

Full Length Research Paper

Modeling the rate of biocorrosion and the effects of redox-reactions of metals in water environment

C. P. Ukpaka^{1*}, S. A. Amadi¹, I. G. Ahuchogu² and J. Odharo³

¹Department of Chemical/Petrochemical Engineering, Rivers State University of Science and Technology, Nkpolu, P. M. B. 5080, Port Harcourt, Nigeria.

²Department of /Petroleum and Natural Gas Processing, Petroleum Training Institute, P. M. B. 20 Effurun, Delta State, Nigeria.

³Engineering, Construction and Projects Division, Civil Works and Survey, Total E and P Nigeria Limited, Port Harcourt, Rivers State, Nigeria.

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Laboratory studies were conducted to assess the effectiveness of biocorrosion through oxygen diffusion in zinc metal in water environment. The present investigation was undertaken to determine the corrosion rate of zinc metal in water environment with respect to Plank-Nernst Equation modified to monitor and predict the biocorrosion rate through oxygen diffusion which resulted to biofilm formation. The modified developed mathematical model of Plank-Nernst equations to evaluate the corrosion rate of zinc metal upon the influence of oxygen diffusion in a flowing system was given as $C_R = \frac{534w}{DA t_o e^{\lambda^2 t}}$

where $\lambda = 0.5$ when compared with the normal corrosion rate equation, $C_R = \frac{534w}{DA t}$ then the results

obtained showed a good match. The biocorrosion rate of zinc metal was tested in salt and fresh water environment and the results obtained showed that corrosion was faster on zinc metal immersed in salt water environment than the fresh water environment; this was attributed to the physicochemical parameters of the salt/fresh water environment.

Key words: Modeling, corrosion, redox-reaction, biocorrosion, metal, water environment.

INTRODUCTION

Corrosion may be defined as the destruction of a material by the action of the surrounding environment. Material resistance to corrosion depends on many variables which include the material properties, and environmental characteristics. The most important aspects in the corrosion of a material are the mass transport characteristics, which occurs by convection, migration and diffusion. But among these characteristics, the aspect that is of emphasis is the diffusion. Before corrosion of metal occurs there are responsible factors, such as physical factor which consists of heat,

temperature changes, water, wind and dust contributes greatly to the corrosion of metals. Another factor being the chemical which aids corrosion follows by the flare gases, acids, alkaline, salt and the biological factor which includes the microorganism, fungi, algae, worms and multi-cellular plants (Degarmo et al., 2003; Gardner, 2002; Johnson, 2000; Mars, 2005; Roy and Rofer, 1999).

The constant failure of metals due to biochemical process is of major concern to the engineers, in this study, suitable mathematical approach including experimental procedures in examining the biocorrosion of metal immersed in water environment will be clearly studied and presented on the findings of the research work. In this paper mathematical model was developed to simulate the corrosion rate of zinc in salt and fresh water

*Corresponding author. E-mail: chukwuemeka24@yahoo.com.

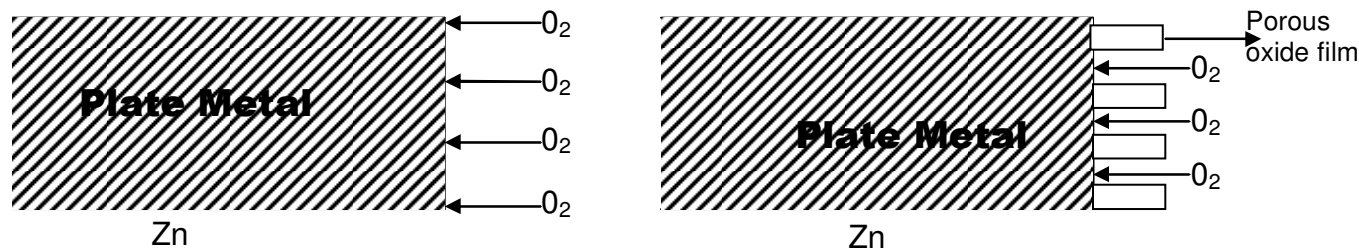


Figure 1. Area of oxide formation.

