Scientific Research Publishing

Advances in Chemical Engineering and Science, 2023, 13, 336-350
https://www.scirp.org/journal/aces
ISSN Online: 2160-0406
ISSN Print: 2160-0392

The Use of Models to Evaluate Corrosion Effects on Mild Steel Heat Exchanger in Water and Mono Ethanol Amine (MEA)

Ojong Elias Ojong[1]*, Jaja Zina[2], Wosu Chimene Omeke[3], Ana Anakri Ekpenyong[4], Dadet Wilson[2], Anaba Catherine Uloma[1], Emenike Aguma[2], Sedi Patrick[5], Forwah Jacques Ndeh[6]

[1]Department of Chemical Engineering, Faculty of Engineering & Technology, University of Calabar, Calabar, Nigeria
[2]Department of Chemical/Petrochemical Engineering, Faculty of Engineering, Rivers State University, Port Harcourt, Nigeria
[3]Department of Chemical Engineering, Federal University Otuoke, Otuoke, Nigeria
[4]Department of Petroleum Engineering, Faculty of Engineering & Technology, University of Calabar, Calabar, Nigeria
[5]Department of Chemical Engineering, University of Benin, Benin, Nigeria
[6]Department of Clinical Biochemistry and Immunology, Faculty of Medical Laboratory Sciences, University of Calabar, Calabar, Nigeria
Email: *ojong.ojong@unical.edu.ng, zina.jaja@ust.edu.ng

How to cite this paper: Ojong, O.E., Zina, J., Omeke, W.C., Ekpenyong, A.A., Wilson, D., Uloma, A.C., Aguma, E., Patrick, S. and Ndeh, F.J. (2023) The Use of Models to Evaluate Corrosion Effects on Mild Steel Heat Exchanger in Water and Mono Ethanol Amine (MEA). *Advances in Chemical Engineering and Science*, **13**, 336-350.
https://doi.org/10.4236/aces.2023.134023

Received: July 5, 2023
Accepted: October 15, 2023
Published: October 18, 2023

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Abstract

Heat exchanger is an important equipment used in process industries for cooling and heating purposes. Its design configuration which involves the flow of cold and hot fluids within the exchanger subjects it to corrosion attack. The article utilized the principle of mass and energy conservation in the development of weight and temperature models to study the effect of corrosion on mild steel coupon inside the exchanger containing water and Mono ethanol amine (MEA). The models developed were resolved analytically using Laplace Transform and simulated using Excel as simulation tool and data obtained from experiment in the laboratory to obtain profiles of weight loss and temperature as a function of time. The weight loss and performance of mild steel under various corrosive conditions were examined which indicates the effect of corrosion on the mild steel heat exchanger in water and MEA media. The result shows that water is more corrosive than MEA at higher temperatures and at lower temperatures of 35˚C and 1 atm, MEA has inhibitive properties than water as indicated by the weight loss result with time. The comparative analysis between the results obtained from the model simulation and experimental results shows that the result obtained from the model is more reliable and demonstrated better performance characteristics as it clearly shows mild steel heat exchanger experiences more corrosive effect in water medium than MEA at higher temperatures. And at lower temperatures, MEA becomes more inhibitive and less corrosive than water. The model simulation results correlate with various literatures and hence, it is valid for future referencing.

Keywords

Model, Corrosion Effect, Heat Exchanger, Simulation, Media, Mild Steel, Coupon

1. Introduction

In both simulated and real geothermal conditions, a variety of engineering materials have been investigated. These materials include non-ferrous metals, carbon and stainless steels, as well as other non-metallic materials, for heat exchangers, turbines, surface pipelines, and well casings [1]. Non-ferrous heat exchangers (HEs) contain very little or no Fe in their component such HEs are made up of Cu, brass, Al and Ti, since these metals are more corrosion resistant compared to ferrous metals, and are used in corrosion media to reduce attack on the material surface [2] [3].

