

Design of a Cost-Effective Gas Stripping Column
for treatment of a TCE, PCE, and Chloroform contaminated groundwater

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April 24, 2015

Chemical Engineering 410
Mass Transfer Operations
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Executive Summary

The final design of the process involves a stripping column that is 8.272 meters tall and a diameter of 0.5564 meters. This column will efficiently treat the water to less than 5 ppm of each of the contaminants with varying inlet concentrations. The column will be filled with ½ inch berl saddles packing as this was the packing factor that most efficiently cleansed the stream while minimizing the size of the column. A heat exchanger will be used in series before the column to drop the inlet temperature of the column to 14°C which will maximize the mass transfer of the contaminants from the ground water to air. The capital cost of the column is \$127,850.66 and \$1,494.17 for the heat exchanger which will result in 20 annual payments of \$15,192.80. The total cost to operate this process is \$1,648.39 annually, and the total annual cost will be \$16,841.19.

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Introduction

Stripping is an operation in which a solute (A) or several solutes (A_1, A_2, \dots, A_N) are absorbed from the liquid phase into the gas phase. It involves the mass transfer of solute(s) A through stagnant liquid B into stagnant, nondiffusing gas C. In the case of this project, contaminants will be removed from a water stream using air. There are many ways to design a stripping column. One way is to use tray towers, which include sieve trays, valve trays, and bubble-cap trays. Another practical design for a stripping column is structured packing, in which thin corrugated-metal sheets form triangular cross sections. Random packing can also be used such that packing materials are dumped into the tower at random. There are many types of packing materials that can be used for random and structured packing, each with different nominal sizes, surface areas, and relative mass-transfer coefficients. When designing a cost effective stripping column, these different design choices must be considered.

Design Conditions

The groundwater near an industrial facility has been contaminated by leaking underground solvent tanks with trichloroethylene (TCE), tetrachloroethylene (PCE), and chloroform. The groundwater is extracted via a pump and treat remediation scheme. The pumps are operated at non-steady state, the cumulative flow to the air stripper averages $1000 \text{ m}^3/\text{day}$. The average concentrations of TCE, PCE, and chloroform are 200, 250, and 40 mg/l, respectively, but may increase by up to 100% of these values on a daily basis. The groundwater temperature varies between 14 and 20 °C. To be able to discharge the treated groundwater into the water shed, the state Department of Environmental Protection (DEP) requires the concentrations to be reduced to less than 5 mg/L. The Best Available Control Technology (BACT) for this process is gas stripping via air. Adsorption and membrane processes are also DEP-approved treatment technologies. The cost and design of this treatment needs to be evaluated. The industrial facility feels that its image is important to its sales, and wishes to maintain a good reputation in the community.

Procedure

Summary of Design Procedure and Objectives

A Mathematica file was set up to evaluate the air flow rate, number of theoretical trays, cross sectional area, and height of the stripping column. All of these parameters rely on temperature and packing factors, which are the variables to be manipulated. The determination of these design parameters is outlined by Geankoplis (2003). The stripping column was designed to meet the specifications set in the design conditions, while also being as cost-effective as possible. A sensitivity analysis was also done to make sure the column could withstand changing conditions like temperature and contaminant concentration. This report contains a summary of the design procedure, discussion of the results, and cost analysis.

Summary of Procedure

The equations used in the procedure come from Geankoplis (2003) and others (see appendix for references).

Henry's Law constant was calculated as a function of temperature using the equation:

$$H = k e^{\left[d(\ln(k_H)) / d\left(\frac{1}{T}\right) \left(\frac{1}{T} - \frac{1}{298.15}\right) \right]}$$

The minimum gas flow rate was calculated using the equation:

$$V_{min} = \frac{L}{H} \left(\frac{x_{TCE}}{x_{TCE} - x_N} \right)^{-1}$$

The actual flow rate (V) was found by multiplying the minimum gas flow rate by 1.5.

Y_{out} was calculated using the actual gas flow rate:

$$y_{out} = (x_{TCE} - x_N) \frac{L}{V}$$

The absorption factor was calculated using:

$$A = \frac{L}{VH}$$

The number of trays was calculated using the absorption factor:

$$N = \frac{\ln \left[\frac{x_{TCE}}{x_N} (1 - A) + A \right]}{\ln[1/A]}$$

The flow parameter was then calculated using the densities of the gas and liquid and assuming the ratio of G_G/G_L is the same as L/V

$$\text{flow parameter} = \frac{G_G}{G_L} \left[\frac{\rho_g}{\rho_L} \right]^{0.5} = \frac{L}{V} \left[\frac{\rho_g}{\rho_L} \right]^{0.5}$$

Random packing was chosen and a packing material with a packing factor above 60 was chosen. At a packing factor of 60 and above, the pressure drop can be assumed to be 2 in. H₂O/m height packing material.

Using Figure 10.6-5 in Geankoplis (found in the Appendix as Fig. 1), the correlation between the flow parameter and capacity parameter with a pressure drop of 2 was found to be:

$$\text{capacity parameter} = -0.332 \ln[\text{flow parameter}] + 0.7854$$

Note: the graph for this relation can be found in the Appendix (Fig. 2).

Using the above correlation, the capacity parameter was found. From this, the superficial gas velocity was found using the following equation (the kinematic viscosity ν_L is found in Appendices):

$$v_g = \frac{\text{capacity parameter}}{F_p^{0.5} \nu_L^{0.05} \left[\frac{\rho_g}{\rho_L - \rho_g} \right]^{0.5}}$$

The gas mass velocity was then solved for using the superficial gas velocity:

$$G_g = \rho_g v_g$$

Cross sectional area was solved for using the gas mass velocity and the gas flow rate:

$$A_{xc} = \frac{V}{G_g}$$

The diameter was then found based on the cross sectional area:

$$D = \left(\frac{4A_{xc}}{\pi} \right)^{0.5}$$

Once the diameter was found, the mass transfer coefficients needed to be solved for in order to solve for the column height. The liquid mass velocity was solved for to use in the Onda Correlations.

$$G_L = \frac{L}{A_{xc}}$$

The Onda Correlations were used to solve for the mass transfer coefficients. To use the Onda Correlations, the Reynolds number, Froude number, and Weber number need to be found. The variables are defined in the Appendix under *Mass Transfer Coefficients via the Onda Correlation*.

$$Re = \frac{G_L}{a_t \mu_L}$$

$$Fr = \frac{G_L^2 a_t}{\rho_L^2 g}$$

$$Wb = \frac{G_L^2}{a_t \rho_L \sigma_L}$$

Once these dimensionless numbers determined, the wetted specific surface area of the packing factor was found.

$$a_w = \left(1 - \exp \left[-1.45 \left(\frac{\sigma_C}{\sigma_L} \right)^{0.75} Re^{0.1} Fr^{-0.05} Wb^{0.2} \right] \right)$$

Next, the liquid and gas diffusivities are found. The SI subscript indicates the units are in SI.

$$Liquid\ Diffusivity_{SI,TCE} = 0.0001518 \left(\frac{T + 273.16}{298.16} \right) \left(\frac{MW_{TCE}}{\rho_{TCE}} \right)^{-0.6}$$

$$Liquid\ Diffusivity_{TCE} = Liquid\ Diffusivity_{SI,TCE} \left(\frac{0.3048}{100} \right)^2$$

$$Gas\ Diffusivity_{SI,TCE} = \frac{0.0029(T - 273.16)^{1.5} \left(0.34 + \frac{1}{MW_{TCE}} \right)^{0.5} MW_{corTCE}}{\left(\left(\frac{MW_{TCE}}{2.5\rho_{TCE}} \right)^{1/3} + 1.8 \right)^2}$$