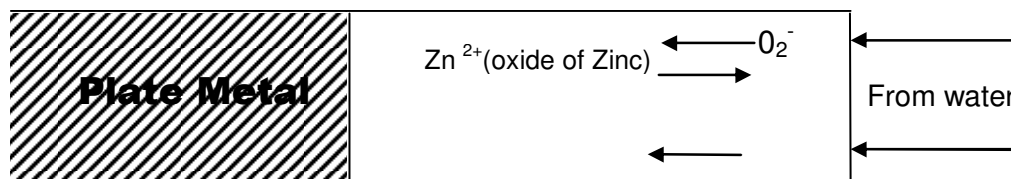
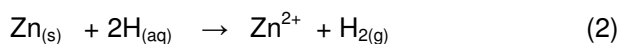
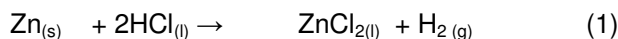


Figure 2. Oxidation reaction of zinc (Robinson and Holt, 1997).

media upon the influence of diffusion of the oxygen through the surface layer. The scope of the study is focused on the effect of redox-reactions on the bio-corrosion of zinc metal in both salt and fresh water medium.

Investigation carried out by various research groups revealed that corrosion is responsible for colossal loss in weight of materials occurring everywhere in the world (Ivor, 2004; Mar, 2005; Melchers, 2006). It is one of the most serious destructive agents and is one of the major technological problems in the modern society. Though a lot of scientific understandings of many phases of corrosion have been developed, and the results obtained are very complex phenomenon as there are a large number of complex variables responsible for it (Alkins, 1990; Ivor, 2004; Johnson, 2000; Melchers, 2006; Shifter, 2005; Sharma, 2003).

Redox reactions or oxidation-reduction reactions have a number of similarities to acid-base reactions. Fundamentally, redox reactions are family of reactions that are concerned with the transfer of electrons between species (metals) (Vijendra, 1999; Melchers, 2006; Mars, 2005; Liudvikas, 2003; John et al., 1999; Ivor, 2004). Oxidation reaction is referred to the loss of an electron, while reduction reaction refers to the gain of an electron. Thus,



In equation 1 the hydrochloric acid reacts with the surface of the metal (Zinc) which resulted to the formation of aqueous zinc chloride and hydrogen gas liberated. In equation 2 the solid zinc reacts with the aqueous

hydrogen which yielded zinc ion and hydrogen gas liberated during the process. The chemical interaction between the solid zinc and aqueous hydrogen resulted to resulting and loss in weight of the metal (zinc).

MATERIALS AND METHODS

This monolayer of oxygen atoms which forms rapidly over the whole surface of the clean metal is said to be chemisorbed. The process involving the dissociation and ionization of oxygen molecules is called chemisorptions. Figure 1 illustrates the area of oxide formation in a metal. Figure 2 illustrate the corrosion oxidation reaction of zinc.

The chemical reaction is as stated as follows:



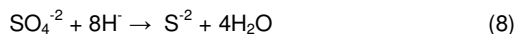
Investigation of sulphur reducing bacteria reveals that the microbes reduce the sulphate to sulphide.



Anodic reaction: The anodic reaction involves dissociation of water and the chemical reaction is as shown in Equation (7).



The depolarization process by SRBS yielded the chemical equation as presented in equation (8) as follows:



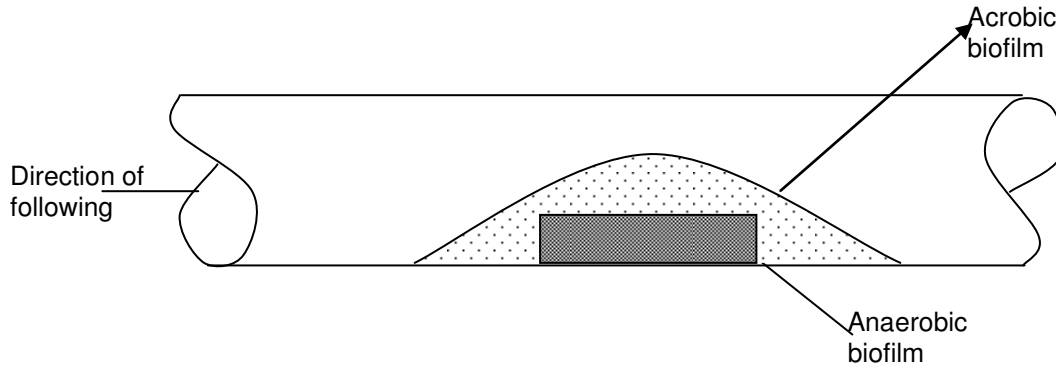
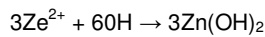
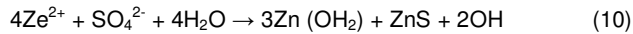


Figure 3. Typical biofilm formation on a pipe internal surface (Atkins, 1990).

