Interactive Effect of Air-Water Ratio and Temperature on the Air Stripping of Benzene

M. E. Abdullahi[1], R. O. Yusuf[2*] and F. D. Aloko[1]

[1]Department of Chemical Engineering, University of Abuja, Abuja, Nigeria.
[2]Department of Chemical Engineering, University of Ilorin, Ilorin, Nigeria.

ABSTRACT: High cost of pilot scale studies has led engineers to use simulation to study the factors that affect process performance. This study focuses on the interactive effect of air-water ratio and temperature on the removal of volatile organic compounds from polluted water using packed column air stripper taking benzene as a case study. The process governing equations developed based on two-film model of mass transfer were solved using MATLAB and a surface response plot was done. The mass transfer coefficient increased from 0.1237×10^{-5} to $0.1932 \times 10^{-5}\, s^{-1}$ as the temperature was raised from 293 to 323 K. Also, the Henry's constant increased from 228.59 to 883.36 K as the temperature was raised from 293 to 323 K. Benzene removal efficiencies of over 99% were obtained for all combinations of temperature and air-water ratio. The result also indicated that air stripping of benzene from wastewater is most dependent on temperature and moderately on air-water ratio.

KEYWORDS: Interactive effect, air-water ratio, temperature, volatile organic compounds, removal efficiency

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I. Introduction

The toxicity of volatile organic compounds (VOCs) such as benzene even at very low concentrations makes their removal from wastewater or contaminated ground water an important issue in our industries (Abdullahi and Chian 2011; Vandenbroucke *et al.,* 2011; Zareei and Ghoreyshi, 2011). VOCs have been reported to be responsible for many acute and chronic health effects and environmental degradations such as global warming (Pooryousef and Mohammad, 2011). Air stripping is conventionally used because of its simplicity, low operating cost and the effectiveness in removing VOCs. Air stripping is a technology that uses an air stripper for VOCs removal from wastewater by increasing the surface area of the contaminated water that is exposed to air. In a packed column, wastewater is distributed over packing materials from the top of column while air is pumped from below in counter current operation using fans. The treated water is collected from the bottom of the tower while the VOCs rich air is released at the top to the surrounding with or without further treatment (Beranek, 2001; Mead and Leibbert, 1998).

Very high VOC removal efficiencies (over 99%) have been reported in the literature for various VOCs, such as benzene, toluene, xylene, chloroform, 1,2-dichloroethane (DCE), 1,1,2-Trichloethane (TCE) using packed column air stripper (Chuang *et al.*, 1992; Negrea *et al.,* 2008; Nirmalakhandan *et al.,* 1993; Zareei and Ghoreyshi, 2011). Several studies investigated the influence of operating parameters on the removal efficiency. In general, VOC removal efficiency was found to depend on temperature, air to water ratio, hydraulic loading rates, packing materials, size, depth and diameter, gas pressure drop, and Henry's constant of the contaminant (Alam and Hossain, 2009; Chuang *et al.,* 1992; Mourad *et al.,* 2012).

The understanding of the hydrodynamic behaviour of packed bed air stripper is a necessary condition to improve its operations and this requires a critical study of many factors that affect the process performance. However, pilot scale studies are a relatively expensive method. A more common and affordable alternative is to use mass transfer correlations. This is also not relatively straight forward because of the number of process variables involved (Djebbar and Narbaitz, 2002; Nirmalakhandan *et al.,* 1993). The iterative nature makes analysis via manual calculation tedious and subject to mathematical errors. This is also coupled with the changing nature of mass transfer relationships from one set of operating conditions to another (Djebbar and Narbaitz, 2002). Though a few computer based models exist, there is need for further studies on the interactive effect of air-water ratio and temperature on the removal efficiency of volatile organic compounds such as benzene.

This study therefore used a MATLAB program (matlab R2012b) to investigate the effects of operating variables such as temperature and gas-liquid ratio on the removal efficiency of benzene in a laboratory scale packed column air stripper and used response surface plot to determine the interactive effect of these factors.

