# Competitive Stripping of Multi-Organic Pollutants from Contaminated Water in Bubble Column Semi-Batch

**Waleed M. Salih**
Department of Environmental College of Engineering
Baghdad University
Email:waleedmsprof@yahoo.com

**Ahmed A. Mohammed**
Department of Environmental College of Engineering
Baghdad University
Email:ahmed.abedm@yahoo.com

**Yaseen R. Hasan**
Department of Environmental College of Engineering
Baghdad University
Email:yaseenrh1963@yahoo.com

## ABSTRACT

Air stripping for removal of Trichloroethylene (TCE), Chloroform (CF) and Dichloromethane (DCM) from water were studied in a bubble column (0.073 m inside dia. and 1.08 m height with several sampling ports). The contaminated water was prepared from deionized water and VOCs. The presence of VOCs in feed solution was single, binary or ternary components. They were diluted to the concentrations ranged between 50 mg/l to 250 mg/l. The experiments were carried out in batch experiments which regard the bubble column as stirred tank and only gas was bubbled through stationary liquid. In this case transient measurements of VOC concentration in the liquid phase and the measured concentration profiles were modeled by bubble aeration model (BAM) to fit the experimental data fairly well. The results from batch experiments show that the removal efficiency of VOCs increases with increasing gas flow rate or gas holdup. It is found a pH=10 give the best removal rate, but all experiments were adjusted at pH=8 which allow to study other operating conditions. TCE is being removed faster than the other two components for all systems and a single component was removed faster than binary or ternary system. The $K_La$ values were evaluated by fitting the BAM to the experimental data. It is found that $K_La$ increased with increasing gas flow rate and TCE exhibits the highest $K_La$ values.

**Key Words: Mass transfer, Bubble column, Air stripping**

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**الانتزاع التنافسي لخليط مركبات عضوية من الماء الملوث باستخدام بــرج الفقاعات في التجارب شبه الساكنة**

**ياسين رشيد حسن**
قسم الهندسة البيئية / كلية الهندسة/جامعة بغداد

**أحمد عبد محمد**
قسم الهندسة البيئية / كلية الهندسة/جامعة بغداد

**وليد محمد صالح**
قسم الهندسة البيئية / كلية الهندسة/جامعة بغداد

**خلاصــة البحث:**

ان الانتزاع الهوائي لإزالة مركبات الترايكلوروايثيلين (TCE)، الكلوروفورم (CF) والدايكلوروميثلين (DCM) من الماء الملوث تمت دراسته باستخدام برج فقاعات (بقطر داخلي ٠،٠٧٣م وارتفاع ١،٠٨م مزود بعدة فتحات جانبية لغرض أخذ النماذج من مادة البلكسكلاس). تم تحضير المحلول الملوث من المواد العضوية المتطايرة (VOCs) بمساعدة محلول الميثانول وتضاف الى الماء المقطر، وبعد ان يحضر المحلول يوضع في خزان التغذية. ان مركبات الـ (VOCs) المذكورة تحضر على شكل نظام فردي او ثنائي او ثلاثي. واما التراكيز المحضرة فتتراوح بين 50 ملغ/لتر الى ٢٥٠ ملغ/لتر. لقد تم اجراء التجارب الشبه ساكنه والذي يعتبر فيها برج الفقاعات كخزان خلط (Stirred Tank) و فقاعات الهواء تتحرك فيه من الاسفل الى الاعلى في الماء الساكن. تم احتساب تراكيز الـ (VOCs) من الطور السائل بأستخدام النموذج الرياضي للفقاعات الهوائية (ABM). وقد وجد ان القيم التجريبية مطابقة بشكل جيد مع النموذح المستخدم. ان النتائج المستحصلة في التجارب اظهرت ان نسبة كفاءة ازالة المواد العضوية المتطايرة تزداد بزيادة معدل جريان الهواء او زيادة معدل التغير الحجمي للهواء(Gas Holdup). لقد وجد ان افضل كفاءة ازالة عند pH=10. كما ان التجارب اظهرت ان مركب الترايكلوروايثيلين (TCE) يزال اسرع من المركبين الاخريين لكل الانظمة، وخاصة في النظام المفرد. ان قيم معامل انتقال المادة الحجمي (KLa) قد تم ايجادها لكل الحالات التي تم بحثها بضبط النموذج الرياضي BAM مع البيانات التجريبية. وبشكل عام فقد وجد ان قيم KLa تزداد بزيادة معدل جريان الهواء وان المركب TCE اظهر اعلى قيم لـ KLa.

**كلمات البحث الرئيسية : انتقال المادة، برج الفقاعات،الانتزاع بالهواء**

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**Waleed M. Salih**
**Ahmed A. Mohammed**
**Yaseen R. Hasan**

# 1. INTRODUCTION

Ground water contamination by trace levels of volatile organic compounds (VOCs) has emerged as a major water quality issue in the last five decades. Interest in VOCs in drinking water began escalating in the mid-70s when it became possible to measure these compounds concentrations μg/l levels. Since then, it has been recognized that volatile compounds are finding their ways into ground water, which is often used as the main source of drinking water, **Djebbar 1998.**

VOCs are organic compounds with a tendency to migrate or diffuse from the aqueous phase (water) to the gaseous phase (air), or vice-versa. They are generally highly volatile, with low molecular weight. VOCs are a widely used class of compounds employed in many types of industrial, commercial, agricultural, and household activities,**DeMarco 1983.**

These compounds find their way into the environment through industrial and municipal wastewater discharges, leachate from deficient, old waste disposal sites that received hazardous chemicals, illegal discharges, and leaks from above or underground storage tanks and pipes. Contamination of drinking water supplies may occur from any combination at relatively high concentrations, and several other compounds will be present at lower concentrations ,**Dyksen et al., 1982.**

A very prevalent water pollution problem pertains to contamination by VOCs that offer potentially very important health risks, when they have a certain propensity to evaporate away from the water into air. Many of these VOCs are only partially miscible with water but in general they all present certain solubility. The problem of reducing VOCs in water applies to ground waters, surface waters, and waste waters alike. The origin of the water has some important design implications that will be discussed later. This write-up will discuss the application of air stripping for the removal of VOCs from water.

