Volatile Organic Chemicals Removal from Contaminated Water using Air Stripping Low Profile Sieve Tray Towers

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Abstract

Ground water is the primary source of drinking water in various parts of the world. This source is threatened by the increase of the number of contaminants resulted from the activities of the chemical and oil industrial activities especially in northern part of the African continent. One group of contaminants that were identified is the Volatile Organic Chemicals that can be either of aromatic or aliphatic class. These organic chemicals have proven to have an adverse health effect to humans. There are several water treatment technologies that can be used in the treatment and ultimate removal of these organic chemicals. These treatment technologies include the activated carbon adsorption, packed tower aeration, and the low profile sieve tray towers. The proper design of any full scale treatment technology requires extensive studies that may include the costly and time consuming bench scale or pilot scale studies.

In this paper, a quick design calculation procedure is outlined for the design of the low profile sieve tray tower for the removal of some volatile organic chemicals identified in some contaminated groundwater.

Introduction

Air stripping is a physical mass transfer process and is generally considered as the best available technology for many volatile organic compounds (VOCs) present in contaminated groundwater. Air stripping uses relatively clean air to remove contaminant VOCs dissolved in water and transfers the contaminants into the gaseous phase. In drinking water treatment, the air stripping concept has actually been employed for a long time and was often referred to also as aeration and degasification. There are various aeration options that have been used in water treatment for quite some time. There are several technologies used in the VOC removal from contaminated water namely: Packed towers or air stripping towers, low profile sieve tray towers, and diffused aeration systems [1].

Air strippers are very popular equipment for mass transfer where air and water are contacted and the contaminants are transferred from water into the air phase. In a typical air-stripper arrangement, water flows from the top and air is blown from the bottom. The increase in surface area between the air and the water phases increases the removal efficiency. In packed towers, high-surface-area packing materials are used to that end. In a sieve tray tower, water flows across the tray through channels separated by baffles and air flows from the bottom, up through holes in the tray. In diffused aerators, air is introduced through a bubbler or a nozzle into the water stream. All these units are commercially available. For use Henry's Law to predict the stripping performance of volatile and semi-volatile contaminants present using the above equipment.

Theory:

Air stripping involves the mass transfer of VOCs that are dissolved in water from the water phase to the air phase. A one-dimensional mass transfer equation is used to describe the mass transfer flux of VOCs transferring from the water phase to the air phase [2]. The equilibrium relationship is linear and is defined by Henry's Law [3,4]. This mass transfer can be accomplished in a packed-column, a low-profile, or a diffused-air air stripper. The theory is available in textbooks [5,6].

Types of Air Strippers

1. Low-profile sieve tray

Low-profile air strippers operate in a similar way to packed-column air strippers (Figure 1). The difference is that the water flows across trays that are perforated with small holes, over a weir to the next lower tray, tray by tray until the water exits the bottom of the stripper. Air is bubbled through holes in the trays. The VOCs are transferred from the water phase to the air phase as the air is bubbled through the water on the trays. Detailed information on low-profile air strippers is available in the literature [5].

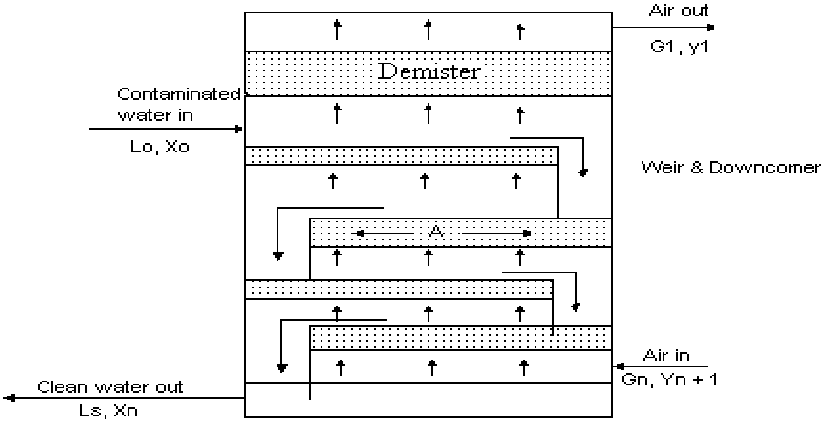

Figure (1). Cross-sectional area of perforated plate section.

2. Diffused-aeration

A diffused-aeration air stripper is a vessel with air diffusers in the bottom of the vessel. Air from the diffusers rises through the water and exits at the top of the vessel. The contaminated water to be air stripped enters the top of the vessel and exits at the bottom (Figure 2). Transfer of the VOCs from the water to the air occurs as the bubbles rise through the water. Transfer of the VOCs from the water to the air can be improved by increasing the vessel depth and by producing smaller bubbles. This kind of air stripper is not as efficient as the other two kinds and is not used as often. Its main advantages are its simplicity, ability to handle high suspended solids, and resistance to fouling. Information on diffused aeration is available in the literatures [3,7].

