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Development and Application of a Mathematical Model for the
Benzene Stripping Columns in the ITP Process (U)

Summary

A mathematical model characterizing the operation of the benzene stripping columns in the In-Tank Precipitation (ITP) process has been developed. The model was verified using operations data of two stripping columns, and the model predicted reasonable, conservative values of the height of a transfer unit (HTU) and outlet solute concentrations. The model was applied to predict general operating efficiency of the ITP strippers, and predictions indicate that the stripping columns will be able to satisfy benzene removal requirements.

Introduction

The In-Tank Precipitation (ITP) process will remove cesium from waste currently stored at SRS. Saltcake containing cesium, sodium, and other ions will be dissolved for transfer to the processing tank. The cesium will be precipitated by addition of sodium tetraphenyl borate (NaTPB) and the resulting slurry concentrated by crossflow filtration. The cycle will be repeated twice more to generate a total of three portions of cesium salts. The precipitate will be washed to remove the remaining soluble ions, and will finally be sent to the DWPF for processing. The salt solution, minus the cesium, will eventually be transferred to Saltstone for solidification in grout form.

Following the precipitation with NaTPB, some of the TPB is expected to decompose due to radiolysis, forming benzene and other compounds. The presence of benzene introduces two problems. First, the benzene concentration in the decontaminated salt solution (DSS) to be sent to saltstone must be below 2.5 mg/l in order for the grout to satisfy the TCLP test. Secondly, during both the processing and the washing stages, if enough benzene is generated, the vapor in the processing tank may reach the lower flammability limit. Although an inert nitrogen atmosphere will be

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present, limiting the amount of benzene will increase the safety of the ITP process. Therefore, the removal of benzene during operation will serve to ensure environmental as well as safety concerns.

In order to remove benzene from the solutions, two stripping columns have been included in the ITP process. Benzene in the DSS is to be removed in a 30-inch diameter column, packed with 20 feet of Koch FLEXIPAC Type 1 structured packing. The DSS column will treat a maximum of 115 gpm with nitrogen at approximately 440 scfm. The second column will treat between 2 and 33 gpm of wash water with 220 scfm of nitrogen, and reduce the benzene concentration to less than 5 mg/l. The wash water (WW) column has a 16 inch diameter and 20 feet of the same packing.

The columns were designed using actual stripping column data for benzene/water and trichloroethylene/water (from M-Area) systems. A pilot scale test was arranged with the Engineering Test Center (Du Pont) to verify the design of the columns, and experimental results from the test are reported elsewhere (Georgeton and Wilson, 1989). In order to be able to predict column performance (DSS, WW, and pilot test columns), a mathematical description of the stripping process was required. A model from theoretical principles would enable comparisons with test data and data evaluation. The model could also be helpful in identifying general trends in stripping efficiency in the full-scale columns resulting from variations in operating conditions. Finally, the model could also be used in the future to evaluate operating data to help isolate potential problems in column operation.

Model Development

The removal of a volatile solute from solution by stripping with a gas involves mass transfer across a vapor-liquid interface. For a solute that is only slightly soluble (implying a very dilute solution), the rate limiting step in the mass transfer operation is the diffusion of the solute from the bulk solvent to the interface (i.e., liquid phase diffusion controlled). Random or structured packing is used to distribute the liquid as a thin film over the packing surface area, greatly reducing the distance for the solute to diffuse to the vapor-liquid interface. Benzene is soluble in water to a level of approximately 1800 mg/l, but is considerably less soluble in aqueous salt solutions. Thus, removal of benzene from the DSS and the WW is considered a liquid phase diffusion controlled operation.

Theoretical expressions for mass transfer in a packed column have been well documented, e.g. Treybal (1980), King (1980). The height of packing necessary to remove a specified amount of solute from the solution is expressed as:

$$Z = HTU_{OL} * NTU_{OL} \quad (1)$$

where Z = height of packing (ft)
 HTU_{OL} = the height of a transfer unit (ft)
 NTU_{OL} = the number of transfer units.

The mass transfer at a given point in a column is related to the driving force at that point. The driving force is the difference between the bulk phase composition of a component and the equilibrium composition of that component at the vapor-liquid interface. The average driving force in the column produces one unit of change in composition in the bulk fluid. The HTU is defined as the amount of packing necessary to produce that one transfer unit of change in composition. The HTU is regarded as an indicator of the efficiency of the packing for promoting mass transfer (the larger the HTU, the less efficient the packing). The NTU is defined as the quantity of transfer units needed to achieve the specified end composition of solute. The subscript OL in equation (1) indicates that transfer units are obtained from mass transfer coefficients (MTC's) based on overall column compositions in the liquid phase, due to the liquid phase diffusion controlling characteristics of the system.

The height of a transfer unit is calculated from:

$$HTU_{OL} = \frac{L}{K_L a \rho_L} \quad (2)$$

where L = the mass flow rate per unit area ($lb_m/hr \cdot ft^2$)
 K_L = the overall liquid phase mass transfer coefficient (ft/hr)
 a = the area available for mass transfer (ft^2/ft^3)
 ρ_L = the liquid density (lb_m/ft^3).

The overall MTC is related to individual liquid and vapor phase coefficients by:

$$\frac{1}{K_L} = \frac{1}{Hk_G} + \frac{1}{k_L} \quad (3)$$

where k_L = the individual liquid phase MTC (ft/hr)
 k_G = the individual gas phase MTC ($lb_m\text{-mole}/ft^2 \cdot hr \cdot atm$)
 H = Henry's constant ($ft^3 \cdot atm/lb_m\text{-mole}$).

The sum of the inverses in equation (3) indicates contributions of individual resistances to mass transfer. In the case of liquid diffusion control, transfer of the solute from the liquid phase (at the vapor-liquid interface) into the gas phase is instantaneous compared to the transfer of the solute to the interface. Diffusion of the solute through the gas phase is also relatively fast, and the result is a small gas phase resistance. Therefore, in order to minimize the HTU, the value of K_L in equation (2) must be increased. This can be accomplished by

reducing the resistance in the liquid phase (i.e., increasing the value of k_L).

The individual MTC's for the liquid and vapor phase were calculated from the generalized correlations (Perry and Green, pg. 18-34, 18-36, 1984):

$$k_L = 0.0051 \left(\frac{\mu_L g}{\rho_L} \right)^{\frac{1}{3}} \left(\frac{L}{a_w \mu_L} \right)^{\frac{2}{3}} \left(\frac{\mu_L}{\rho_L D_L} \right)^{-0.50} (a_t D_p)^{0.4} \quad (4)$$

and

$$k_G = 5.23 \left(\frac{a_t D_G}{R T_G} \right) \left(\frac{G}{a_t \mu_G} \right)^{0.7} \left(\frac{\mu_G}{\rho_G D_G} \right)^{\frac{1}{3}} (a_t D_p)^{-2.0} \quad (5)$$

where G = mass flow rate of gas stream ($\text{lb}_m/\text{hr}\cdot\text{ft}^2$)
 μ_L = liquid viscosity ($\text{lb}_m/\text{ft}\cdot\text{hr}$)
 μ_G = gas viscosity ($\text{lb}_m/\text{ft}\cdot\text{hr}$)
 ρ_G = gas density (lb_m/ft^3)
 D_L = diffusivity of solute in the liquid phase (ft^2/hr)
 D_G = diffusivity of solute in the gas phase (ft^2/hr)
 a_t = total surface area of the packing (ft^2/ft^3)
 a_w = wetted area of the packing (ft^2/ft^3)
 D_p = equivalent diameter of sphere with same surface area as one particle of packing (ft)
 T_G = gas temperature (K)
 R = gas constant (= $1.314 \text{ ft}^3\cdot\text{atm}/\text{lb}_m\text{-mole}\cdot\text{K}$)
 g = gravitational constant (= $32.17 \text{ ft}/\text{sec}^2$).

These correlations were developed by fitting large quantities of experimental data to within $\pm 20\%$. In equation (4), the wetted area of the packing is calculated from the expression (Perry and Green, pg. 18-34, 1984):

$$\frac{a_w}{a_t} = 1 - \exp\left[-1.45 \left(\frac{\sigma_c}{\sigma} \right)^{0.75} N_{Re}^{0.1} N_{Fr}^{-0.05} N_{We}^{0.2}\right] \quad (6)$$

where σ = the liquid surface tension (dyne/cm)
 σ_c = the critical surface tension of the packing material (dyne/cm),

and the dimensionless Reynolds, Froude, and Weber numbers are defined, respectively, as:

$$N_{Re} = \frac{L}{a_t \mu_L} \quad (7)$$

$$N_{Fr} = \frac{L^2 a_t}{\rho_l^2 g} \quad (8)$$

$$N_{We} = \frac{L^2}{\rho_l \sigma a_t} \quad (9)$$

The number of transfer units is calculated from:

$$NTU_{OL} = \int_{x_{A,in}}^{x_{A,out}} \frac{dx_A}{x_{AE} - x_A} \quad (10)$$

where x_A = mole fraction of solute A in the bulk liquid

x_{AE} = mole fraction of solute A at equilibrium.