Depending on the contaminant and site characteristics, volatilization can be an important mechanism for the loss of hazardous compounds from soils and liquid waste systems. Volatilization may decrease the concentrations of the wastes at a facility or site; however, because of the law of mass conservation, contaminants will subsequently be found in the atmosphere. Therefore, air emissions, may become hazardous air pollutants (HAPs) and result in short or long-term health effects. Volatilization can also be applied as a hazardous waste treatment process to clean up contaminated ground water through air stripping and to remediate soils by soil vapor extraction. If volatilization occurs, it will do so primarily as a function of the contaminants vapor pressure (if the compound is in relatively pure form) and the Henry's Law constant (if it is in aqueous solution), **Richard, 1997.**

One of the most useful methods to remove the VOCs from contaminated water by using the dispersion aeration (bubble column technique) which include flow of air bubbles in water, and mass transfer from liquid phase to gas phase will occur (VOCs move from the water to the air as the bubbles rise through the water). Several types of air stripper technologies are currently available for removal of VOCs from water. This evaluation focuses on the capabilities and limitations of several major established and emerging air stripper technologies that are potentially applicable for VOCs removal such as Packed tower Aeration, low profile aeration, bubble diffusion aeration, spray towers, aspiration ,**Andrew et al., 1995.**

Transfer of the VOCs from the water to the air can be improved by increasing the column length or by producing smaller bubbles. Its main advantages are that it is simple and that it can handle water having high levels of suspended solids, **Dwight, 2001.**

As far as published studies are concerned, the main interest is concentrated on

design  and scale-up, fluid dynamics and regime analysis and characteristic parameters, especially gas holdup, bubble characteristics, mass transfer coefficient  and heat  transfer  coefficient., the effects  of  superficial  gas  velocity,  liquid properties,  operating  conditions  ,  column dimensions, gas distributor design , solid type and concentrations are presented, **Nigar et al. 2004.**

Bubble columns are intensively used as multiple contactors in chemical, biochemical and petrochemical industries. They provide several advantages such as high heat and mass transfer rates,  compactness  and  low  operating  and maintenance cost, **Andrews et al., 1995 and Sulaymon and Mohammed 2010**.

Investigation  of  design  parameters characterizing  the  operation  and transport phenomena of bubble columns  have led  to better understanding  of  the  hydrodynamic properties, **Onder et al., 2004.**

## 2.OBJECTIVES

The main objective of this work is to investigate competitive removal of identified VOCs (TCE, CF and DCM) pollutants from water by air stripping batch wise, and to investigate stripping of dangerous VOCs from wastewater by air using bubble column from liquid phase to gas phase through single, binary and ternary systems of VOCs in water, also to determine the volumetric mass transfer coefficient $K_La$ for a particular component as single and in the presence of other components (binary and ternary systems).

## 3.MATHAMATICAL MODEL

For a VOC with a Henry's law coefficient much greater than approximately $(1.6*10^{-4}$ atm. $m^3$/mole at $25°C$), however, the gas-film resistance is  negligible compared  with  the  liquid-film resistance ,**Mackay and Leimonen, 1975.**

$K_La$ values for VOCs are not easily predicted because they are highly system dependent. However, a relative value of $K_La$ can be computed because $K_La$ is proportional to the VOCs diffusion coefficient in water, which is proportional to the molar volume at its normal boiling point ,**Wilke and Chang, 1955**.

As mass transfer occurs between water and air in a bubble, the VOC concentration in a bubble increases as the bubble moves through the water  column  to  the  water  surface.  This phenomenon was considered by **Matter–Muller et al., 1981 and Roberts et al, 1983**, who developed a kinetic model for bubble transfer with the  following  assumptions;  the  system  is isothermal;  mass-  transfer  coefficents  are constant and  independent  of time and location, if hydraulic  conditions  are  stable;  equilibrium follows  Henry's law; complete mixing  occurs in the  water;  the  change of VOC concentration in water during  the  retention time of a bubble  in the water  is  insignificant  compared  with concentration change in a bubble; and although the upward velocity, surface area, and volume of a bubble depend on the actual depth of the bubble, use of the mean values over that total depth is a acceptable .

The bubble–transfer model is based on the continuity equation for a VOC in a bubble rising through the water ,**Matter-Muller et al,. 1981.**

$$\frac{d}{dt}\left(\frac{P.V_b.y}{R.T}\right)\frac{(K_L)_b}{H}.\frac{A_b}{V_b}.P.V_b.\left(-\frac{C_1.H}{M.P}\right) \qquad (1)$$

Integrating **Eq. (1)** yields a relationship between water depth and the mole fraction of VOC in the bubble phase.

$$y(Z) = \frac{1}{P.\exp(-\Phi.Z)} \times \left[\frac{C_l}{M}.H_c.R.T.\exp(-\Phi Z)\,con\right] \qquad (2)$$