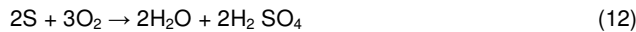
Corrosion product are obtained as presented below in terms of the possible chemical reaction.



Other corrosion product formed as a result of the chemical process is shown as follows.



Sulphur oxidizing bacteria are capable of oxidizing elemental sulphur or sulphur-bearing components to produce acidic compounds, which is corrosive to many metals. The typical reaction for this sulphur oxidizing bacteria (SOB) as:



The instant, a metallic surface is immersed in water, a biofilm begins to form. The phenomenon can be described as a biomass composed of different aquatic microorganisms. Many species of these microorganism bind to various metals and form biofilm that develops in our stages. This is very common in pipes and has been associated to many pipe line failures (Figure 3).

The model

The model is restricted to that part of the corrosion process of steel subjected in aqueous medium which is controlled by the diffusion of the oxygen through the result layer neglecting the convective motion of species K (in our case, oxygen molecules) and considering by the plank – Nernst law as:

$$\vec{J}_K = -D_K^* \vec{\nabla} C_K + \left(\frac{-Z_K D_K^* f}{RT} C_K \right) \vec{\nabla} \phi \quad (13)$$

The migration and diffusion are considered here. The transport of each specie satisfies the mass transport equation as follows:

$$\frac{\partial C_K}{\partial t} + \vec{\nabla} \cdot \vec{J}_K = S_R \quad (14)$$

Where S_K is the source term that takes into account the production and/or consumption of oxygen. Assuming S_K equals zero which can

be justified if we assume that oxygen consumption due to biochemical reaction, can only occur at the interface of the metallic surface and the rust, and considering only the 1 D problem on x-axis by replacing Equation (13) into Equation (14).

$$\frac{\partial C_K}{\partial t} + \frac{\partial}{\partial x} \left[\left(\frac{-Z f D^*}{RT} \frac{\partial \phi}{\partial x} \right) C - D^* \frac{\partial C}{\partial x} \right] = 0 \quad (15)$$

This is a migration diffusion equation. Now, let's only consider the diffusion process. Then,

$$\phi = \frac{\partial C}{\partial t} - \frac{\partial}{\partial x} \left[\frac{\partial C}{\partial x} \right] = 0 \quad (16)$$

Let is suppose that $D^* = W(x) D$ which is a dimensionless mathematical function representing the rust layer porosity and D the diffusivity constant of oxygen in the water which is independent of the position (x). Therefore, the Equation (16) can be written as:

$$\frac{\partial C}{\partial t} - D \frac{\partial}{\partial x} \left[W(x) \frac{\partial C}{\partial x} \right] = 0 \quad (17)$$

The Equation (17) can be expressed as:

$$\frac{\partial C}{\partial t} - DW(x) \frac{\partial^2 C}{\partial x^2} = 0 \quad (18)$$

The Equation (18) is a second order differential

The mathematical application to equation (18)

The mathematical tool known as the separation of variables and Laplace transformation, was applied in resolving the problem as stated in equation (19)

$$\frac{\partial C}{\partial t} + D(x) \frac{\partial^2 C}{\partial x^2} \quad (19)$$

Equation (19) was resolved by using Laplace approach. Thus,

$$C = TX \quad (20)$$

where T is the coefficient of t (time) which is dependent, x is the coefficient of position or distance and C is the concentration of oxygen. From Equation (20), the following expressions can be obtained as:

$$\frac{\partial C}{\partial t} = T^1 X \quad (21)$$

$$\frac{\partial^2 C}{\partial x^2} = TX'' \quad (22)$$

Substituting the Equations (21) and (22) into Equation (19) we have:

$$T^1 X = DW(x) TX'' \quad (23)$$

Equation (23) can be written as shown in equation (24) in terms of a real constant value of λ^2 .

$$\frac{T^1 X}{T} = DW(x) \frac{TX''}{TX} = \lambda^2 \quad (24)$$

$$\frac{T^1}{T} = \lambda^2 \quad (25)$$

and

$$DW(x) \frac{11}{X} = \lambda^2 \quad (26)$$

Resolving the equation (25) mathematically using the necessary boundary conditions, it is noted that the equation (25) is a first order differential equation. That is:

$$T^1 = \lambda^2 T \quad (27)$$

$$T^1 - \lambda^2 T = 0 \quad (28)$$

The quadratic equation obtained in equation (28) can be resolved using Laplace approach.