At equilibrium, the liquid mole fraction is related to the vapor mole fraction through Henry's Law by:

$$y_{AE} = H' x_{AE} \quad (11)$$

where H' = dimensionless form of Henry's constant.

The compositions of the liquid and vapor streams passing at any point in the column are related through the expression (the operating line):

$$y_A = \frac{L'}{G'} (x_A - x_{A,out}) \quad (12)$$

where y_A = mole fraction of solute in the bulk vapor

$x_{A,out}$ = outlet liquid solute composition

L' = molar flow rate of liquid stream (lb_m-mole/hr·ft²)

G' = molar flow rate of vapor stream (lb_m-mole/hr·ft²).

Several assumptions are inherent in the development of equations (1) through (12). The model was developed for mass transfer of one solute only (i.e., transfer of other solutes follows the same equations, but is independent of transfer of the solute in question). Consequently, there is no "competition" for different solutes to get into the vapor, and the amount of a particular solute in the vapor will be below its saturation point. The use of Henry's Law to describe the vapor-liquid equilibrium limits the use of the model to systems in which the solute is extremely dilute. Since the solute is at very low concentration, only a small amount of solute is transferred between phases. The stream flow rates were, therefore, assumed to be constant over the height of the packing, implying that the mass of solute is insignificant in the calculations. Vapor properties were taken as properties of pure nitrogen. Finally, no estimation of flooding was included, as the vendor indicated that the packing would only be at 30% of

the flood rate at the flow conditions expected in the ITP strippers (diFulgentiz, 1989).

Physical Property Calculation

In the model development above, it is apparent that mass transfer depends strongly upon physical properties of the fluids, as well as on operating parameters. Many mathematical expressions exist to describe the thermophysical properties of organics in aqueous solution and dissolved salts in aqueous solution. However, data and/or correlations for aqueous solutions of organics and salts are scarce, at best. In tailoring this model to the ITP strippers, experimental data for basic physical properties -- viscosity, density, solubility -- of simulated salt solutions were used (Walker, 1989; Walker and Georgetown, 1989). Physical parameters that are determined from these properties, such as diffusivity, were calculated using these experimental data in generalized estimation relations. This is based on the assumption that the salt solution behaves identically to a pure organic fluid having the same density, viscosity, etc., and that the physical properties of the solution fall within the application range of the relations.

The diffusivity of a solute through a liquid solvent was estimated from the generalized correlation for aqueous solutions (Reid, Prausnitz, and Poling, pg. 602, 1987):

$$D_L \text{ (cm}^2\text{/sec)} = 1.25 \cdot 10^{-8} (V_A^{0.19} - 0.292) T^{1.32} \mu_L^{\epsilon} \quad (13)$$

where

$$\epsilon = \left(\frac{9.58}{V_A} \right) - 1.12 \quad (14)$$

and T = liquid temperature (K)
 μ_L = liquid viscosity (cp)
 V_A = molar volume of the solute at the normal boiling temperature (cm³/mole).

For benzene, the molar volume is 96 cm³/mole.

The surface tension of aqueous salt solutions was estimated from the expression (Horvath, pg. 309, 1985):

$$\sigma = \sigma_w + \frac{79.517}{D} C_2 \log_{10} \left[1.143 \cdot 10^{-13} \frac{(DT)^3}{C_2} \right] \quad (15)$$

where C_2 = salt concentration
 σ_w = surface tension of water, 72.0 dyne/cm at 20°C

and D , the dielectric constant of water, was obtained from the

relation (Horvath, pg. 310, 1985):

$$D = 78.54 [1 - 0.0046(T-298.2) + 8.8 \cdot 10^{-6}(T-298.2)^2] \quad (16)$$

The surface tension of water was assumed to be constant over the temperature range considered in this work. The molar concentration of the sodium ion was used in equation (15) for the salt concentration.

For the vapor phase, the density was calculated using the ideal gas law:

$$\rho_g = \frac{P \cdot MW_g}{R \cdot T_g} \quad (17)$$

where P = system pressure (atm)
 MW_g = gas molecular weight (lb_m/lb_m-mole).

The molecular weight of the vapor was assumed to remain constant over the entire column, implying that the amount of solute in the gas phase is negligible in the calculation of vapor properties.

The viscosity of the gas was obtained from kinetic theory (Reid, Prausnitz, and Poling, pg. 391, 1987):

$$\mu_g (\mu p) = \frac{26.69 \sqrt{MW_g T_g}}{D_{HS}^2} \quad (18)$$

where D_{HS} = hard sphere diameter of the gas molecules (Å).

The general expression for the diffusivity of a solute in the gas phase (Reid, Prausnitz, and Sherwood, pg. 554, 1977) is

$$D_o = \frac{10^{-3} T_g^{1.75} \left(\frac{MW_A + MW_B}{MW_A * MW_B} \right)^{1/2}}{P \left[\left(\sum v_A \right)^{1/3} + \left(\sum v_B \right)^{1/3} \right]^2} \quad (19)$$

In equation (19),

- MW_A = gas molecular weight (gm/mole)
- MW_B = solute molecular weight (gm/mole)
- $\sum v_A$ = atomic diffusion volume of the gas
- $\sum v_B$ = atomic diffusion volume of the solute.

For benzene diffusing through nitrogen, the atomic diffusion volumes are 90.68 and 17.9, respectively.

Henry's Law constant (based on concentration) for benzene in solution was estimated from the equation for nonideal systems (Matter-Muller, et al., 1981)

$$H_c = \frac{P^\circ MW_b}{R T} \left(\frac{1}{S_b} \right) = \frac{\text{Solute Concentration in Gas Phase}}{\text{Solute Concentration in Liquid Phase}} \quad (20)$$

where H_c = Henry's Law constant relating gas and liquid concentrations

P° = vapor pressure of pure solute (atm)

R = gas constant (= 0.082055 l·atm/mole·K)

S_b = solute solubility in the liquid (gm/ml).

The vapor pressure of benzene was calculated using an Antoine expression:

$$\ln P^\circ = 9.2675 - \frac{2788.51}{T - 52.36} \quad (21)$$

The dimensionless form of Henry's constant used in equation (11) was calculated from the ratio of gas and liquid mole fractions obtained from H_c in equation (20). Henry's constant in equation (3) was calculated via the expression:

$$H' = \frac{P_b}{C_b} \quad (22)$$

where P_b = partial pressure of solute in the gas phase (atm)

C_b = solute concentration in the liquid phase (gm/l).

The partial pressure was calculated using the ideal gas law.

The correlations for the mass transfer coefficients were obtained from experimental data of vapor-liquid contactors where random, dumped packing was used. To develop the model, the packing was assumed to be 1" steel Pall rings. However, the ITP process strippers will be filled with Koch Flexipac structured packing. The vendor has indicated that this type of structured packing has a surface area of 152 ft²/ft³, and is at least 75% more efficient than 1" Pall rings (diFulgentiz, 1989). The efficiency increase is attributed to greater surface area, less pressure drop across the packing, and improved gas-liquid contacting. To implement the efficiency increase in the model, it was assumed that the improvement was entirely due to the increased surface area. The consequence of this assumption was that there were more Pall rings per unit volume. However, flow characteristics were assumed to remain the same, analogous to the structured packing, which has more surface area but less pressure drop. The data used for the packing were:

Dumped Packing	Structured Packing
$a_t = 63 \text{ ft}^2/\text{ft}^3$	$a_t = 150 \text{ ft}^2/\text{ft}^3$
$\#/vol = 1405/\text{ft}^3$	$\#/vol = 3345/\text{ft}^3$
$\sigma_c = 75 \text{ dyne/cm}$	$\sigma_c = 75 \text{ dyne/cm}$

A good deal of conservatism was included in the model. The values of the individual MTC's calculated with equations (4) and (5) were reduced by 20% before being used to determine the overall MTC. This implied that the values were at the +20% limit of the correlation, so the smaller values effectively reduced the transport rate of solute through the liquid and vapor phases. In addition, this correction acted to balance any improvements that may have been a consequence of error in the physical property calculations. Also related to the physical properties, equation (20) was used to estimate Henry's constant from solubility data, rather than using experimental vapor-liquid equilibrium data. Walker (1989) compared the predicted values against experimental values, and found that the experimental values were slightly larger. The result is that smaller Henry's constants in the model translate into less benzene going into the vapor phase at a given liquid composition, thereby making the separation more difficult.

Finally, the effective mass transfer area was assumed to be only the wetted area, as calculated from equation (6). In reality, mass transfer also occurs in the space above and below the packing, around the distributor, by droplets, and other places away from the wetted area of the packing.

Calculation Procedure

Column conditions were first specified, including liquid and gas flow rates, concentrations of benzene and salts, and temperature and pressure. All benzene concentrations were converted to mole fractions. The physical properties of the streams were calculated next using equations (13) through (22). Individual mass transfer coefficients from equations (4) and (5) were then calculated, and these values were used in equation (3) to calculate the overall MTC. Finally the HTU was obtained from equation (2).

