Modeling Analysis of CO\textsubscript{2} Solubility in Solutions of DEA, MDEA and Their Mixtures Using Kent-Eisenberg and Deshmukh-Mather models

Abdelbaki Benamor; Abdelwahab Aroussi

Abstract—Amine based solvents are widely used in the industry for the removal of acid gases such as CO\textsubscript{2} and H\textsubscript{2}S from process streams containing these components. The technique has been proven to be reliable and has found wide application in many chemical industries such as ammonia production, coal gasification and natural gas processing. In this work, solubility data of CO\textsubscript{2} absorption in aqueous solutions of single and mixed amine was analysed using two different models; i.e, the Kent Eisenberg model and the Deshmukh-Mather model. CO\textsubscript{2} loading data in aqueous solutions of DEA and MDEA at temperatures ranging from 303K to 323K and CO\textsubscript{2} partial pressure from 0.09 kPa to 100 kPa obtained using a stirred cell reactor was fitted to the two models separately to generate the different parameters required in each model. Using the generated parameters, the models were applied to predict the CO\textsubscript{2} loading in solutions of DEA and MDEA reported in the literature. In all cases, it was found that both models were found to give a good prediction of CO\textsubscript{2} loading over a wide range of operating conditions. However, the Deshmukh-Mather model was found to be more accurate compared to the Kent Eisenberg model in predicting CO\textsubscript{2} loading especially at low CO\textsubscript{2} partial pressures.

Keywords—Absorption, carbon dioxide, Diethanolamine, Methyldiethanolamine, modeling.

I. INTRODUCTION

The use of aqueous solutions of alkanolamine to remove CO\textsubscript{2} from process streams is still the choice in the industries. Alkanolamine is broadly classified into primary, secondary and tertiary depending on the number of alkyl group(s) attached to the nitrogen atom in the molecule structure. Both primary and secondary amines generally exhibit low CO\textsubscript{2} loadings (mol of captured CO\textsubscript{2} /mol of amine) and a high rate of absorption. Tertiary amine showed the opposite behaviour. Another class of amine known as sterically hindered amine shows high absorption rate and high maximum gas loading. However, the choice of a particular amine will depend not only on the absorption rate and maximum loading that can be achieved, but also on other factors such as regeneration energy, corrosion tendency and the cost of the solvent.

The absorption of CO\textsubscript{2} in amine solutions couples physical absorption with chemical reaction which fixes the CO\textsubscript{2} in the solution as carbonates, bicarbonates and carbamates depending on the type of amine being used. The mechanisms for these reactions are available in the literature [1]. It is agreed that similar reaction steps are involved for all types of amine including the protonation of amine as well as the ionization of different species in the solution. However, for system involving primary and secondary amines, an additional step, which is the formation of carbamate ion has been proposed. This reaction limits the maximum CO\textsubscript{2} loading for these classes of amine to 0.5.

Several models are available to analyse the CO\textsubscript{2} solubility of in amine solutions and to predict the equilibrium CO\textsubscript{2} loading. Among the models which have been used widely is that of the electrolyte-NRTL model [2], the Deshmukh and Mather [3] model and that of Kent and Eisenberg [4]. The NRTL model and that of Deshmukh and Mather were developed based on sound thermodynamic principles. Non idealities of solution are taken into consideration by allowing long and short range interactions between the different species that are present in the solution. The NRTL model used a combination of Debye-Hückel theory and the electrolyte-NRTL equation to calculate the activity coefficients. The Deshmukh and Mather model is much simpler to handle as compared to the previous model. It employed the Guggenheim equation to represent activity coefficients. The Kent and Eisenberg model is the simplest among these models. The non-idealities present in the system are lumped together into the K values.

In this work, solubility data of CO\textsubscript{2} absorption in aqueous solutions of single and mixed amine was analysed using two different models; i.e, the Kent Eisenberg model and the Deshmukh–Mather model. CO\textsubscript{2} loading data in aqueous solutions of DEA and MDEA at temperatures ranging from 303K to 323K and CO\textsubscript{2} partial pressure from 0.09 kPa to 100 kPa was fitted to the two models separately to generate the different parameters required in each model. Using the generated parameters, the models were applied to predict the CO\textsubscript{2} loading in solutions of DEA and MDEA reported in the literature.
II. THEORY