When **Eq. (2)** applied for the entire bubble rise for  typical  unsteady–state  gas  transfer,  $C_L$ becomes  a  function  of  the  aeration  time  (t), according to:

$$\text{Ln}\left(\frac{C_{L,i}}{C_{L,o}}\right) = -Q_G.\frac{H_c}{V_L}.[1 - \exp(-\Phi.Z_s)].t \qquad (3)$$

The slope of the relationship between $\ln(C_{L.t}/C_{L.O})$ versus t of **Eq. (4)** is expressed as :

$$S_b = -Q_G \cdot \frac{H_c}{V_L}[1 - \exp(-\Phi \cdot Z_s]] \qquad (4)$$

Because $\phi$ in **Eq. (4)** is a function of $(K_L a)_b$, $(K_L a)_b$ of any $VOC_i$ can

be obtained from **Eq. (5)** as rearranged to solve for $(K_L a)_{b,i}$

$$(K_L a)_{b,i} = -Q_G \cdot \frac{H_{c,i}}{V_L} \cdot \ln\left(1 - \frac{S_{b,i} V_L}{Q_G \cdot H_{c,i}}\right) \qquad (5)$$

## 4. EXPERIMENTAL SET UP

**Fig.1** the experimental set up which consists mainly of a pixglass bubble column 73 mm inside dia. and 1.08 m height with several sampling ports, the column; a feed pump, a feed tank, a stock solution tank, an air compressor and air rotameter. The distributor plate is a 1/8 in metal sheet having 50 orifices of 0.5mm in diameter arranged on a square pitch. mm polyethylene. The liquid line is a plastic pipe with nominal diameter of 1/2 inch. The column has a two 3/4 in overflow pipes, and all fittings are either PVC or galvanized steel. The gas holdup was measured according to the volume fraction of the gas phase occupied by the gas bubbles, which defined as the volume of gas phase divided by the total volume.
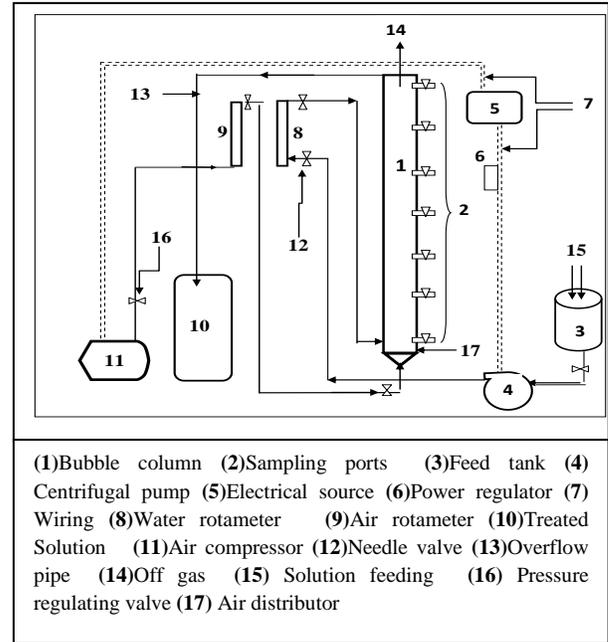


**(1)**Bubble column **(2)**Sampling ports **(3)**Feed tank **(4)** Centrifugal pump **(5)**Electrical source **(6)**Power regulator **(7)** Wiring **(8)**Water rotameter **(9)**Air rotameter **(10)**Treated Solution **(11)**Air compressor **(12)**Needle valve **(13)**Overflow pipe **(14)**Off gas **(15)** Solution feeding **(16)** Pressure regulating valve **(17)** Air distributor

**Figure 1.** Experimental setup.

## 5. MATERIALS

VOCs used for the experiments were trichloroethylene TCE, chloroform CF and dichloromethane DCM. Alternatively DCM is known as methylene chloride. All these chemicals were of purity greater than 99.6 % and they were used without further purification. In this study deionized water was used for the preparation of the feed solution, i.e. aqueous solution of VOCs. Due to a low solubility of these VOCs in water, high purity methanol was used as a co-solvent which assisted in obtaining homogeneous solutions of VOCs in water.

The physical-chemical properties of the three VOCs used in the present work are summarized in **Table 1**.

**Table 1.** Physical and chemical properties of VOCs.

| property | Compound | | |
|---|---|---|---|
| | TCE | CF | DCM |
| Formula | $C_2HCl_3$ | $CHCl_3$ | $CH_2Cl_2$ |
| Molecular weight (g/mol) | 131.4 | 119.39 | 84.93 |
| Solubility in water at 20C°, (g/100mL) | 0.10 | 0.8 | 2.0 |
| Henry´s constant at 20C° (dimensionless) | 0.376 | 0.141 | 0.11 |
| Density, at 20C° (g/cm³) | 1.464 | 1.483 | 1.327 |
| Wave length, λ (nm) | 244 | 214 | 211 |

## 6. PREPARATION OF FEED SOLUTION

Contaminated water was used as feed solution. This was prepared by dissolving VOCs in deionized water. However, VOCs chosen for this study are of little solubility in water and consequently the aqueous solutions produced were heterogeneous.

**Fatima et al, 2009**, suggested the use of a co-solvent before mixing with water. Their procedure is simple, in which 1gm of a VOCs e.g TCE or CF or DCM  is dissolved in 10 mL of high purity  methanol  e.g > 99.6%  purity and the mixture is added to 10L of deionized water.

This step yielded a homogeneous aqueous solution of a single component of VOC of concentration 100 mg/l. Employing this technique, aqueous solutions of   single VOC of initial concentrations of   50,100,150,200 and 250 mg/l were prepared for the experiments. By a similar method binary and ternary solution were prepared with initial concentration of 50,150 and 250 mg/L of each component. The use of methanol proved to be an effective solvent which assisted in the dissolution of VOCs in water with the result that homogenous aqueous solution were obtained. Methanol concentration is too low to have an effect  on  desorption  performance  and  it´s volatilization during bubble aeration processes can be neglected according to blank test.