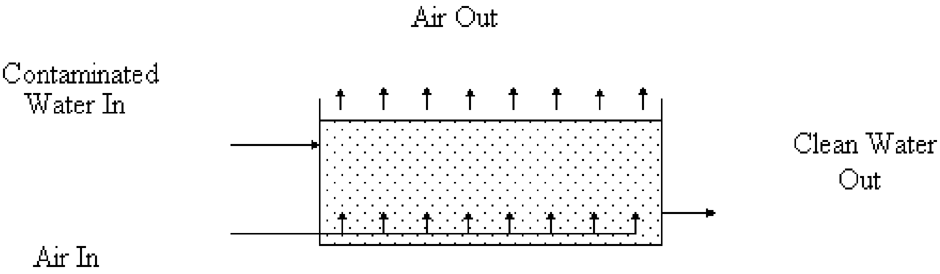

Figure (2) Diffused aeration air stripper

3. Packed-column

A packed-column air stripper consists of a cylindrical column that contains an open-structured packing material (Figure 3). The water containing the VOCs enters the top of the column and flows down through packing material [8]. At the same time, air flows up through the column (countercurrent flow). As the water and air pass each other, the VOCs are transferred from the water phase to the air phase. The water phase leaves the bottom of the column with most of the VOCs removed. The VOCs that are now in the air phase exit from the top of the column. Detailed information on packed-column air strippers is available in the literature [3,5,9]

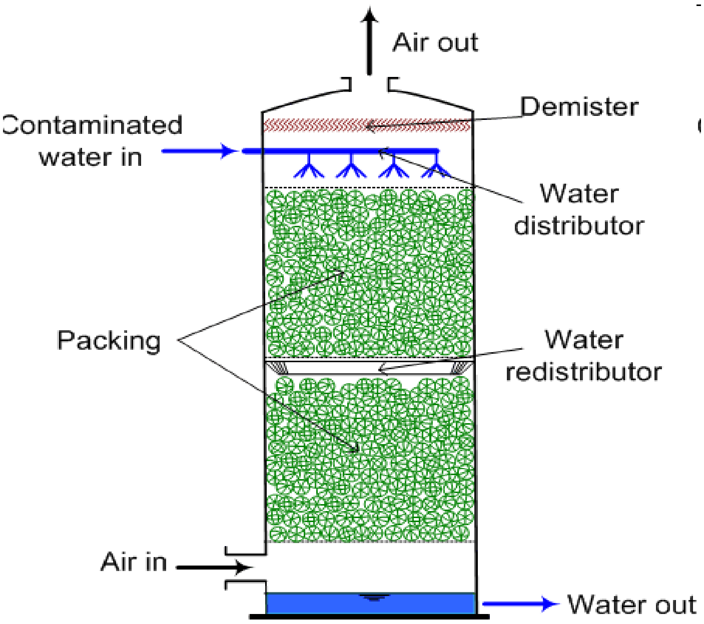

Figure (3) Packed column air stripper

Comparison of air strippers

General: The advantages and disadvantages of each type of stripper should be considered when making a selection. Either packed column or low profile air stripper will work in most situations, and are used extensively, but one may be more appropriate for the particular application. Diffused aeration strippers are less efficient for most applications, but their simplicity, ability to handle higher suspended solids, and better resistance to fouling are advantages. It may be necessary to do an economic analysis to help make the decision. Institutional factors, such as height restrictions or architectural restrictions, may require that a low profile air stripper be chosen even if a packed column stripper is more cost effective.

Efficiency: Packed column and low profile air strippers are capable of removing more than 99% of most VOC contaminants. Increasing the depth of the packing or the number of trays will increase the stripping. Increasing the airflow through a packed column may increase the efficiency. However, increasing the airflow beyond a certain point will induce a high pressure drop and will cause flooding.

Fouling: Air strippers frequently become fouled by mineral deposits when calcium exceeds 40 mg/L, iron exceeds 0.3 mg/L, magnesium exceeds 10 mg/L, or manganese exceeds 0.05 mg/L, or from biological growth. Air strippers may become plugged with solids that must be removed. Packed column air strippers must either have the packing removed for cleaning or the packing must be washed with an acid solution. Both operations are time consuming and costly. Low profile air strippers are often desirable when fouling is expected. Low profile units are often fastened together, tray by tray. Small units can easily be dissembled to physically remove the biological or mineral deposits. Larger units have access ports on the side of each tray for cleaning with a high-pressure water spray. Pretreatment of the water prior to stripping is often required. Foaming control agents may be required for some liquids.