An equilibrium solution of CO$_2$ in aqueous amine solution is governed by the following set of equations:

\[ RR'NH_2 \leftrightarrow RR'NH + H^+ \]  
\[ RR'NCOO^- + H_2O \leftrightarrow RR'NH + HCO_3^- \]  
\[ CO_2 + H_2O \leftrightarrow HCO_3^- + H^+ \]  
\[ HCO_3^- \leftrightarrow CO_3^{2-} + H^+ \]  
\[ H_2O \leftrightarrow OH^- + H^+ \]  

The equilibrium constants for the above equations are expressed as follows:

\[ K_i = \frac{[RR'NH][H^+]}{[RR'NH]^2} \]  
\[ K'_i = \frac{[RR'NCOO^-][H^+]}{[RR'NH][CO_3^-]} \]  
\[ K_j = \frac{[CO_3^{2-}][H^+]}{[CO_3^-]^2} \]  
\[ K_3 = \frac{[OH^-][H^+]}{[OH^-]^2} \]  

Where, \([I] \) is the concentration of the various species, and \( \gamma_i \) is the activity coefficient of each species.

In addition, the following balances must hold.

Amine balance:

\[ [RR'NH] = [RR'NH]^2 + [RR'NH]^3 + [RR'NCOO^-] \]  

CO$_2$ balance:

\[ \alpha[RR'NH] = [HCO_3^-] + [RR'NCOO^-] + [CO_3^{2-}] + P_{\text{CO}_2}/H_{\text{CO}_2} \]  

Charge balance:

\[ [RR'NH]^2] = [HCO_3^-] + [RR'NCOO^-] + 2[CO_3^{2-}] \]  

Where \( \alpha \) is the CO$_2$ loading. The concentration of carbon dioxide in the liquid phase can be estimated from Henry’s law, i.e.

\[ P_{CO_2} = H_{CO_2} \times \text{CO}_2 \]

II.1. Deshmukh-Mather Model

The model is based on an activity coefficient approach according to Debye-Hückel theory [5]. The activity coefficient is calculated by the equation proposed by Guggenheim and Stokes [6] and Scatchard [7]:

\[ \ln \gamma_i = -\frac{AZ_i^2\sqrt{I}}{1 + B\sqrt{I}} + \sum \beta_i m_i \]  

Where \( Z_i \) and \( m_i \) are respectively the electrical charges and concentrations of the corresponding species and \( I \) is the ionic strength. The value of \( A \) is taken as a function of temperature as proposed by Lewis et al. [8] and \( B \) equals to 1.2 as suggested by Pitzer [9, 10]. The interaction parameters, \( \beta_{ij} \), between the different species in the system are represented in the following form:

\[ \beta_{ij} = a_{ij} + b_{ij}T \]

Where parameters \( a_{ij}, b_{ij} \) were taken from a previous work [11], they are summarized in Tables 1-3. It should be noted that interactions between solutes and solvent were excluded. The ionic strength, \( I \), of the solution was calculated by the following equation:

\[ I = \frac{1}{2} \sum m_j Z_j^2 \]

<table>
<thead>
<tr>
<th>Ions/molecules interactions</th>
<th>Values for Equation 16.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[L/mol]</td>
<td>a$_i$ [L/mol]</td>
</tr>
<tr>
<td>DEA'H-DEA</td>
<td>0.801x10$^{-3}$</td>
</tr>
<tr>
<td>DEA'H-DEACOO</td>
<td>4.700</td>
</tr>
<tr>
<td>DEA'H-HCO$_3$^-</td>
<td>0.377</td>
</tr>
<tr>
<td>DEA-DEA</td>
<td>0.703</td>
</tr>
<tr>
<td>DEA-DEACOO^-</td>
<td>4.521</td>
</tr>
<tr>
<td>CO$_2$-DEACOO^-</td>
<td>0.184x10$^{-5}$</td>
</tr>
<tr>
<td>CO$_2$-HCO$_3$^-</td>
<td>0.661x10$^{-3}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Species interactions</th>
<th>Values for Equation 16.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[L/mol]</td>
<td>a$_i$ [L/mol]</td>
</tr>
<tr>
<td>MDEA'H-CO$_2$</td>
<td>0.617x10$^{-4}$</td>
</tr>
<tr>
<td>MDEA'H-HCO$_3$^-</td>
<td>1.024</td>
</tr>
<tr>
<td>MDEA'H-DEACOO</td>
<td>0.725</td>
</tr>
<tr>
<td>MDEA'H-DEACOO^-</td>
<td>0.334x10$^{-4}$</td>
</tr>
<tr>
<td>MDEA-CO$_2$</td>
<td>0.172</td>
</tr>
<tr>
<td>MDEA-CO$_2$^-</td>
<td>0.276x10$^{-2}$</td>
</tr>
<tr>
<td>CO$_2$-HCO$_3$^-</td>
<td>0.958 x 10$^{-3}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ions/molecules interactions</th>
<th>Regressed values for Equation 16.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[L/mol]</td>
<td>a$_i$ [L/mol]</td>
</tr>
<tr>
<td>DEA'H-MDEA</td>
<td>0.618x10$^{-3}$</td>
</tr>
<tr>
<td>DEA-MDEA</td>
<td>0.317x10$^{-4}$</td>
</tr>
<tr>
<td>DEA-MDEA^-</td>
<td>0.344x10$^{-5}$</td>
</tr>
<tr>
<td>MDEA'-DEACOO</td>
<td>0.890</td>
</tr>
<tr>
<td>MDEA-DEACOO^-</td>
<td>0.416</td>
</tr>
</tbody>
</table>
II.2. Modified Kent-Eisenberg Model