The NTU was calculated via numerical integration, using the trapezoidal rule. The range of integration (the liquid inlet composition to the specified outlet composition for benzene) was first divided into 100 "steps". For a given bulk liquid composition, the corresponding vapor composition was determined from the operating line expression, equation (12). The equilibrium liquid composition was then calculated from Henry's Law, equation (11). The integrand in equation (10) was calculated, and the procedure was repeated for each remaining step along the composition range. The total area obtained from the integration (the NTU) was multiplied by the HTU in equation (1) to determine the height of packing required to reduce the benzene to the specified level.

The calculation procedure was incorporated into a FORTRAN program, and the computer code is included as Appendix A in the record copy of this document.

Model Verification

Operating data from the M-Area trichloroethylene (TCE) stripping column (Jacobs, 1988) packed with 1" plastic Pall rings were used in verifying the model. The data were used as a qualification of the basic mathematical model, without including any assumptions for structured packing. Physical properties of TCE in water and of plastic packing were substituted for benzene in salt solution and for steel packing, and data for operating conditions were used. The HTU was predicted to be 3.2 feet, compared to an HTU of 2.9 feet obtained during operation. During normal column operation, the TCE concentration was reduced to below 1 ppb, whereas the model predicted a final benzene concentration of less than 20 ppb. The validity of the semi-empirical model was confirmed by agreement to within 10% (with results being conservative).

The assumptions for characterizing the structured packing were then verified using data from a benzene stripping column at a Du Pont Facility in Corpus Christi (Jacobs, 1988). The stripper was packed with the same structured packing that will be used in the ITP process strippers. Operating data indicated an HTU of approximately 2.0 feet, compared to the model prediction of 2.2 feet. For an inlet stream containing 200 ppm of benzene, the model predicted the benzene outlet concentration to be 27 ppm, compared to the 25 ppm concentration observed during column operation. The conservative agreement to 10% indicated that the assumptions made in the model for describing the structured packing were reasonable, and that the model can be used with confidence to predict the performance of the stripping columns in the ITP process.

Model Application to ITP Strippers

Following verification, the model was used to predict operating efficiencies to be used as a baseline for the ITP benzene strippers. Calculations were made for each column at the maximum and minimum liquid rates, at 20°C. Gas flow rates for each column were taken as the specified design rates, also at 20°C. The outlet benzene concentrations were predicted for both the maximum expected and for relatively low inlet concentrations.

For the DSS column, at a maximum liquid flow of 115 gpm, the HTU was calculated to be 4.9 feet. At a maximum inlet concentration of 110 mg/l, the column was predicted to reduce the amount of benzene to 2 mg/l. Similarly, at the low inlet value of 20 mg/l, the outlet concentration was estimated to be 0.4 mg/l. For the minimum liquid rate (same vapor flow), the efficiency of the packing was expected to improve, and this was confirmed by the predicted HTU of 3.2 feet at 20 gpm. The estimated outlet concentration was 0.3 mg/l at 110 mg/l inlet level, and 0.05 mg/l at 20 mg/l inlet level.

At the maximum liquid rate (33 gpm) in the WW column, the HTU was

predicted to be 2.8 feet. At 3000 mg/l inlet concentration, the effluent was predicted to contain 4.0 mg/l benzene, and at 500 mg/l, the effluent was estimated to contain 0.7 mg/l benzene. (The solubility of benzene in the wash water is approximately 500 mg/l, and, therefore, 3000 mg/l would result in the formation of a second liquid phase. This organic phase would come into direct contact with the nitrogen. The result is that excess benzene would be removed much more easily and completely, since the excess amount would not have to diffuse through water.) For a liquid flow of 5.5 gpm, the HTU was predicted to be 1.8 feet, and the outlet concentrations to be 1.0 mg/l and 0.2 mg/l for inlet concentrations of 3000 mg/l and 500 mg/l, respectively.

Conclusions

The mathematical model developed and tailored to the stripping columns in the ITP process was useful in establishing a baseline of operating efficiency. Predictions with the model indicated that both columns will be able to reduce benzene to the required levels. It should be noted that at maximum liquid rates and benzene concentrations, both columns will be producing effluent that contains close to the maximum amount of benzene allowed (DSS column: 2 mg/l vs. 2.5 mg/l limit; WW column: 4.0 mg/l vs. 5.0 mg/l limit), thereby minimizing the operating margin.

However, as seen in the predictions, the efficiency can be affected by changes in liquid rate and inlet composition, and the effect of changes in these and other variables on benzene removal needs to be examined. Predictions of packing efficiency with this model, dependent upon operating conditions, are summarized in the report by Georgeton (1989).

Quality Assurance

The mathematical model was developed from well established chemical engineering principles in accordance with specifications in the SRL QA Manual. Appendices to this document are included in the Record Copy. The FORTRAN program listing is included as Appendix A. A hand calculation used to validate the program and a sample output from the program are included as Appendices B and C, respectively.

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APPENDIX A. FORTRAN Program of Stripping Column Model

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PROGRAM MAIN
C
C program to model the packed column stripper.
C
C NOTE!! the physical properties generated in this program are based
C NOTE!! on data for the following distribution of salt. If the
C NOTE!! program is used with solutions having different relative
C NOTE!! amounts of salts, then the accuracy of the calculations
C NOTE!! cannot be guaranteed.
C
C      Na+      6M
C      OH-      1.7M
C      NO3-     2.4M
C      NO2-     0.74M
C      CO3-     0.21M
C      SO4-     0.18M
C      AlO2-    0.40M
C
C real variables
C
C REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
C REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
+ XIN, XOUT, LIQUID, HDIMLS
C REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C REAL PPMIN, PPMOUT, PPMNST, H, CVAREA, NTU, HTUL
C
C character variables
C
C CHARACTER DFILE*15
C
C common blocks
C
C COMMON /LIQDAT/ LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
+ SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
C COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
+ VAPOR
C COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C data
C
C GASMW = 28.02
C
C data files
C
C WRITE (6,601)
601 FORMAT(2X,'What is the name of the data file? --->:')
C READ (5,501) DFILE
501 FORMAT (A15)
C OPEN ( UNIT = 7, FILE = DFILE, STATUS = 'OLD' )
C
C read in the data
C
C READ (7,*) HEIGHT, DIAM
C READ (7,*) ATOT, PACKIN, SIGMAC
C READ (7,*) LIQUID, LTEMP
C READ (7,*) MLRITY, PPMIN, PPMOUT
C READ (7,*) VAPOR, GTEMP
C READ (7,*) PRESS
C
C WRITE (6,602)
C READ (5,*) FUDGE

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C
C   convert input data to proper units
C
C   LTEMP = LTEMP + 273.2
C   GTEMP = GTEMP + 273.2
C
C   get the packing and column data
C
C   CALL COLUMN ( DIAM, PACKIN )
C
C   calculate the physical properties of the streams
C
C   CALL VPROPS
C   CALL LPROPS
C
C   output information
C
C   WRITE (6,610) LIQUID, VAPOR, LMASS, GMASS, MLRITY,
C   +           MUL, RHOL, RHOG, DIFFL, HENRYS, HDIMLS
C
C   calculate mass transfer coefficient
C
C   CALL LTLKG ( SMALKG )
C   CALL LTLKL ( SMALKL )
C   WRITE (6,609) HEIGHT, DIAM, ATOT, AWET, AEFF
C
C   the correlations used for the mass transfer coefficients are reported
C   accurate to +/- 20%. for a conservative calculation, the calculated
C   values are reduced by 20%.
C
C   BIGKL = 1. / ( (1. / (HENRYS * FUDGE * SMALKG)) +
C   +           (1. / (FUDGE * SMALKL)) )
C
C   calculate the HTU's
C
C   HTUL = LMASS / (BIGKL * RHOL * AEFF)
C   WRITE (6,613) SMALKL, SMALKG, BIGKL, FUDGE, HTUL
C
C   loop construction to allow user input of inlet and outlet benzene
C   concentrations. used to determine exit concentration for a given
C   height of packing by trial and error.
C
C 1 WRITE (6,611)
C   READ (5,*) PPMIN, PPMOUT
C   IF ( PPMIN .EQ. 0. ) STOP
C
C   now integrate the NTU expression to determine total height required
C   for the desired separation, and how far we can get with what we
C   have now.
C
C   controlling loop to numerically evaluate the integral
C
C   NTU = 0.
C   CALL CNCTOX ( PPMIN, XIN )
C   CALL CNCTOX ( PPMOUT, XOUT )
C   H = (XIN - XOUT) / 100.
C   XA = XIN
C   XB = XIN - H
C   DO 10 I=1,100
C     CALL INTGRT ( XA, XB, H, CVAREA )
C
C   use the negative of the area, since going in opposite direction of
C   the integral summing the area
C
C   NTU = NTU + (-CVAREA)

```