Airflow Rate: The ratio of air to water flow rates is generally lower for a packed column stripper than for a low profile air stripper for the same level of VOC removal. Packed column air strippers are typically operated at 5 to 250 cfm/ft^2 (1.5 to 76 (m^3/min)/m^2) of column cross sectional area (Iowa State University, 1988) Low profile air strippers typically operate at 30 to 60 cfm/ft^2 (9 to 18 (m^3/min)/m^2) of tray area. Thus, the tray area of a low profile air stripper will usually be much larger than the tower cross-sectional area for the same treatment conditions. Low profile units are designed to operate over a fairly narrow range of airflow rates. If the airflow rate is too high for a low profile unit, the air blowing through the trays will form a jet and disperse most of the water. This results in low removal of the VOCs. If the airflow rate is too low, the water will flow down through the holes in the sieve trays. If the water flow rate decreases to a sieve tray as the result of changed operating conditions, the airflow rate through a low profile stripper cannot be reduced correspondingly, as it will be outside the operating range specified by the manufacturer. The cost of treating the off- gas will not be decreased in proportion with the liquid loading. Packed column air strippers can operate over a wide range of Airflow rates. The advantage of this is that, if the water flow rate to the column decreases, the airflow rates can also be decreased. This will reduce the cost of treating the off- gas.

Water Flow Rate: In contrast to the airflow rate, the flow rate of water through a sieve tray unit will be between 1 and 15 gpm/ft^2 (0.04 to 0.6 (m^3/min)/m^2). Packed column strippers operate most efficiently over a narrow range of water flows, between 20 to 45 gpm/ft^2 (0.8 to 1.8 (m^3/min)/m^2) of tower cross-sectional area manufacturer usually designs sieve tray air strippers. Items such as the length, location, and height of the overflow weirs, weir geometry, clearance under the downcomer, fractional hold area, etc., are very important and must be designed by a manufacturer who is experienced with sieve tray columns. Additional trays can be added to many low profile air strippers if additional treatment is needed and the blower and motor are capable of handling the additional pressure drop from additional trays. Combining the airflow rate and the water flow rate results in an air-to water ratio as low as 30 to as high as several hundred (volume to volume) for sieve tray units.

Pressure Drop and Power Consumption. The pressure drop through the packing of a packed tower air stripper is often lower than the pressure drop through a comparable low profile unit. This allows a smaller blower and motor, with reduced electrical operating costs.

Performance of VOC removal equipment

The stripping of various chemicals from water depends on the properties of a chemical, such as vapor pressure, solubility, density and the molecular weight of the chemical. Henry's Law describes the stripping of various chemicals. It states that the amount of chemicals present in air (transferred from water) is directly proportional to its equilibrium concentration in the water. The chemicals that have low solubility and are present in low concentrations in water obey Henry's Law. It is also assumed the solution (or the mixture) is ideal.

The constant is expressed in different units. The most common units are atmosphere-mol/mol or simply atm, or unit less (the ratio of the mole fraction of the chemical in air to the mole fraction of the chemical in water). Other units in which Henry's Law constant can be expressed, and the conversions, are presented in Table (1) [10].

Table (1) Henry's Law constants conversion factors

To convert from	To	Multiply by
atm.-m^3 H_2O/mol. air	atm	55600
Dimensionless (y/x)	atm	1335
atm.-L/mg	atm	55600
atm.-m^3/m^3	atm	124.5
atm.-L/m^3	atm	5.5

Empirical determination of Henry's Law constant

Henry's Law constant also can be calculated using solubility, molecular weight, density and the vapor pressure of the chemical. The equation to calculate Henry's Law constant from the above properties is presented in Equation (1) [11,12,13].

$$H = \frac{16{,}034 MwtVP}{CsT} \qquad \textbf{(1)}$$

The following table presents the value of Henry's law constant for several organic chemicals found in contaminated ground water.

Table (2) Henry's constant for some volatile organic compounds in atm at 20 ^{0}C

Chemical	H, atm	Chemical	H, atm
Trichloroethylene	550	Toluene	372
p-Xylene	394	Ethylbenzene	367
m-Xylene	389	Benzene	240
o-Xylene	278	Chlorobenzene	219

Data for mathematical model calculation

The VOC's investigated in this study along with its physical properties are shown on the following table.

Table (3) Physical properties of selected volatile organic compounds at 20 ^{0}C

Compounds	**Mwt, kg/kgmole**	**Vp,mm Hg**	**Solubility, mg/L**
Benzene	78.11	76	1780
Chlorobenzene	112.56	8.8	500
Ethylbenzene	106.17	7.0	152
Trichloroethane	131.5	60	1100
Toluene	92.14	22	515
m-xylene	106.17	6	130
o-xylene	106.17	5	175
p-xylene	106.17	6.5	196

Low profile sieve tray tower design procedure:

The following are the step by step design calculations for each VOC selected for this study:

1. The minimum and maximum volume of water to be air stripped, the minimum temperature of the water, and the maximum concentration of the volatile organic chemical (VOC) to be air stripped using the low profile sieve tray tower were selected for the design and model calculations.
2. The influent concentration of the VOC in contaminated water as a function of the removal efficiency was determined by applying the following equation:

$$\% \text{ Removal} = \frac{(X_0 - X_n) * 100}{X_0} \qquad (2)$$

C_e is equal to the maximum contaminant level (MCL) as assigned by the USEPA shown in table 4.