Ferrous HEs are materials made up of stainless steel with elemental % composition of Fe (69.27), Cr (17.41), Si (1.44), Mn (1.9), Mo (0.39), Co (0.34), Cu (0.17) and Nb (0.08), and carbon steel, with elemental composition of Fe (9.74%), Si (1.86%), Ti (0.30%), Cr (0.4%), Mn (0.37%), Zn (0.05%) as characterized by [4]. Carbon steel comprises of Fe and carbon as its basic components, not highly corrosion resistive in the presence of corrosion agent (such as media, environment and air) and has high thermal conductivity but may not be as efficient as some non-ferrous steel [5] [6]. Stainless steel is an alloy comprises of Fe, Cr and some other elements with good thermal conductivity but exposed to corrosion attack because of Fe content in it [7] [8]. Non-metallic materials include ceramics, polymers and composites etc., which do not conduct heat effectively as metals and are use in areas where weight and cost needed to be minimized [9]. They are special purpose materials as polymers for instance, are used in low-temperature and low-pressure heat exchangers while ceramics are for high temperature in highly corrosive environment because of good resistance to corrosion [10] [11] [12]. Hence selecting material for heat exchanger will depends on factors such as temperature, pressure, operation, requirements and cost.

To implement diagnostic mechanisms of the type and degree of corrosion, it is necessary to understand the factors involved in the process [13]. For example, the physicochemical characteristics of solution, properties of the equipment material, and conditions of the experimental system such as temperature, pressure, oxygen content are just a few examples of the factors that need to be understood [14].

Thermal process operation in chemical industries usually involve vapour and gases being cooled near the dew point of water [15] [16]. Sometimes the temperature falls below the indicated dew point, which eventually leads to pitting corrosion [17]. Pitting corrosion, which manifests itself as highly localized corrosion attacks, progresses in depth and results in trough penetration in a short period of time. Pitting corrosion reduction of heat-exchanging surfaces is a challenging task that necessitates a thorough understanding of the process and the impact of operating conditions on the corrosion rate. Pitting corrosion is one of the major causes of equipment failure and it can easily remain undetected for long [18]. Utilizing corrosion inhibitors is one method that might be used to prevent "pitting," but doing so would result in a considerable cost increase and make it challenging to administer the inhibitors under different process conditions [19]. To overcome this, most thermal processes are designed using thermal safety distance in term of temperature and pressure, however, the limitation of this process is that the heat exchanger capacity will not be fully utilized. Corrosion is a major problem face in chemical processes involving fluids, hence, ways to reduce or eradicate it [20] [21] are; proper selection of materials (the use of corrosion resistive materials such as stainless steel), corrosion resistive alloy and non-ferrous metals [22], corrosion inhibitor-substances that reduce the rate of corrosions by forming protective layer or altering electrochemical reaction causing corrosion, cathodic protection via controlling electrochemical reaction [23] [24], surface preparation with protective coating [25], protective coatings and linings (such as paint, epoxies and polymers) to serve as a barrier for to corrosive substances, monitoring and inspecting materials for possible corrosion attack in other to apply adequate maintenance measures [26], and other corrosion measures such as testing, corrosion management programs, corrosion education and training [27].

Mono ethanol amine (MEA) is a weak acid which denotes proton (H^+) in solution forming H_3O^+ thereby making it slightly acidic when dissolved in water. As such, increasing the concentration of MEA in solution, decrease the rate of corrosion since MEA act as inhibitor, but due to cases where there are side reactions, more MEA in solution lead to increase in corrosion rate [24] [28] and its impact on mild steel heat exchangers depends on temperature, side reactions etc.

Recent literatures on this area of study are highlighted as, [29] worked on Model-based real-time prediction of heat exchanger, for predicting real-time estimation of the lowest heat exchanger surface temperature achievable via maximizing the process's potential via optimization; [30] investigated the need to optimally design heat exchanger taking corrosion into account due to heat transfer surface facing uniform corrosion (corrosion fouling)with a view that, utilizing a corroding material is feasible at a cheaper cost if corrosion rate does not surpass a particular threshold; [31] used NORSOK CO_2 corrosion rate prediction model and computational fluid dynamics for an out-header piping of air-cooled heat exchange with NORSOK M-506rand Euler-Euler technique solver, which gave good alignment of the model data with field observations and that integrating computational fluid dynamics with models, can accurately forecast regional rates of corrosion and identify areas prone to CO_2 corrosion; and [21] reviewed corrosion problems in pipelines of the oil and gas industries in API 5L steel pipelines, and suggested that corrosion inhibitors, protective coatings and protective coatings together with cathodic protection be widely used to enable oil and gas materials last longer(from microbial, sulfide stress cracking, H_2-stress cracking and H_2-induced cracking corrosion on the pipelines). The need to develop temperature models [32] to predict corrosion effect in a typical mild steel heat exchanger using two different fluids (water and MEA) at varying temperature has become necessary due to the usefulness of it in the industries. To successfully achieve this, then, derivation of the weight loss and temperature models of mild steel heat exchanger to predict corrosion effect, simulate the developed models with experimental data, and compare the models with the experiment results to determine the effect of temperature variation in mild steel heat exchanger using water and MEA is targeted in this study.