```

      XA = XB
      XB = XB - H
10 CONTINUE
      WRITE (6,640) PPMIN, PPMOUT, HTUL*NTU
C
      GO TO 1
C
      format statements
C
602 FORMAT(2X,'Enter the Mass Transfer Coefficient Adjustment Value'
+         /5X,'( 0 < Value < 5 )')
C
609 FORMAT(/2X,'COLUMN HEIGHT = ',F4.1,' FEET, WITH DIAMETER = ',F5.1,
+         ' INCHES'/2X,'PACKING AREA = ',F5.1,' FT**2/FT**3 ',
-         ' WETTED AREA = ',F5.1,' FT**2/FT**3'/2X,
*         'EFFECTIVE AREA = ',F5.1,' FT**2/FT**3')
C
610 FORMAT(/2X,'LIQUID RATE = ',F6.1,' GAL/MIN  VAPOR RATE = ',
+         F6.1,' SCFM'/2X,'LIQUID MASS RATE = ',F8.2,' LBM/HR-FT**2'
-         ', VAPOR MASS RATE = ',F8.2,' LBM/HR-FT**2'/2X,
*         'LIQUID SALT CONC = ',F3.1,' M    LIQUID VISCOSITY = ',
/         F6.2,' LBM/FT-HR'/2X,'LIQUID DENSITY = ',F7.2,
-         ' LBM/FT**3    VAPOR DENSITY = ',E9.4,' LBM/FT**3'/2X,
>         'LIQUID DIFFUSION COEFFICIENT = ', E9.4,' FT**2/HR'//2X,
<         'HENRY'S CONSTANT = ',F6.1,' FT**3-ATM/LBMMOLE'/2X,
!         'DIMENSIONLESS HENRY'S CONSTANT = ',F7.1)
C
611 FORMAT(/2X,'Enter the inlet and desired outlet concentration',
+         ' in PPM'/5X,'(Enter 0,0 to end run)')
C
613 FORMAT(/2X,'INDIVIDUAL LIQUID PHASE MASS TRANSFER COEFF = ',F8.4
+         /2X,'INDIVIDUAL VAPOR PHASE MASS TRANSFER COEFF = ',F8.4
-         /2X,'OVERALL LIQUID PHASE MASS TRANSFER COEFF = ',F8.4,
*         ' (AT ',F4.1,' TIMES THE MTC'S) '//2X,
/         'HEIGHT OF A LIQUID PHASE TRANSFER UNIT = ',F5.2,' FEET')
C
640 FORMAT(/2X,'IN ORDER TO GO FROM ',F6.1,' TO ',F6.1,' PPM, WE NEED'
+         ,F6.1,' FEET OF COLUMN')
C
      END
C
      subroutine to generate information about column and packing
C
      SUBROUTINE COLUMN ( DIAM, PACKIN )
C
      real variables
C
      REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
      REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
+       XIN, XOUT, LIQUID, HDIMLS
      REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
      common blocks
C
      COMMON /LIQDAT/ LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
+       SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
      COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
+       VAPOR
      COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
      AREA = 3.14159 * (DIAM/12.)**2 / 4.
C
      EACH = ATOT / PACKIN
      PDIAM = SQRT(EACH / (4. * 3.14159)) * 2.

```

```

C
C   RETURN
C   END
C
C   subroutine to convert concentration (mg/l) to mole fraction
C
C   SUBROUTINE CNCTOX ( PPM, X )
C
C   real variables
C
C   REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
C   REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
C +   XIN, XOUT, LIQUID, HDIMLS
C   REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C   REAL PPM, X, ERTS, INERTS
C
C   common blocks
C
C   COMMON /LIQDAT/ IMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
C +   SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
C   COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
C +   VAPOR
C   COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C   this assumes constant liquid rate
C
C   benzene - moles based on the concentration
C
C   ERTS = PPM * LIQUID * 3.785 * 60. / 454000.
C           mg/l   gal/min  l/gal  min/hr  mg/lbm
C
C   rest of solution - assumes benzene does not affect solution density
C
C   INERTS = (LIQUID * 60. * RHOL / 7.48) - ERTS
C           gal/min  min/hr  lbm/ft**3  gal/ft**3
C
C   convert to moles
C
C   ERTS = ERTS / 78.12
C   INERTS = INERTS / LIQMW
C
C   mole fraction benzene
C
C   X = ERTS / (INERTS + ERTS)
C
C   RETURN
C   END
C
C   subroutine to perform numerical integration using Simpson's rule
C
C   SUBROUTINE INTGRT( XA, XB, H, CVAREA )
C
C   REAL XA, XB, H, CVAREA, XMID, NTUCRV
C
C   function values are from user supplied function. using simpson's
C   three-point estimation extension of trapezoid rule. NOTE that this
C   expression is written for an interval size of 2h, rather than h,
C   and is adjusted in the expression below.
C
C   XMID = (XA + XB) / 2.
C   CVAREA = (H / 2.) * ( NTUCRV(XA)/3. + (4./3.)*NTUCRV(XMID)
C +   + NTUCRV(XB)/3. )

```

```

C      RETURN
C      END
C
C      subroutine to calculate the liquid phase properties
C
C      SUBROUTINE LPROPS
C
C      real variables
C
C      REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
C      REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
C      +   XIN, XOUT, LIQUID, HDIMLS
C      REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C      REAL SLOPE, SOL40, SOL50, YINT, SOLUB, VAPPRS, BENZMW, GASCNS,
C      +   PRTLPR, X, Y, MUC30, CAPLAR, REYNOL
C
C      common blocks
C
C      COMMON /LIQDAT/ LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
C      +   SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
C      COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
C      +   VAPOR
C      COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C      BENZMW = 78.12
C      GASCNS = 0.082055
C
C      calculate the liquid molecular weight from Molarity.
C
C      LIQMW = 18.005 + (1.1143 * MLRITY) + (1.19252E-02 * MLRITY**2)
C      +   + (8.8727E-04 * MLRITY**3)
C
C      calculate the liquid viscosity. interpolation of data from
C      WSRC-RP-89-1088
C
C      MUC30 = 0.79776 + (9.9524E-02 * MLRITY) + (1.7381E-02 * MLRITY**2)
C      +   + (3.3333E-03 * MLRITY**3)
C      SLOPE = (-0.0073772 * MLRITY) - 0.017839
C      YINT = MUC30 - (SLOPE * 30.)
C
C      MUL = ((SLOPE * (LTEMP-273.2) ) + YINT) * 2.419
C
C      lbm/ft-hr / cp
C
C      calculate liquid density
C
C      RHOL = (0.99455 + (4.5792E-02 * MLRITY) ) * 62.36
C
C      lbm/ft**3 / gm/ml
C
C      liquid phase diffusivity, Reid Prausnitz and Poling, pg 602
C
C      VA = 96.5
C      GOODMU = MUL / 2.419
C      EPSLON = (9.58 / VA) - 1.12
C      DIFFL = (1.25E-08 * (VA**(-0.19) - 0.292) * (LTEMP**1.52)
C      +   * (GOODMU**EPSLON) ) * 3600. / 30.48**2
C
C      surface tension of the liquid, from "handbook of aqueous electrolyte
C      solutions" pg 309. reference solution - water at 25 deg c
C
C      DIELEC = 78.54 * (.1 - (0.0046 * (LTEMP-273.2-25.))
C      +   + (8.8E-06 * (LTEMP-273.2-25.))**2) )
C      TERM = 1.143E-13 * (DIELEC * LTEMP)**3 / MLRITY
C      SIGMA = 72.0 + ( 79.517 / DIELEC * MLRITY * ALOG10(TERM) )

```

```

C
C   put liquid rate in appropriate units
C
C   LMASS = LIQUID * RHOL * 60. / (7.48 * AREA)
C
C   henry's constant calculation, two forms. dimensionless form is
C   from solubility data of benzene in salt solution, and dimensioned
C   form is from assumption for mass transfer coefficient equations.
C
C   start with solubility of average salt solution at 40 and 50 deg C.
C
C   SOL40 = 1.9434 * EXP(-0.4446 * MLRITY)
C   SOL50 = 1.9811 * EXP(-0.4075 * MLRITY)
C
C   linearize
C
C   SLOPE = (SOL50 - SOL40) / (50. - 40.)
C   YINT = SOL40 - (SLOPE * 40.)
C   SOLUB = (SLOPE * (LTEMP-273.2)) + YINT
C
C   now dimensionless henry's constant, concentration version
C
C   VAPPRS = 15.9008 - (2788.51 / (LTEMP - 52.36) )
C   VAPPRS = EXP(VAPPRS) / 760.
C   HDIMLS = VAPPRS * BENZMW / (GASCNS * LTEMP * SOLUB)
C
C   now correct to mole fraction version. since henry's constant is that,
C   any composition can be used.
C
C   XPPM = 100.
C
C   get vapor composition, then convert to mole fractions.
C
C   YPPM = HDIMLS * XPPM
C   CALL CNCTOX ( XPPM, X )
C   YMOLEB = (YPPM / 1000.) * 3.785 * 7.48 / (454. * BENZMW)
C           gm/l          l/gal gal/ft**3  gm/lbm  lbm/lbmole
C   PRTLPR = YMOLEB * 1.314 * GTEMP
C
C   YMOLEN = RHOG / GASMW
C
C   when average gas properties are used, YMOLEN will actually be the
C   moles of gas (nitrogen + benzene)
C
C   Y = YMOLEB / (YMOLEB + YMOLEN)
C
C   dimensionless form
C
C   HDIMLS = Y / X
C
C   dimensioned form
C
C   HENRYS = PRTLPR / (XPPM/1000.) * BENZMW * 454. / (3.785 * 7.48)
C           atm-l/gm          gm/lbm  l/gal  gal/ft**3
C
C   RETURN
C   END
C
C   subroutine to calculate the gas phase, local mass transfer
C   coefficient  KG
C
C   SUBROUTINE LTLKG ( SMALKG )
C
C   real variables

```