II. Theoretical Analysis

Mass transfer of VOCs can occur through volatilization which may be induced by mechanical surface aeration. The process of removal of dissolved gas from liquid proceeds through the following consecutive steps (Montgomery, 1985);

(i) transfer from the bulk fluid to the interface;
(ii) transfer across the interface; and
(iii) transfer away from the interface into the bulk of new phase.

*Corresponding author's e-mail address: rafiuyusuf@yahoo.com

The rate of mass transfer of a VOC from wastewater to the atmosphere across an air-wastewater interface (dM/dt) is described by (Hand *et al.*, 2011; Montgomery, 1985).

$$\frac{dM}{dt} = -K_{La}\left(\frac{C - C_g}{H}\right)A \tag{1}$$

where K_{La} is the overall mass transfer coefficient (s^{-1}), C is VOC concentration (g/m^3), C_g is the gas phase VOC concentration (g/m^3), H is Henry's constant (atm) and A is surface area (m^2).
The variables necessary to determine the percentage VOC removal include,

A. Henry's Constant

The Henry's constant is an important parameter affecting the performance of air stripping towers; via its direct appearance in performance equations (Equation 1). It is also sometimes difficult to find exact literature values for Henry's constant for VOCs at the desired temperature (T) (Kutzer *et al.*, 1995, Staudinger and Roberts, 2001). Wide ranges of variation are also observed on the data published by different authors. From a thermodynamic analysis point, the temperature (T) dependence of the Henry's constant can be modelled by a Van't Hoff-type relation given in the integrated form (Hand *et al.*, 2011).

$$log(H) = \left(\frac{-\Delta H^o}{RT}\right) + C \tag{2}$$

where ΔH^o is heat of evaporation of 1 mole of component (kcal/kmol), R is universal gas constant (kcal/K.kmol) and C is empirical constant for van't Hoff's equation.

B. Stripping Factor

The capacity for transfer relative to equilibrium condition in an air stripper is usually expressed by the term "stripping factor" (S). It relates to the air-liquid ratio (G/L) and the Henry's constant (Taricska *et al.*, 2006).

$$S = H \times \left(\frac{G}{L}\right) \times 0.00075 \tag{3}$$

C. Liquid Mass Loading Rate

Most counter-current packed towers used for air-stripping in environmental applications are generally designed to operate under low liquid and gas loading rates (Nirmalakhandan *et al.*, 1993). When the loading rates are increased to a point where the water is prevented from flowing down, flooding will occur. The liquid mass loading (L) can be determined using

$$L = \frac{Q \times C_{in}}{Ax3.6 \times 10^6} \tag{4}$$

where Q is the water flow rate (m^3/h), A is packed column area (m^3) and C_{in} is VOC concentration in influent water (g/m^3).

D. Liquid Phase Mass Transfer Coefficient

According to the two-film model, laminar films exist at the gas/liquid interface. The resistance to the rate of mass transfer is therefore estimated by summing the resistances offered by the liquid- and gas-phase boundary layers (Huang and Shang, 2006). Many empirical correlations are available in the literature for determining the liquid phase transfer coefficient for a specific compound in towers containing randomly packed materials. An example is the Sherwood-Holloway equation

$$K_L a = \alpha D_L \left(0.305\frac{L}{\mu}\right)^{1-n}\left(\frac{\mu}{\rho D_L}\right)^{0.5} \tag{5}$$

where α and n are constants, D_L is liquid diffusion coefficient (m^2/s), μ is viscosity of water (Pa-s or Ns/m^2) and ρ is water density (kg/m^3).

E. Height of Transfer Unit (HTU)

This is a measure of the separation effectiveness of a particular packing for a particular separation process. It characterizes the efficiency of mass transfer from water to air. It is expressed mathematically as.

$$HTU = \frac{L}{K_L a C_o} \tag{6}$$

where C_o is VOC concentration in influent water (g/m^3).(Huang and Shang, 2006)

F. Number of Transfer Unit (NTU)

A design factor termed NTU was introduced by Kavanaugh to characterize the difficulty of removing the contaminant from the liquid phase (Huang and Shang, 2006). A single transfer unit gives the change of composition of the phases equal to the average driving force producing the change and it is determined from (7).

$$NTU = \frac{Z}{HTU} \tag{7}$$

where Z is the packing height (m).