2. Materials and Method

This covers the development of weight loss and temperature models, simulation of the models with experimental data obtained from the experiment conducted, and model results comparison with experimental results via profiles.

2.1. Materials

The materials used for this article were mild steel coupons measuring 3 cm × 8 cm × 0.2 cm, heat exchanger laptop, and physiochemical data (experimental data and thermodynamics data).

2.2. Method

The weight loss and temperature models are developed based on the mass and energy balance equations and principles.

Model Development for Corrosion Check in Heat Exchanger

The modeling of the heat exchanger, specifically, the shell and tube to obtained unsteady state weight loss and temperature variation is based on material and energy balance.

For the weight loss model, Equation (1) is used to obtain the transient weight loss model as,

$$\begin{aligned}&\text{Rate of accumulation of weight of materials}\\&=\text{Rate of inflow of material}-\text{Rate of outflow of materials}\end{aligned} \tag{1}$$

Mathematical analysis of Equation (1) gives the weight loss model in wight/weight basis as,

$$\frac{\mathrm{d}W}{\mathrm{d}t}=-\frac{1}{\tau}\left(W-W_0\right)-k_C C \tag{2}$$

where, τ is space time defined mathematically as the ratio of volume of the fluid to volumetric flow rate ($\frac{V}{v_0}=\frac{W}{\rho v_0}$) [s], ρ is mass density of coupon [g/cm^3], v_0 is volumetric flow rate [cm^3/s], k_C is rate constant for corrosion [day^{-1}], W_0 is initial weight of the coupon[g], V is volume of the fluid [cm^3], W

is the final weight of the coupon measured [g], and C is the mass concentration defined as ($C = \frac{W}{V}$) [g/cm^3].

The dynamic model for the weight loss to predict the corrosion effect on the mild steel coupon in the HE in different fluid is given by,

$$\frac{\mathrm{d}W}{\mathrm{d}t} = -\frac{1}{\tau}W + \frac{1}{\tau}W_0 - k_C W \tag{3}$$

The energy balance Equation (4) is applied to obtain the unsteady state temperature model, used to predict the corrosion effect in the exchanger. The derivation of the temperature model follows some assumptions made as reported in work carried out by Uzono and Ojong, (2022)

$$\begin{aligned} &\text{Rate of Accumulation of energy within the exchanger} \\ &= \text{Rate of inflow of energy into the exchanger} \\ &\quad - \text{Rate of outflow of energy from the exchanger} \\ &\quad \pm \text{Rate of heat added/removed from the exchanger} \end{aligned} \tag{4}$$

Applying Equation (4) mathematically, then the transient temperature model for the heat exchanger becomes,

$$\rho C_\rho V \frac{\mathrm{d}T}{\mathrm{d}t} = \rho v_0 C_\rho T_i - \rho v_0 C_\rho T_0 + UA\left(T - T_C\right) \tag{5}$$

where, ρC_ρ is the product of the density [g/cm^3] and the specific heat capacity [J/kg K] of the fluid in the exchanger, T is the temperature of the fluid [K] under measurement, T_i is the initial temperature of the fluid [K], T_0 is the output temperature of the fluid [K], UA is the product of the overall heat transfer coefficient [J/s·m^{2}K] and the surface area of the exchanger [m^2], and T_C is the coolant temperature [K].