## 7. ANALYTICAL TECHNIQUES

Water  samples  drawn  from  bubble column during the course of experiments were analyzed  to  determine  VOCs  concentration. Single component samples were analyzed using the  UV-spectrophotometer  system  at  190-1100 wavelength  spread .The  injection  volume  of samples was 5 ml. For the two-component systems binary systems the spectro-photometric method is also used but the technique is different from that used for single-component systems. The bivariate  calibration  method  presented  by **Pedrol.et.al   ,1997**,   was   applied   for   the simultaneous  determination  of  two  VOCs components in a mixture, particularly when the two components have close wavelengths.

## 8. AIR STRIPPING EXPERIMENTS

All stripping experiments were carried out under   isothermal   conditions   of   temperature ranging  within  22-28  C°  average  25C°.  The experiments were operated as semi-batch wise by allowing air to bubble through non flowing water. The experiments involved desorption of single component solutions. To investigate competitive desorption, binary and ternary experiments were done for this purpose. The removal efficiency of VOCs and values of the mass transfer coefficient $K_La$ could be determined.

In these experiments, the stripping air was allowed  bubble  through  stationary  water  at different rates of flow. In each run about 4L of wastewater aqueous solution of VOCs were charged into the column. Different flow rates of air were used for the experiments. The pH of solution was varied covering five values 3, 5, 7, 8, and10 and pH was adjusted by sodium hydroxide or hydrochloric acid. After initialization the air flow water samples were withdrawn at discrete time intervals through a sampling port in the middle of the bubble column. The samples were immediately kept in sealed vials 10mL volume and placed in a cold box to prevent volatilization. The sparging process was terminated when the VOC concentration in the column was low or relatively constant. In most of the runs steady state

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situation was attained within around 80 min. Variability was randomly tested by taking two samples one right after the other and their concentrations were immediately measured. **Table 2** summarizes the operating conditions used in the experiments.

**Table 2.** Operation conditions.

| Run | $Q_G$(l/min) | pH | Con(mg/l) |
|---|---|---|---|
| Single system | | | |
| 1 | 3 | 3 | 250 |
| 2 | 3 | 5 | 250 |
| 3 | 3 | 7 | 250 |
| 4 | 3 | 8 | 250 |
| 5 | 3 | 10 | 250 |
| 6 | 1.5 | 8 | 250 |
| 7 | 2 | 8 | 250 |
| 8 | 4 | 8 | 250 |
| 9 | 6 | 8 | 250 |
| 10 | 3 | 8 | 200 |
| 11 | 3 | 8 | 150 |
| 12 | 3 | 8 | 100 |
| 13 | 3 | 8 | 50 |
| Binary system | | | |
| 1 | 3 | 8 | 250 |
| 2 | 2 | 8 | 250 |
| 3 | 1 | 8 | 250 |
| 4 | 2 | 8 | 150 |
| 5 | 2 | 8 | 50 |
| Ternary system | | | |
| 1 | 2 | 8 | 100 |
| 2 | 3 | 8 | 250 |
| 3 | 4 | 8 | 250 |
| 4 | 2 | 8 | 250 |
| 5 | 2 | 8 | 150 |
| 6 | 2 | 8 | 50 |

The removal rate or removal efficiency for each run was calculated as the difference between initial and residual concentrations. The results shows that a pH =8 was the most favorable value for recovering VOCs from wastewater consequently.

## 9. RESULTS AND DISCUSSIONS

A series of desorption tables and curves were obtained experimentally for air stripping from water of single, binary and ternary systems in a bubble column. In all experiments the overall mass transfer coefficient ($K_La$) was obtained by Bubble Aeration Model (BAM), the results were obtained by solving the model by using STATISTICA software computer program.

The mass transfer coefficient ($K_La$) assumed as an unknown parameter, was obtained from the model using the experiment data. The experimental and predicted curves are presented as plots of removal factors ($C_L/Co$) versus time.

Several experiments were carried out to investigate the effect of different experimental parameters on the removal efficiency of VOCs from water. The parameters studied were pH, air flow rate and the initial concentration of solutions for single, binary and ternary systems of VOCs.

*1*-**Effect of pH**  The effect of pH on the removal of TCE ,CF and DCM was studied in single system as shown in figures 2, 3 and 4 respectively plotting the concentration ratio $C_L/Co$ versus time at various pH values  while the other variables remained constant. From these three figures it can be seen that concentration ratio decreases sharply at the beginning of the runs, then it began to decrease slowly with time and it was found that the best pH value for the removal of all components to be 10 highly alkaline but all experiments were adjusted at pH=8 for laboratory purposes to control experiments easily and to be easy to study another operation conditions.

*2*.**Effect of Air Flow Rate** The removal of  VOCs from water was studied at different gas flow rates 1, 2, 3, 4, 6 l/min with the pH adjusted at 8, and for three systems single, binary and ternary. The results are presented in **Figs. 3, 4,** and **5,** as plots of $C_L/Co$ versus time with air flow rate as parameters.  It can be seen that high removal occurs with higher gas flow rates. This is due to the fact that the hydrodynamics of bubble columns depend on superficial gas velocity $U_G$. If $U_G$ increases hinder liquid flow indicating that the Liquid is getting more agitated and hence more removal. At low gas velocity, bubbles are small, and rise uniformly without much interaction with the liquid. On the other hand, at higher gas velocity, large fast-rising bubbles appear which disrupt the system contents, resulting in an increase in the liquid dispersion, Moustiri et al., 2001. Thus increasing the gas flow rate increases the removal of volatile solutes by gas transfer in

the range of interest for both surface and bubble aeration ,**Paul et al. 1985**.

