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Simulationof the Effect of Process Variables on Packed Column Air Stripper Performance

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Abstract: Mass transfer operation such as air stripping is used in the removal of volatile organic compounds from wastewater and to improve its performance requires a critical study of many factors that affect the process performance.Using a MATLAB simulation of the process governing equations of the air stripper, the effect of process variables such as temperature, air to water flow rate, stripping factor, Henry's constant of the VOC and the overall mass transfer coefficienton the performance of air stripper in the removal of volatile organic compounds from wastewater (benzene) was carried.The result shows that removal efficiency increases with temperature, air to water flow and the overall mass transfer coefficient.A temperature of 303K is therefore considered as the optimum operating point, since further heating will not give any commensurate change in the removal efficiency and hence uneconomical.

Key words: Air stripper · MATLAB · Simulation · Overall mass transfer coefficient · Removal efficiency

INTRODUCTION

The transfer of material from gas phase to water or from water to gas plays an important role in water and wastewater treatment. Inorganic compounds can be oxidized and pathogenic bacteria can be destroyed by dissolution of chlorine or ozone gas in water. In another way, chemical conditioning of certain low-pH groundwater having excess carbon dioxide (CO_2) depends on removal of the gas from water. The addition of gases to water is known as gas absorption, while the opposite process is designated desorption or more commonly, as stripping [1]. A common and effective application of gas transfer process is in air stripping of ammonia gas and variety of volatile organic compounds from wastewaters, ground and surface waters [2, 3].

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. Various types include packed column, sieve tray and diffused aeration. The applicability of each technology is based on its performance as reported in engineering literatures, vendor information and professional experience with the equipment. The removal efficiency of the packed tower principally depends on the Henry's constant and the overall mass transfer coefficient [4, 5].

For any given transfer problem, equipment must be selected and sized to provide the maximum rate of mass transfer at a minimum cost. Analytical design of this equipment requires knowledge of gas-water equilibria, equipment hydraulics and the effect of system variables on mass transfer coefficients [1, 4]. Design of an air stripping unit is performed using a well-developed mathematical model of the process based on principles of mass transfer. However, because the number of process variables involved exceeds the number of constraining equations, designs are carried out by assuming or estimating values for extra variables [4]. Also, to improve the performance of these processes requires a critical study of many factors that affect the process performance. This can be achieved either by using pilot scale studies or mass transfer correlations. However, the

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costs of pilot scale studies are usually high. More also, the use of mass transfer correlations is also not relatively straight forward because of the number of process variables involved [6, 7]. The iterative nature makes analysis via manual calculation tedious and subject to mathematical errors. This is also coupled with the changingnature of mass transfer relationships from one set of operatingconditions to another [6]. More also, it may be necessary to calculate the Henry's constant for compounds for which sufficient data do not exist.

MATLAB is a powerful computing system for handling the calculations involved in scientific and engineering problems. It offers immediate execution statements or even groups of statements, in the command window. It also offers conventional programming by means of scripts files [8]. A good program is measured by its robustness in performance against the changes of the problem properties. And its accuracy is a measure of a nearness of a value to the true value. MATLAB have been successfully used in the theoretical study of air stripping of ammonia from wastewater with a relative error of 0.001 [9]. This paperstudies the effect of temperature on Henry's constant and mass transfer coefficient and the packed column air stripper performance using MATLAB program.

Development of Process Model: Air stripping is a mass transfer operation involving the transfer of dissolved VOCs in water from liquid phase to gas phase [10-12]. The air and water are contacted in a column specially designed to maximize the contact surface area between the water and air. An equilibrium results when two phases are brought into contact. This means, water in contact with air evaporates until the air is saturated with water vapour and the air is absorbed by the water until it becomes saturated with the individual gases. The equilibrium relationship is linear and it is defined by Henry's law. Henry's law states that for low concentration of volatile compound a, at equilibrium, the partial pressure of a gas, p_a, above a liquid is directly proportional to the mole fraction of the gas, x_a, dissolved in the liquid. This can be mathematically stated as equation 1.

$$P_a = H_a x_a \tag{1}$$

The proportionality constant, H_a, is known as the Henry's constant. This constant is a primary indicator of a compound's potential for removal by air stripping and it increases with increase in temperature. The application of air stripping is limited to compounds with Henry's constant values greater than 100 atmospheres [4, 13].