$$T^1 = ST_{(s)} - T_{(0)} \quad (29)$$

$$T = T_{(s)}$$

Substituting Equation (29) into Equation (28) we have:

$$ST_{(s)} - T_{(0)} - \lambda^2 T_{(s)} = 0$$

$$ST_{(s)} - \lambda^2 T_{(s)} = T_{(0)}$$

Considering $T_{(0)} = t_0$,

$$T_{(s)} (S - \lambda^2) = t_0, T_{(s)} = \frac{t_0}{S - \lambda^2}$$

$$T_{(s)} = \frac{t_0}{S - \lambda^2} \quad (30)$$

The inverse of equation (30) from S – domain to t – domain is given as:

$$T_{(t)} = t_0 e^{\lambda^2 t} \quad (31)$$

From Equation (26) we have:

$$\begin{aligned} DW(x) \frac{X^{11}}{x} &= \lambda^2 \\ DW(x) X^{11} &= \lambda^2 x \\ DW(x) S^{11} - \lambda^2 x &= 0 \end{aligned} \quad (32)$$

Applying the Laplace approach to the Equation (32) gives:

$$X^{11} = S^2 X_{(s)} - SX_{(0)} - x \cdot 0 \quad (33)$$

$$X = X_{(s)}$$

Putting the Equations (33) and (34) into Equation (32) gives the following expression:

$$\begin{aligned} DW_{(x)} [S^2 X_{(2)} - S^1 x(0) - x(0)] - \lambda^2 X_s &= 0 \\ DW_{(x)} [S^2 - DW_{(x)}] S^1 x(0) - DW_{(x)} x(0) \lambda^2 X_s &= 0 \\ \text{Considering the boundary conditions;} \\ X^1(0) = 0 \text{ and } X(0) = X_0 \\ DW_{(x)} S^2 X_{(s)} - DW_{(x)} X_0 - \lambda^2 X_s &= 0 \\ DW_{(x)} S^2 X_{(s)} - \lambda^2 X_s &= DW_{(x)} X_0 \\ X_s (DW_{(x)} S^2 - \lambda^2) &= DW_{(x)} X_0 \\ \text{Making } X_{(s)} \text{ the subject of the formula we have:} \end{aligned}$$

$$X_{(s)} = \frac{DW(x) X_0}{DW(x) S^2 - \lambda^2} \quad (34a)$$

Assuming $DW(x) = 1$ at equilibrium when the rate of diffusion of oxygen molecular is equal to the corrosion rate. Therefore Equation (34a) can be written as:

$$X_s = \frac{X_0}{S^2 - \lambda^2} \quad (34b)$$

Also Equation (34b) can be expressed as:

$$X_s = \frac{X_0}{(S - \lambda)(S + \lambda)} \quad (35)$$

Applying the law of partial fraction into Equation (35) yields;

$$\frac{X_0}{(S + \lambda)(S - \lambda)} = \frac{A}{(S - \lambda)} + \frac{B}{(S + \lambda)} \quad (35)$$

Multiplying Equation (35) by $(S - \lambda)(S + \lambda)$ gives,

$$X_0 = A(S - \lambda) + B(S + \lambda)$$

$$X_o = AS + A\lambda + BS - B\lambda$$

By collecting the like terms we have

$$\begin{aligned} X_o &= AS + BS + A\lambda - B\lambda \\ X_o &= AS + BS \end{aligned} \quad (36)$$

$$X_o = A\lambda - B\lambda \quad (37)$$

From equation (37), let $S = \lambda$, the equations becomes;

$$X_o = A\lambda + B\lambda \quad (38)$$

Solving Equation (37) and (38) simultaneously,

$$X_o = A\lambda + B\lambda \quad (39)$$

By adding these above equations give;

$$\begin{aligned} 2X_o &= 2A\lambda \\ \therefore A &= X_o/\lambda \end{aligned} \quad (40)$$