The first point of significance from these plots is the systematic increase in the extent of VOCs removal with increase in air flow rate. The general shape of these curves is as expected based on the solution of the mass transfer equation BAM, it was an exponential removal rate with time. The effect of air flow rate is depicted in figures above and as found with single the binary and ternary the removal efficiency was increased with increasing air flow rate for all components in the mixture. Similarly, TCE was removed faster than the other components.

**3-Competitive Desorption***:* To show the effect of operating conditions on desorption experiments of a component by the presence of other components in the mixture; TCE is taken as a case. **Fig. 6** and **Table 3** illustrate the removal rate of TCE as a single system, as a binary system first with CF and second with DCM and as ternary system TCE-CF-DCM. It can be seen from the curves of experiments, TCE is being removed at a faster rate in a single system in comparison with binary and ternary cases. For example, after 700 s of operation, 82% of TCE is removed in the single case, whereas 68% is removed in the presence of CF and 70% is removed in the presence of DCM. In the case of ternary system, 66% of TCE is removed over the same period of time and operating conditions. Another example taken near the end of stripping operation (nearly after 2000 s), we note that 99% of TCE is removed in the single case, 96% and 97% with CF and DCM respectively, and 93%in the ternary case. It is clear that TCE in all these cases is the components with highest tendency for removal. The closeness of the removal CF and DCM is possibly due to the closeness of their Henry's constant and their molecular weight.

**Table 3.**Competitive desorption of TCE in presence of CF or DCM in binary system and in presence of CF-DCM in ternary system, $Q_G=2$ l/min, $C_o=250$ mg/l, T≈25°C.

| TCE ($C_L/Co$) | | | |
|---|---|---|---|
| Time (sec) | single | with CF | with DCM | with CF-DCM |
| 0 | 0.993 | 0.997 | 0.997 | 0.994 |
| 180 | 0.625 | 0.813 | 0.745 | 0.824 |
| 360 | 0.419 | 0.638 | 0.557 | 0.673 |
| 540 | 0.288 | 0.493 | 0.417 | 0.515 |
| 720 | 0.183 | 0.361 | 0.34 | 0.32 |
| 1020 | 0.087 | 0.195 | 0.174 | 0.156 |
| 1320 | 0.044 | 0.107 | 0.1 | 0.0794 |
| 1920 | 0.005 | 0.0326 | 0.055 | 0.069 |
| 2520 | 0.0022 | 0.013 | 0.033 | 0.044 |
| 3420 | 0.0016 | 0.008 | 0.012 | 0.013 |
| 4320 | 0.001 | 0.001 | 0.004 | 0.005 |
| 5520 | 0.0001 | 0.001 | 0.002 | 0.003 |

## 4-Evaluation of the Volumetric Mass Transfer Coefficient ($K_L a$)

The overall liquid phase mass transfer coefficient for each compound (as single, binary, and ternary systems) was evaluated by applying the experimental data to the aeration bubble model **Eqs. 4** and **5** using STATISTICA program. The results of calculations are presented in **Tables 4, 5 and 6,** for all systems investigated. **Fig. 7** presents the results for single component systems which show that $K_L a$ increases with increasing gas flow rate or gas holdup for the three VOC compounds. This result indicates the dependency of $K_L a$ on bubbling behavior created by gas flow through the liquid phase. A large number of small size bubbles observed at high gas flow rate caused the creation of large interfacial area for mass transfer and in turn this led to higher values of $K_L a$. As can be seen from **Fig. 7**, TCE exhibits the highest value of $K_L a$ in comparison with other two VOC compound and the order is:

$$K_L a_{|TCE} > K_L a_{|CF} > K_L a_{|DCM}$$

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This result is probably due to difference in diffusion coefficients of VOC compounds in the liquid phase. $K_La$ is directly proportional to the Henry's law constant and molecular diffusion in the liquid ,cited by Wilke and Change, 1955, i.e.

$$K_La \propto \sqrt{D_l} \tag{6}$$

Where:

$D_l$: is the diffusivity coefficient of VOC in the liquid phase.

And from **Table 3**, we noted that experiments of VOCs with mechanical stirring and found that $K_La$ values increased when stirring speed increased. Mechanical stirring has improved the interfacial area by producing large number of small size bubbles. **Figs.8, 9** and **10** present the results for binary systems. As can be seen, the highest value of $K_La$ is exhibited by the component with the highest value of Henry's constant, we note that CF and DCM exhibit weak competition, i.e. their $K_La$ values are close and this is probably due to the closeness of their diffusion coefficients. This discrepancy in the results is possibly due to variations in experimental conditions, particularly temperature which is difficult to control. The results shown in **Fig.11** for the ternary system indicate weak competition among the three VOC compounds, particularly at low gas flow rate. At higher air rate, value.

The effect of flow rate on $K_La$ value is in agreements with Matter-Muller et al., 1981, who carried out batch desorption.

$$v_{ml\ TCE} < v_{ml\ CF} < v_{mlTCE}$$

It can be seen from **Table 1** the $D_l$ values of DCM and CF is rather close and the diffusion coefficient in a solution could be different from that in pure solvent. The observed effect of gas flow rate on $K_La$ is in agreements with Matter-Muller et al., 1981 who carried out batch desorption experiments of VOCs with mechanical stirring and found that $K_La$ values increased with stirring

speed. Mechanical stirring has improved the interfacial area for mass transfer by producing large number of small size bubbles.