Note: MW_{corTCE} can be found in the Diffusion Coefficient section of the Appendix

$$Gas\ Diffusivity_{TCE} = Gas\ Diffusivity_{SI,TCE} \left(\frac{0.3048}{100} \right)^2$$

$$k_y = ca_t Gas\ Diffusivity_{TCE} \left(\frac{G_g}{a_w \mu_g} \right)^{0.7} \left(\frac{\mu_g}{\rho_g Gas\ Diffusivity_{TCE}} \right)^{1/3} (a_t d_p)^{-2}$$

$$k_x = 0.0051 \left(\frac{G_l}{a_w \mu_L} \right)^{2/3} \left(\frac{\mu_L}{\rho_L Liquid\ Diffusivity_{TCE}} \right)^{-1/2} (a_t d_p)^{0.4} \left(\frac{\rho_L}{\mu_L g} \right)^{-1/3}$$

Since the solution is dilute, the k'_x found from the Onda Correlations is the same as k_x . This is the same for k'_y . Since the k_x we found was two orders of magnitude larger than the k_y , k_y is negligible. This means that k'_x is equal to K'_x . Because the K'_x is now known, the height of the column can easily be found using the number of transfer units (N_{OL}) and height of the transfer unit (H_{OL}). When solving for the height (z), a conversion factor is used to convert the units from feet to meters.

$$H_{OL} = \frac{L}{K'_x a S}$$

$$N_{OL} = \frac{1}{1-A} \log \left[(1-A) \frac{x_{TCE}}{x_n} + A \right]$$

$$z = \frac{H_{OL} N_{OL}}{3.2808}$$

This is the general procedure used for TCE. The procedure is the same for PCE and chloroform, but with different Henry's constants and mass transfer coefficients. The intermediate variables to get to these are outlined in the Appendix.

Economic Analysis

Capital Costs. After optimizing the most efficient stripping column to clean the groundwater a cost analysis was conducted to provide an estimation of what the yearly cost would be to clean the toxic contaminants. The capital cost was composed of the price of the packing material for the column and the heat exchanger. The column was priced off of the volumetric price of the packing material which was \$1800/ft³. The capital cost of the heat exchanger was modeled from the correlations from Peter, Timmerhaus, and West based off of the area.

Description	Size	Item Cost
Column	D = 0.5564 m H = 8.272 m	\$ 127,850.66
Heat Exchanger	60 m ²	\$ 1,494.17
Total Capital Cost		\$ 129,344.83

Table 1. Capital Costs

Operating Costs. The operating costs of the process involve the electricity required to operate the blower for the air, electricity for the pump, and the required steam for the heat exchanger. The electricity for the blower was based off the mass flow of air, inlet temperature and the pressure needed to force the gas up the column. The constant k of the ratio of C_p to C_v was assumed to be 1.4. The change in pressure was found to become 2.0 atm so the outlet air pressure was made to be 3.0 atm. This returned the adiabatic power necessary and assuming an efficiency of 70% the actual electricity needed was determined. The electricity for the water pump was calculated using the volumetric flow rate of water, the column height, and the density of the water. The cooling water needed for the heat exchanger was determined using the area, heat transfer coefficient, and change in temperature of the inlet and outlet streams. The heat transfer coefficient was assumed to be $142 \text{ W/m}^2\text{K}$. The prices of all three of these operations were calculated assuming the equipment was run 8760 hours per year.

Description	Energy	Rates	Operating Time	Total Costs
Blower for Air	0.0193 kW	\$0.10/kW-hr	8760 hr/yr	\$ 16.89
Water Pump	0.4089 kW	\$0.10/kW-hr	8760 hr/yr	\$ 358.22
Heat Exchanger	0.1454 MMBtu	\$1/MMBtu	8760 hr/yr	\$ 1,273.28
Total Operating Cost (\$/yr)				\$ 1,648.39

Table 2. Operating Costs

Annual Costs. The total annual costs were determined by the sum of the yearly operating costs and the annual cost of the capital costs. The capital costs were annualized based off of annual payments over the course of 20 years with an interest of 10%.

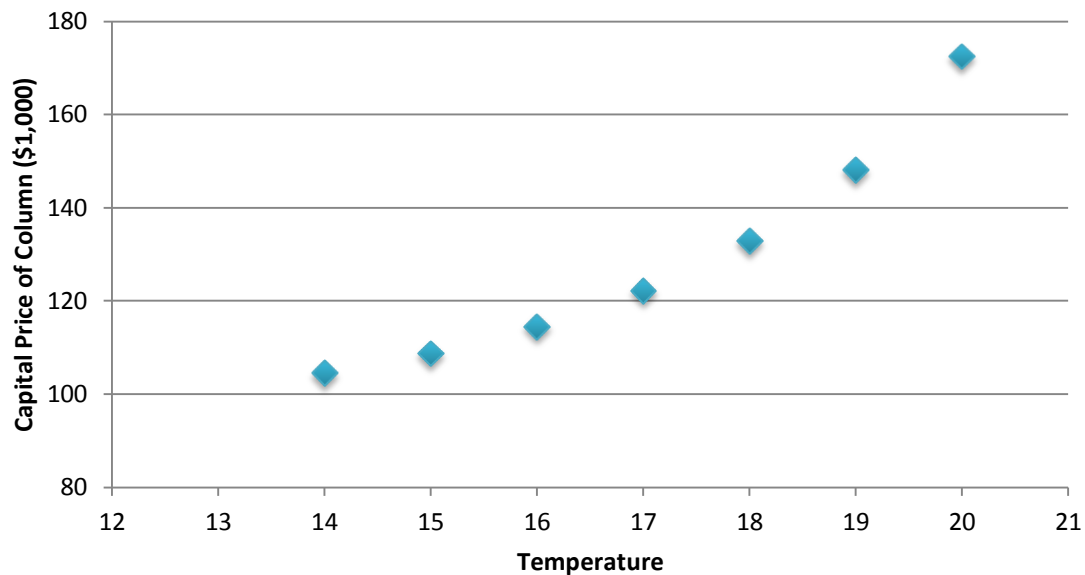
Total Capital Cost	Annualized Capital Cost	Operating Cost	Total Annual Cost
\$ 129,344.83	\$ 15,192.80	\$ 1,648.39	\$ 16,841.19

Table 3. Annual Costs

Sensitivity/Optimization

In the design of the stripping column it was needed to take into account the variable temperatures and concentrations of the toxins. The temperature of the incoming water could range from 14°C to 20°C. Due to the range of incoming temperatures, columns were designed with a constant incoming value of 200 ppm TCE that would be reduced to 5 ppm and a constant type of packing, ½ in berl saddles while varying the temperature. By varying the temperature a column was found with a specific height and diameter and the capital cost to build these columns was found. It was determined that the temperature at 14°C yielded the lowest costing column.

Chart 1. Capital Price of Column with Temperature



It was desired to have the column run with an inlet water flow with a temperature of 14°C so a heat exchanger was needed to part of the design. A heat exchanger of 60 m² was found to be appropriate to decrease the inlet flow to the desired 14°C with cooling water. The capital and operation of a heat exchanger was found to annually be cheaper than building a tower that would properly operate at the higher inlet temperatures.

Different types of packings have different packing factor values and volumetric to surface area values which will affect the size of the column needed. To optimize the type of packing different packings were evaluated and a chart was made with the type of packing compared to the size of

the column needed to achieve the low concentration of toxins. It was determined that the ½ in berl saddles required the smallest column and lowest price so this type of packing will be used for the final process.

