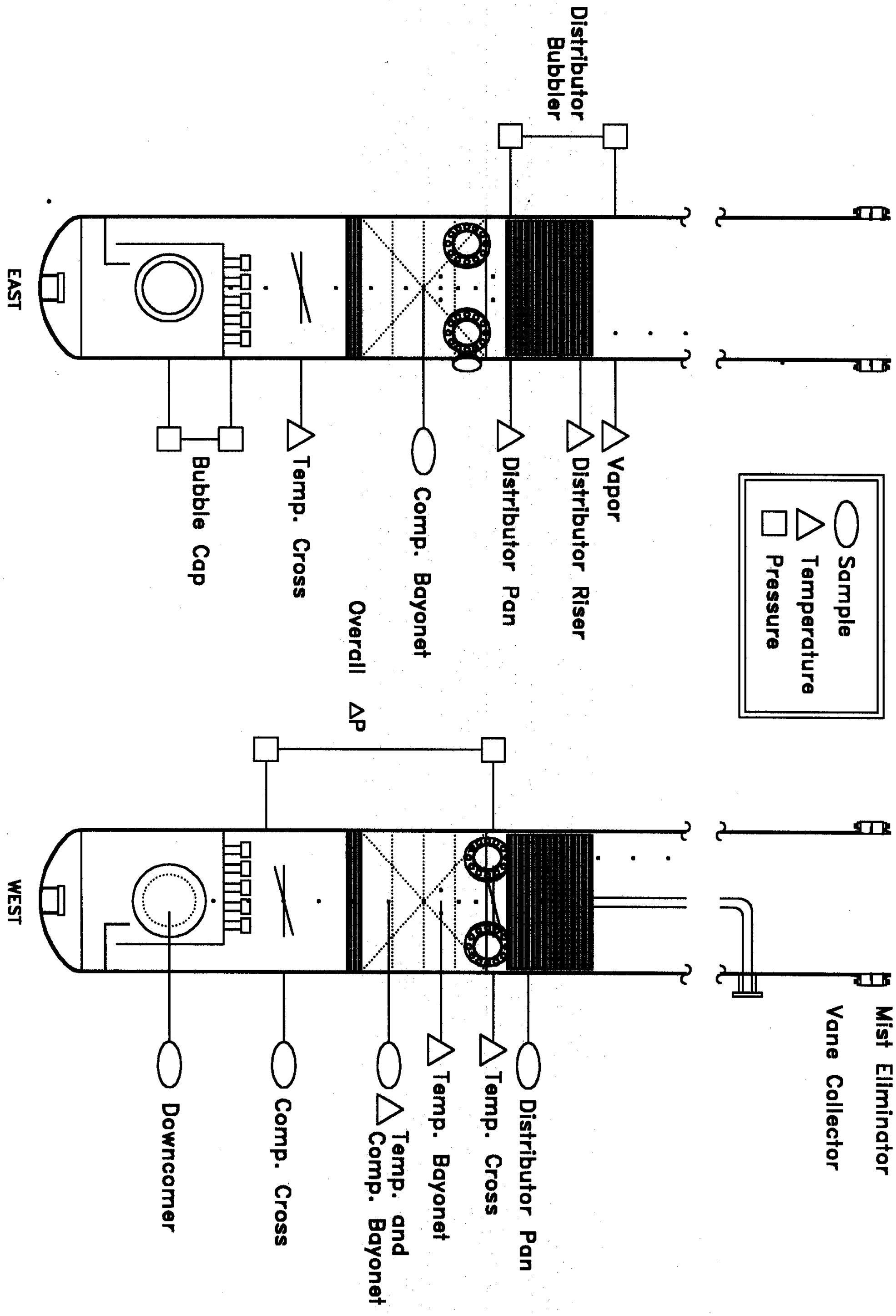


Figure 9. Sketch of the Heat Transfer Measurement Zone for Heat Transfer Analysis