The approach considered here, is that the apparent equilibrium constants, $K'_i$, for reactions 1 and 2 as defined in terms of the concentration of the corresponding species are taken to be dependent on the partial pressure of CO$_2$ and the amine concentration. Thus, $K'_i$ is introduced to take into account the effects of CO$_2$ partial pressure and amine concentration. Thus,

$$K'_i = K_i F_i$$

(18)

Where, $F_i$ is defined in a general form as:

$$F_i = \exp \left( \frac{f_i + g_i \ln P_{CO_2} + h_i P_{CO_2} + j_i \ln [RRNH] + m_i [RRNH]}{P_{CO_2}} \right)$$

(19)

Similarly, the coefficients ($f_i$, $g_i$, $h_i$, $k_i$, $m_i$) are constants and were taken from a previous work [12], they are defined in terms of the concentration of the corresponding species are taken to be depended on the partial pressure of CO$_2$ and the amine concentration in the solution as previously shown by Haji-Sulaiman et al [12]. Since the equilibrium constant at infinite dilution, $K_i$, is only a parameter, Equation (18) is modified to account for free MDEA and MDEAH$^+$. In addition, Equations (11) and (13) should be used to account for DEA and a second time to account for MDEA. Then, the reduced equation in terms of hydrogen ions concentration, $[H^+]$, and the equilibrium constants is given as follows:

$$[MDEA]_t = K'_1[MDEA] + K'_2[DEA] + \ldots + K'_n[MDEA]^n[DEA]^n$$

(20)

where $A = 1$

$$B = [DEA] + K'_1[DEA]$$

$$C = K'_1[DEA]K'_2[DEA] + \ldots + K'_n[DEA]^n$$

$$D = \left( [DEA]K'_1[DEA]K'_2[DEA] + \ldots + K'_n[DEA]^n \right)$$

$$E = 2K'_1[DEA]K'_2[DEA] + \ldots + K'_n[DEA]^n$$

$$F = -K'_1[DEA]^2K'_2[DEA]^2$$

Finally, the reduced equation in terms of hydrogen ions concentration, $[H^+]$, and the equilibrium constants is given as:

$$\alpha = \frac{P_{CO_2}}{\frac{K'_1[DEA] + K'_2[DEA]}{H^+} + \ldots + \frac{K'_n[DEA]^n}{H^+}}$$

(21)

For MDEA solutions, no stable carbamates are formed. Thus Reaction 2 does not exist in the system. Hence, Equation 20 becomes:

$$[H^+]^3 + B[H^+]^2 + C[H^+] + D[H^+] + E = 0$$

(22)

where, $A = 1$

$$B = [MDEA] + K'_1[MDEA]$$

$$C = -\left( K'_3P_{CO_2} + K'_3 \right)$$

$$D = \left( 2K'_3K'_2 \frac{P_{CO_2}}{H_{CO_2}} + K'_1[MDEA]K'_3 + K'_2[MDEA]K'_3 \frac{P_{CO_2}}{H_{CO_2}} \right)$$

$$E = -2K'_1[MDEA]K'_3 \frac{P_{CO_2}}{H_{CO_2}}$$

Finally the total CO$_2$ loading becomes

$$\alpha = \frac{P_{CO_2} + P_{CO_2}}{\frac{[MDEA]}{H_{CO_2}}}$$

(23)