G. Concentration of Effluent Water

The concentration of the contaminant in the effluent water (C_{out}) was determined using (Hand *et al.*, 2011).

$$C_{out} = \frac{C_{in}(S-1)}{exp\left[\frac{NTU(S-1)}{S}\right] - \frac{1}{S}} \tag{8}$$

G. Air Stripper Efficiency

The percentage removal of the contaminant is used to evaluate the efficiency of the air stripper. This was determined using (9) (El-Behlil and Adma, 2012).

$$efficiency = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \ (\%) \tag{9}$$

Table 1 shows the efficiency of air stripper for various substances as reported in literature.

Table 1: Data from the literature for various VOCs removal using air stripper.

Compound	Removal efficiency (%)	References
Benzene	> 95	Chuang *et al.*, 1992, Negrea *et al.*, 2008
Toluene	> 95	Chuang *et al.*, 1992, Negrea *et al.*, 2008
Xylene	> 95	Chuang *et al.*, 1992, Negrea *et al.*, 2008
Chloroform	87.4	Samadi *et al.*, 2004
1,2–dichloroethane (DCE)	>90	Harrison *et al.*, 1993
1,2-dibromo-3-chloropropane	89.2 – 96.2	Nirmalakhandan *et al.*, 1993
1,1,1-trichloroethane (TCE)	99	Byer and Morton, 1985
1,1,2,2-tetrachloroethane	94 – 98	Byer and Morton, 1985

III. METHODOLOGY

A laboratory scale packed column air stripper with the data shown in Table 2 was used in this study (Chuang *et al.*, 1992).The system was assumed to operate at 100mg/L influent concentration of benzene, air-water ratio range of 10 to 18 and at different temperatures of 293K, 303K, 313K and 323K referred to as T_1, T_2, T_3 and T_4 respectively. The choice of temperature was based on the studies of Abdullahi *et al.* (2014) and Chuang *et al.* (1992) which reported that a convergence in the performance efficiencies occurs at temperature above 50 ^{0}C and high air-water ratios for air stripping of benzene, toluene and xylene. The effects of temperature and air-water ratio on the removal efficiency were determined by solving the process governing equations 2-9 using a MATLAB program with data obtained from literature (Beranek, 2001; Hand *et al.*, 2011; Huang and Shang, 2006; Montgomery, 1985; Taricska *et al.*, 2004). The flow chart of the simulation process is shown in Figure 1.

Table 2: Air stripper specifications.

Parameter	Values
Wastewater flow rate	$0.05 m^3/h$
Packing volume	$2.26 \times 10^{-3} m^3$
Packing area	$0.1846 m^2$
Column diameter	0.05m
Height of packing	1.15m
Packing material	Ceramic raschig ring (6mm)