From Equation (37) let $A = 0$ to obtain the value of B

$$\begin{aligned} X_o &= A\lambda - B\lambda, A = 0 \\ X_o &= 0 - B\lambda \\ \therefore B &= -X_o/\lambda \end{aligned} \quad (41)$$

$$\therefore X_s = \frac{A}{S - \lambda} + \frac{B}{S + \lambda} \quad (42)$$

As $A = X_o/\lambda$ and $B = -X_o/\lambda$ the Equation (42) becomes;

$$\begin{aligned} X_s &= \frac{X_o}{\lambda(S - \lambda)} - \frac{X_o}{\lambda(S + \lambda)} = \frac{X_o}{\lambda} \left[\frac{1}{S - \lambda} - \frac{1}{S + \lambda} \right] \\ X_s &= \frac{X_o}{\lambda} \left[\frac{1}{S - \lambda} - \frac{1}{S + \lambda} \right] \end{aligned} \quad (43)$$

By transforming the equation (43) from S-domain to t-domain by the approach as Laplace transform gives;

$$X_t = \frac{X_o}{\lambda} (e^{\lambda t} - e^{-\lambda t}) \quad (44)$$

The Equation (44) obtained can be found useful in evaluating the functional parameters of the bio-corrosion reaction of the metal. From knowledge of corrosion engineering the general formula or mathematical expression to calculate the rate of corrosion is given as:

$$C_R = \frac{534W}{DA\lambda t} \quad (45)$$

Recall that $T_{(t)} = t_o e^{\lambda^2 t}$ in Equation (31)

where $T(t) = T$, and substitute into Equation (45) then CR becomes;

$$C_R = \frac{534W}{DA t_o e^{\lambda^2 t}} \quad (46)$$

Therefore, the Equation (46) becomes the developed model in terms of corrosion rate due to transport of oxygen diffusion in water environment. Since

$$C = TX$$

Therefore substituting equation (31) and (44) into equation (20) we have

$$C_{(t)} = t_o e^{\lambda^2 t} \left[\frac{X_o}{\lambda} (e^{\lambda t} - e^{-\lambda t}) \right] \quad (47)$$

Simplifying equation (47) yields

$$C_{(t)} = 0.679 \frac{X_o}{\lambda} t_o e^{\lambda^2 t} \quad (48)$$

Equation (48) defines the rate of oxygen molecular diffusion and transport upon the metal per unit time in any given environment.

Experimental

The working specimens

The zinc metal plate was purchased in mile 3 market in Port Harcourt city of Rivers State in Nigeria. The specimens of zinc metal samples were transported to the Department of Chemical/Petrochemical Engineering Laboratory in Rivers State University of Science and Technology (RSUST) Nkpolu, Port Harcourt. The salt and fresh water samples were collected from Ntawogba and Orashi river all in Niger Delta area of Nigeria. The salt and fresh water samples were collected using plastic materials and all the samples collected were transported to the Chemical/Petrochemical Laboratory in the RSUST Port Harcourt for further investigation. The water samples were subjected to the physicochemical analysis to ascertain some of the functional parameters that influence biocorrosion of metals.

Experimental procedures

The zinc metal specimens was sub divided into two categories, group A of initial weight of 3230 mg and group B of 754 mg. Group A of 3230 mg by initial weight contains two specimens which were immersed in both salt and fresh water environment. Similarly, group B of 750 mg by initial weight contains two specimens which were immersed in both salt and fresh water.

The physiochemical parameters of the salt and fresh water environment were measured and the results obtained recorded as presented in this paper. The experimental work was monitored for a period 112 day at various days such as; 14, 28, 56 and 112 days and level of corrosion was evaluated. The microbial species present in the water medium upon the surface of the zinc metal was isolated, identified and characterized as presented in this paper.

Microbial isolation and identification

The microbes from the water environment in counted with zinc metal interface on the water/zinc metal environment were isolated

Table 1. Analysis of some physicochemical parameters of salt and fresh water samples.

Samples	Unit (mg/l)	Salt water	Fresh water
pH	-	6.70	9.82
Chloride Ion	-	1560	3.8
Sulphate Ion	-	0.100	0.020
Total hardness	-	4.60	2.60
Iron content	-	1.08	0.24
Biochemical oxygen demand (BOD)	-	280	19.0
Chemical oxygen demand (COD)	-	500	135
Total suspended solids (TSS)	-	100.00	8.00
Temperature	-	35.0	29.5
Total dissolved solid (TDS)	-	530	186

Table 2. Evaluation of the weight loss of Zn in various days of sampling.