III. MATHEMATICAL FRAMEWORK

III.1. Single amine solutions

For aqueous solutions of DEA, Equations (6)-(14) were reduced to a single polynomial equation of sixth order. In this case, Equation 1 is applied twice, once to account for DEA and a second time to account for MDEA. In addition, Equations (11) and (13) should be modified to account for free MDEA and MDEAH$^+$. Finally, the reduced equation in terms of hydrogen ions concentration, $[H^+]$, and the equilibrium constants is given as follows:

$$\alpha = \frac{P_{CO_2} + P_{CO_2}}{\frac{[DEA]}{H_{CO_2}}}$$

(24)

where $A = 1$

$$B = [DEA]^2 + [DEA]^2 + K'_1[K'_1]$$

$$C = K'_1[DEA][MDEA] - K'_3$$

$$D = K'_1[DEA][MDEA] + K'_1[DEA][MDEA]$$

$$E = K'_1[DEA][MDEA] + [MDEA] - K'_1[DEA][MDEA]$$

$$F = -K'_1[DEA][MDEA]^2$$

Consequently, the total CO$_2$ loading, $\alpha$, can be expressed as:

$$\alpha = \frac{P_{CO_2} + P_{CO_2}}{\frac{[MDEA]}{H_{CO_2}}}$$

III.2. Mixed Amine Solutions

For aqueous mixtures of DEA and MDEA, Equations (6)-(14) were reduced to a single polynomial equation of sixth order. In this case, Equation 1 is applied twice, once to account for DEA and a second time to account for MDEA. In addition, Equations (11) and (13) should be modified to account for free MDEA and MDEAH$^+$. Finally, the reduced equation in terms of hydrogen ions concentration, $[H^+]$, and the equilibrium constants is given as follows:

$$\alpha = \frac{P_{CO_2} + P_{CO_2}}{\frac{[DEA]}{H_{CO_2}}}$$

(25)

where $A = 1$

$$B = [DEA]^2 + [DEA]^2 + K'_1[K'_1]$$

$$C = K'_1[DEA][MDEA] - K'_3$$

$$D = K'_1[DEA][MDEA] + K'_1[DEA][MDEA]$$

$$E = K'_1[DEA][MDEA] + [MDEA] - K'_1[DEA][MDEA]$$

$$F = -K'_1[DEA][MDEA]^2$$

Consequently, the total CO$_2$ loading, $\alpha$, can be expressed as:
While carbamate concentration is given by:

\[
\text{Carbamate} = \frac{P_{\text{CO}_2}}{[\text{H}^+]_\text{HCO}_3^-} \left( \frac{K_i^{\text{DEA}}}{1 + [\text{H}^+]_\text{H}_\text{CO}_3^-} + \frac{K_i^{\text{MDEA}}}{[\text{H}^+]_\text{H}_\text{CO}_3^-} \right)_{(\text{DEA})+\text{MDEA}}
\]  
(26)

### III.3. Thermodynamic Parameters

The equilibrium constant, \( K_i \), as well as the Henry’s constant, \( H_i \), were expressed as:

\[
\ln K_i (\text{or} H_i) = \frac{a_i}{T} + b_i \ln T + c_i T + d_i
\]  
(27)

Values of these constants (\( a_i \) - \( d_i \)) were taken from the literature and are given in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( a_i )</th>
<th>( b_i )</th>
<th>( c_i )</th>
<th>( d_i )</th>
<th>Range (°C)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_1^{\text{DEA}} )</td>
<td>-3071.15</td>
<td>6.776904</td>
<td>0</td>
<td>-48.7594</td>
<td>0–80</td>
<td>[13]</td>
</tr>
<tr>
<td>( K_1^{\text{MDEA}} )</td>
<td>-8483.95</td>
<td>-13.8328</td>
<td>0</td>
<td>87.39717</td>
<td>20–60</td>
<td>[14]</td>
</tr>
<tr>
<td>( K_2 )</td>
<td>-17967.2</td>
<td>-66.8087</td>
<td>0</td>
<td>439.709</td>
<td>30–58</td>
<td>[15]</td>
</tr>
<tr>
<td>( K_3 )</td>
<td>-12431.7</td>
<td>-35.4819</td>
<td>0</td>
<td>220.067</td>
<td>0–225</td>
<td>[16]</td>
</tr>
<tr>
<td>( K_4 )</td>
<td>-12092.1</td>
<td>-36.7816</td>
<td>0</td>
<td>235.482</td>
<td>0–225</td>
<td>[16]</td>
</tr>
<tr>
<td>( H_{\text{CO}_2} )</td>
<td>-6789.04</td>
<td>-11.4519</td>
<td>-0.010454</td>
<td>94.4914</td>
<td>0–225</td>
<td>[16]</td>
</tr>
</tbody>
</table>