Table (4) USEPA National Primary Drinking Water Standards for some VOC's [14]

VOC	**MCL**	**VOC**	**MCL**
Benzene	5 ppb	Xylene	10 ppm
Toluene	1 ppm	Trichloroethylene	5 ppb
Ethylbenzene	0.7 ppm	Chlorobenzene	0.1 ppm

MCL : Maximum Contaminant Level , VOC: Volatile Organic Chemical

3. Calculate the theoretical number of sieve trays needed to remove VOC to the maximum contaminated level.

$$m = H / P_t \qquad (3)$$

$$S = m\frac{G}{L} \qquad (4)$$

$$N_{theor} = \frac{\log\left[\dfrac{X_0 - \dfrac{Y_{n+1}}{m}(1-\dfrac{1}{S}) + \dfrac{1}{S}}{Xn - \dfrac{Y_{n+1}}{m}}\right]}{LogS} \qquad (5)$$

4. Estimate the tray efficiency and the number of actual trays needed

$$N_{act} = \frac{N_{theor}}{E} \qquad (6)$$

5. Estimate the cross-sectional area of the perforated plate section of each tray.

$$A_x = Q_L * \frac{G}{W} * \frac{1}{G/A} \qquad (7)$$

6. Estimate the pressure drop through air stripper

$$\Delta P_P = N_{act} * \Delta P_L + \Delta P_{losses} \qquad (8)$$

Mathematical model calculation strategies

For the process calculations conditions listed on the table.

Table (5) Input data for all mathematical model simulation.

Parameter	value
Contaminated water flow rate (Q_L)	0.04 – 0.6 m^3/min
Air to water ratio(G/W)	30, 50, 70, and 100 m^3 of air/ m^3 of water
Operating temperature	10, 20, and 25 ^{0}C
Operating pressure	1 atm
Contaminate effluent concentration	Listed on Table (4) as MCL
Percent removal range	90-99.999
Volatile organic chemicals	Listed on Table (4) as MCL

- The number of trays and the total pressure drop will be determined for all model simulation for a pre specified VOC removal range.
- The optimum number of trays and optimum pressure drop for each VOC will be determined at the pre specified VOC removal range.
- Impact of operating temperature on performance of the low profile sieve tray air stripper.

Model simulations results

All mathematical model simulations for all VOC's under investigation using low profile sieve tray air stripper are summarized below starting from table (6) and figures from (4.A) up to Figure (8.B).

Table (6) Optimum actual number of tray and optimum total pressure drop for all VOC's under investigation at these treatment process conditions (99 % removal, G/W = 30 m^3 air / m^3 water, Q_L = 0.2 m^3/min, T= 20 ^{0}C, P = 1 atm)

chemical	Actual number of tray, N_{act}	Total Pressure drop in stripper, cm of water
Benzene	5.2	77.12
Chloro benzene	5.5	79.84
Ethyl benzene	4.3	67.36
Trichloroethylene	3.6	60.91
Toluene	4.2	67.11
m-xylene	4.2	66.29
o-xylene	4.9	73.28
p-xylene	4.1	66.07