The weight loss of Zn in 14 Days (336 h)			
Aqueous solution	Zinc		Weight loss values of zinc specimen (mg)
	Initial (mg)	Final (mg)	
Salt water A + Zn	8230	8198	32
Fresh water B + Zn	7450	7457	18
The weight loss of Zn in 28 Days (572h)			
Aqueous solution	Zinc		Weight loss values of zinc specimen (mg)
	Initial (mg)	Final (mg)	
Salt water A + Zn	8198	8122	76
Fresh water B + Zn	7457	7411	46
The weight loss of Zn in 56 Days (1344h)			
Aqueous solution	Zinc		Weight loss values of zinc specimen (mg)
	Initial (mg)	Final (mg)	
Salt water A + Zn	8122	8000	122
Fresh water B + Zn	7411	7323	88
The weight loss of Zn in 112 Days (2866-h)			
Aqueous solution	Zinc		Weight loss values of zinc specimen (mg)
	Initial (mg)	Final (mg)	
Salt water A + Zn	8000	7823	177
Fresh water B + Zn	7323	7101	172

and identified according to the method of Buchana and Gibbons (1974) and Gerbardt et al. (1981).

Physicochemical parameter analysis

The physicochemical parameters of the salt and fresh water composition were analyzed using the APHA (1992) standard method.

RESULTS AND DISCUSSION

The analysis results obtained from the investigation were presented in Tables 1, 2 and 3 for both salt and fresh water environment.

The pH, chloride ion, sulphate ion, total hardness, iron content, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), temperature and total dissolved solid of both the salt and fresh water samples were examined and the results obtained are presented in Table 1.

The results presented in Table 2 illustrate the weight loss by the metal at various days of exposure to the salt and fresh water environment. Increase in weight loss was observed with increase in period of the exposure (time). The weight loss was more in metal deposited in salt water environment than fresh water environment. The variation in weight loss of the metal in both salt and fresh water environment can be attributed to the physicochemical

Table 3. Comparison of existing model result with theoretical developed model result for corrosion rate of metal.

	Modeled equation	General formula
Aqueous solution	$C_R = \frac{534 W}{D A t_o e^{\lambda^2 t}}$	$C_R = \frac{534 W}{D A T}$
For 14 days (336 h)		
Salt Water A + Zn	1.7 Mpy	1.7 Mpy
Fresh Water B + Zn	1.0 Mpy	1.0 Mpy
For 28 days (672h)		
	Modeled equation	General formula
Aqueous solution	$C_R = \frac{534 W}{D A t_o e^{\lambda^2 t}}$	$C_R = \frac{534 W}{D A T}$
Salt Water A + Zn	2.0 Mpy	2.0 Mpy
Fresh Water B + Zn	1.2 Mpy	1.2 Mpy
For 56 Days (1344h)		
	Modeled equation	General formula
Aqueous solution	$C_R = \frac{534 W}{D A t_o e^{\lambda^2 t}}$	$C_R = \frac{534 W}{D A T}$
Salt Water A + Zn	1.6 Mpy	1.6 Mpy
Fresh Water B + Zn	1.2 Mpy	1.2 Mpy
For 112 Days (2866 h)		
	Modeled equation	General formula
Aqueous solution	$C_R = \frac{534 W}{D A t_o e^{\lambda^2 t}}$	$C_R = \frac{534 W}{D A T}$
Salt Water A + Zn	1.2 Mpy	1.2 Mpy
Fresh Water B + Zn	1.0 Mpy	1.0 Mpy

properties as well as period of exposure as presented in Table 2.

The results presented in Table 3 illustrate the corrosion rate of metal in both salt and fresh water environment. The results of the existing general corrosion model was compared with the developed model which shown a good match indicating that the developed model can be used in monitoring and predicting the corrosion rate of any metal.

The results presented in Table 1, illustrate the pH value of salt water and fresh water medium. It can be seen that the pH value of salt water is 6.70, which is acidic in nature while the fresh water medium is 9.82 alkaline in nature. From the characteristic of acid and base; acidic substance are more corrosive than alkaline. The microbial growth in salt water environment hereby increases the microbial activity as well facilitating corrosion.

All the physiochemical parameters considered are major factor's that influence corrosion, microbial activity is

higher in the salt water medium than the fresh water medium as presented in Table 1. These parameters includes concentration of chloride ion, shulphate ion, total hardness, iron content, biochemical oxygen demand (BOD), chemical oxygen demand (COD) temperature, total suspended solids (TSS) and total dissolved solids (TDS).