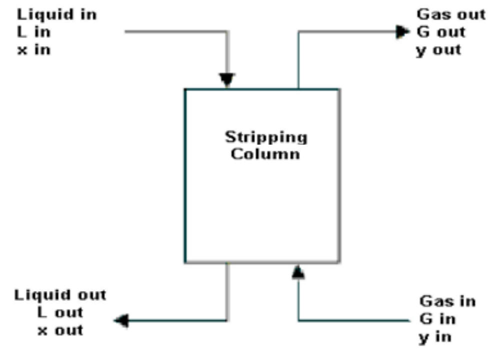

Fig. 1: Stripping column

The rate of mass transfer of a VOC from wastewater to the atmosphere across an air-wastewater interface can be described by equation 2.

$$\frac{dM}{dt} = -K_L a\left(\frac{C - C_g}{H}\right)A \tag{2}$$

whered M/dt is the rate of mass transfer, K_L a is the overall mass transfer coefficient (s^{-1}), C is the concentration of VOC in the influent water (g/m^3), C_g is the concentration of VOC in the gas phase (g/m^3), H is the Henry's constant (atm) and A is the surface area (m^3).

From a thermodynamic analysis, the temperature dependence of the Henry's constant can be modeled by a Van't Hoff-type relation, given in the integrated form by equation 3 [14].

$$\log(H) = \left(\frac{-\Delta H^\circ}{RT}\right) + C \tag{3}$$

where ΔH^o is the heat of evaporation of 1 mole of component (kcal/kmole), R is the universal gas constant (kcal/K.kmole), T is the temperature (K) and C is constant.

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 shown as equation 4 below [15].

$$K_L a = aD_L\left(0.305\frac{L}{\mu}\right)^{1-n}\left(\frac{\mu}{\rho D_L}\right)^{0.5} \tag{4}$$

where a and n are constant depending on the type of packing material, L is the mass loading rate ($kg/m^2.s$), μ is the viscosity of water (Ns/m^2), ρ is the density of water (kg/m^3) and D_L is the liquid diffusion coefficient of the VOC (m^2/s).

In packed tower air stripping, the total length is often defined as the product of the height of a transfer unit (or HTU) and the number of transfer units (or NTU) as shown in equation 5.

$$L = HTU \, x \, NTU \quad (5)$$

HTU is a measure of the separation effectiveness of particular packing for a particular separation process. It therefore incorporates mass transfer coefficient. Equation (6) defines HTU [14]:

$$HTU = \frac{Q}{AK_L a} \quad (6)$$

Where Q is the water flow rate (m^3/s)

NTU is a measure of the difficulty of separation. A single transfer unit gives the change of composition of the phases equal to the driving force producing the change. NTU depends upon stripping factor, R and VOC removal efficiency. The minimum air to water ratio is the lowest air to water ratio that can be applied for a packed tower to meet a specific VOC removal target. The performance of the tower under different air-water ratios can be explained using the stripping factor, R. R represents an equilibrium capacity parameter and when it is greater than 1, there is sufficient capacity in the air to convey all the solute in the water to be treated, when R < 1, the system is limited by equilibrium and when R = 1, the tower is operating at equilibrium [14]. Equation (7) defines the NTU.

$$NTU = \left[\frac{R}{R-1}\right] ln \left[\frac{\frac{C_o}{C_e}(R-1)+1}{R}\right] \quad (7)$$

where C_o is the concentration of VOC in the influent water (g/m^3), C_e is the concentration of VOC in the effluent water (g/m^3) andR is the stripping factor.