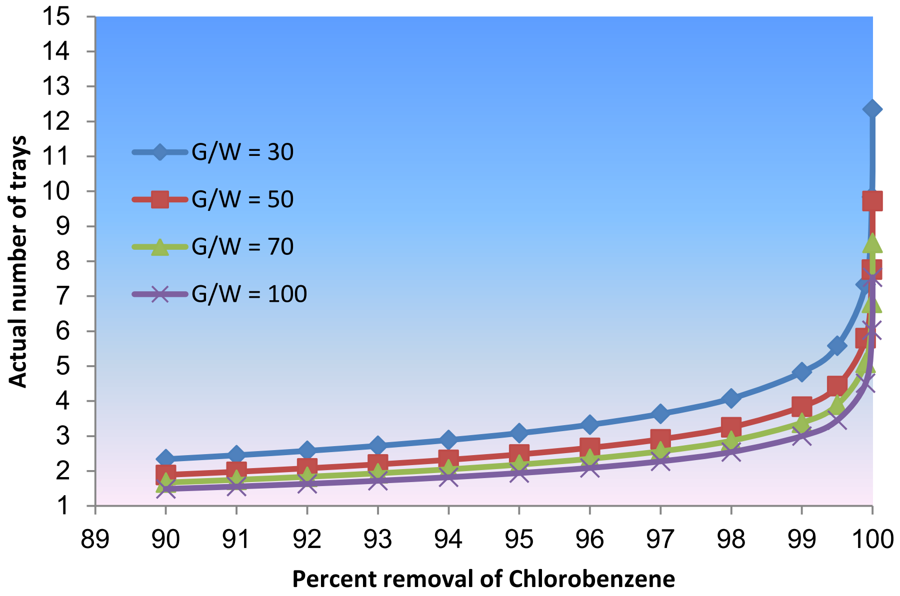

Figure (4.A) Variation of the number of trays with the removal efficiency of Chlorobenzene for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 ^{0}C and 1 atm).

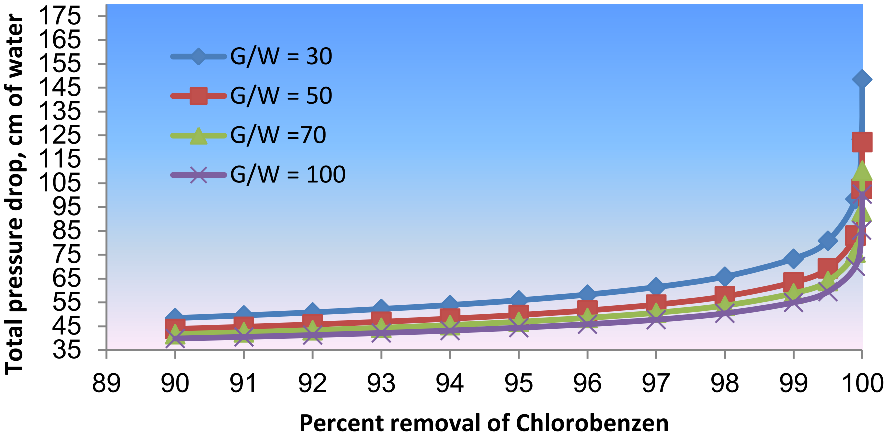

Figure (4.B) Variation of the total pressure drop with the removal efficiency of Chlorobenzene for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 0C and 1 atm).

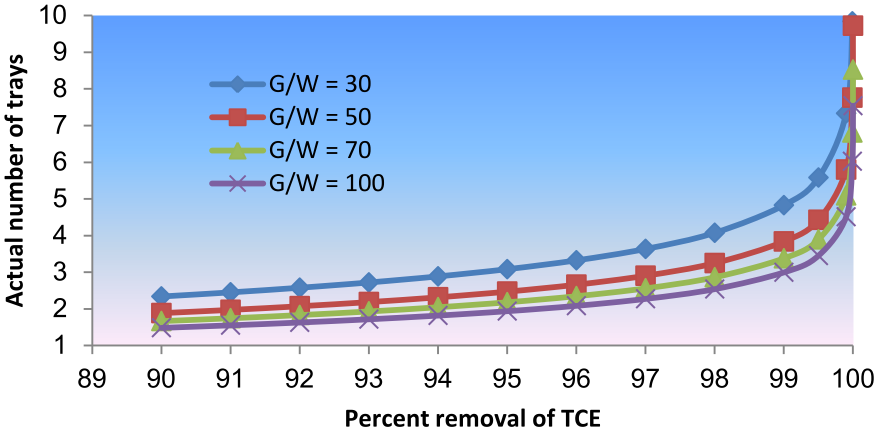

Figure (5.A) Variation of the number of trays with the removal efficiency of TCE for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 ^{0}C and 1 atm).

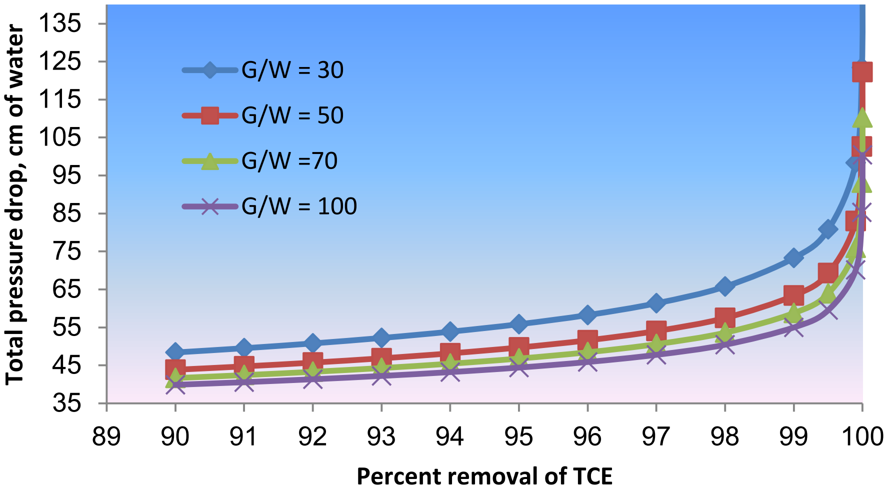

Figure (5.B) Variation of the total pressure drop with the removal efficiency of TCE for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 ^{0}C and 1 atm).