The various microorganisms isolated and identified includes, *disiicforibrio*, *desulfobacter*, *gallionella*, *thiobacillus*, *pseudomomas sp*, *bacillus substillis*, *E-coli*, *desic formaculum* and *thooxidants*. From Table 2, it is seen that there is a decrease in weight of zinc metal with respect to sampling days as presented in the paper. The corrosion rate increases with increase in time. The weight loss values of zinc metal for salt water is given as 32 mg for 14days, 76 mg for 28day, 122 mg for 56days and 177 mg for 112days whereas for fresh water medium we have 18 mg for 14days, 46 mg for 28days, 58 mg for 56days and 172 mg for 112days.

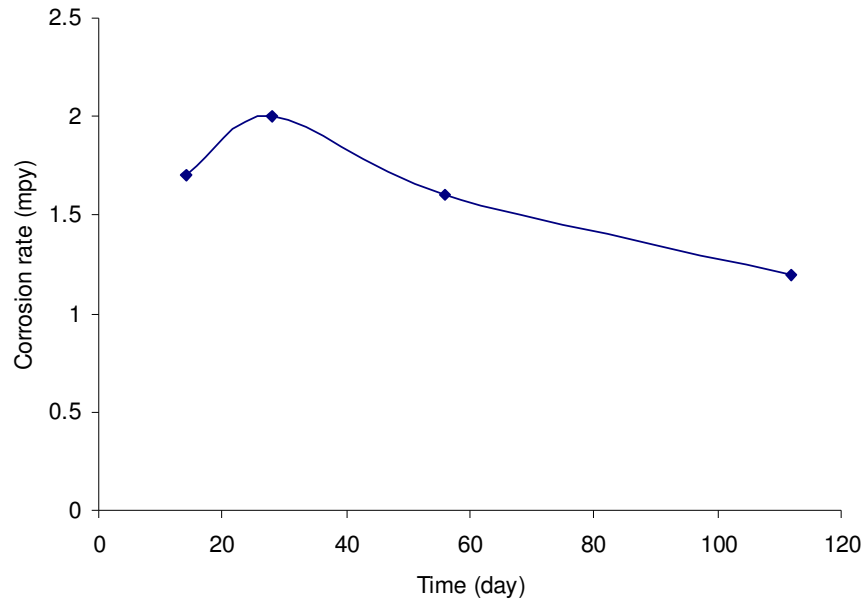


Figure 4. Corrosion rate of zinc metal in salt water medium versus time.

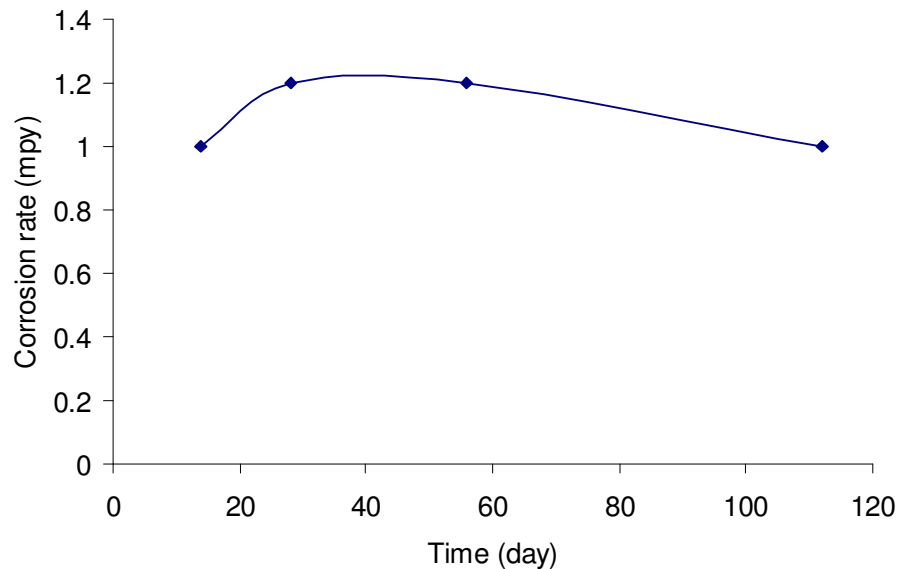


Figure 5. Corrosion rate of zinc metal in fresh water medium versus time.