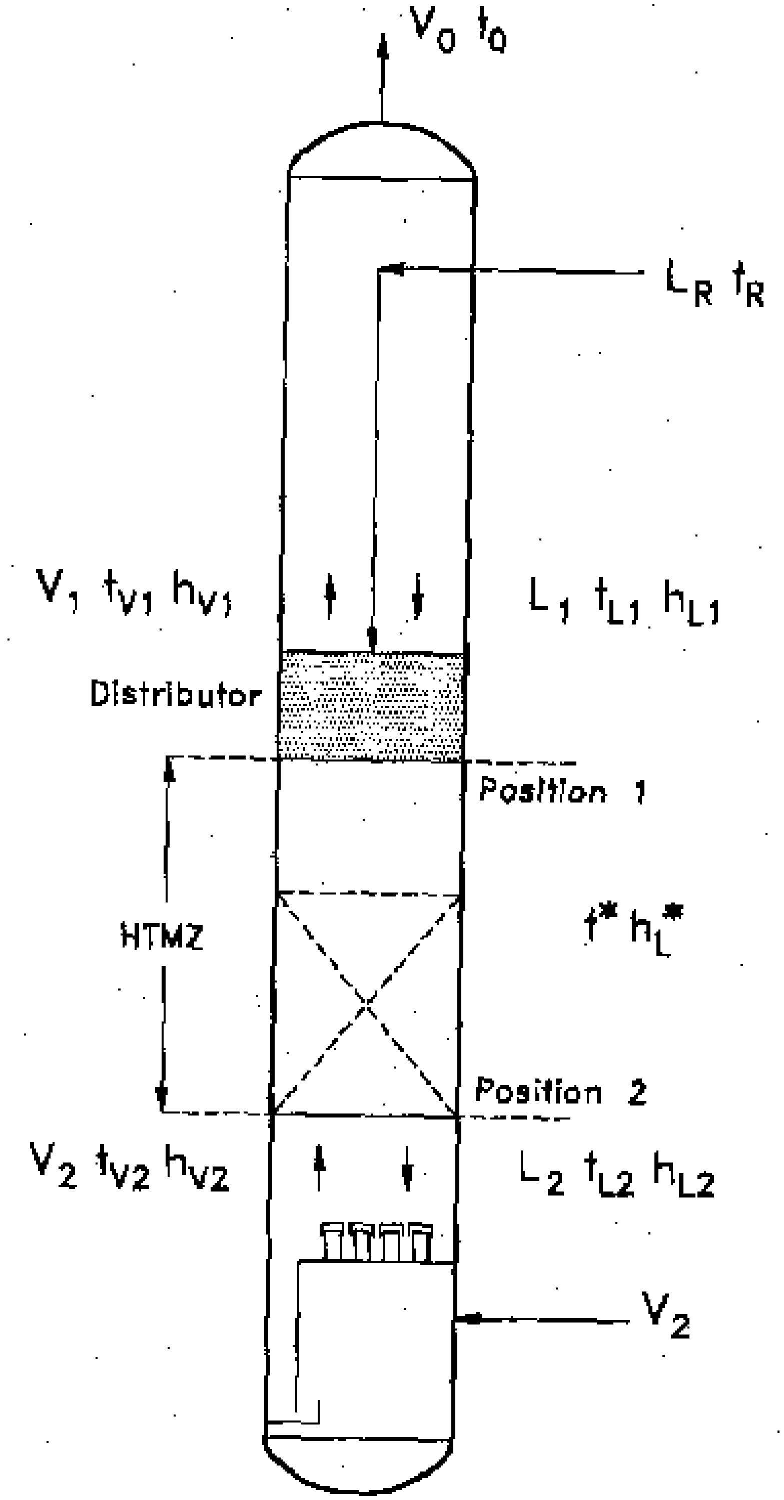


Figure 10. Temperature Profiles of Empty Column with Spray Nozzle Tests

Temperature Difference vs Elevation, C_6/C_7 System 1.65 bar (24 psia)