```

REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
+   XIN, XOUT, LIQUID, HDIMLS
REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C   common blocks
C
COMMON /LIQDAT/ LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
+   SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
+   VAPOR
COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C
GASCNS = 1.314
C1 = 5.23
C
C   KG calculation
C
TERM1 = ATOT * DIFFG / (GASCNS * GTEMP) * C1
TERM2 = ( GMASS / (ATOT * MUG) )**0.7
TERM3 = ( MUG / (RHOG * DIFFG) )**(1./3.)
TERM4 = ( ATOT * PDIAM )**(-2.0)
SMALKG = TERM1 * TERM2 * TERM3 * TERM4
C
RETURN
END
C
C   subroutine to calculate the liquid phase, local mass transfer
C   coefficient kL
C
SUBROUTINE LTLKL ( SMALKL )
C
C   real variables
C
REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
+   XIN, XOUT, LIQUID, HDIMLS
REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C   common blocks
C
COMMON /LIQDAT/ LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
+   SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
+   VAPOR
COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C   gravity constant in ft/hr**2
C
GRAV = 32.17 * 3600.**2
C
C   calculate wetted area of packing
C
REYNOL = LMASS / (ATOT * MUL)
FROUDE = (LMASS**2 * ATOT) / (RHOL**2 * GRAV)
WESSEL = LMASS**2 / (RHOL * SIGMA * 28568. * ATOT)
TERMS = -1.45 * (SIGMAC / SIGMA)**0.75 * REYNOL**0.1
+   * FROUDE**(-0.05) * WESSEL**0.2
AWET = ATOT * ( 1. - EXP(TERMS) )
C
C   assume that the effective area is equal to the wetted area.  this
C   should be a minimum value for the effective area, providing some
C   conservatism.

```

```

C
C   AEFF = AWET
C
C   calculate little k sub 1
C
C   TERM1 = ( LMASS/(AWET * MUL) )**(2./3.)
C   TERM2 = ( MUL/(RHOL * DIFFL) )**(-0.5)
C   TERM3 = ( ATOT * PDIAM )**0.4
C   TERM4 = ( RHOL/(MUL * GRAV) )**(1./3.)
C   SMALKL = 0.0051 * TERM1 * TERM2 * TERM3 / TERM4
C
C   RETURN
C   END
C
C
C   function to evaluate the integrand in the NTU expression
C
C   REAL FUNCTION NTUCRV ( X )
C
C   REAL X
C
C   real variables
C
C   REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
C   REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
C   +   XIN, XOUT, LIQUID, HDIMLS
C   REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C   common blocks
C
C   COMMON /LIQDAT/ LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
C   +   SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
C   COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
C   +   VAPOR
C   COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
C   calculate the passing vapor stream composition from the operating
C   line
C
C   Y = (LMASS/LIQMW) / (GMASS/28.02) * (X - XOUT)
C
C   now calculate the liquid stream in equilibrium with the vapor
C   stream
C
C   XE = Y / HDIMLS
C
C   and now the function
C
C   NTUCRV = 1. / (XE - X)
C
C   RETURN
C   END
C
C
C   subroutine to calculate the gas physical properties
C
C   SUBROUTINE VPROPS
C
C   real variables
C
C   REAL GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS, VAPOR
C   REAL LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY, SIGMA, HENRYS,
C   +   XIN, XOUT, LIQUID, HDIMLS
C   REAL AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C

```

```

REAL MWRAT, NITROG, BENZEN, HSDIAM, GASCNS, MWBENZ
C
C common blocks
C
COMMON /LIQDAT/ LMASS, LIQMW, LTEMP, MUL, RHOL, DIFFL, MLRITY,
+ SIGMA, HENRYS, XIN, XOUT, LIQUID, HDIMLS
COMMON /GASDAT/ GMASS, GASMW, GTEMP, MUG, RHOG, DIFFG, PRESS,
+ VAPOR
COMMON /COLUMN/ AREA, ATOT, AWET, PDIAM, SIGMAC, AEFF, HEIGHT
C
GASCNS = 0.7302
NITROG = 17.9
BENZEN = 90.68
HSDIAM = 3.798
MWBENZ = 78.12
C
C use ideal gas law to calculate density in lbm/ft**3
C
RHOG = PRESS * GASMW / (GASCNS * GTEMP * 1.8)
C
C gas diffusivity, Reid Prausnitz and Sherwood, pg 554
C
MWRAT = ( GASMW + MWBENZ ) / (GASMW * MWBENZ)
DENOM = ( (NITROG**(1./3.) + BENZEN**(1./3.))**2) * PRESS
DIFFG = ( 0.001 * GTEMP**(1.75) * SQRT(MWRAT) / DENOM ) * 3600.
+ / 30.48**2
C
C gas viscosity, from kinetic theory, Reid Prausnitz and Poling, pg 391
C
MUG = ( 26.69 * SQRT(GASMW * GTEMP) / HSDIAM**2 ) / 10000. * 2.419
C
C
C put vapor rate in appropriate units
C
GMASS = (VAPOR*GTEMP/294.) * RHOG * 60. / AREA
C
RETURN
END
C
C
C variable definitions
C
BLOCK DATA DFNSHN
C
C global variables
C
DIFFL - diffusivity of benzene through the liquid, ft**2/hr
C
HDIMLS - dimensionless form of Henry's constant
C
HENRYS - henry's constant for benzene in salt solution,
C
LMASS - liquid flow rate, lbm/hr-ft**2
C
LIQMW - liquid molecular weight, lbm/lbm-mole
C
LIQUID - liquid flow rate, gal/min
C
LTEMP - liquid temperature, K
C
MLRITY - sodium ion concentration, moles/liter
C
MUL - liquid viscosity, lbm/ft-hr
C
RHOL - liquid density, lbm/ft**3
C
SIGMA - surface tension of liquid, dynes/cm or lbf/ft
C
ft**3-atm/lbmole
C
XIN - benzene composition in liquid phase at inlet, mole fraction
C
XOUT - benzene composition in liquid phase at outlet, mole fraction
C
C
DIFFG - benzene diffusivity in gas phase, ft**2/hr
C
GMASS - gas flow rate, lbm/hr-ft**2
C
GASMW - gas molecular weight, lbm/lbm-mole
C
GTEMP - temperature of inlet gas stream, K

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C   MUG      - gas phase viscosity, lbm/ft-hr
C   PRESS    - column pressure, atm
C   RHOG     - gas phase density, lbm/ft**3
C   VAPOR    - gas flow rate at STP, scfm
C
C   AEFF     - effective area of packing used in mass transfer, ft**2
C   AREA     - packing cross sectional area, ft**2
C   ATOT     - total available packing surface area, ft**2/ft**3
C   AWET     - wetted area of packing, ft**2/ft**3
C   HEIGHT   - height of packing, ft
C   PDIAM    - diameter of sphere with same surface area as 1 piece
C             of packing, ft
C   SIGMAC   - critical surface tension for the packing, dynes/cm
C
C   main program
C
C   BIGKL    - overall liquid phase mass transfer coefficient, ft/hr
C   CVAREA   - summation of integrands evaluated at each step
C   DFILE    - name of the data file
C   FUDGE    - factor to adjust individual mass transfer coefficients
C   H        - step size in numerical integration
C   HTUL     - height of a transfer unit, ft
C   NTU      - number of transfer units
C   PACKIN   - number of pieces of packing per ft**3
C   PPMIN    - benzene concentration in inlet, mg/l
C   PPMOUT   - benzene concentration in outlet, mg/l
C   SMALKL   - individual liquid phase mass transfer coefficient, ft/hr
C   SMALKG   - individual gas phase mass transfer coefficient,
C             lbmmole/hr-ft**2-atm
C   XA       - benzene composition in liquid at beginning of step
C   XB       - benzene composition in liquid at end of step
C
C   subroutine COLUMN
C
C   DIAM     - diameter of the packing, inches
C   EACH     - surface area of 1 particle of packing, ft**2
C   PACKIN   - number of packing particles per ft**3
C
C   subroutine CNCTOX
C
C   ERTS     - amount of benzene in entering liquid, lbm/hr
C   INERTS   - amount of non-benzene components, lbm/hr
C   PPM      - benzene concentration, mg/l
C   X        - mole fraction of benzene
C
C   subroutine INTGRT
C
C   CVAREA   - area under the curve for the increment
C   H        - increment size
C   XA       - value at the beginning of the increment
C   XB       - value at the endpoint of the increment
C   XMID     - midpoint of step
C
C   subroutine LPROPS
C
C   BENZMW   - benzene molecular weight, lbm/lbm-mole
C   DIELEC   - dielectric constant of water
C   EPSLON   - exponent of mu in diffusivity equation
C   GASCNS   - gas constant, 0.082055 l-atm/mole-K
C   GOODMU   - viscosity, cP