**Table 4.** $K_La$ and gas holdup for single experiments.

| VOC | $Q_G$(l/min) | $K_La$(sec$^{-1}$) | $\varepsilon_G$ |
|-----|-----|-----|-----|
| TCE | 1 | | 0.0185 |
| | 2 | 0.0026 | 0.023 |
| | 3 | 0.0032 | 0.034 |
| | 4 | 0.0037 | 0.046 |
| | 6 | 0.0044 | 0.057 |
| CF | 1 | 0.0009 | 0.0185 |
| | 2 | 0.0012 | 0.023 |
| | 3 | 0.0018 | 0.034 |
| | 4 | 0.0029 | 0.046 |
| | 6 | 0.0034 | 0.057 |
| DCM | 1 | 0.001 | 0.0185 |
| | 2 | 0.00124 | 0.023 |
| | 3 | 0.00154 | 0.034 |
| | 4 | 0.0017 | 0.046 |
| | 6 | 0.00237 | 0.057 |

**Table 5.** $K_La$ and gas holdup for binary experiments.

| Group | VOC | $Q_G$(l/min) | $K_La$(sec$^1$) | $\varepsilon_G$ |
|-----|-----|-----|-----|-----|
| TCE-CF | TCE | 3 | 0.00199 | 0.034 |
| | | 2 | 0.00149 | 0.023 |
| | | 1 | 0.00089 | 0.014 |
| | CF | 3 | 0.00124 | 0.034 |
| | | 2 | 0.0071 | 0.023 |
| | | 1 | 0.0005 | 0.014 |
| TCE-DCM | TCE | 3 | 0.00134 | 0.034 |
| | | 2 | 0.0011 | 0.023 |
| | | 1 | 0.00087 | 0.014 |
| | DCM | 3 | 0.00087 | 0.034 |
| | | 2 | 0.0007 | 0.023 |
| | | 1 | 0.0005 | 0.014 |
| CF-DCM | CF | 3 | 0.0014 | 0.034 |
| | | 2 | 0.001 | 0.023 |
| | | 1 | 0.0008 | 0.014 |
| | DCM | 3 | 0.00146 | 0.034 |
| | | 2 | 0.0012 | 0.023 |
| | | 1 | 0.00058 | 0.014 |

**Table 6**. $K_L$a and gas holdup for ternary-batch experiments.

| VOC | $Q_G$(l/min) | $K_L$a(sec$^{-1}$) | $\varepsilon_G$ |
|---|---|---|---|
| TCE | 2 | 0.00125 | 0.023 |
| | 3 | 0.00149 | 0.034 |
| | 4 | 0.00198 | 0.046 |
| CF | 2 | 0.00117 | 0.023 |
| | 3 | 0.00201 | 0.034 |
| | 4 | 0.00249 | 0.046 |
| DCM | 2 | 0.0014 | 0.023 |
| | 3 | 0.00215 | 0.034 |
| | 4 | 0.00252 | 0.046 |

## 10. CONCLUSIONS

The main goals of this work were to investigate competitive removal of identified VOCs from water by air stripping in a concurrent bubble column. The results obtained led to the following conclusions:

- From experiments it was found that the best pH value for removal of VOCs to be 10.

- High removal rates occur with high gas flow rates. The percentage removal increases proportionally with gas flow rate or gas holdup. This result can be generalized for the three systems.

- The removal efficiency affected slightly with increasing initial concentration of the solution for all systems.

- Component TCE is being removed faster than CF and DCM because of the difference in their Henry's constants. TCE has the highest value of Henry's constant and hence it is the most volatile component and the order of removal can be written as follows:
  TCE >CF >DCM
- The competition between the components in binary and ternary systems caused reduction in the material removed of each

solute compared with that in single solute systems.

- It is found that $K_L$a increases with increasing gas flow rate for all systems.

- The $k_L$a values for TCE in all systems were the highest compared with other components. This was due to its highest value of Henry's coefficients.
  The order of $K_L$a values in single and ternary systems can be summarized as follow:

$$K_La_{|DCM}< K_La_{|CF} < K_La_{|TCE}$$

and for the binary system is:

$$\underline{K_La_{TCE}{>}K_La_{CF,}} \quad \underline{K_La_{TCE}{>}K_La_{DCM,}} \quad \underline{K_La_{CF} {>}} \\ \underline{K_La_{DCM}}$$