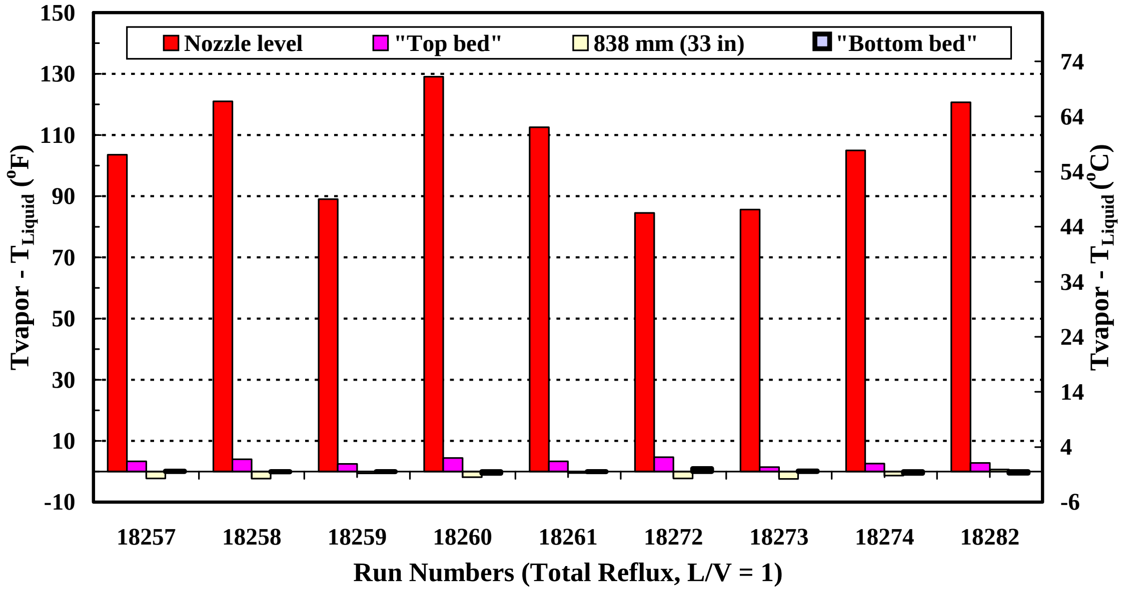


Figure 11. Temperature Profiles of Empty Column with Spray Nozzle Tests

Temperature Difference vs Elevation, C_6/C_7 System 1.65 bar (24 psia)

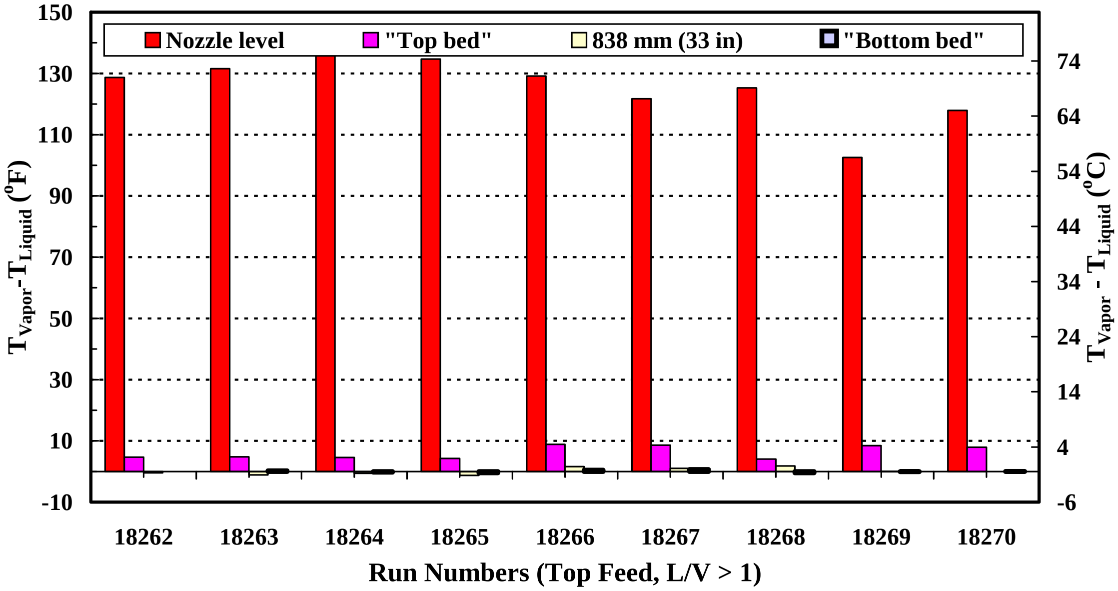


Figure 12. Temperature Profiles
Intalox 4T Short Bed with Spray Nozzle Tests
Temperature Difference vs Elevation, C_6/C_7 System 1.65 bar (24 psia)