Type of Packing	Diameter (m)	Height (m)	Price
1/2 in Berl Saddles	0.5597	6.678	\$ 104,442.01
1 in Berl Saddles	0.461	12.028	\$ 127,618.46
1/2 in Rasching Rings	0.698	6.906	\$ 167,979.25
1 in Rasching Rings	0.52	13.522	\$ 182,543.27
1.5 in Rasching Rings	0.444	20.896	\$ 205,658.81
2 in Rasching Rings	0.404	27.308	\$ 222,520.92

Table 4. Varying Packing Types

The concentration of the inlet toxins were found to fluctuate up to 100% on a daily basis so a stripping column would need to be designed for the maximum concentrations. The design of the column was originally made to strip an inlet stream of 200 ppm TCE. This was done because to clean the inlet of PCE and chloroform a smaller column would be needed so a larger stripping column for the TCE would easily lower these concentrations to below 5 ppm. Due to the fluctuations a new column was designed that could strip an inlet stream of 400 ppm TCE down to 5 ppm. This final column had a height of 8.272 m and diameter of 0.5564 m and would be able to safely treat the maximum concentration of contaminants that may be encountered.

Recommendations

Mathematical modeling of a stripping column can be inherently difficult. Due to the difficulty of this modeling, it is recommended that the inlet stream to the column be constantly monitored for both the concentration, and also the temperature. In this case, the column is severely sensitive to both of these. When the concentration is increased by 100 percent, the overall size increases. If this is allowed to happen, the column may not be able to handle the increased concentration while still yielding the desired result. The column also changes greatly with changes in temperature. This will yield similar changes in cost as seen in chart 1. Do not intentionally damage the device, as parts are slightly expensive.

Appendix

Molecular Weights:

The following molecular weights were used to convert mass to moles:

Molecular Weight of Trichloroethylene: 131.4 g/mol

Molecular Weight of Tetrachloroethylene: 165.83 g/mol

Molecular Weight of Chloroform: 119.38 g/mol

Molecular Weight of Water: 18.02 g/mol

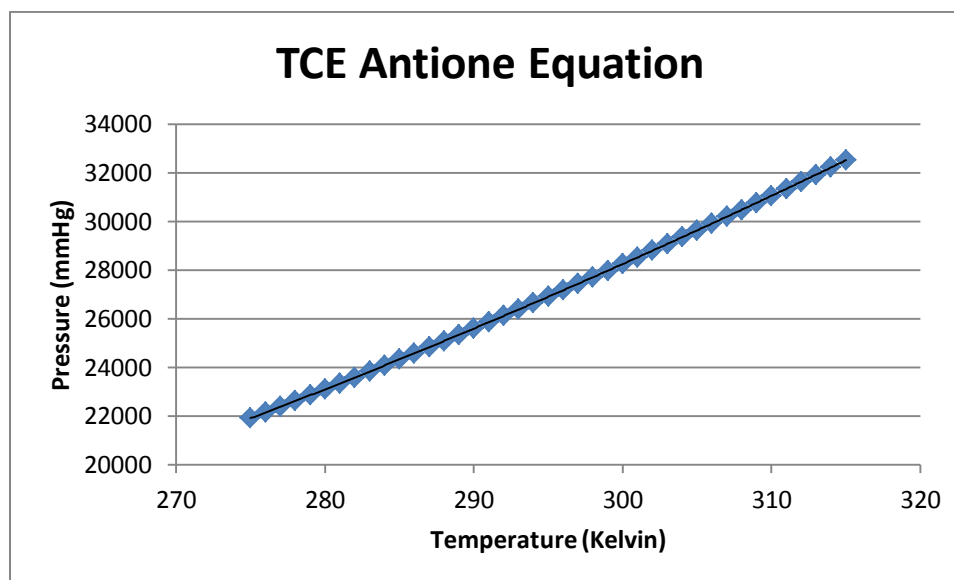
Molecular Weight of Air: 28.97 g/mol

Boiling Points:

The following equations were derived from the Antoine Equation and corresponding coefficients:

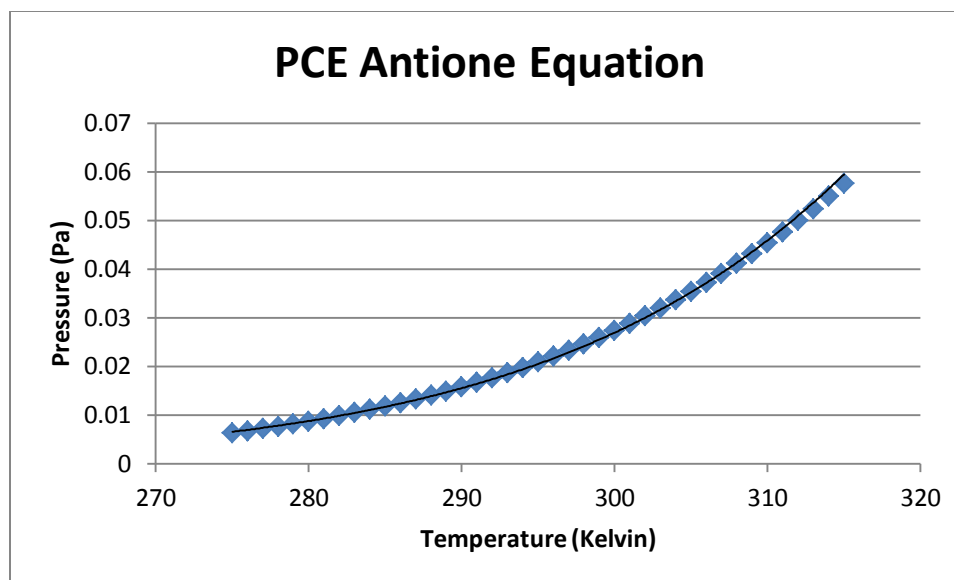
Trichloroethylene: $P(\text{mmHg}) = .763167 * T(\text{K})^2 - 185.027 * T(\text{K}) + 15068.07$

“Elementary Principles of Chemical Processes” Third Edition by Richard M. Felder and Ronald W. Rousseau



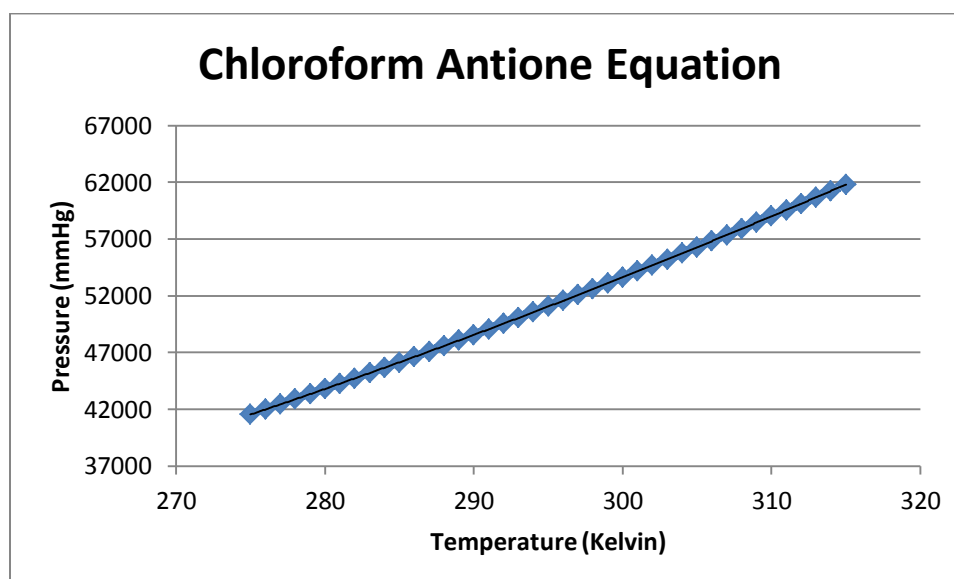
Tetrachloroethylene: $P(\text{Pa}) = 1 \times 10^{(-42)} * T(\text{K})^{16.254}$