### IV. SOURCE OF DATA

All data used in the model regression were experimentally determined in the laboratory in a previous work. The absorption experiments were conducted using a stirred cell reactor where the amine solution was exposed to a flowing gas consisting of a mixture of \( \text{CO}_2 \) and \( \text{N}_2 \) of known composition. Details of the experimental apparatus and procedure are provided by Haji-Sulaiman et al [11].

### V. RESULTS AND DISCUSSION

#### V.1. Single Amine Solutions

Using the regressed parameters, the predicted \( \text{CO}_2 \) loadings for 2M and 4M aqueous solutions of DEA and MDEA were compared with experimental loadings at different temperatures. The results are given as plots of \( \text{CO}_2 \) loading against \( \text{CO}_2 \) partial pressure as shown in Fig. 1 and Fig. 2 respectively.
predicting CO₂ loading at the higher operating temperatures which are beyond those used to regress the constants also introduced some errors. For practical purposes and within the range of conditions employed in this work, it is clear that both models together are able to predict CO₂ loadings comparable to the experimental results as shown in Fig. 1 and Fig. 2.

V.2. Mixed Amine Solutions

For a solution containing a mixture of DEA and MDEA, the system is also described by the set of Equations (6)–(14). In addition, Equation (1) must be considered twice, once for MDEA and once for DEA to account for their effects in the mixture. Using the same parameters generated from single amine experiments, and regressing the remaining parameters that do not appear in single cases, the predicted CO₂ loading and carbamate concentration are compared with those obtained experimentally in this work as shown in Fig. 3 for total 2M mixtures of DEA+MDEA at varying ratios and temperatures.

Over the entire range of investigated CO₂ partial pressure, the models can correlate well both; the total gas loading that could be achieved and carbamate concentration in the solution. A maximum deviation of about 30% was reached at high pressures. It should be noted that the Deshmukh-Mather model has a superior ability to predict CO₂ loading and especially carbamate concentration in the solution as compared to the one of Kent–Eisenberg.

V.3. Comparison with literature data

To assess the validity of the models further, comparison was made with the available data reported by Austgen et al.[17] as shown in Fig. 4. The data was obtained at two different temperatures of 313 and 353 K in 4M mixtures containing equal proportion of DEA and MDEA.

A slightly higher loading of about 0.7 could be achieved in practice using DEA due to the formation of bicarbonate. As the CO₂ partial pressure is increased, a higher loading greater than about 0.7 is only possible through absorption into MDEA, where the CO₂ is fixed.
mainly as the bicarbonate. This explanation is in agreement with the observed experimental data as well as the model correlation in Fig. 5 that shows the liquid phase concentration profile for an aqueous mixture of DEA and MDEA.

Comparing the carbamate experimental results to those obtained by both models, shows that the Deshmukh-Mather model has a superior ability to closely correlate the carbamate concentration in the solution as compared to the model of Kent-Eisenberg. Furthermore, comparing results obtained by both models to those obtained by Austgen et al. [17] using NRTL model, for the same proportion of DEA /MDEA but higher total amine concentration and temperature, an excellent agreement regarding the trend of the concentration profile exist between the NRTL model and the Deshmukh-Mather model compared to the results obtained by Kent-Eisenberg model.

VI. CONCLUSION

The modified Deshmukh-Mather model was used to analyze the solubility of CO$_2$ and carbamate concentration for the absorption of CO$_2$ in aqueous solutions of DEA, MDEA and their mixtures. Compared to its original form two new parameters were included in this model; namely, the experimental value of the equilibrium constant for the formation of carbamate, and the concentration of carbamate in case of DEA which was fitted simultaneously with CO$_2$ loading to generate the corresponding interaction parameters. Using the generated parameters from each case, the model is able to give generally good correlations of the total CO$_2$ loading and carbamate concentration in solutions of single and blended amines. The different interaction parameters expressing the equilibrium constant in terms of CO$_2$ pressure and amine concentration which were generated from experiments using single amine can be used to describe the observed data for blended amines and those published in the literature.