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C   MUC30   - viscosity at 30 deg C, cP
C   PRTLPR  - partial pressure of benzene, atm
C   SLOPE   - slope of mu vs. T line at constant salt concentration, also
C             slope of solubility vs. temp line
C   SOL40   - benzene solubility at 40 deg C, mg/l
C   SOL50   - benzene solubility at 50 deg C, mg/l
C   SOLUB   - solubility of benzene at given temperature, mg/l
C   TERM    - logarithmic term in surface tension equation
C   VA      - solute molar volume at normal boiling point, cm**3/mole
C   VAPPRS  - benzene vapor pressure, atm
C   XPPM    - assumed benzene liquid concentration for calculation of
C             Henry's constant, mg/l
C   Y        - mole fraction of benzene in vapor
C   YINT    - y-intercept of mu vs. T line at constant salt concentration,
C             also y-intercept of solubility vs. temp line
C   YMOLEB  - moles of benzene in vapor, lbm-moles/ft**3
C   YMOLEN  - moles of nitrogen, lbm-moles/ft**3
C   YPPM    - benzene vapor concentration, mg/l
C
C   subroutine LTLKG
C
C   C1       - constant in gas mass transfer coefficient equation
C   GASCNS  - gas constant, 1.314 ft**3-atm/lbm-mole-K
C   SMALKG  - individual gas phase mass transfer coefficient,
C             lbm-mole/ft**2-hr-atm
C   TERM1   - first parentheses in kG calculation
C   TERM2   - second parentheses in kG calculation
C   TERM3   - third parentheses in kG calculation
C   TERM4   - fourth parentheses in kG calculation
C
C
C   subroutine LTLKL
C
C   FROUDE  - froude number, dimensionless
C   GRAV    - gravity constant, ft/hr**2
C   REYNOL  - reynolds' number
C   SMALKL  - individual liquid phase mass transfer coefficient, ft/hr
C   TERMS   - exponential term in wetted area calculation
C   TERM1   - first parentheses in kL calculation
C   TERM2   - second parentheses in kL calculation
C   TERM3   - third parentheses in kL calculation
C   TERM4   - fourth parentheses in kL calculation
C   WESSEL  - wesselt number, dimensionless
C
C
C   function NTUCRV
C
C   NTUCRV  - value of integrand in numerical integration
C   X        - mole fraction benzene in passing liquid stream
C   XE       - liquid mole fraction of benzene at equilibrium
C   Y        - mole fraction benzene in passing vapor stream
C
C
C   subroutine VPROPS
C
C   BENZEN  - atomic diffusion volume of benzene
C   GASCNS  - gas constant, 0.7302 ft**3-atm/lbm-mole-deg R
C   HSDIAM  - hard sphere diameter of nitrogen, Angstroms
C   MWBENZ  - benzene molecular weight, gm/mole
C   NITROG  - atomic diffusion volume of nitrogen
C
C
C   END

```

APPENDIX B. Benzene Stripper Hand Calculation

- Case 3A → 4.4 gpm liquid, 4.5m, 195 mg/l benzene inlet, 30.3 mg/l out
 23.7°C = 296.9K
 → 20 scfm gas, 20°C (nitrogen)
 → 1 atm column pressure
 → 6" packing diameter

A) HTU

$$HTU = \frac{L}{K_L a \rho_L}$$

A1) ρ_L

$$\rho_L (\text{gm/ml}) = 0.99455 + 0.04579(m) \quad (\text{from data regression})$$

$$\rho_L = \{0.99455 + 0.04579(4.5)\} \left(62.36 \frac{\text{lb}_m/\text{ft}^3}{\text{gm/ml}}\right)$$

$$\boxed{\rho_L} = 74.87 \frac{\text{lb}_m}{\text{ft}^3}$$

A2) L

$$\boxed{L} = \frac{4.4 \frac{\text{gal}}{\text{min}} \times \frac{14.3}{2.10 \text{ gal}} \times \frac{60 \text{ min}}{\text{hr}} \times 74.87 \frac{\text{lb}_m}{\text{ft}^3}}{\frac{\pi}{4} (0.5 \text{ ft})^2} = 13458.0 \frac{\text{lb}_m}{\text{hr ft}^2}$$

assume \boxed{a} = a_{wet} (see below)A3) K_L

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{Hk_G}$$

$$A3a) k_L = 0.0051 \left(\frac{\rho_L g}{\rho_L}\right)^{1/3} \left(\frac{L}{a \rho_L}\right)^{2/3} \left(\frac{\rho_L}{\rho_L \Delta_L}\right)^{-0.50} (a \Delta_P)^{0.4}$$

A3a1) μ_L

$$\mu_L(30^\circ\text{C}) = 0.79776 + 0.099524(m) + 0.017381(m)^2 + 0.0033333(m)^3$$

from data regression

$$= 0.79776 + 0.099524(4.5) + 0.017381(4.5)^2 + 0.0033333(4.5)^3$$

$$= 1.9013 \text{ cp}$$

$$\begin{array}{l} \text{slope of } \mu \text{ vs } T \text{ at } 5m \Rightarrow -0.054725 \\ 0M \Rightarrow -0.017839 \end{array} \quad \left. \begin{array}{l} y_{int} \Rightarrow 3.8319 \\ y_{int} \Rightarrow 1.3396 \end{array} \right\} \begin{array}{l} \text{data} \\ \text{regression} \end{array}$$

$$\mu_{5m, 30^\circ} = 3.8319 - 0.054725(30) = 2.1902 \text{ cp}$$

$$\mu_{0m, 30^\circ} = 1.3396 - 0.017839(30) = 0.8044 \text{ cp}$$

$$\text{fraction change of slope of } 4.5m \text{ soln} = \frac{1.9013 - 0.8044}{2.1902 - 0.8044} = 0.7915$$

$$S_{20, 4.5} = -0.017839 + \{0.7915(-0.054725 - [-0.017839])\}$$

$$= -0.04704$$

$$y_{int} = 1.9013 - (-0.04704)(30) = 3.3125$$

$$\boxed{\mu_L} = \{(-0.04704)(23.7) + 3.3125\} \left(2.419 \frac{15_{5m}}{F_{5m} \text{ cp}}\right) = 5.3161 \frac{15_{5m}}{F_{5m} \text{ hr}}$$

A3a2) q_t, D_p

$$\text{For 1" steel Pallrings} \quad \boxed{q_t} = 63 \frac{F_1^2}{F_2^3}, \quad \frac{\# \text{ pieces}}{F_2^3} = 1405$$

$$\text{each particle} \Rightarrow \frac{63 \frac{F_1^2}{F_2^3}}{1405/F_2^3} = 0.04484 \text{ ft}^2$$

$$\text{equivalent sphere diameter} = \boxed{D_p} = \left(\frac{0.04484}{\pi}\right)^{1/2} = 0.11947 \text{ ft}$$

A3a) q_w

$$\frac{q_w}{a_t} = 1 - \exp \left[-1.45 \left(\frac{\sigma_c}{\sigma} \right)^{0.75} N_{Re}^{0.1} N_{Fr}^{-0.05} N_{We}^{0.2} \right]$$

A3a3a) σ

$$\sigma = \sigma_w + \frac{79.517}{D} C_2 \log \left[1.143 \times 10^{-13} \frac{(\Delta T)^3}{C_2} \right]$$

$$\begin{aligned} D &= 78.54 \left[1 - 0.0046 (T - 298.2) + 8.8 \times 10^{-6} (T - 298.2)^2 \right] \\ &= 78.54 \left[1 - 0.0046 (296.9 - 298.2) + 8.8 \times 10^{-6} (296.9 - 298.2)^2 \right] \\ &= 79.011 \end{aligned}$$

$$\sigma_w = 72.0 \frac{\text{dyne}}{\text{cm}}$$