NIST Webbook



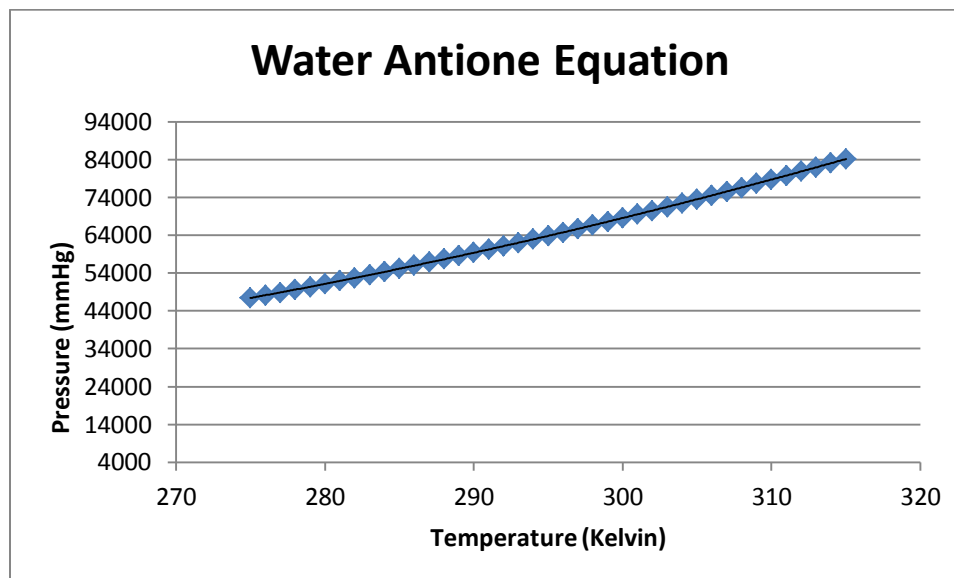
Chloroform: $P(\text{mmHg}) = 1.541261 \cdot T(\text{K})^2 - 402.458 \cdot T(\text{K}) + 35660.81$

“Elementary Principles of Chemical Processes” Third Edition by Richard M. Felder and Ronald W. Rousseau



Water: $4.842608 \cdot T(K)^2 - 1938.83 \cdot T(K) + 214385.6$

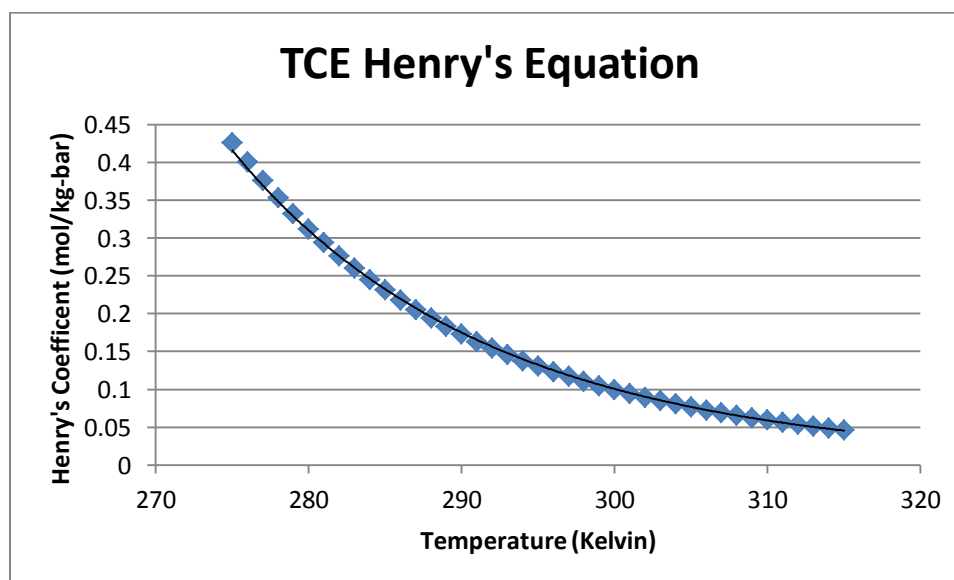
“Elementary Principles of Chemical Processes” Third Edition by Richard M. Felder and Ronald W. Rousseau



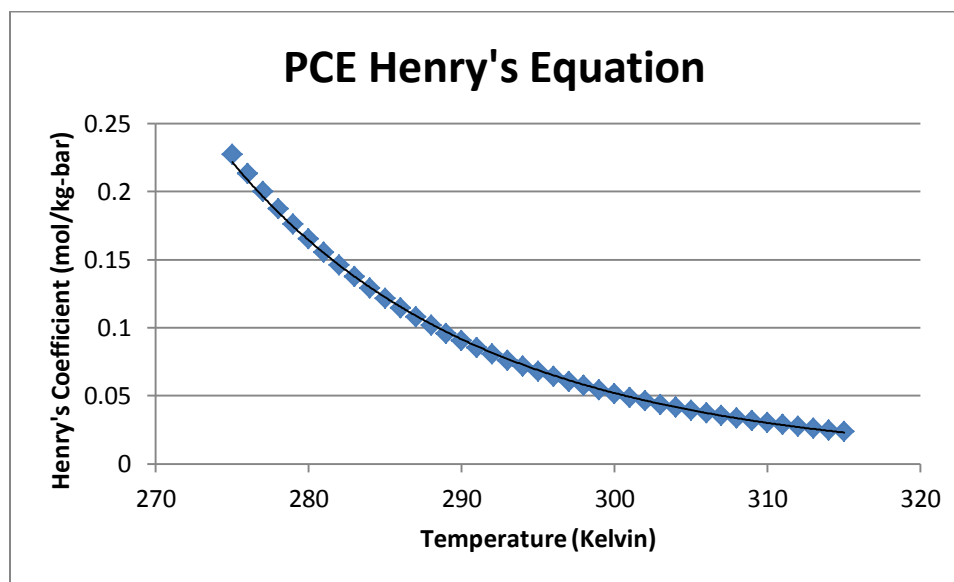
Henry's Constants:

The following correlations of Henry's constant versus temperature were obtained from *NIST Webbook*:

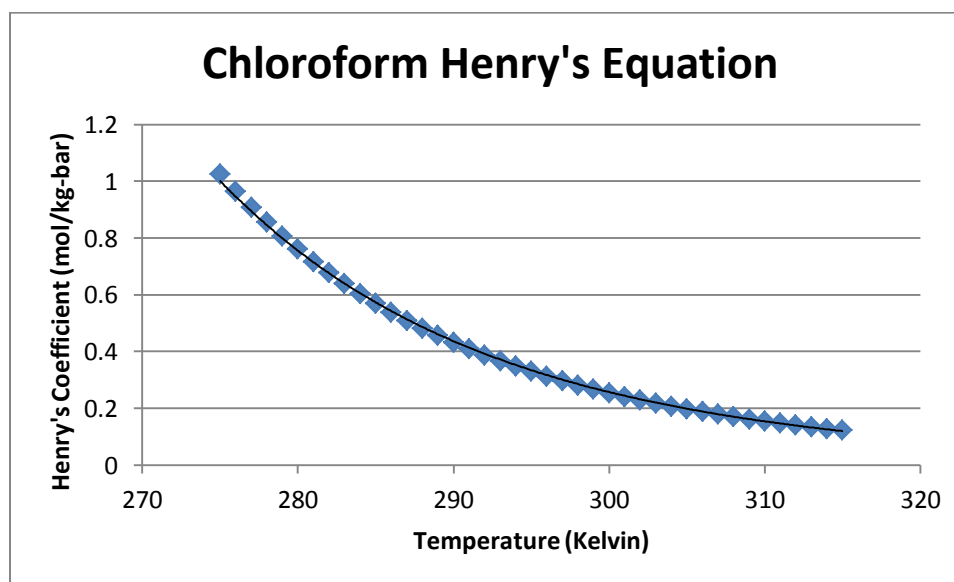
Trichloroethylene: $H(\text{mol/kg-bar}) = .11 \cdot \exp[4800 \cdot (1/T(K) - 1/298.15)]$



Tetrachloroethylene: $H(\text{mol/kg-bar}) = .057 \cdot \exp[4900 \cdot (1/T(\text{K}) - 1/298.15)]$