REFERENCES


Sensitivity of freshwater organisms to zinc

M. Shuhaimi-Othman, N. Yakub, and N.A. Ramle

Abstract—A study was conducted in the laboratory to determine acute toxicity of heavy metal zinc (Zn) to six species of freshwater organisms i.e. one species of shrimp (Macrobrachium lanchesteri), two species of fish (Rasbora sumatrana (Seluang) and Poecilia reticulata (guppy)), one species of gastropod (Melanoïdes tuberculata), one species of ostracod Stenocypris major and one species of midge (larvae) Chironomus javanus. All organisms were exposed for a four-day period in the controlled laboratory condition to a range of Zn for 96 hours. Mortality was assessed and median lethal concentrations (LC$_{50}$) were calculated. 96 hours LC$_{50}$ for M. lanchesteri, R. sumatrana, P. reticulata, M. tuberculata, S. major and C. javanus of Zn were 0.52, 0.46, 1.05, 3.9, 1.19 and 5.57 mg/L, respectively. This study indicated that R. sumatrana was the most sensitive to Zn.

Keywords—Acute, freshwater, heavy metals, sensitivity, soft water, toxicity.

I. INTRODUCTION

Toxicity testing has been widely used as a tool to identify suitable organisms as a bioindicator and to derive water quality standards for chemicals. Toxicity testing is an essential tool for assessing the effect and fate of toxicants in aquatic ecosystems. Metal contamination has been shown to have serious effects on the both environment and humans. Malaysia, as a developing country, is no exception and faces metal pollution caused especially by anthropogenic activities such as manufacturing, agriculture, sewage and motor vehicle emissions [1], [2]. Metals such as Zn are released from natural sources as well as human activity. Despite the adverse effect of metal on the environment and organisms, Zn is essential to living organisms and plays an important role as an enzyme carbonic anhydrase.

Macroinvertebrate and fish as a test organisms in toxicity tests has several valuable characteristics such as its widespread distribution and common occurrence in freshwater, its ecological importance and ease of handling during testing, as well as its rapid growth, short life cycle and sensitivity to contaminants [3], [4]. Therefore, these organisms have the potential to act as a bioindicator of heavy metals pollution in an aquatic environment and as organisms for toxicity testing.

The purpose of this study was to determine the acute toxicity of Zn to six local freshwater organisms and to compare the sensitivity between them.

II. MATERIALS AND METHODS

A. Organisms and test chemicals

In this study six local freshwater organisms have been used in toxicity testing i.e. a prawn Macrobrachium lanchesteri, two fish Poecilia reticulata (guppy, family Poeciliidae) and Rasbora sumatrana (family Cyprinidae), a snail (Gastropoda) Melanoïdes tuberculata (family Thiaridae), an ostracod Stenocypris major, and a midge larvae Chironomus javanus (Diptera, Chironomidae). M. lanchesteri and R. sumatrana were obtained from local pet stores. P. reticulata and M. tuberculata were collected from the field. S. major and C. javanus were collected from a fish pond filter system. Prior to toxicity testing, the organisms were acclimatized for one week to a range of Zn for 96 hours. Mortality was assessed and median lethal concentrations (LC$_{50}$) were calculated. 96 hours LC$_{50}$ for M. lanchesteri, R. sumatrana, P. reticulata, M. tuberculata, S. major and C. javanus of Zn were 0.52, 0.46, 1.05, 3.9, 1.19 and 5.57 mg/L, respectively. This study indicated that R. sumatrana was the most sensitive to Zn.

Keywords—Acute, freshwater, heavy metals, sensitivity, soft water, toxicity.

M. Shuhaimi-Othman is with the School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia (corresponding author phone: 603-8321 3804; fax: 603-8925 3357; e-mail: shuhaimi@ukm.my).

Y. Nadzifah is with the School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia (corresponding author phone: 603-8321 3804; fax: 603-8925 3357; e-mail: shuhaimi@ukm.my).

N.A. Ramle is with the School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia (UKM), 43600 Bangi, Selangor, Malaysia (e-mail: lina_cxora84@yahoo.com).