$$\sigma = 72.0 + \frac{79.517}{79.011} (1.5) \log \left[1.143 \times 10^{-13} \frac{(79.011 + 296.9)^3}{4.5} \right] = 69.807 \frac{\text{dyne}}{\text{cm}}$$

A3a3b) N_{Re}, N_{Fr}, N_{We}

$$\boxed{N_{Re}} = \frac{L}{a_t \mu} = \frac{13458.0 \frac{\text{lb}_m}{\text{ft}^2 \text{hr}}}{\left(\frac{63 \text{ ft}^2}{\text{ft}^3} \right) \left(5.3161 \frac{\text{lb}_m}{\text{ft} \text{hr}} \right)} = 40.1934$$

$$\boxed{N_{Fr}} = \frac{L^2 a_t}{\rho_c^2 g} = \frac{\left(13458 \frac{\text{lb}_m}{\text{ft}^2 \text{hr}} \right)^2 \left(63 \frac{\text{ft}^2}{\text{ft}^3} \right)}{\left(74.87 \frac{\text{lb}_m}{\text{ft}^3} \right)^2 \left(32.17 \frac{\text{ft}}{\text{sec}^2} + 3600^2 \frac{\text{sec}^2}{\text{hr}^2} \right)} = 0.004892$$

$$\begin{aligned} \boxed{N_{We}} &= \frac{L^2}{A \sigma a_t} = \frac{\left(13458 \frac{\text{lb}_m}{\text{ft}^2 \text{hr}} \right)^2}{\left(74.87 \frac{\text{lb}_m}{\text{ft}^3} \right) \left(63 \frac{\text{ft}^2}{\text{ft}^3} \right) \left(69.807 \frac{\text{dyne}}{\text{cm}} + 28568 \frac{\text{lb}_m \text{ft}}{\text{ft}^2 \text{hr}} \right)} \\ &= 0.01926 \end{aligned}$$

A3a3) $\sigma_c = 75 \text{ dynes/cm}$

$$a_w = \left(63 \frac{\text{ft}^2}{\text{ft}^2} \right) \left[1 - \exp \left\{ -1.45 \left(\frac{75.0 \frac{\text{dynes}}{\text{cm}}}{69.807 \frac{\text{dynes}}{\text{cm}}} \right)^{0.75} (40.1834)^{0.1} (0.004882)^{-0.05} \right. \right. \\ \left. \left. * (0.01925)^{0.2} \right\} \right]$$

$$\boxed{a_w} = 46.018 \frac{\text{ft}^2}{\text{ft}^2}$$

A3a4) D_L

$$D_L (\text{cm}^2/\text{sec}) = 1.25 \times 10^{-8} (V_A^{-0.19} - 0.292) T^{1.52} \mu_L^{\epsilon} (\text{cP})$$

$$V_A = 96.5 \frac{\text{cm}^3}{\text{mole}}$$

$$\mu_L (\text{cP}) = 2.1976$$

$$\epsilon = \frac{9.58}{V_A} - 1.12 = \frac{9.58}{96.5} - 1.12 = -1.0207$$

$$\boxed{D_L} = 1.25 \times 10^{-8} \left[(96.5)^{-0.19} - 0.292 \right] (296.9)^{1.52} (2.1976)^{-1.0207}$$

$$= 4.0968 \times 10^{-6} \frac{\text{cm}^2}{\text{sec}} * \frac{3600 \text{ sec}}{\text{hr}} * \left(\frac{1 \text{ ft}}{30.48 \text{ cm}} \right)^2 = 6.5875 \times 10^{-5} \frac{\text{ft}^2}{\text{hr}}$$

A3a) k_L

$$k_L = \left(\frac{5.3161 \frac{\text{lbm}}{\text{ft}^2 \text{ hr}} * 32.17 \frac{\text{ft}}{\text{sec}^2}}{76.87 \frac{\text{lbm}}{\text{ft}^2} * \frac{1 \text{ hr}^2}{3600^2 \text{ sec}^2}} \right)^{1/3} \left(\frac{13458 \frac{\text{lbm}}{\text{ft}^2 \text{ hr}}}{46.018 \frac{\text{ft}^2}{\text{ft}^2} * 5.3161 \frac{\text{lbm}}{\text{ft}^2 \text{ hr}}} \right)^{2/3}$$

$$* \left(\frac{5.3161 \frac{\text{lbm}}{\text{ft}^2 \text{ hr}}}{76.87 \frac{\text{lbm}}{\text{ft}^2} * 1.5875 * 5.3161 \frac{\text{ft}^2}{\text{hr}}} \right)^{-0.5} \left(63 \frac{\text{ft}^2}{\text{ft}^2} + 0.11947 \text{ ft} \right)^{0.4} * 0.0051$$

$$\boxed{k_L} = 0.76503 \text{ ft/hr}$$

A36) k_c

$$k_c = 5.23 \left(\frac{a_c \Delta G}{R T_c} \right) \left(\frac{G}{a_c \mu_c} \right)^{0.7} \left(\frac{\mu_c}{A_c \Delta G} \right)^{1/2} (a_c \Delta p)^{-2}$$

A361) μ_G

$$\mu_G (\mu P) = \frac{26.69 (MW_G T_c)^{1/2}}{D_{HS}^2}$$

for N_2 , $MW_G = 28.02$
 $D_{HS} = 3.798$

$$\boxed{\mu_G} = \frac{26.69 (28.02)^{1/2} (293.2)^{1/2}}{(3.798)^2} + \frac{100 \text{ cP}}{10^6 \mu P} \times 2.419 \frac{15_m}{\text{hr}} \frac{1}{\text{cP}} = 0.040569 \frac{15_m}{\text{hr}}$$

A362) A_G

$$\boxed{A_G} = \frac{P MW_G}{R T_c} = \frac{(1 \text{ atm}) \left(28.02 \frac{15_m}{15_m\text{-mole}} \right)}{\left(1.314 \frac{\text{atm}}{15_m\text{-mole K}} \right) (293.2 \text{ K})} = 0.072729 \frac{15_m}{\text{hr}}$$

A363) G (scfm \Rightarrow hr^3/min at $294 \text{ K} \approx 70^\circ \text{F}$)

$$\boxed{G} = \frac{\left(20 \frac{\text{scfm}}{\text{min}} + \frac{293.2}{294} \right) \left(0.072729 \frac{15_m}{\text{hr}} \right) \left(\frac{60 \text{ min}}{\text{hr}} \right)}{\frac{\pi}{4} (0.5 \text{ ft})^2} = 443.28 \frac{15_m}{\text{hr A}^2}$$

A364) D_G

$$D_G = \frac{10^{-3} T_c^{1.75} \left(\frac{MW_A + MW_B}{MW_A + MW_B} \right)^{1/2}}{P \left[(\Sigma v_A)^{1/3} + (\Sigma v_B)^{1/3} \right]^2}$$

$MW_A = 78.12$
 $MW_B = 28.02$
 $v_A = 90.68$
 $v_B = 17.9$

$$\boxed{D_G} = \frac{10^{-3} (293.2)^{1.75} \left(\frac{78.12 + 28.02}{78.12 + 28.02} \right)^{1/2}}{(1) \left[(90.68)^{1/3} + (17.9)^{1/3} \right]^2} \left(3600 \frac{\text{sec}}{\text{hr}} \right) \left(\frac{1 \text{ ft}}{30.48 \text{ cm}} \right)^2 = 0.257 \frac{1}{\text{hr}}$$

$$A3b) \quad k_G = 5.23 \left(\frac{63 \frac{F_2}{F_2} + 0.35081 \frac{F_2}{hr}}{1.314 \frac{F_2 \text{ atm}}{lb\text{-mole}\cdot K} + 293.2 K} \right) \left(\frac{443.28 \frac{lb\text{-mole}}{hr \cdot F_2}}{63 \frac{F_2}{F_2} + 0.040569 \frac{lb\text{-mole}}{hr \cdot F_2}} \right)^{0.7} \\ + \left(\frac{0.040569 \frac{lb\text{-mole}}{hr \cdot F_2}}{0.072729 \frac{lb\text{-mole}}{F_2} + 0.35081 \frac{F_2}{hr}} \right)^{1/3} \left(63 \frac{F_2}{F_2} + 0.11947 F_2 \right)^{-2}$$

$$k_G = 0.22829 \frac{lb\text{-mole}}{F_2 \cdot hr \cdot atm}$$

A3c) H

$$H_c = \frac{P^0 MW_B}{RT} \frac{1}{S_B}$$

A3c1) S_0 - using linear extrapolation based on 40°C & 50°C data

$$S_0 = 1.9434 e^{-0.9006(Na^+)} = 1.9434 e^{(-0.9006 + 4.5)} = 0.26283 \text{ gm/l}$$

$$S_{50} = 1.9811 e^{-0.9075(Na^+)} = 1.9811 e^{(-0.9075 + 4.5)} = 0.31661 \text{ gm/l}$$

$$\text{slope} = \frac{0.31661 - 0.26283}{50 - 40} = 5.378 \times 10^{-3} \frac{\text{gm/l}}{^\circ\text{C}}$$

$$y_{40} = S_{40} - (\text{slope})(40) = 0.26283 - (5.378 \times 10^{-3})(40) = 0.04771 \text{ gm/l}$$

$$S_T = 5.378 \times 10^{-3} T + 0.04771$$

at 23.7°C

$$S_B = (5.378 \times 10^{-3})(23.7) + 0.04771 = 0.17577 \text{ gm/l}$$

A3c2) P^0

$$\ln P^0 = 9.2675 - \frac{2788.51}{T - 52.36} = 9.2675 - \frac{2788.51}{296.9 - 52.36}$$