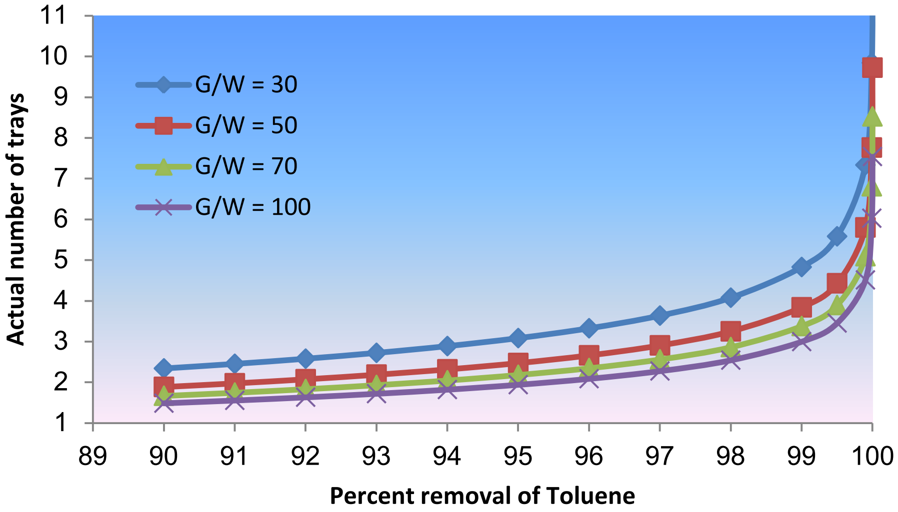

Figure (6.A) Variation of the number of trays with the removal efficiency of Toluene for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 ^{0}C and 1 atm).

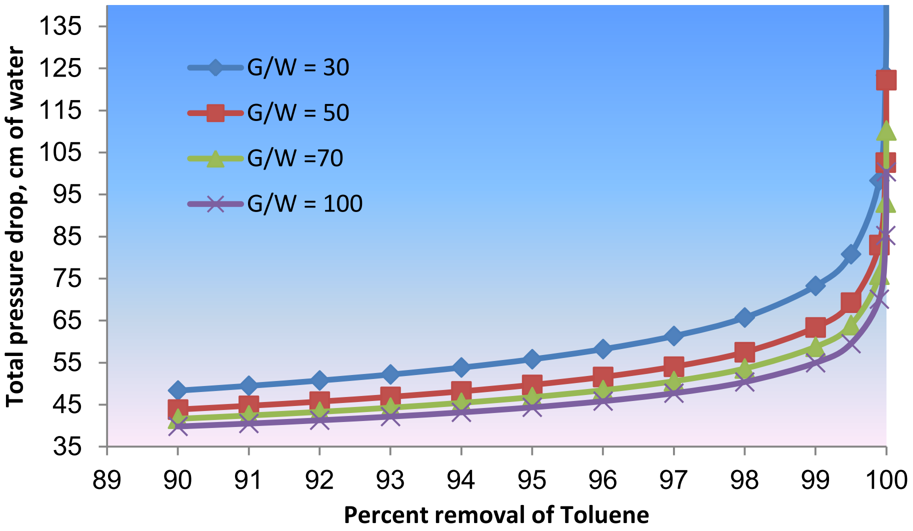

Figure (6.B) Variation of the total pressure drop with the removal efficiency of Toluene for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 ^{0}C and 1 atm).