Further simplification of Equation (5) and assigning specific constants to group of parameters gives,

$$\tau \frac{\mathrm{d}T}{\mathrm{d}t} = T_i - T_0 + j\left(T - T_C\right) \tag{6}$$

where, $j = \frac{UA}{\rho C_\rho v_0}$ [-], $\tau = \frac{V}{v_0}$

Considering the fact that, the fluid in the exchanger is uniformly mixed, then $T = T_0$ then Equation (6) gives,

$$\tau \frac{\mathrm{d}T}{\mathrm{d}t} = T_i - T + jT - jT_C$$

$$\tau \frac{\mathrm{d}T}{\mathrm{d}t} - \left(j - 1\right)T = T_i - jT_C \tag{7}$$

2.3. Solution Technique

Analytical approach is used to resolve the ordinary differential equations developed (see Equations (3) and (7)) using Laplace transform technique to obtain of weight loss and temperature solution models as shown in Equations (8) and (9) respectively.

$$W_{(t)} = \frac{1}{\tau}\frac{W_0}{a_1}\left\{1 - \mathrm{e}^{-a_1 t}\right\} \tag{8}$$

$$T_{(t)} = \frac{a}{j-1} - \frac{25_j}{j-1} - \frac{1}{\tau(j-1)}\left\{a - 25_j\right\}\mathrm{e}^{-\left(\frac{j-1}{\tau}\right)t} \tag{9}$$

where, $a = \frac{1}{A}$, and $a_1 = \frac{1}{\tau} + k_C$.

These solution models are simulated with experimental data using MS Excel package to generate profiles of weight loss and temperature with time.

Summary of Models and Comments

The material and energy balance equations were performed on the heat exchanger to obtain wight loss and temperature models developed using principles of conservation of mass and energy. The models were resolved analytically with Laplace Transform technique to give weight loss and temperature as function of time. The experimental value obtained were used to simulate the models with MS Excel to generate data and profiles of weigh and temperature with time and comparison of the models result based on the different media (MEA and water) with experimental results are focused.

2.4. Input Parameters for Simulation of the Wight Loss and Temperature Models Developed

The experimental analysis in the laboratory gave experimental data used for the simulation of the models as shown in Table 1.

3. Results and Discussion

Corrosion effects on Shell and Tube Heat Exchanger was investigated with mild steel coupons of sizes 3 cm × 8 cm × 0.2 cm in water and MEA respectively allowed at different days and varying temperatures. The data obtained from the experiment was used to simulate the solution models (see Equations (8) and (9)). The profiles are then generated as shown in Figures 1-4 and also the comparison profiles for the experimental data and the model are presented and discussed in Figures 5-8.

3.1. Variation of Weight Loss with Time

Figure 1 indicates the model results of the corrosion effects on the mild steel corrosion in heat exchanger in the presence of water and 3 molar concentration of MEA media with time. The weight loss shows that corrosion effect actually took place in water but little or no corrosion effect is felt in the acid media as shown in the corrosion constant for water 0.028 is >>> the one for acid (6×10^{-5}), since the MEA is acting as an inhibitor at this higher concentration with lower temperature, hence preventing or hindering corrosion effect of the coupon in the HE, which is in line with literature argument [28]. This indicate that the modeling data obtained for measuring corrosion effect of mild steel in water and MEA media are reliable, good and acceptable.

Table 1. Input parameters for model simulation.

Parameter	Mild Steel in Water	Mild Steel in Acid (3 M of MEA)	Unit
Dimension	(25.35 × 50.12 × 1.27)	(22.83 × 48.84 × 1.28)	mm
Density, ρ	1000	7850	kg/m^3
Initial weight, w_0	1	1	g
Weight loss, w	0.01	0.01	g
Observation	72	72	hr

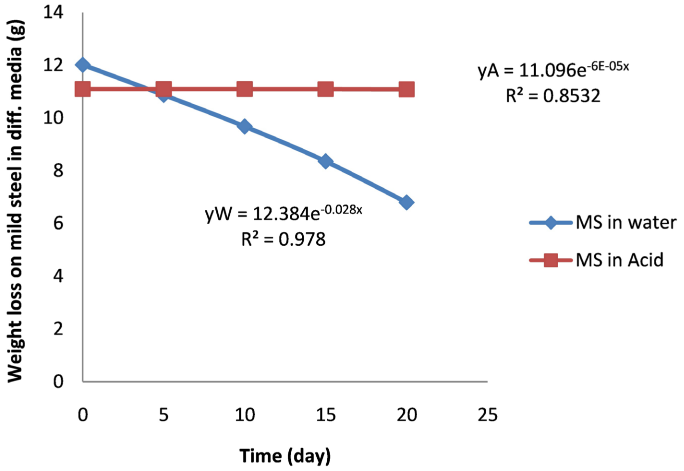

Figure 1. Profile of Weight Loss due to Corrosion Effect on Mild Steel Coupon in Water and Acid Media versus Time.