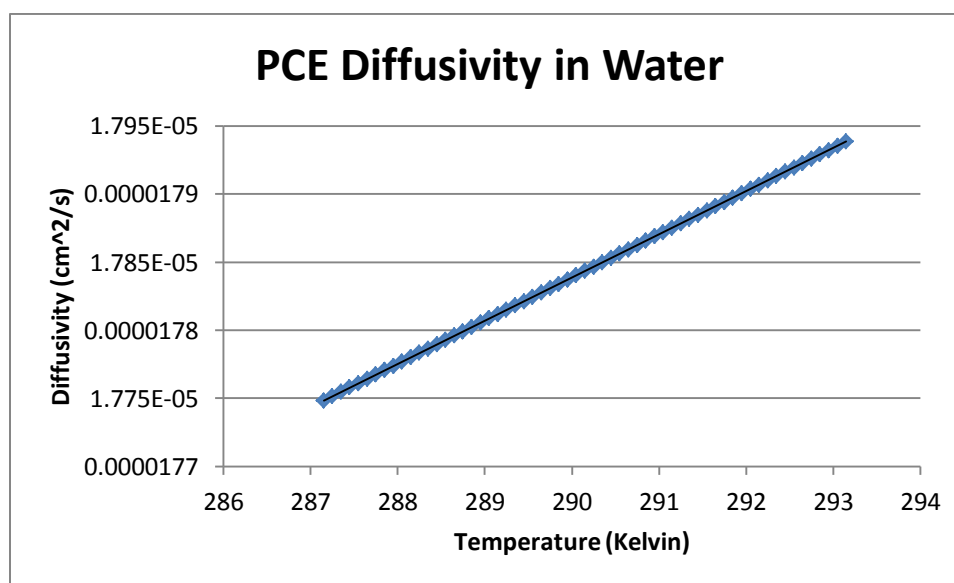
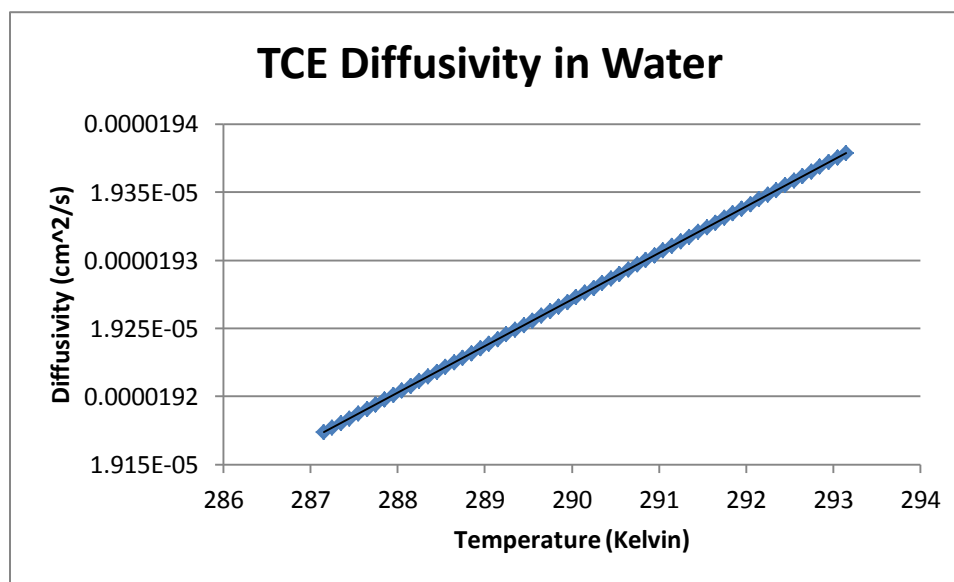
Chloroform: $H(\text{mol/kg-bar}) = .28 \cdot \exp[4600 \cdot (1/T(\text{K}) - 1/298.15)]$

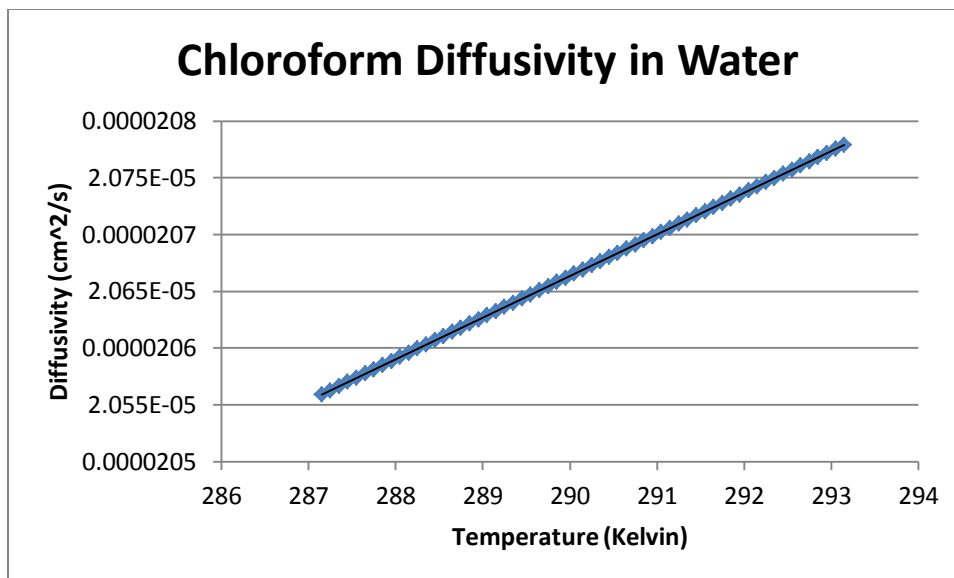


Diffusion Coefficients:

The following correlation of diffusion coefficients versus temperature was obtained from <http://www.epa.gov/epawaste/nonhaz/industrial/tools/iwair/iwairt-2.pdf> in conjunction with CHEMDAT8

Diffusion in Water: $D \text{ (cm}^2\text{/s)} = 0.0001518((T(K)+273.16)/298.16)(M_w/\rho)^{-0.6}$