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## 10. NOTATIONS

| | | |
|---|---|---|
| * | Denotes equilibrium | |
| a | Interfacial area | $m^2$ |
| A | Cross section area | $m^2$ |
| $A_b$ | Absorbency | Angstrom |
| *b* | Denote bubble | |
| $C^*_G$ | Gas phase at | mg/l |
| $C_{AI1}$ | Molar concentration inside the film | mole/l |
| $C_{AO1}$ | Molar concentration outside the film | mole/l |
| $C_L$ | liquid phase concentration at ~~equilibrium~~ | mg/l |
| $C_L^*$ | liquid concentration in equilibrium with | mg/ |
| d | Column inside | m |
| Dl | Water phase diffusion coefficient | $m^2/sec$ |
| G | denotes gas phase | |
| *H* | Henry's Law constant | atm-$m^3$/mole |
| $H_c$ | Henry's law constant | dimensionless |
| *i,j* | Subscript denote to Compound | |
| $k_L$ | Low flux mass transfer coefficient | $sec^{-1}$ |
| $K_La$ | Overall mass transfer coefficient | |
| *L* | denotes liquid phase | |
| *M* | Molar weight | g/mole |
| *o* | Denotes initial | |
| *R* | Gas constant | $8.2*10^{-5}$ $m^3$- |
| *S* | water solubility | mole/$m^3$ |
| *Sb* | Denotes slope | |
| *T* | Temperature | K |
| t | Time | sec |
| $U_G$ | Superficial gas | m/sec |
| $U_G$ | Superficial liquid | m/sec |
| Vc | Critical volume | $cm^3$/mole |
| $V_L$ | water solution volume | $m^3$ |
| Z | Axial distance | m |
| Φ | $= ([K_La]_b .V_L)/(H_C.Q_G.Z_s)$ | 1/m |
| ρ | Density | g/$mm^3$ |
| $\varepsilon_G$ | Gas holdup | |
| $\varepsilon_L$ | Liquid holdup | |
| ψ | High flux correlation | |
| | Ratio of mass-transfer coefficients | |
| ABM | Aeration bubble | |
| CF | Chloroform | |
| DCM | Dichloromethane | |
| GC | Gas chromatography | |
| TCE | Trichloroethylene | |
| UV | Ultra-Violet spectro-photometry | |
| VOCs | Volatile organic compounds | |



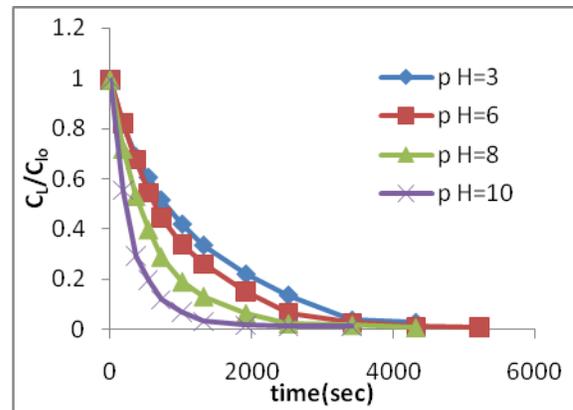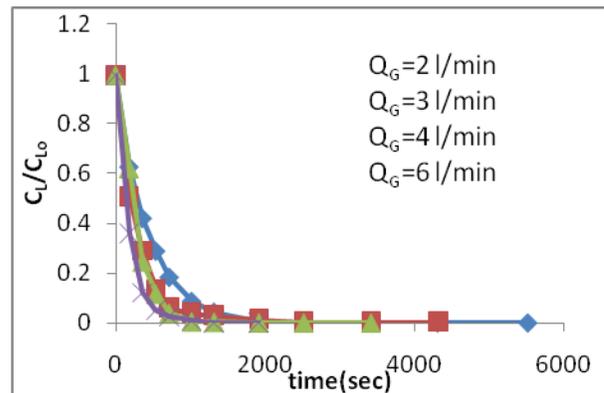**Figure 2.** Effect of pH on the removal of DCM single-batch, $Q_G$= 3 l/min, $C_{Lo}$=250mg/l, T≈ 25°C.



**Figure 3.** Effect of air flow rate on the removal of TCE single system, pH=8, $C_{Lo}$=250mg/l, T ≈ 25°C.

**Waleed M. Salih**
**Ahmed A. Mohammed**
**Yaseen R. Hasan**

**Competitive Stripping of Multi-Organic**
**Pollutants from Contaminated Water in Bubble**
**Column Semi-Batch**



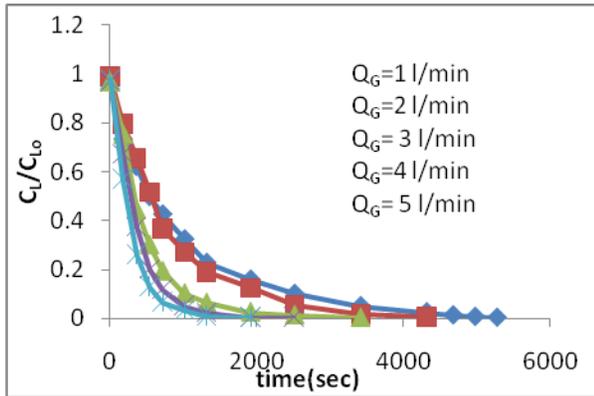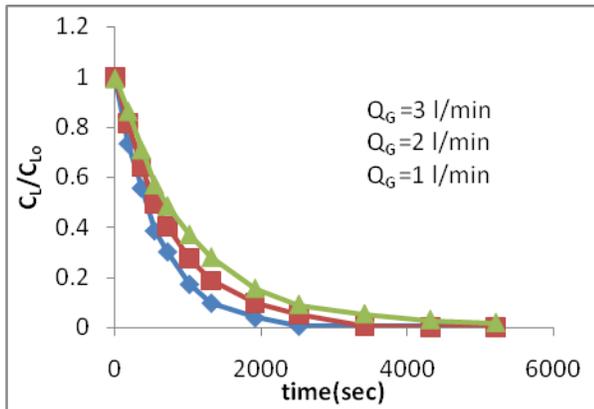**Figure 4.** Effect of air flow rate on the removal of CF single system pH=8, $C_{Lo}$=250 mg/l, T ≈ 25°C.