3.2. Variation of Weight Loss with Temperature

Corrosion effects on mild steel coupon in the heat exchanger under investigation in water and MEA media due to temperature variation is shown in **Figure 2**. As said earlier, with or without temperature increase, the corrosion effect of mild steel coupon in water and MEA still remains the same as **Figure 1**, but the model results gave a better explanation. Corrosion effect of mild steel coupon in water is high compared to that in MEA medium as the corrosion constant is 0.1295 >> 0.0003 for water and MEA acid respectively. This shows that there is little effect of corrosion compared to **Figure 1**, on mild steel coupon dip into the heat exchanger containing MEA as temperature increases due to possible side reaction and temperature variation affects the inhibiting properties of the MEA as reported in the literature [28] whereas, there is an effect of corrosion felt on the mild steel coupon in the exchanger with water at higher temperature in line with literature studies [33]. The reliability and acceptability of the model results proved that the models are good and suitable to described corrosion effects on heat exchanger at varying temperature (see coefficient of determination of 0.996 and 0.853 for water and MEA acid respectively). Hence temperature is an essential factor considered in investigating corrosion effects in heat exchanger in line with literatures considerations [14] [16].

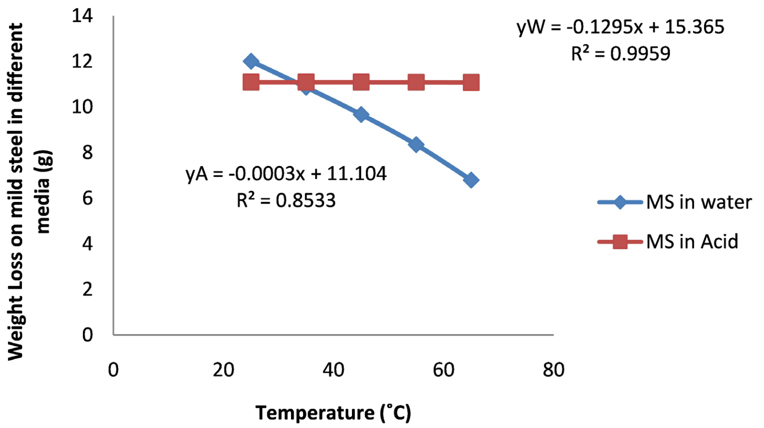

Figure 2. Profile of Weight Loss due to Corrosion Effect of Mild Steel Coupon in Heat Exchanger with Water and Acid versus Temperature.

3.3. Temperature Variation with Time for Different Media in Heat Exchanger (HE)

Figure 3 depicts the temperature profile variation with time due to corrosion effects of mild steel coupon in water and MEA. The temperature model developed for heat exchanger was simulated with experimental data and the result indicates that corrosion attack the mild steel coupon in water more, with corrosion rate value of 0.0148 compared to less corrosion attack of mild steel coupon in MEA where there is little or no corrosion effect felt on the coupon since the corrosion constant is very small (0.0005). The reason as explained in Figure 1 holds here, as MEA is acting as an inhibitor that prevent corrosion effect [28]. The model result also indicates that the data for the corrosion effect of mild steel coupon in MEA and water fitted well, reliable and acceptable due to the R^2 values are 1 and 0.984 respectively. The data for both processes are reliable, acceptable and good. The heat exchanger is a heating equipment as it is only modeled using energy balance technique. This also can be reasoned that at increasing time, the temperature decreases exponentially and the effect of corrosion of the mild steel coupon in water is felt while the effects of corrosion of the mild steel in MEA is less felt due to side reaction as shown in the linear plot in Figure 3.