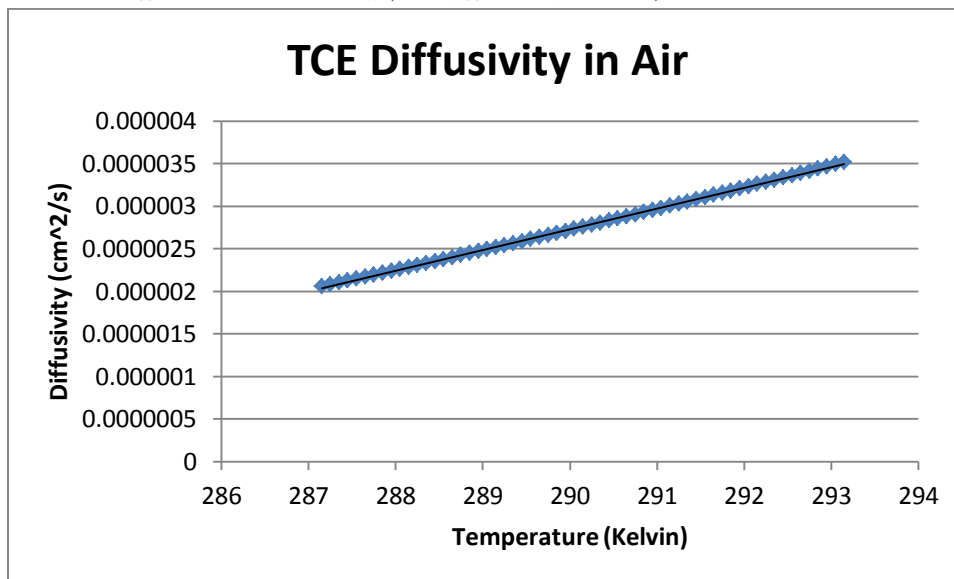


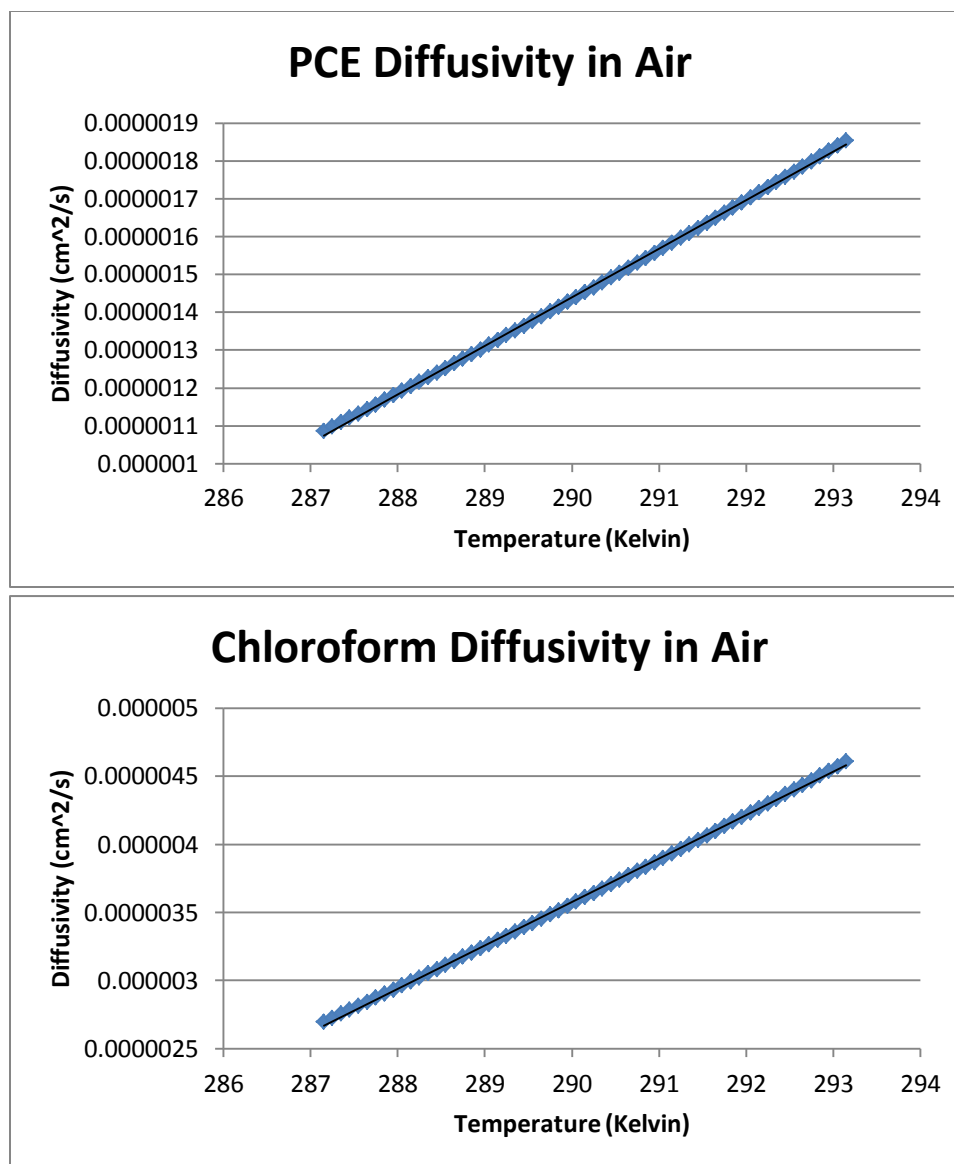


Diffusion in Air:

$$D \text{ (cm}^2\text{/s)} = (0.0029(T(K)-273.16)^{1.5} * (0.34 + 1/M_w)^{0.5} * M_{w\text{cor}}) / ((M_w/2.5\rho)^{0.333} + 1.8)^2$$

Where $M_{w\text{cor}} = 1 - 0.000015M_w^2$ (If $M_{w\text{cor}} < 0.4$, use 0.4)

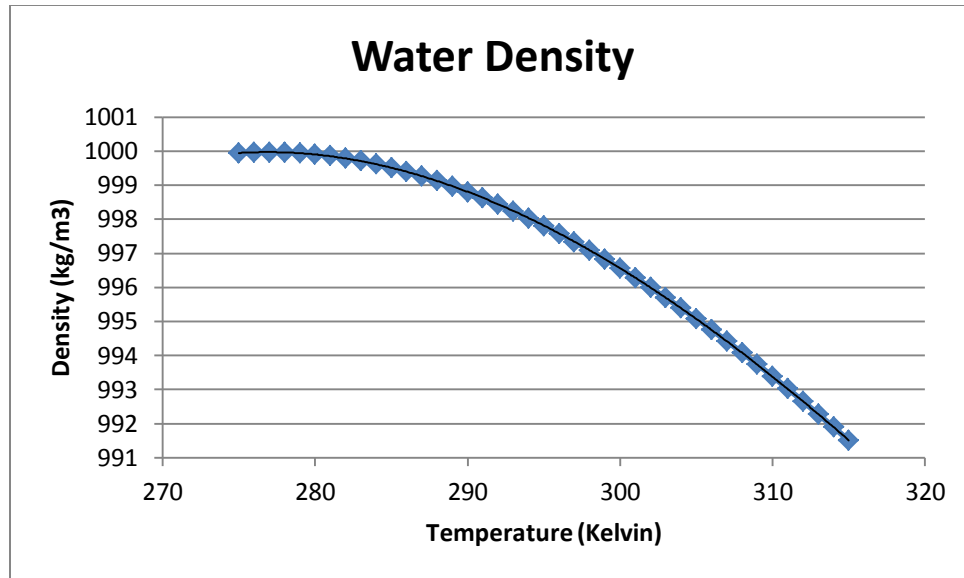




Water Density:

The following correlation of water density versus temperature was obtained from *NIST Webbook*:

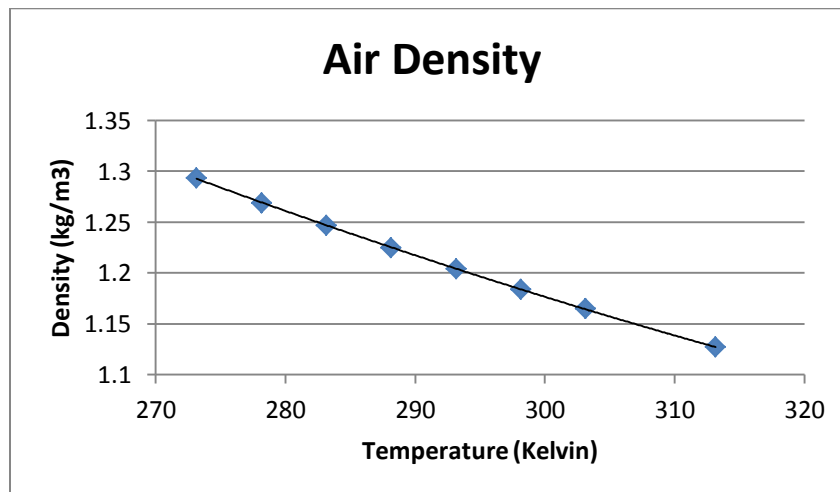
$$\rho(\text{kg/m}^3) = 3.69831 \times 10^{-5} \cdot T(\text{K})^3 - .038 \cdot T(\text{K})^2 + 12.531 \cdot T(\text{K}) - 341.31$$



Air Density:

The following correlation for air density versus temperature was obtained from www.engineeringtoolbox.com:

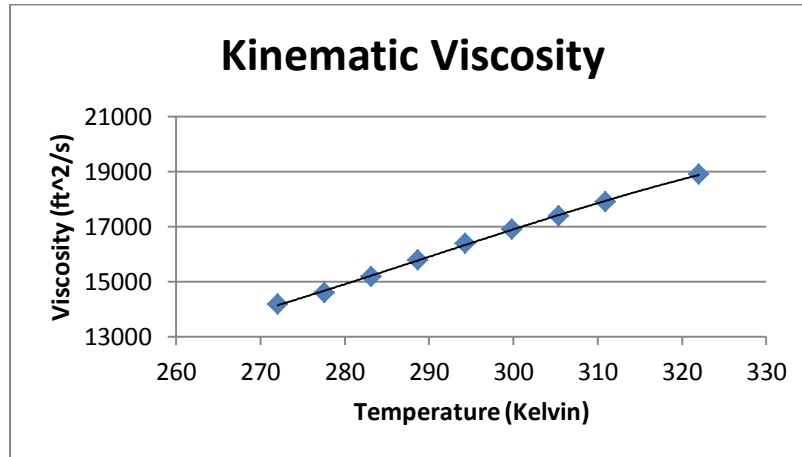
$$\rho(\text{kg/m}^3) = 1.1 \times 10^{-5} * T(\text{K})^2 - .01056 * T(\text{K}) + 3.355607$$



Air Viscosity:

The following correlation for kinematic viscosity versus temperature was obtained from www.engineeringtoolbox.com:

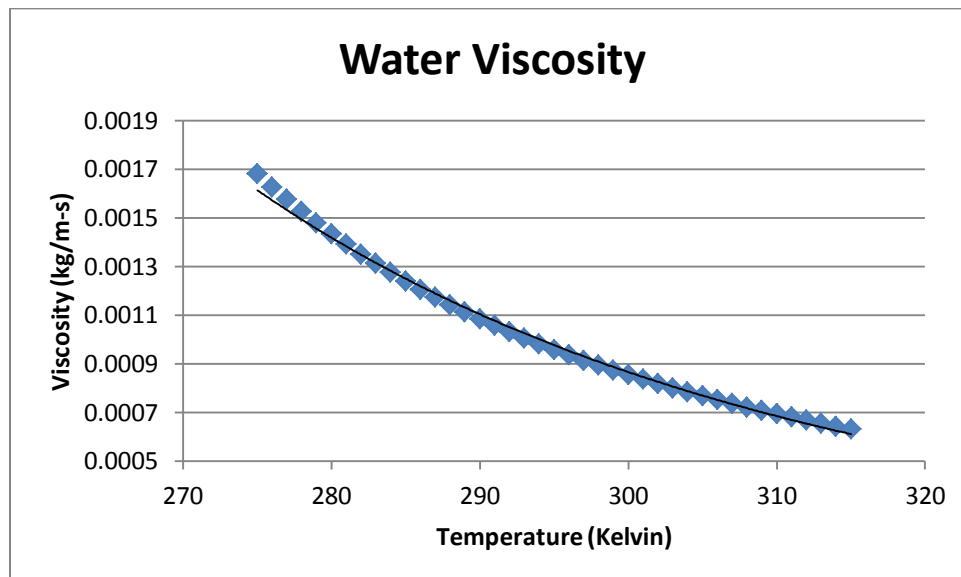
$$\nu(\text{ft}^2/\text{s}) = -0.0071 * T(\text{K})^3 + 2.513527 * T(\text{K})^2 - 1392.74 * T(\text{K}) + 208035.6$$



Water Viscosity:

The following correlation for water viscosity versus temperature was obtained from *NIST Webbook*:

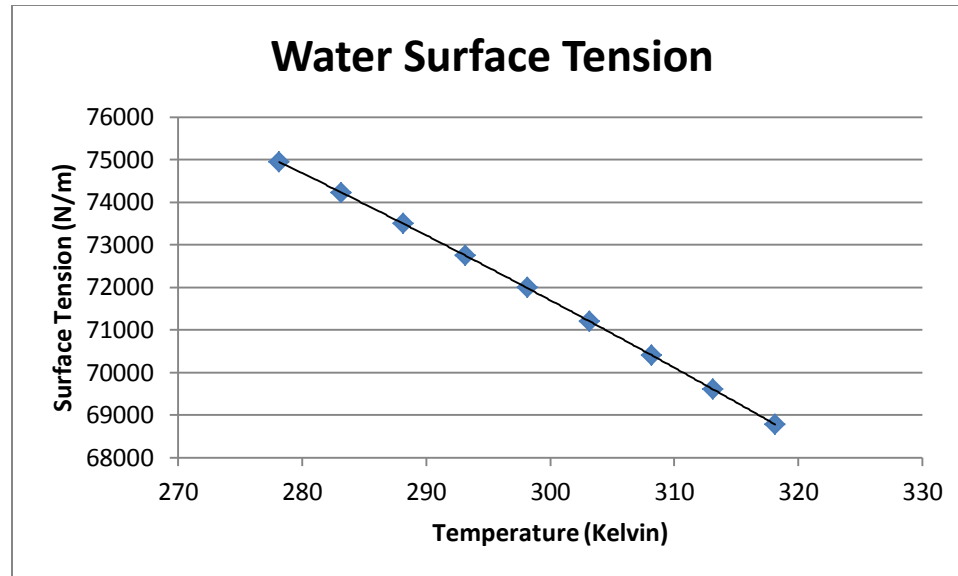
$$\mu(\text{kg/m-s}) = 5.49 \times 10^{14} * T(\text{K})^{-7.19}$$



Water Surface Tension:

The following correlation of surface tension versus temperature was obtained from *NIST Webbook*:

$$\sigma(\text{N/m}) = -0.30221 * T(\text{K})^2 + 25.84663 * T(\text{K}) + 91142.47$$



Pressure Drop as a Function of Packing Type:

Capacity Parameter: $v_G[\rho_G/(\rho_L-\rho_G)]^{0.5} F_p^{0.5} v^{0.05}$

Flow Parameter: $(G_L/G_G)(\rho_G/\rho_L)^{0.5}$

where $v_G = G_G/\rho_G$ and $v = \mu_L/(\rho_L/62.4)$

- v_G = superficial gas velocity (ft/s)
- ρ_G = gas density (lb_m/ft^3)
- ρ_L = liquid density (lb_m/ft^3)
- F_p = packing factor (ft^{-1})
- v = kinematic viscosity (centistokes)
- G_L = liquid mass velocity ($\text{lb}_m/(\text{s}\cdot\text{ft}^2)$)
- G_G = gas mass velocity ($\text{lb}_m/(\text{s}\cdot\text{ft}^2)$)
- μ_L = liquid viscosity (cp)
- ΔP = pressure change (in $\text{H}_2\text{O}/\text{ft}$)

Pressure change as a function of packing type (packing factor) can be obtained from Figure 10.6-5 **Pressure-drop correlation for random packings by Strigle** in Geankoplis' *Transport Processes AND Separation Process Principles*. If too much pressure is applied to the gas, interference with the liquid flow will occur and cause flooding at the top of the column. The associated pressure change limitations are as follows: If the packing factor is less than 60ft^{-1} , $\Delta P_{\text{flood}} = 0.115F_p^{0.7}$, and if the packing factor is greater than or equal to 60ft^{-1} , $\Delta P_{\text{flood}} = 2.00\text{inH}_2\text{O}/\text{ft}$.

There was a fit made for the $\Delta P_{\text{flood}} = 2.00\text{inH}_2\text{O}/\text{ft}$ curve by reading the values from (Fig 1) and plotting them in Microsoft Excel, and then simply using Excel's logarithmic fit function.