Stripping factor relates to the air-liquid ratio and the Henry's constant as shown by equation (8) below [16].

$$R = H \times \left(\frac{G}{L}\right) \times 0.00075 \quad (8)$$

The percentage removal of the contaminant is used to evaluate the efficiency of the air stripper. This was determined using equation 9 [10].

$$efficiency = \frac{C_{in} - C_{out}}{C_{in}} \; x \; 100(\%) \quad (9)$$

Algorithm of Solution: The specifications of a laboratory scale packed column air stripper used by Chuang *et al*. in their report of removal and destruction of benzene, toluene and xylene from wastewater by air stripping and catalytic oxidation were adopted for this study [18]. These include 0.05 m^3/h wastewater flow rate, packing height of 1.15m, column diameter of 0.05m, packing area and volume of 0.1846 m^2 and $2.26x10^{-3}$ m^3 respectively. The column is packed with 6mm ceramic raschig ring.

The process governing equations (1-9) were solved using MATLAB program to determine the Henry's constant, stripping factor, overall mass transfer coefficient and the VOC removal efficiency using data obtained from literature [1, 11, 14-16]. The system was assumed to operate at 100mg/L influent concentration of benzene, air-water ratio range of 10 to 18 and a temperature range of 293K to 323K.

RESULTS AND DISCUSSION

Henry's Constant and Temperature: Henry's constant of the VOCs is one important parameter affecting the performance of air stripping column. The Henry's constant for most of the compounds are equal to vapour pressure divided by water solubility [19]. However,exact literature values for Henry constant for VOC at the desired temperature are scarce [3].

Figure 2 shows that the values of Henry's constant for benzene increases with temperature. This is because the change of temperatures influences the physical properties of both the liquid and gas and has a significant impact on the mass transfer process. For example, an increase in temperature would lead to a pronounced reduction of liquid viscosity and surface tension of air bubbles, resulting in formation of small and stable bubbles and increases the probability of coalescence. It is this duality that alters the interfacial area and influences significantly on the mass transfer process [18, 20-21] and thus increases Henry's coefficient and hence improves VOC removal efficiency [20]. This is reflected in the variation of benzene removal efficiency with increases in Henry' constant at different air – water flow ratios shown in Figure 3 below. It can also be seen from the graph that an increase in Henry's constant beyond 370 atm. (equivalent to 303K) gave no significant change in the percentage removal efficiency of benzene

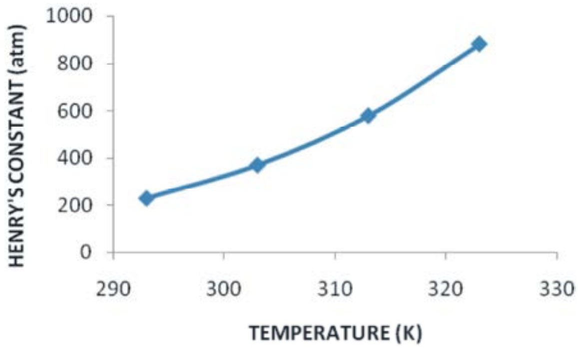

Fig. 2: Effect of temperature on Henry's constant of benzene

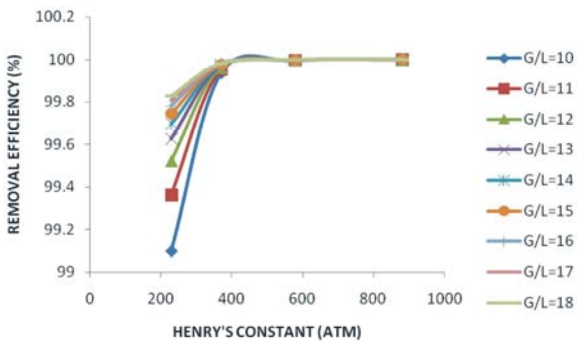

Fig. 3: Variation of removal efficiency with Henry's constant at different air-water flow ratios

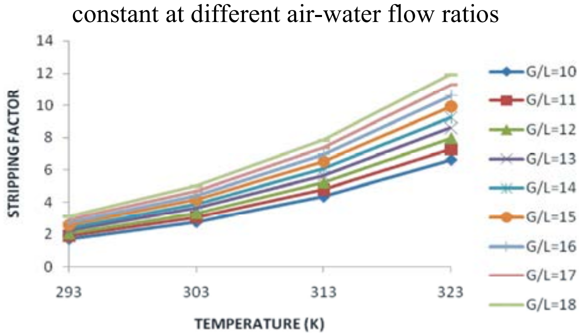

Fig. 4: Variation of stripping factors with temperature at different gas-liquid ratios

for all air to water ratios. A temperature of 303K is therefore considered as the optimum operating point, since further heating will not give any commensurate change in the removal efficiency and hence uneconomical.