Table 3 illustrates the corrosion rate of existing model with the modified model equation. The existing corrosion rate equation is given as $C_R = \frac{534w}{DAT}$ and the modified

corrosion rate equation is given as $C_R = \frac{534w}{DA t_0 e^{\lambda^2 t}}$. The

data obtained experimentally was feed into the existing and developed model and the same results were

obtained as shown in Table 3. The corrosion rate of zinc metal increases with increase in time, from Figure 4, it is seen that the corrosion rate of zinc metal increase with increase in time for salt water environment. The variation in the corrosion rate of zinc metal can be attributed to variation in time as well as physicochemical parameters of the salt water medium. The variation was experienced for both equations (developed and general equation of corrosion). From Figure 5, it is observed that the corrosion rate of the zinc metal increase with increase in time. The increase in corrosion rate of zinc metal can be

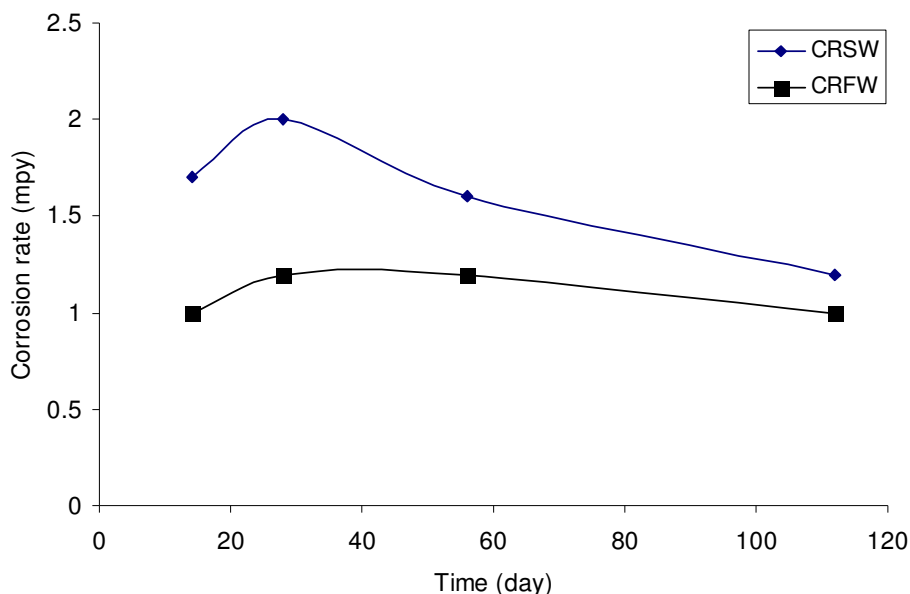


Figure 6. Comparison of corrosion rate of salt/fresh water medium versus time.

attributed to the microbial growth, physicochemical parameters and other environmental factors.

Figure 6 illustrates the comparison of the corrosion rate of zinc metal in salt and fresh water environment. The results obtained showed that corrosion of zinc is more effective in salt water medium than fresh water medium. This was attributed to the physicochemical properties of the salt and fresh water medium.

Conclusion

The following conclusions were drawn from the research work;

- 1) Redox reactions could contribute to the corrosion of metals
- 2) Physicochemical properties of the environment influence the rate of corrosion of any metal.
- 3) The rate of oxygen diffusion influence the corrosion rate of metal
- 4) Microbial growth influence the corrosion rate of any metal in the environment
- 5) Corrosion of metal is faster in salt water medium than fresh water medium.
- 6) The developed model in this paper as presented is found useful in monitoring and predicting the corrosion rate of any metal in any environment.

Based on the mathematical model developed on this paper, Ukpaka can write the mathematical formula of

corrosion rate as $C_R = \frac{534w}{DA t_o e^{\lambda^2 t}}$, where $\lambda = 0.5$,

thus, the value of t_o changes with change in corrosion rate.

Nomenclature: λ , Constant rate of corrosion which is assumed to be 0.5; \vec{J}_k is the mass flux of species K; λ the constant rate of the reaction (dimensionless); ϕ the electric potential in the electrolyte; A area of metal (m^2); C_k the concentration of specie K (mg/l); C_R corrosion rate of specimen (mpy); D density of specimen in g/cm^3 ; D^*_k the diffusivity constant of oxygen in rust layer (mg/l); F is the faraday's constant (colomb); R the ideal gas constant; t constant corrosion time (day); w weight loss (mg); T the absolute temperature ($^{\circ}C$); t_o changing time for corrosion; W weight loss of specimen (mg); X_o the original distance before the bio-corrosion reaction of the metal (m).

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