3.4. Weight Loss with Time for Different Media Aiding Corrosion on the Mild Steel Coupon

The weight loss corrosion model in the heat exchanger developed generated profile shown in Figure 4 which indicates the variation of weight loss of mild steel coupon in water and MEA media as a function of time due to corrosion effects. The corrosion constants for the model results of the mild steel coupon in water and MEA are 0.0963 and 0.1407 respectively, indicating the presence of corrosion. The loss of weight decreases as time increases, meaning that the corrosion effect is felt more at longer time compared to short period the coupon stays in the media. However, water medium affects the mild steel coupon more than the MEA medium as indicated by the corrosion rate of −0.141 << −0.096. This can

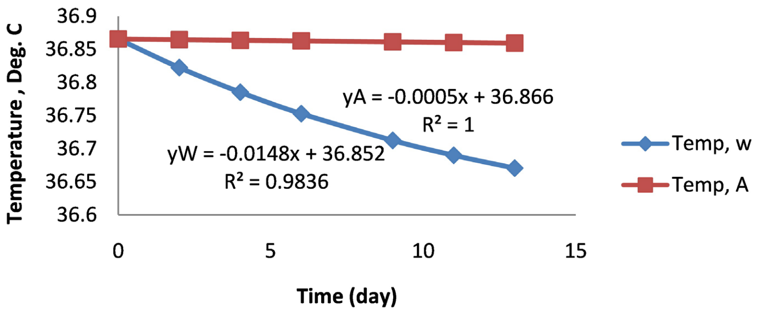

Figure 3. Effects of Temperature on Corrosion of Mild Steel Coupon in Water and MEA in HE versus time.

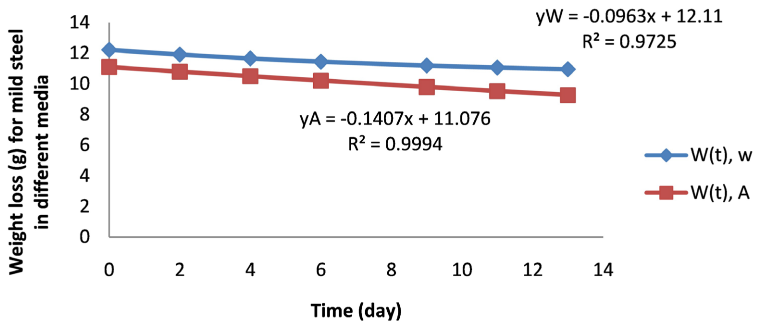

Figure 4. Profiles of Weight Loss due to Corrosion of Mild Steel Coupon in Water and MEA Environment versus Time.

only happen when the temperature slightly increases with time, thereby increasing the corrosiveness of the media and side reaction occurrence in line with the data from the model and the coefficient of determination values of 0.999 and 0.973 respectively for MEA and water.

3.5. Comparison of Weight Loss with Time on Mild Steel in Water Medium for Model and Experimental Results

The experimental result is compared to the model results with profile shown in Figure 5 for corrosion effect of mild steel coupon in water medium. The model results are better compared to the experimental result since the corrosion constant values are 0.0963 and 0.0083 for model and experimental respectively. This implies that the models best explain the corrosion effect of mild steel coupon in water for heat exchanger than the experimental work as indicative on the R^2-values of 0.973 > 0.940. Both processes are first order and the coefficient of determination values shows that model results are more reliable, acceptable and better than the experimental data. The profiles in Figure 5 indicate that corrosion actually took place on the mild steel coupon in water medium of the HE.

3.6. Weight Loss for Model and Experimental Results of Mild Steel Coupon in MEA Medium with Time

The comparison profiles of the effects of corrosion of mild steel coupon in MEA for the model and experimental results obtained is shown in Figure 6. The

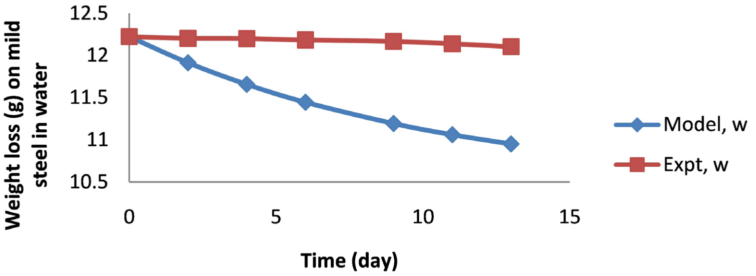

Figure 5. Comparison Profiles of Weight Loss for Model and Experimental Results versus Time due to Corrosion Effect of Mild Steel Coupon in Water.