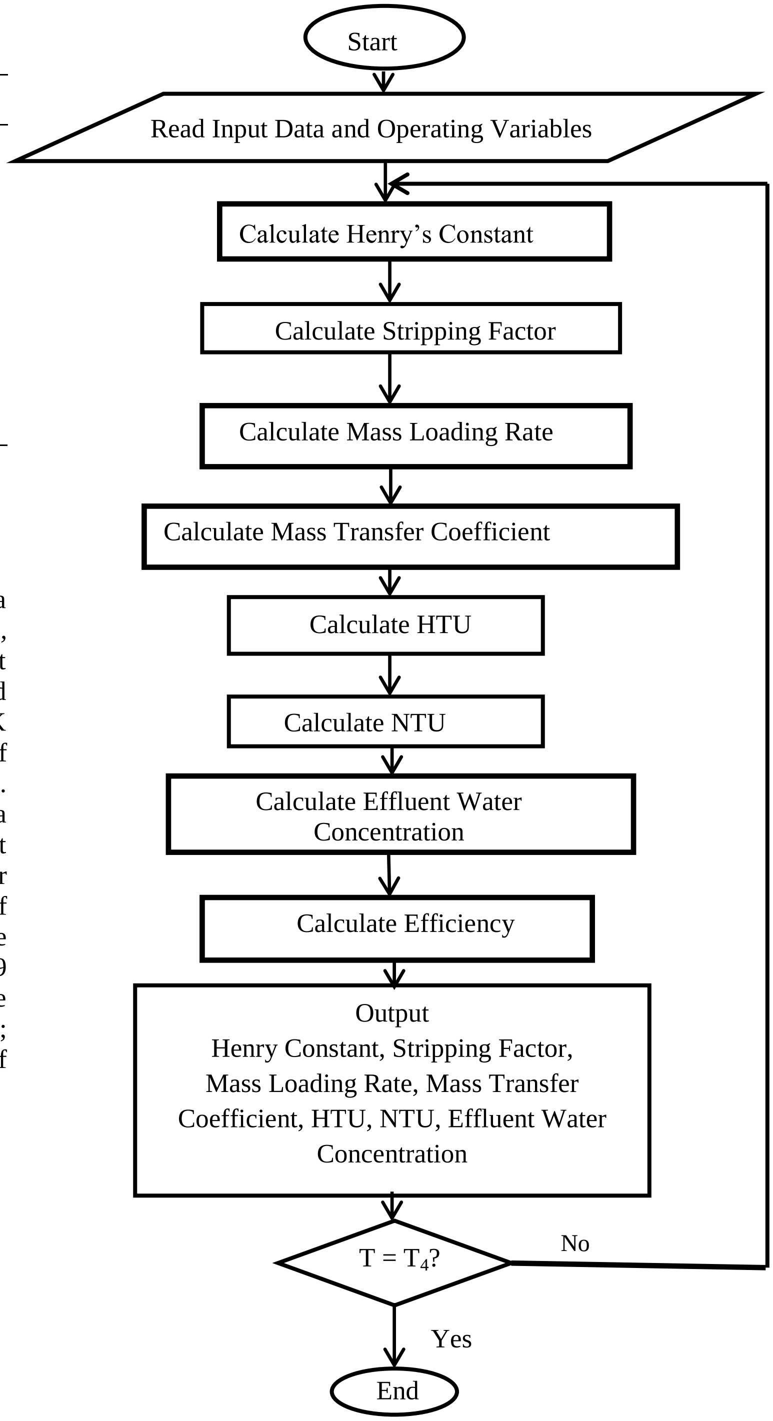

Figure 1: Flowchart of the simulation program.

IV. RESULTS AND DISCUSSION

A. Removal Efficiency

The effectiveness or accuracy of a model depends on how close the predicted values are to the practical results. The simulation results showed a good prediction of benzene removal. The results in Table 3 showed that over 99% benzene removal efficiencies were obtained for all the combinations of temperature and air-water ratio.

Studies on the air stripping of benzene at low G/L ratios (0-0.06) were conducted by Chuang *et al*. (1992). The result shows that a removal efficiency of 64% and 95% were obtained for G/L ratio of 0.018at 22 ^{0}C and 55 ^{0}C respectively. More also, very high VOC removal efficiencies (over 95%) have been reported in the literature for various VOCs, such as benzene, toluene, xylene, chloroform, 1,2-dichloroethane (DCE), 1,1,2-Trichloroethane (TCE) using packed column air stripper as shown in Table 2 (Negrea *et al.*, 2008; Nirmalakhandan *et al.*, 1993).

B. Influence of Air-Water Ratio

Figure 2 shows the trend of removal efficiencies of benzene at different air-water ratios and temperatures. At any given temperature, increase in air-water ratio results in higher benzene removal efficiency. This is because, increased air flow rate increases the interfacial area, decreases gases phase resistance and hence increase the mass transfer efficiency. Previous studies show similar result (Alam and Hossain, 2009; Chuang *et al.*, 1992; Zareei and Ghoreyshi, 2011). Another effect of increased air-water ratio is that, it causes a decrease in partial pressure of the solute in the gas phase, decreases its solubility and improves its removal efficiency. More also, the capacity for transfer of VOCs relative to equilibrium condition in an air stripper referred to as "stripping factor" (S) also increases with temperature and air-water ratio as shown in Table 4.