Mass Transfer Coefficients via the Onda Correlation

The Onda Correlation for calculating Mass Transfer Coefficients was used as printed in the following journal citation:

DJEBBAR, Y (1998). "Improved Onda correlations for mass transfer in packed towers". *Water science and technology* (0273-1223), 38 (6), p. 295.

$$a_w \text{ (ft}^2\text{/ft}^3\text{)} = a_t \{ 1 - \exp[-1.45(\sigma_c/\sigma_L)^{0.75}(\text{Reynolds})^{0.1}(\text{Froude})^{-0.05}(\text{Weber})^{0.2}] \}$$

$$k_L \text{ (ft/s)} = 0.0051(G_1/a_w\mu_L)^{2/3}(\mu_L/\rho_L D_L)^{-1/2}(a_t d_p)^{0.4}(\rho_L \mu_L g)^{-1/3}$$

$$k_G \text{ (ft/s)} = c a_t D_G (G_g/a_w \mu_G)^{0.7} (\mu_G \rho_G D_G)^{1/3} (a_t d_p)^{-2}$$

Where

a_w = Wetted specific surface area of the packing (ft²/ft³)

σ_c = Surface tension of packing material (lb_m/s²)

σ_L = Surface tension of the liquid (lb_m/s²)

Reynolds = Liquid phase Reynolds Number = $G_1/a_t \mu_L$

Where

G_1 = Liquid mass flux (lb_m/ft²-s)

μ_L = Liquid viscosity (lb_m/ft-s)

Froude = Liquid phase Froude Number = $G_1^2 a_t / \rho_L^2 g$

Where

ρ_L = Density of the liquid (lb_m/ft³)

g = Gravitational constant (ft/s²)

Weber = Liquid phase Weber Number = $G_1^2 / a_t \rho_L \sigma_L$

D_L = Liquid diffusion coefficient (ft²/s)

d_p = Nominal packing diameter (ft)

c = 2 if $d_p < 15\text{mm}$, 5.83 otherwise

D_G = Gas diffusion coefficient (ft²/s)

G_g = Gas mass flux (lb_m/ft²-s)

μ_G = Gas viscosity (lb_m/ft-s)

ρ_G = Density of the gas (lb_m/ft³)

Figures

Fig 1:

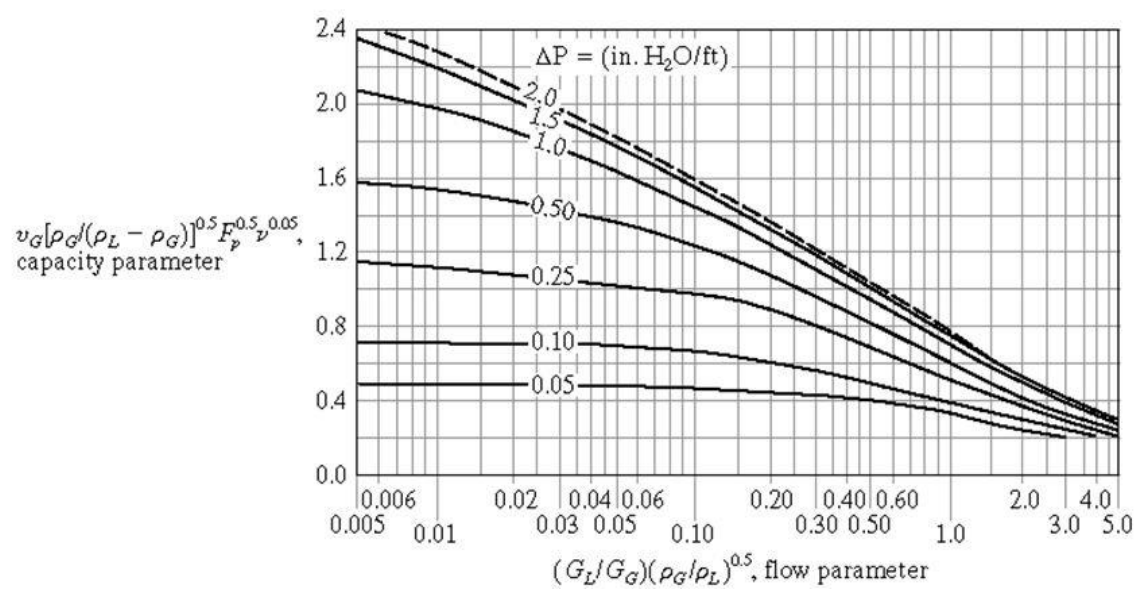
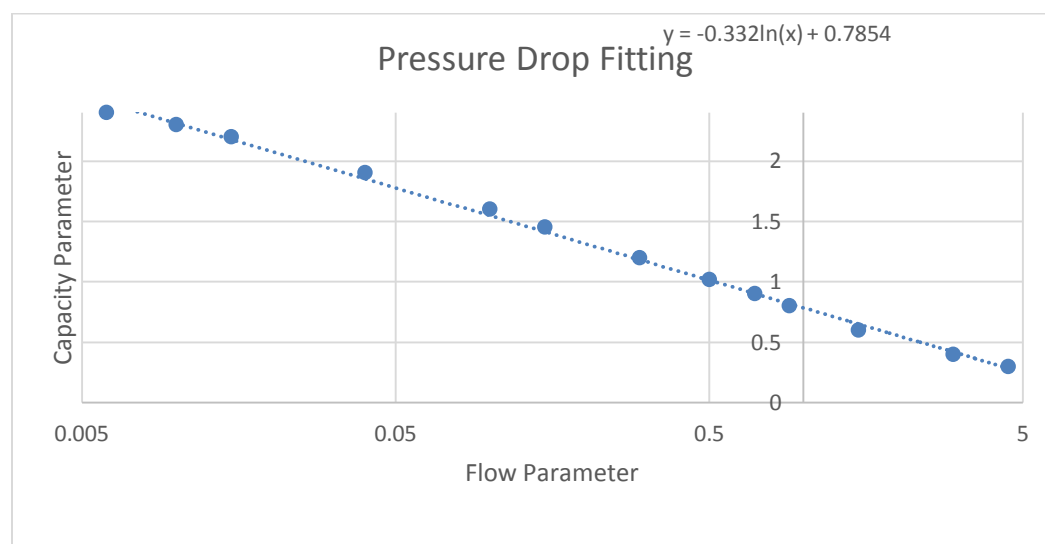


Fig 2:



Appendix Project Management

Progress Report 3/19/15:

Having met on Wednesday, March 19, we have successfully discussed the terms and conditions defined by the group. These have been formatted into the formal contract that all members have agreed upon and signed at the bottom. We have also laid the foundation for both the project and communication networks. Various means of contact have been established for ways to reach each other and meeting dates have been established. The next meeting is scheduled for Sunday, March 22.

As a group, we have decided to begin the project together and to split parts along the way as deemed necessary. When splitting up parts, there will always be at least two people working together on any one part to ensure both accuracy and effective progress. Finally, we have agreed that for all group homework assignments that it would be best to independently attempt all problems then come together to finalize all sheets to be handed in.

Progress Report 4/3/15

We have met up as a group several times throughout the past two weeks to complete intermediate project assignment #2. On Mathematica we have outlined initial design and sizing calculations. We analyzed TCE in the stripper at 20C. We also set up a code to analyze various packing materials. The entirety of our Mathematica file is meant to find the most efficient stripper when considering many different variables like temperature, packing material, and so on.

In our previous memo, we had decided that we would try to split up parts of the project, get them done separately, and then put them together at the end. So far, we have not really split up parts and we have moved as a group through the project.

One of the major issues we ran into as we were setting up intermediate assignment #2 was unit analysis due to the fact that the units in our appendix were different from those in the book. We are getting to a point where the lectures are behind how far along we are in the project and it is getting difficult to continue without further guidance.

The parameters we found for our column was that it would have a gas flow rate of 8833.08 m³/day. The column was found to get 7 trays and have an area of 19.03 ft² which resulted in a diameter of 2.46 feet. The total column is roughly 15 feet.