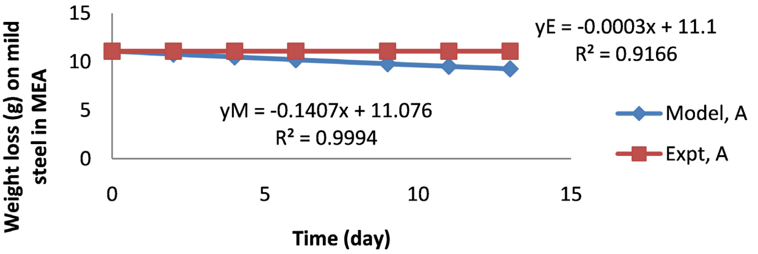

Figure 6. Comparison Profiles of Weight Loss for the Model and Experimental Results versus Time due to Corrosion Effect of Mild Steel Coupon in the HE with MEA.

profiles indicate that the model results perform better than the experimental results as noticed on the R^2-values of 0.999 and 0.917 respectively. The reason might be due to the fact that the models gave the best result and predict corrosion effect of mild steel coupon in MEA medium than the experiment. The data obtained from the model simulation are good, reliable and acceptable more than those from the experiment. The corrosion constants for both processes are -0.1407 and 3×10^{-4} resulted from the model and experiment respectively, indicating that corrosion effect is more visible in the model result because of side reaction at higher temperatures that might occurs in the process leads to corrosion effect on the mild steel as reported in literature [28] [34]. The values of the corrosion constants 0.141 and 0.0003 for model results and experimental data respectively indicate that corrosion actually took place and is real on the mild steel coupon from the reading of the model compared to the experimental results.

3.7. Corrosion Effects on Mild Steel Coupon in Water and MEA with Time Using the Models Developed

The increase in weight loss with time to investigate corrosion effects on mild steel in water and MEA is shown in Figure 7. The weight loss with time of mild steel coupon in water shows an exponential increase to a point of where it started declining, whereas that of mild steel coupon in MEA increases linearly without point of decrease, indicating that corrosion of the mild steel coupon took place. The models' results are reliable, good and be acceptable since the coefficient of determination values are all close to unity (0.999 and 0.972) for the

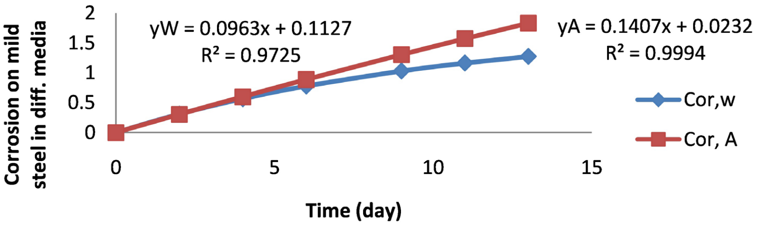

Figure 7. Profiles of Corrosion effects of Mild Steel coupon in Water and Acid versus Time.

two media. The weight loss results obtained from mild steel coupon in MEA medium are better, more reliable and highly efficient because the model give a more predictive description of the process compared to that obtained from mild steel coupon in water due to the corrosiveness of the media.

3.8. Temperature Variation of Corrosion Effect on Mild Steel in Water of the Model and Experimental Result with Weight Loss

Figure 8 depicts the comparison of corrosion effect of coupon mild steel in water for the model results and the experiment due to temperature data obtained. The heat exchanger is modeled as temperature, as a function of time. As shown earlier, the temperature model developed for corrosion on the metal coupon investigated in water affects the corrosion of the equipment in the fluid used. Increase in temperature result to increase in weight loss as shown in Figure 8. Temperature affects the properties of the heat exchanger and hence corrosion on the equipment since the HE is a ferrous material, more corrosion attacks is felt greatly, this is in line with literature studies [6] [7]. The model result of temperature with weight loss gave better data reliability and acceptability compared to experimental result. This is proven from the R^2-values of 0.950 for model against 0.909 for experiment obtained. Again, higher temperature increases the conductivity of water, hence corrosion effects on the mild steel coupon increases at slightly increase in temperature for model result compared to experimental result which indicate increase in temperature increases weight loss. From Figure 8, at weight loss of 1.2 g, the temperature for model and experimental result are 45˚C and 65˚C respectively, indicating that the experimental result agrees with literatures reading since higher temperatures increases corrosion rate in water medium such a case of pitting type corrosion [15] [17] [18], such a case where the properties of the environment are corrosive and damages the material that houses the corrosion activities. But in highly conducting media, corrosion effect reduces as explained better with the model result.