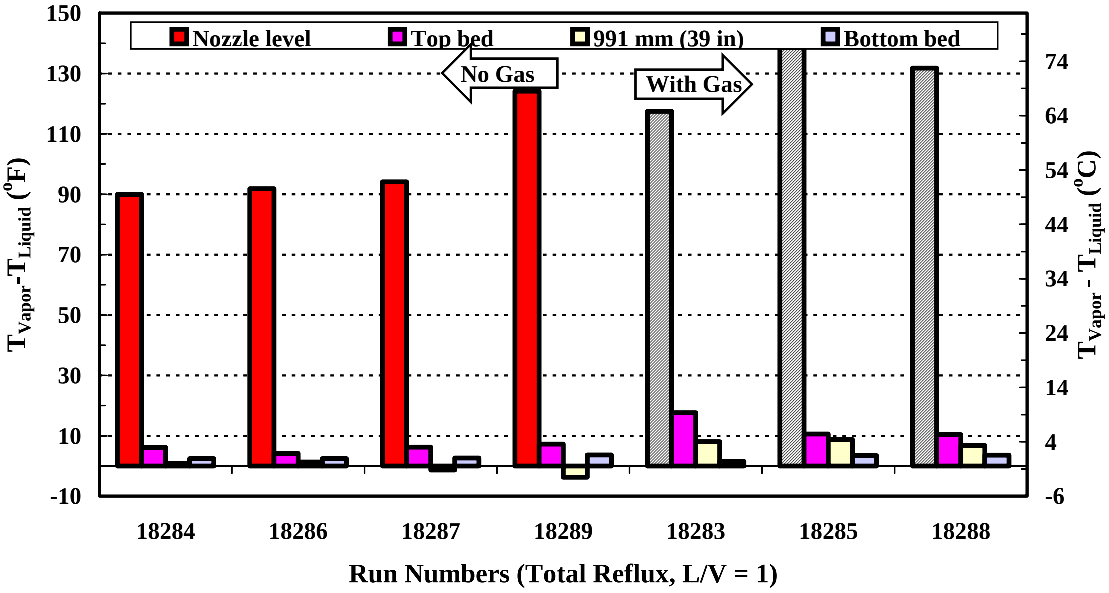


Figure 13. Temperature Profiles
Intalox 4T Short Bed with Spray Nozzle Tests
Temperature Difference vs Elevation, C_6/C_7 System 1.65 bar (24 psia)

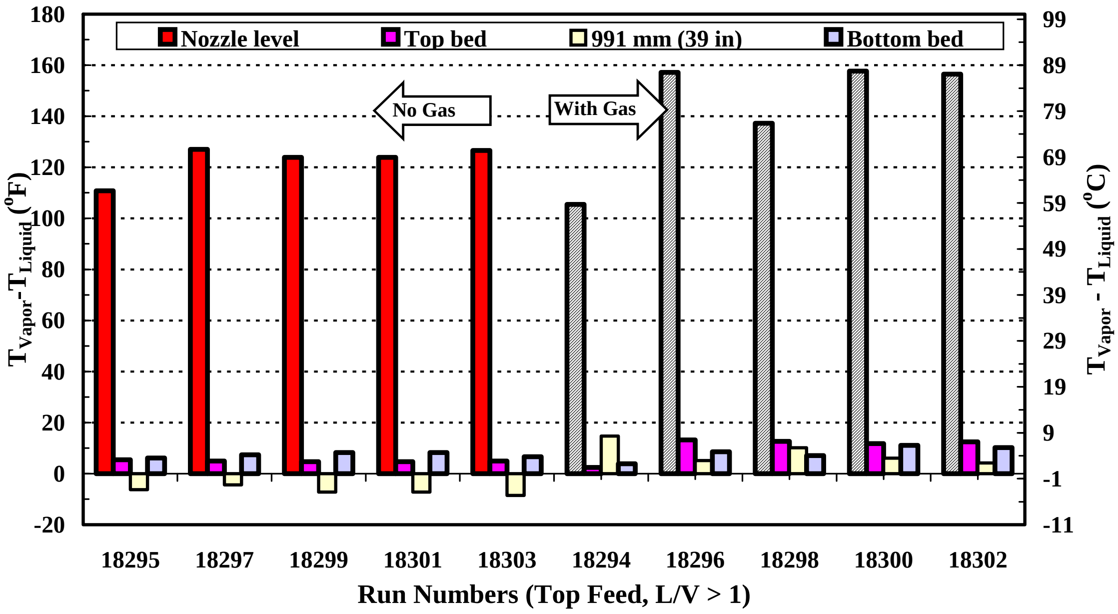


Figure 14. Temperature Profiles
Intalox 4T Short Bed with Norton Liquid Distributor Tests
Temperature Difference vs Elevation, C_6/C_7 System 1.65 bar (24 psia)