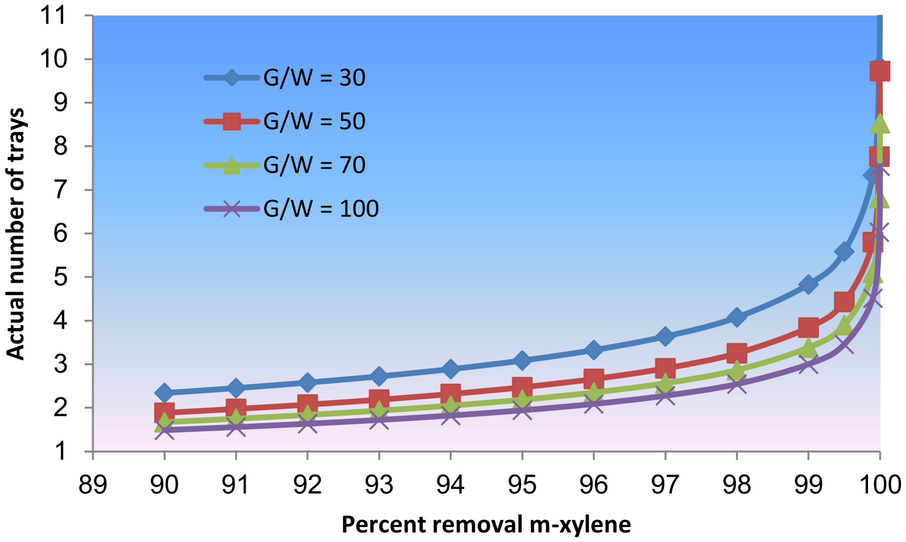

Figure (7.A) Variation of the number of trays with the removal efficiency of m-xylene for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 ^{0}C and 1 atm).

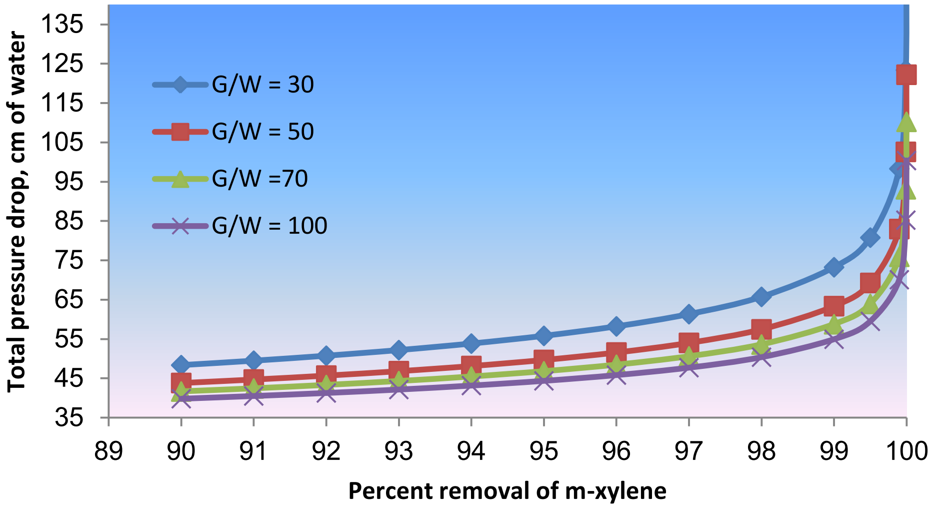

Figure (7.B) Variation of the total pressure drop with the removal efficiency of m-xylene for different air/ water ratio at (Q_L =0.2 m^3/min, MCL 20 ^{0}C and 1 atm).

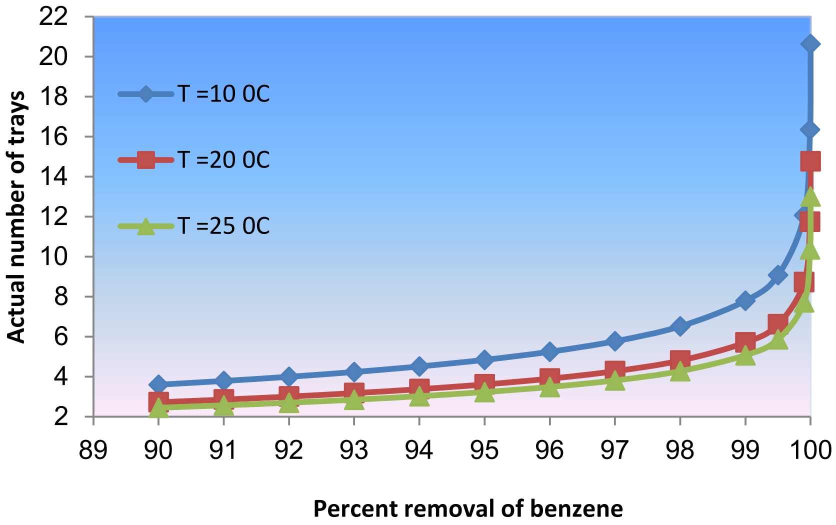

Figure (8.A) impact of operating temperature on actual number of trays for the specified percent removal range for Benzene at a constant air to water ratio (G/W = 30), Q_L =0.2 m3/min, MCL, 1 atm).