3.9. Corrosion Weight Loss on Mild Steel Coupon in MEA for the Model and Experimental Results with Time Due to Temperature

Figure 9 present the temperature profiles with time for the model and experimental

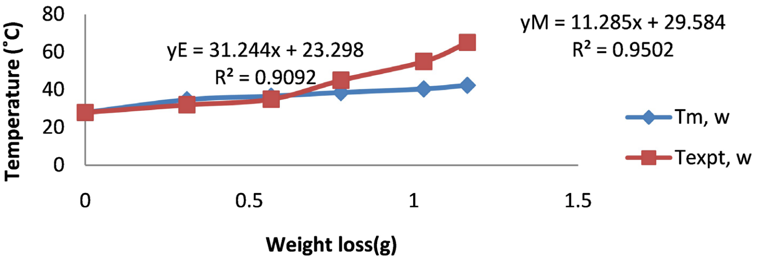

Figure 8. Comparison of Corrosion effects of Mild Steel Coupon in Water due to Temperature Profiles from the Model and Experimental Results versus Time.

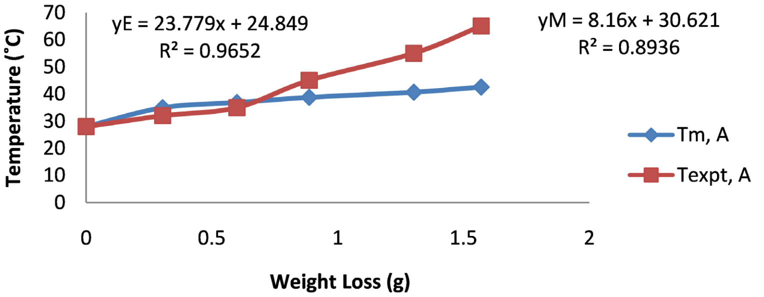

Figure 9. Effect of Corrosion on Mild Steel in MEA for the Model and Experimental Results versus Weight due to Temperature.

results on the corrosion effect of mild steel coupon in MEA medium. The experimental result performs better than the model result as indicated by the R^2 values of 0.965 and 0.894 respectively. This implies that the experimental results better describe the process than the models and based on this, it can be deduced that the experimental analysis of the metal coupon in MEA at varying temperature is poor and by all indication, the corrosion rate is independent to the concentration of the MEA whereas, it is dependent only on the concentration of water at higher temperature. Data analysis shows good performance and acceptability for both processes. Experimentally, at higher temperature say 65˚C, the weight loss is 1.2 g and vise versa, indicating that the inhibition properties of the MEA reduce as side reaction positively affects the corrosion rate of the mild steel, agreeing with literature finding [24] [28] against the model result, where higher weight loss occurs at little temperature increment of 45˚C.

4. Conclusion

The use of models to evaluate corrosion effects on mild steel heat exchanger with water and MEA was investigated; the weight loss and temperature models were developed and simulated with the experimental result. It has been established from the finding of the experiments and models that temperature and media are very important criteria when selecting a material for a process, as corrosion can cause damages to an entire design, process or structure. The corrosion type is a uniform one as indicated by the corrosion constants for mild steel coupon in water and low values for mild steel coupons in MEA medium. That the model results prove otherwise, corrosion effects are felt for both MEA and water media, indicating further that MEA medium has minimal weight loss of mild steel coupon compared to water medium at higher temperature. Compare the results, the model predicted corrosion effects of mild steel in water better, reliable and follow literatures trends than the experimental result, while the experimental results predict better corrosion results of the mild steel coupon in MEA acid than model. This implies that the developed models are précised, and acceptable for future references.

5. Recommendations

This article should be highly recommended and used by academia and industries working on energy equipment and the effects of corrosion on the equipment. The use of models to evaluate corrosion effects on metals conveying fluids was studied and highly recommended as investigated in this article.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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