$$P^0 = 0.11818 \text{ atm}$$

A3c)

$$H_c = \frac{(0.11818 \text{ atm}) \left(78.12 \frac{\text{lb}_m}{\text{mole}} \right)}{(0.082055 \frac{\text{ft}^3 \text{ atm}}{\text{mole K}}) (296.9 \text{ K})} + \frac{1}{0.17517 \frac{\text{ft}^3}{\text{ft}^2}} = 2.1634$$

$$H = \frac{P_b}{C_b}$$

Assume 100 mg/l benzene in liq \Rightarrow 216.34 mg/l in vapor

$$\text{moles benzene in vapor} = \frac{216.34 \frac{\text{mg}}{\text{ft}^3} + 3.785 \frac{\text{g}}{\text{ft}^3} + 7.98 \frac{\text{g}}{\text{ft}^3}}{\frac{78.12 \text{ lb}_m}{15.4 \text{ mole}} + \frac{454000 \text{ mg}}{15.4 \text{ mole}}} = 1.7270 \times 10^{-4} \frac{15.4 \text{ mole}}{\text{ft}^3}$$

$$P_b = \frac{RT}{V} = \left(1.7270 \times 10^{-4} \frac{15.4 \text{ mole}}{\text{ft}^3} \right) \left(1.314 \frac{\text{ft}^3 \text{ atm}}{\text{lb}_m \text{ mole K}} \right) (293.2 \text{ K})$$

$$= 0.066535 \text{ atm}$$

$$\boxed{H} = \frac{0.066535 \text{ atm}}{\frac{100 \text{ mg}}{\text{ft}^3} + \frac{15.4 \text{ lb}_m}{454000 \text{ mg}} + \frac{3.785 \text{ g}}{\text{ft}^3} + \frac{7.98 \text{ g}}{\text{ft}^3} + \frac{15.4 \text{ lb}_m}{78.12 \text{ lb}_m}} = 833.49 \frac{\text{ft}^3 \text{ atm}}{\text{lb}_m \text{ mole}}$$

$$A3) \frac{1}{K_L} = \frac{1}{0.76503 \frac{\text{ft}}{\text{hr}}} + \frac{1}{\left(833.49 \frac{\text{ft}^3 \text{ atm}}{\text{lb}_m \text{ mole}} \right) \left(0.22829 \frac{15.4 \text{ mole}}{\text{ft}^3 \text{ hr atm}} \right)} = 1.3124 \frac{\text{hr}}{\text{ft}}$$

$$\boxed{K_L} = 0.76197 \frac{\text{ft}}{\text{hr}}$$

reduce k_L, k_c by 20%, $\Rightarrow K_L = 0.60957$

$$A) \boxed{HTU} = \frac{13458 \frac{15.4}{\text{hr ft}^2}}{(0.60957 \frac{\text{ft}}{\text{hr}}) \left(46.018 \frac{\text{ft}^2}{\text{ft}^3} \right) \left(24.87 \frac{15.4}{\text{ft}^2} \right)} = 6.41 \text{ ft}$$

B) Calculate NTU

$$NTU = \int_{x_{A,in}}^{x_{A,out}} \frac{dx_A}{y_{AE} - x_A}$$

B1) mole fractions at inlet & outlet

$$C_{B,in} = 145 \frac{mg}{l} * 3.785 \frac{l}{gal} * 7.48 \frac{gal}{ft^3} * \frac{1 gm}{1000 mg} * \frac{1 lb_m}{454 gm} = 9.0423 * 10^{-3} \frac{lb_m}{ft^3}$$

$$VFR = 4.4 \frac{gal}{min} * \frac{(ft^3)}{7.48 gal} * \frac{60 min}{hr} = 35.294 \frac{ft^3}{hr}$$

$$Benzin = 35.294 \frac{ft^3}{hr} * 9.0423 * 10^{-3} \frac{lb_m}{ft^3} = 0.31914 \frac{lb_m benz}{hr} = 4.0852 * 10^{-3} \frac{lb_m benz}{hr}$$

$$Total Lig in = 35.294 \frac{ft^3}{hr} * 74.87 \frac{lb_m}{ft^3} = 2642.5 \frac{lb_m}{hr}$$

$$\begin{aligned} \text{Liquid Avg Mol wt} &= 18.005 + (1.1143 M) + 1.19252 * 10^{-2} M^2 + 8.8727 * 10^{-4} M^3 \\ &= 18.005 + (1.1143)(4.5) + (1.19252 * 10^{-2})(4.5)^2 + 8.8727 * 10^{-4} (4.5)^3 \\ &= 23.342 \frac{lb_m}{lb_m\text{-mole}} \end{aligned}$$

$$\text{Moles Lig in} = \frac{2642.5 \frac{lb_m}{hr}}{23.342 \frac{lb_m}{lb_m\text{-mole}}} = 113.21 \frac{lb_m\text{-mole}}{hr}$$

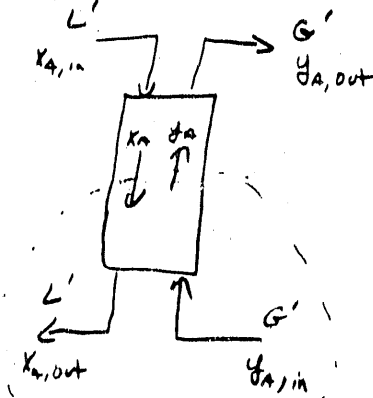
$$x_{A,in} = \frac{4.0852 * 10^{-3} \frac{lb_m\text{-mole}}{hr}}{113.21 \frac{lb_m\text{-mole}}{hr}} = 3.6085 * 10^{-5}$$

B1) Continued

$$\begin{aligned} \text{Benz out} &= 30.3 \frac{\text{mg}}{\text{l}} \times 3.785 \frac{\text{l}}{\text{gal}} + 7.48 \frac{\text{gal}}{\text{ft}^3} \times \frac{1 \text{ ftm}}{1000 \text{ mg}} + \frac{1 \text{ km}}{154 \text{ gm}} + \frac{1 \text{ km-mole}}{78.12 \text{ km}} \\ &\Rightarrow 2.4188 \times 10^{-5} \frac{\text{km-mole}}{\text{ft}^3} + 35.294 \frac{\text{ft}^3}{\text{hr}} \\ &= 8.5369 \times 10^{-4} \frac{\text{km-mole}}{\text{hr}} \end{aligned}$$

$$x_{a,out} = \frac{8.5369 \times 10^{-4} \frac{\text{km-mole}}{\text{hr}}}{113.21 \frac{\text{km-mole}}{\text{hr}}} = 7.5408 \times 10^{-6}$$

B2) operating line



$$L'x_a + G'y_{a,in} = G'y_a + L'x_{a,out}$$

$$y_{a,in} = 0$$

$$y_a = \frac{L'}{G'} (x_a - x_{a,out})$$

B2a) L', G'

$$L' = \frac{L}{MW_L} = \frac{13458 \frac{\text{kg}}{\text{hr}}}{23.342 \frac{\text{kg}}{\text{km-mole}}} = 576.56 \frac{\text{km-mole}}{\text{hr}}$$

$$G' = \frac{G}{MW_G} = \frac{44328 \frac{\text{kg}}{\text{hr}}}{28.02 \frac{\text{kg}}{\text{km-mole}}} = 15.820 \frac{\text{km-mole}}{\text{hr}}$$

$$B2) \quad y_A = \frac{576.56}{15.820} (x_A - 7.5408 \times 10^{-6}) = 36.445 (x_A - 7.5408 \times 10^{-6})$$

B3) equilibrium relation

$$\text{liquid} \quad \frac{100 \text{ mg}}{\text{l}} \times \frac{3.705 \text{ l}}{\text{gal}} \times \frac{7.48 \text{ gal}}{\text{ft}^3} \times \frac{1 \text{ km}}{2.54000 \text{ cm}} = 6.2361 \times 10^{-2} \frac{\text{kg}}{\text{ft}^3}$$

$$\begin{aligned} & \frac{4.4 \text{ gal}}{\text{min}} \times \frac{1 \text{ ft}^3}{2.90 \text{ gal}} \times \frac{60 \text{ min}}{\text{hr}} \times 6.2361 \times 10^{-2} \frac{\text{kg}}{\text{hr}} \times \frac{1 \text{ km-mole}}{78.12} \\ & = 2.8174 \times 10^{-2} \frac{\text{kg-mole}}{\text{hr}} \text{ benzene} \end{aligned}$$

$$\text{kg flow} = 35.294 \frac{\text{ft}^3}{\text{hr}} \times \frac{4.87 \text{ kg}}{\text{ft}^3} \times \frac{1 \text{ km-mole}}{23.342 \text{ km}} = 113.21 \frac{\text{kg-mole}}{\text{hr}}$$

$$x = \frac{2.8174 \times 10^{-2}}{113.21} = 2.4886 \times 10^{-5}$$

$$\text{vapor} \quad 1.7270 \times 10^{-4} \frac{\text{kg-mole}}{\text{ft}^3} \times \left(\frac{20 \text{ ft}^3}{\text{min}} \times \frac{293.2}{294} \right) \times \frac{60 \text{ min}}{\text{hr}} = 0.20668 \frac{\text{kg-mole}}{\text{hr}}$$

$$\text{nitrogen} = \frac{G'}{MW} = \frac{83.037 \frac{\text{kg}}{\text{hr}}}{28.02 \frac{\text{kg}}{\text{km-mole}}} = 3.1062$$

$$y = \frac{0.20668}{0.20668 + 3.1062} = 0.062387$$

$$H = \frac{y}{x} = \frac{0.062387}{2.4886 \times 10^{-5}} = 2506.9$$

- END -

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