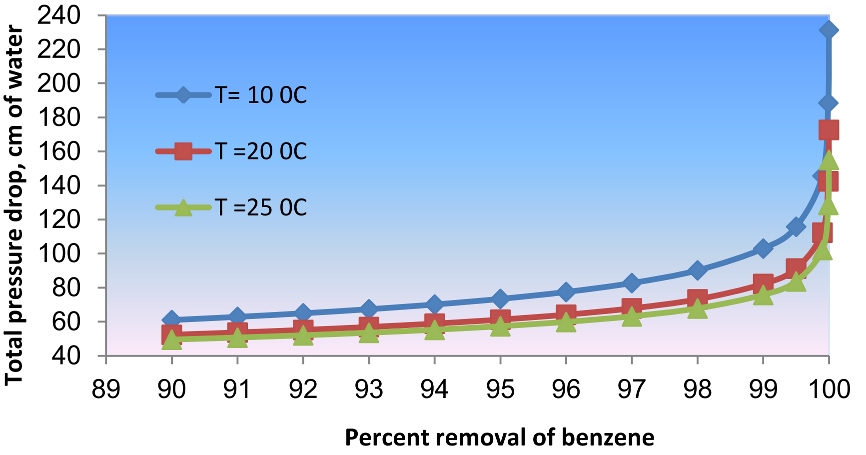

Figure (8.B) impact of operating temperature on the total pressure drop for the specified percent removal range for Benzene at a constant air to water ratio (G/W = 30), Q_L =0.2 m^3/min, MCL, 1 atm).

Discussion

Volatile Organic Chemicals such as benzene, ethyl benzene, toluene, xylene (BETX) and chlorinated solvents such as trichloroethylene (TCE) are often removed from groundwater by air stripping. Packed-column air strippers and low-profile sieve tray air strippers are often used for this. Other types of air strippers such as diffused air strippers or cooling towers are sometimes used, but for most applications they are not as efficient. The following are characteristics of low-profile sieve tray air strippers:

- Efficiency increases as the number of trays increases,
- Fouling is easier to remove.
- Operate over a fairly narrow range of air flow rates.
- Operate over a fairly wide range of water flow rates.
- Compact.
- Aesthetically pleasing.
- Fabricated by manufacturer.
- Designs include trays that can be stacked.

Low profile units are designed to operate over a fairly narrow range of airflow rates. If the airflow rate is too high for a low profile unit, the air blowing through the trays will form a jet and disperse most of the water. This results in low removal of the VOCs. If the airflow rate is too low, the water will flow down through the holes in the sieve trays.

If the water flow rate decreases to a sieve tray as the result of changed operating conditions, the airflow rate through a low profile stripper cannot be reduced correspondingly, as it will be outside the operating range specified by the manufacturer.

Conclusions and recommendations

- Mathematical model calculations can be considerable as a quick and accurate tool for the design of the law profile sieve tray air stripper tower. However, it is essential to compare the design finding to an actual treatment field process.
- To effectively remove the VOC's examined in this study (BTEX, TCE, Chlorobenzene, and Toluene), model calculations suggested that an actual number of trays required will be in the range 4 – 6 trays.
- The total pressure drop which includes the air blower, water pump, and pressure head on each tray for all VOC's under investigation was found to be in the range (60 – 80) cm H_2O [6 – 8] kPa.
- Attempting to reach a very high removal percentage (99.999%) for any VOC using low profile air stripper can be achieved, but it will require a higher number of trays which in turn will cause an increase in the cost of the treatment process.

- Higher percent removal (more than 99%) for any VOC using the low profile sieve tray tower can be achieved with an actual number of trays of about 5 trays, and an average total pressure drop of 70 cm of water [7 kPa].
- The optimum air to water ratio (G/W) for all VOC's under this investigation was found to be in the range (30 –70) m^3 air/m^3 water.
- The low profile sieve tray can operate at a flow rate of air in the range 9 – 18 (m^3/min)/m^2 of tray area at the same treatment conditions for all VOC's under investigation, while the flow rate of water (Q_L) will be in the range 0.04 – 0.6 (m^3/min).

Nomenclature

C_s = Solubility of contaminate in water, mg/L.

E = Overall plate efficiency.

G/A = Air flow rate per tray area, m^3 of air/ m^2 of tray area.

G/W = Air to water ratio, m^3 of air/ m^3 of water.

G' = Molar flow rate of air, Kg-moles air/min.

H = Henry's constant, kPa.

L' = Molar flow rate of water, Kg-moles of water/min.

m = Slope of equilibrium curve.

MCL = Maximum contaminant level, mg/L.

M_{wt} = Molecular weight of the contaminant, Kg/Kgmole.

N_{act} = Actual number of trays.

N_{theor} = Theoretical number of trays.

ΔP_L = Pressure drop per tray, cm water/tray.

ΔP_{losses} = Pressure losses from piping and blower, cm water.

ΔP_p = Pressure drop through the air stripper, cm water.

P_t = Ambient pressure, kPa.

S = Stripping factor.

VOC = Volatile Organic Chemical.

VP = Vapor pressure of the contaminant, mm of Hg.

X_0 = Concentration of contaminant in the inlet water.

X_n = Concentration of contaminant in the treated water.

Y_{n+1} = Concentration of contaminant in the air entering the air tripper.

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