**Figure 5.** Effect of air flow rate on the removal of TCE in TCE-CF binary system, $C_{Lo}$= 250 mg/l, pH=8, T ≈ 25°C.
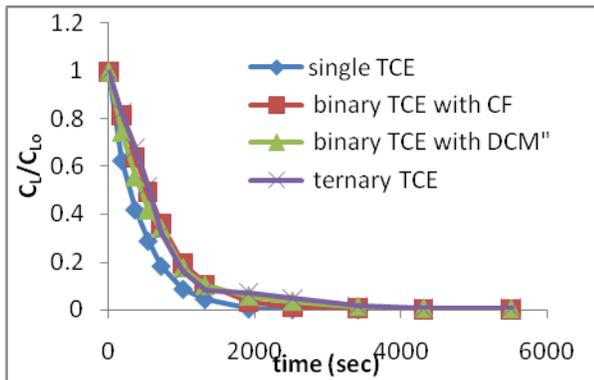


**Figure 6.** Competitive desorption of TCE in presence of CF or DCM in binary system and CF-DCM in ternary, $Q_G$=2 l/min, $C_{Lo}$=250 mg/l, T ≈ 25°C.
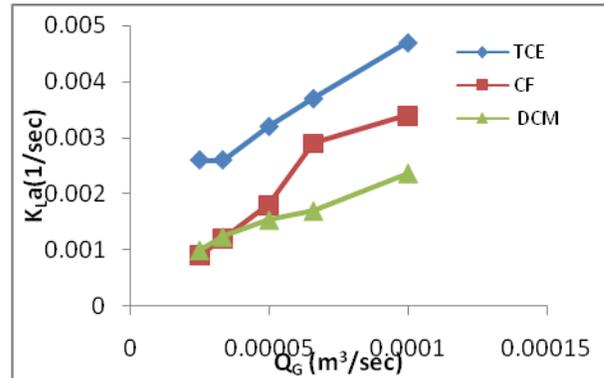


**Figure 7.** Effect of air flow rate on $K_La$ single system component $C_{Lo}$ =250 mg/l , pH= 8, T≈ 25°C.
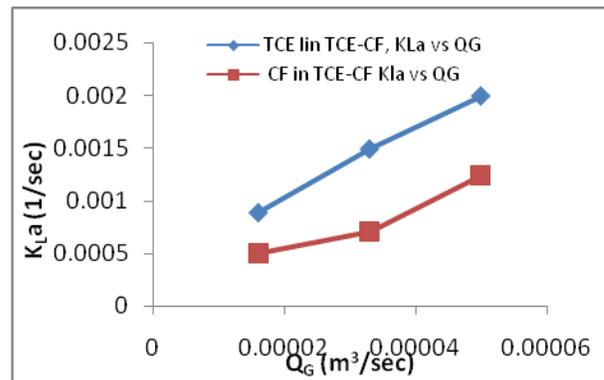


**Figure 8.** Effect of gas flow rate on $K_La$ in binary system (TCE-CF) component, $C_{Lo}$ =250 mg /l , pH= 8, T =25°C.
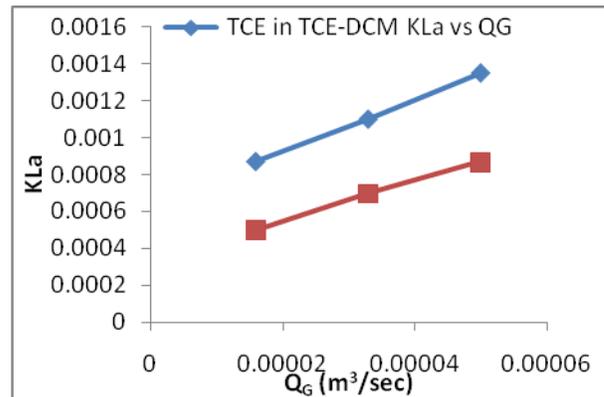


**Figure 9.** Effect of gas flow rate on $K_La$ in binary system (TCE-DCM) component, $C_{Lo}$ =250 mg/l pH= 8, T =25°C.
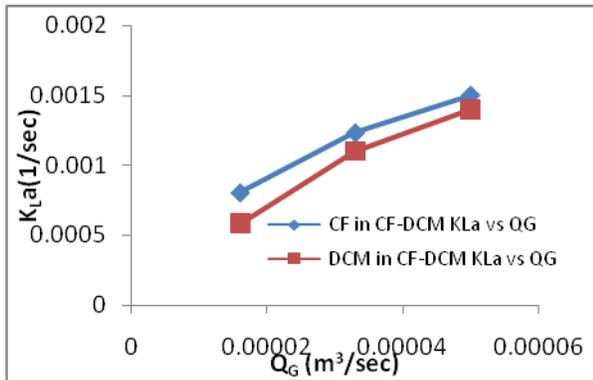
**Figure 10.** Effect of gas flow rate on $K_L a$ in binary system (CF-DCM) component, $C_{Lo}=250$ mg/l, pH= 8, T≈ 25°C.



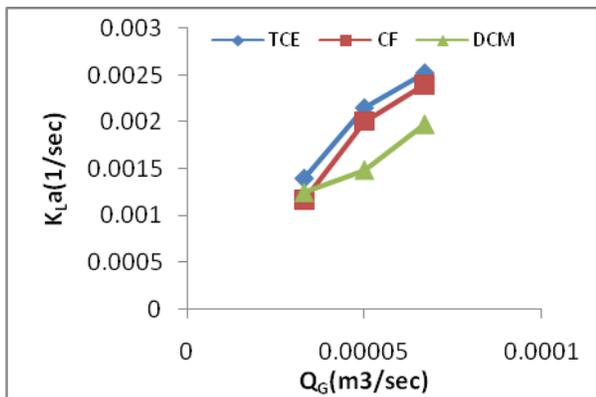**Figure 11.** Effect of gas flow rate on $K_L a$ ternary System (TCE-CF-DCM) component, $C_{Lo}=250$ mg/l, pH=8, T≈ 25°C.

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