Similarly, the VOCs removal efficiency increases with temperature because increase in temperature causes a decrease in the solubility of organic compounds in water and increases Henry coefficient and hence improves removal efficiency [3, 18, 20]. While Reidy *et al*. attributed this effect to increase in vapour pressure with temperature because as the vapour pressure increases the ease of contaminant removal increases. If it is assumed that the effect of temperature on Henry's constant is due almost entirely to changes in vapour pressure, the relationship between Henry's constant and temperature can be approximated by Clausius-Clapeyron equation [22]:

$$In\left(\frac{H_1}{H_2}\right) \approx \ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_V}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad (1)$$

Bass and Sylvia reported that the Henry's constant for MTBE is doubled by a 17°C temperature increase, from 12°C to 29°C. Therefore, heating the wastewater by this amount before treatment would reduce the stripping air requirement by half [23].

Stripping Factor and Temperature: Stripping factor is defined as the ratio of the air flow rate actually used to the minimum required for air stripping and it is a very important factor to be considered in minimizing the capital and operating costs of stripping plants. This because the operating costs of the stripping process is mainly affected by air blower power consumption [3]. The effect of temperature on the stripping factor at different air to water ratios (G/L) is shown on Figure 4. The stripping factors were observed to increase with increase in temperature and the G/L.

Research results show that at any given temperature, increase in air-water ratio results in higher VOCs removal efficiency. This is because increased air flow rate increases the interfacial area, decrease gas phase resistance and hence increase the efficiency of mass transfer. Another effect of increased air-water ratio is it causes a decrease in partial pressure of the solute in the gas phase, decreases its solubility and improves its removal efficiency [2, 18, 20]. In another study, Lin *et al*., reported that the effect of air flow rate on chlorobenzene removal was moresignificant when the system was operated at a lower flow rate (1–2 lmin^{-1}) than higher flow rates especially for higher temperature [21]. It was explained that the increase in interfacial area while the air flow rateincreases is nonlinear. Traditionally, the decreasing of bubble size(or the increasing in bubble concentration) would leadto an increase in air–aqueous interfacial area at lower airflow rate. However, frequent bubble collision at higherair flow rate condition would increase the diameter of airbubbles during the air stripping; as a result, the interfacialarea does not linearly increased with an increase in airflow rate. More also, since the total air–water interface surface area is proportional to the number and size of the air bubbles, an increase in air