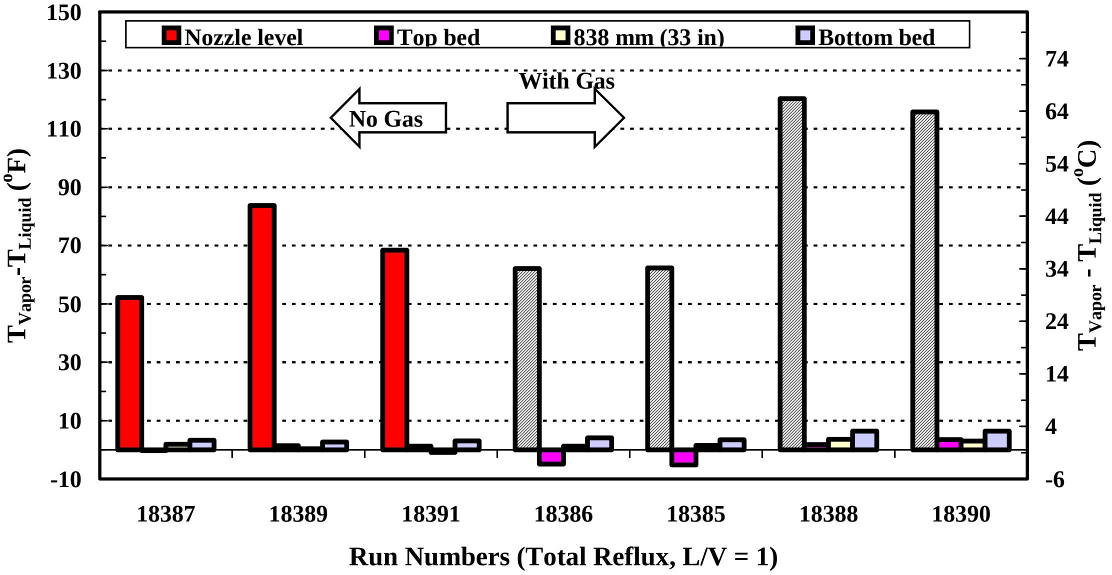


Figure 15. Temperature Profiles
Intalox 4T Short Bed with Norton Liquid Distributor Tests
Temperature Difference vs Elevation, C_6/C_7 System 1.65 bar (24 psia)

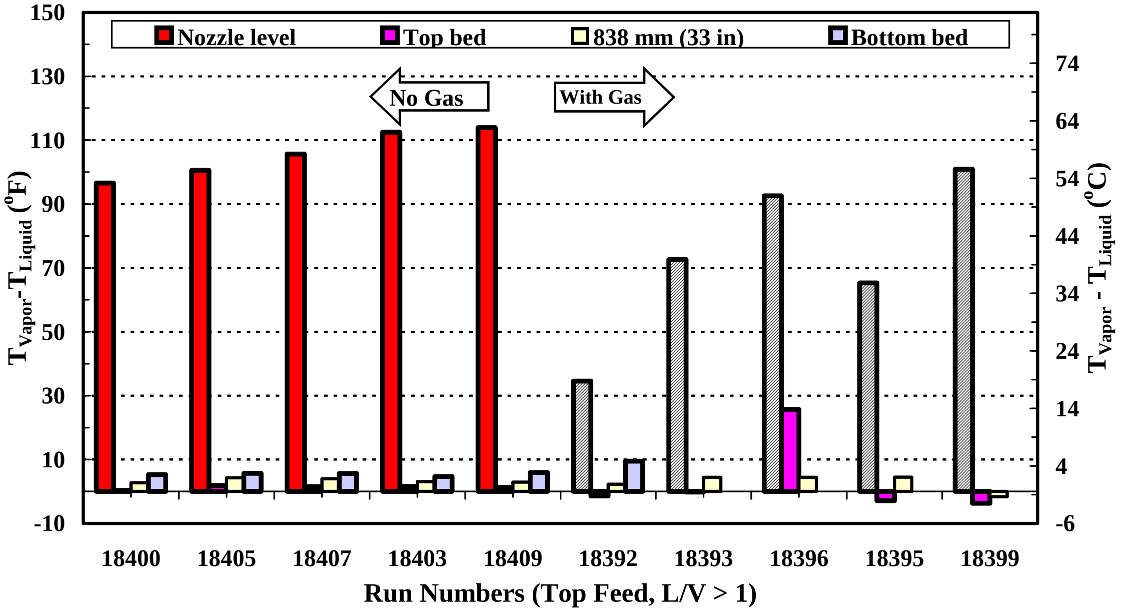


Figure 16. UA at Different Liquid Flow Rates

Empty Column Tests with Spray Nozzle

C_6/C_7 System 1.65 bar (24 psia)