The result also shows that the trend becomes less significant at high temperatures (303K-323K) where the difference in percentage removal under different air-water ratio becomes smaller. At these conditions, the maximum removal efficiency is reached because the combined effect of high temperature and high air-water ratio accelerate mass transfer of benzene between the liquid and the gas phase. This is similar to the result obtained by Chuang *et al.*, (1992) in the air stripping of benzene, toluene and xylene (BTX) in a pilot scale packed column air stripper. However, the air-water must be chosen to maximize transfer while keeping pressure gradients under normal levels. Excessively high air-water ratio will result in flooding (Nirmalakhandan *et al.*, 1993).

C. Influence of Temperature

The influence of temperature on the removal efficiency was considered within a temperature range of 293-323K and at different air-water ratios as shown in Figure 3.

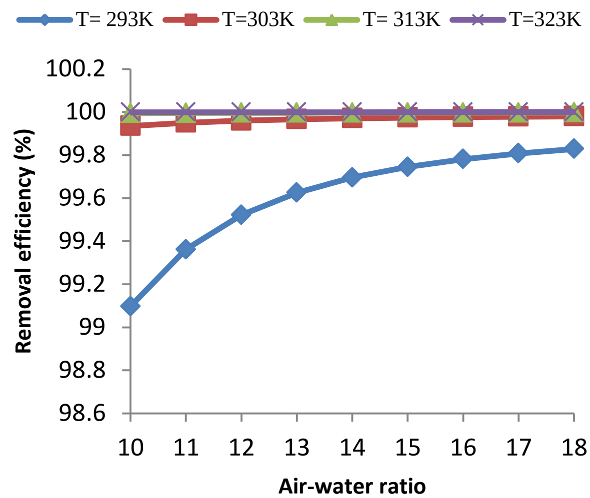

Figure 2: Effect of air-water ratio on the removal efficiency.

Figure 3 also showed that at high temperature (303 to 323K) and for all air-water ratios, an equilibrium removal efficiency of over 99.999% is reached and further increase in temperature gives no significant change in removal efficiency. The removal efficiency increases with increase in temperature at all air-water flow rates. This is because an increase in temperature causes a decrease in the solubility of organic compounds in water and increases Henry's coefficient as shown in Table 5 and hence improves removal efficiency (Zareei and Ghoreyshi, 2011).

Table 3: Removal efficiencies at different temperatures and air-water flow rates.

G/L	10	11	12	13	14	15	16	17	18
293K	99.0974	99.3612	99.5219	99.6253	99.6953	99.7447	99.7808	99.8078	99.8287
303K	99.9357	99.9505	99.9600	99.9664	99.9709	99.9742	99.9767	99.9787	99.9802
313K	99.9948	99.9956	99.9962	99.9966	99.9969	99.9971	99.9973	99.9974	99.9976
323K	99.9995	99.9996	99.9996	99.9996	99.9996	99.9997	99.9997	99.9997	99.9997

Table 4: Effect of temperature and air-water ratios on stripping factor of benzene.

G/L	10	11	12	13	14	15	16	17	18
T= 293K	1.71	1.88	2.06	2.23	2.40	2.57	2.74	2.91	3.08
T=303K	2.77	3.05	3.32	3.60	3.88	4.16	4.43	4.71	4.99
T= 313K	4.34	4.78	5.21	5.65	6.08	6.52	6.95	7.38	7.82
T=323K	6.62	7.28	7.95	8.61	9.27	9.93	10.60	11.26	11.92

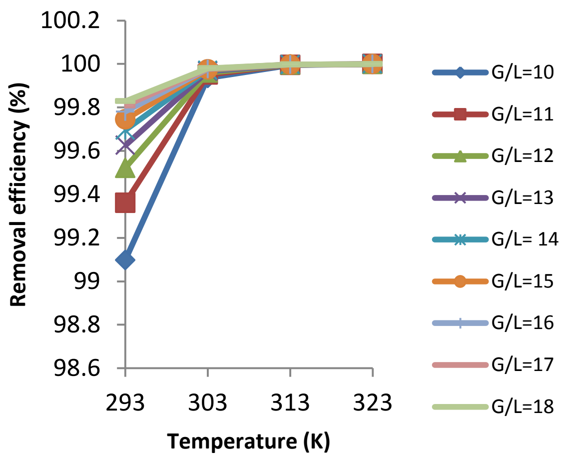

Figure 3: Effect of air-water ratio on removal efficiency.