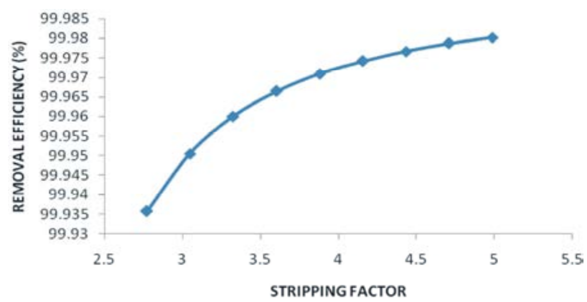

Fig. 5: Variation of removal efficiency with stripping factor at 303K

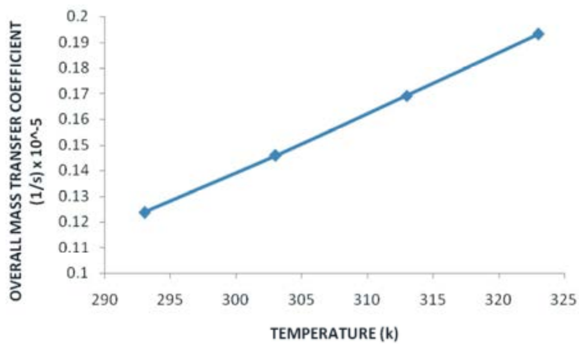

Fig. 6: Variation of overall mass transfer coefficient

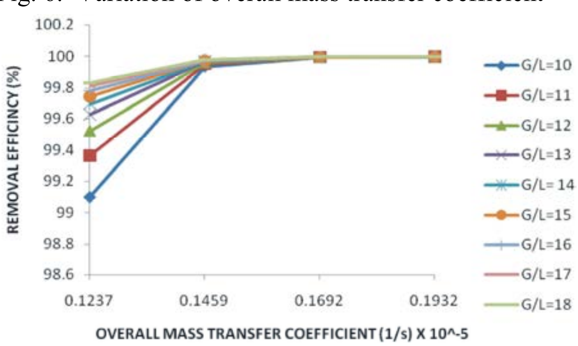

Fig. 7: Variation of removal efficiency with overall mass transfer coefficient at different air-water ratios

flow rate will result in an increase in the K_L values hence the removal efficiency. Alam and Hossain also reported an increase in ammonia removal from industrial wastewater with increase in air-water flow ratio [2].

The stripping factor is also crucial in determining the ability of an air stripper to remove a specific contaminant. Theoretically, if S > 1, complete removal of the contaminant could be achieved by increasing the height of the packed tower to infinity. Conversely, if S < 1, the removal rate could have an upper limit despite further limits in tower height. It is necessary to design for a stripping factor greater than 1 [15]. Figure 5 shows the relationship between stripping factor and removal efficiency at 303K.It can be observed that the removal efficiency increases with increase in stripping factor. It also shows that at a stripping factor beyond 4-5, little additional contaminant removal occurs. This agrees with the literature value which recommends a stripping factor of 3 for most calculations [15].

Overall Mass Transfer Coefficient and Temperature: 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 [15]. Figure 6 shows that the overall mass transfer coefficient increases with temperature. The dependence of the overall mass transfer coefficient on temperature is a function of physical properties such as viscosity, density, surface tension and diffusivity. It is also known that temperature affects all these physical properties. In addition, the change in physical properties of the liquid and gas with increasing temperature has also a great influence on diffusion coefficient. Viscosity decrease leads to a decrease in the thickness of the stagnant film at gas/liquid interface, resulting in a lower mass transfer resistance and hence increases diffusion coefficient. Both effects lead to an increase in K_L. The removal efficiency increases with increase in overall mass transfer coefficient at all air-water flow rates as shown in Figure 7. This is because an increase in temperature causes a decrease in the solubility of organic compounds in water and increases Henry's constant and hence improves removal efficiency [20]. This is also reflected in a graphical representation of the effect of temperature on Henry's constant for benzene under the operating conditions of this study as shown in Figure 2. Figure 7 also shows that at a value of overall mass transfer coefficient of 0.1459 (which is equivalent to 303K), an equilibrium removal efficiency of over 99.999% is reached for all and further air-water ratios such that a change in overall mass transfer coefficient gives no significant change in removal efficiency. This is due to the combined effect of high temperature and air-water ratioaccelerates mass transfer of benzene between the liquid and the gas phase. This is similar to the result obtained by Chuang *et al*. [18].

CONCLUSION

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. In this study the interactive effect of process variables on the dynamics of air stripper was carried out using a MATLAB simulation. The result shows that an economical operation of an air stripper requires the a balance consideration of all the critical process factors such as temperature, air to water flow rate, stripping factor, Henry's constant of the VOC and the overall mass transfer coefficient of the system. The research found out that an increase in Henry's constant beyond 370 atm. (equivalent to 303K) gave no significant change in the percentage removal efficiency of benzene for all air to water ratios. A temperature of 303K is therefore considered as the optimum operating point, since further heating will not give any commensurate change in the removal efficiency and hence uneconomical.

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