Table 5: Change in mass transfer coefficient and Henry's constant with temperature.

Temperature (K)	293	303	313	323
Mass transfer coefficient (1/s) x10^{-5}	0.1237	0.1459	0.1692	0.1932
Henry's constant (atm)	228.59	369.54	579.36	883.36

A graphical representation of the effect of temperature on Henry's constant for benzene under the operating conditions is shown in Figure 4.

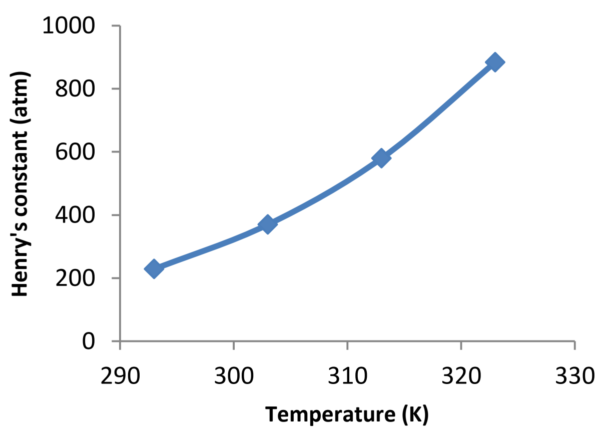

Figure 4: Effect of temperature on Henry's constant for benzene.

D. Surface Graph of the Effect of Air-Water Ratio and Temperature

The effects of independent variables on the dependent variable are elaborated by visualization using response surface plot. Here, the dependent variable is the removal efficiency while the independent variables are temperature and air-water ratio. The combined effect of temperature and air-water ratio on the removal efficiency is shown on Figure 5. The surface plot shows the dominant effect of temperature on the removal efficiency. The result implies that air stripping of benzene from wastewater is most dependent on temperature and moderately on air-water ratio.

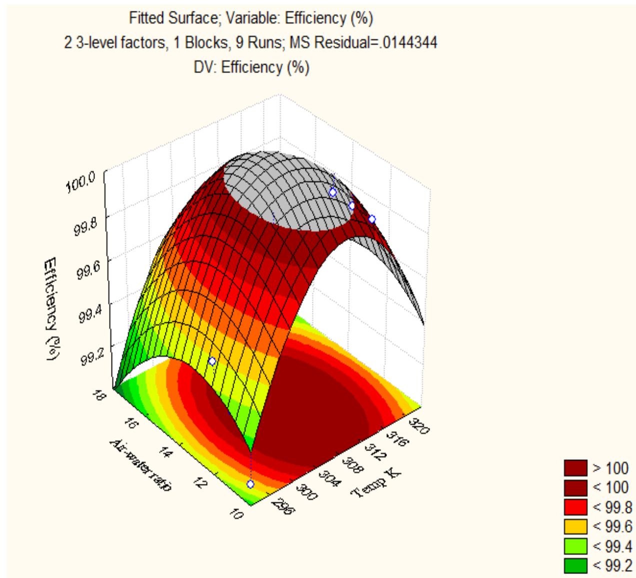

Figure 5: Surface plot of the effect of air-water ratio and temperature.

V. CONCLUSION

The effects of temperature and air-water flow rate on the air stripping of benzene were studied using MATLAB simulation of the process governing equations. The results showed that the over 99% benzene removal efficiencies were obtained for all the combinations of temperature and air-water ratio. This is an indication of effectiveness or accuracy of the process as it compares favourably with results from the literature. The results also showed that temperature effect is more dominant than the effect of air-water on the removal of benzene using packed column air stripper

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