INHIBITION OF GALVANIC CORROSION IN SODIUM CHLORIDE SOLUTIONS

A Thesis
Submitted to the College of Engineering
of Nahrain University in Partial Fulfillment of the
Requirements for the Degree of
Master of Science
in
Chemical Engineering

by

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B.Sc. in Chemical Engineering 2006

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December 2010

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Abstract

Because of the importance of galvanic corrosion the need arises to study the effect of corrosion inhibitors, area ratio of cathode to anode (A_c/A_a), on galvanic corrosion of several industrially important metals and also to follow the behavior of corrosion rate of each member of the couple. In the present experiments at the first stage, the corrosion potential with time was measured for four types of metals in solution of four pH values. The purpose of this stage is to find out the cathode metal from the anode. The weight loss technique is used as an indicator for determining the efficiency of the inhibition process using four types of metals carbon steel,stainless steel, cadmium,and tin,four values of solution pH 0,1,2, &3 and four concentrations of inhibitor 177.2, 354.4, 531.6, &708.8 ppm .

Corrosion cell has been used to measure current and potential versus time for the metals coupled. Galvanic corrosion and inhibitor performance have been tested for four important factors that affect the process:Two values of solution pH (0 &1) in 0.1N NaCl ,three types of metals: carbon steel ,stainless steel ,and cadmium,four area ratios 1,0.75,0.5,&0.25,one concentration of dimethalaminoethanol inhibitor (708.8) ppm in air-saturated 0.1N NaCl solution at T= 40 ^{o}C, & t=120min .

It is found in this study the corrosion rate decreases with increasing inhibitor concentration under single and coupled conditions. Efficiency of inhibitor reaches about 98% for cadmium in solution of pH=3 and in the presence of 708.8 ppm inhibitor concentration.Current and potential were measured for the couples cadmium/carbon steel, carbon steel/stainless steel, and cadmium/stainless.The value of galvanic current decreases with increasing inhibitor concentration and the galvanic potential difference

decreases, i.e., approaching each other, especially at pH(0). But this is not for all metals, area ratios and PH values.

Galvanic dissolution current density was calculated for the two members of each couple obtained experimentally under zero resistance conditions. The results show that the two members of the couple corrode. This would verify that the galvanic corrosion systems are composed of two corroding metal members with the more noble metal being partially protected.

List of Contents

Chapter Two: Galvani Corrosion

Chapter Three: Experimental Work

Chapter Four: Results

Chapter Five :Discussion

Nomenclature

SYMBOL	MEANING	UNIT
A	Surface area	m^2
AR	Area ratio	-
t	Time of exposure	h
L	Metal specimen length	cm
W	Width of sample	cm
i_o	Exchange current density	(A/m_2)
$E_{coup.}$	Coupling potential	mV
i_L	Limiting current density	$\mu A/cm^2$
E_{corr}	Corrosion potential	mV
$A_{a,}$ A_c	Anodic and cathodic area	m^2
C	Inhibitor concentration	ppm
CR	Corrosion rate	-
CS	Carbon steel	-
St.St	Stainless steel	-
Cd	Cadmium	-
Sn	Tin	-
E	Potential difference	V
$E_{eq.}$	Equilibrium potential	V
E_o	Standard potentials	V
SCE	Saturated Calomel Electrode	V
I	Current density	$\mu A/cm^2$
I_o	Exchange current density	$\mu A/cm^2$
ΔW	Weight loss	gm
I	Current	mA
Mw	Molecular weight of metal	g/mol
mm/y	Millimeter penetration per year	-
mpy	Millinch penetration per year	-

Greek Symbols

η	Polarization overpotential (mV)
η_A	Activation overpotential (mV)
η_c	Concentration overpotential (mV)
η_T	Total overpotential (mV)
ρ	Density of metal (g/cm^3)

List of Tables

List of Figures

Chapter One

Introduction

Corrosion

Corrosion is the deterioration of materials by chemical interaction with their environment. The term corrosion is sometimes also applied to the degradation of plastics, concrete, and wood but generally refers to metals [1]. It leads to serious problems because it definitely .Contributes to the depletion of natural resources ,for example, steel is made from iron that has been dwindled .Another important factor concerns the world's supply of metal resources .The rapid industrialization of many countries indicates that the competition for and the price of metal resources will increase[2].

The two major factors affecting the severity of galvanic corrosion are :

1. The voltage difference between the two metals on the galvanic series.
2. The size of the exposed area of cathodic metal relative to that of the anodic metal (Ac\Aa) .

Corrosion of the anodic metal is more rapid and more damaging as the voltage difference increases and as the cathode area increases relative to the anode area [3].

Galvanic corrosion often misnamed "electrolysis " is one common form of corrosion in marine environment . It occurs when two (or more) dissimilar metals are brought into electrical contact under corrosive environment. When a galvanic couple forms one of the metals in the couple it becomes the anode and corrodes faster than it would all by itself, while the other becomes the cathode and corrodes slower than it would alone [4]. Many corrosion products are chemically similar to the corresponding metallic minerals [5] .

Most corrosion reaction are electrochemical, an example illustrating the electrochemical nature of corrosion is attack of iron which is the most commonly used industrial metal whose electrochemical reaction in acid is:

$$Fe + 2HCl \longrightarrow FeCl_2 + H_2$$

Noting that the chloride ion is not involved in the reaction. This equation can be written in the simplified form as:

$$Fe + 2H^{+} \longrightarrow H_2 + Fe^{2+}$$

The equation can be conveniently divided into two reactions :

Oxidation (anode reaction) : $Fe \longrightarrow Fe^{+2} + 2e$

Reduction (cathodic reaction) : $2H^{+} + 2e \longrightarrow H_2$

Both the oxidation reaction and the reduction reaction proceed at the same rate during electrochemical corrosion. Any changes in the system which affect the rate of one must of necessity affect the other [6]

The Scope of Present work

To study they galvanic corrosion for different coupled metals carbon steel\stainless steel,carbon steel \cadmium,stainless steel \cadmium under various factors : .types of metals in contact, metals area ratio, and the presence and type of an inhibitor and its concentration.

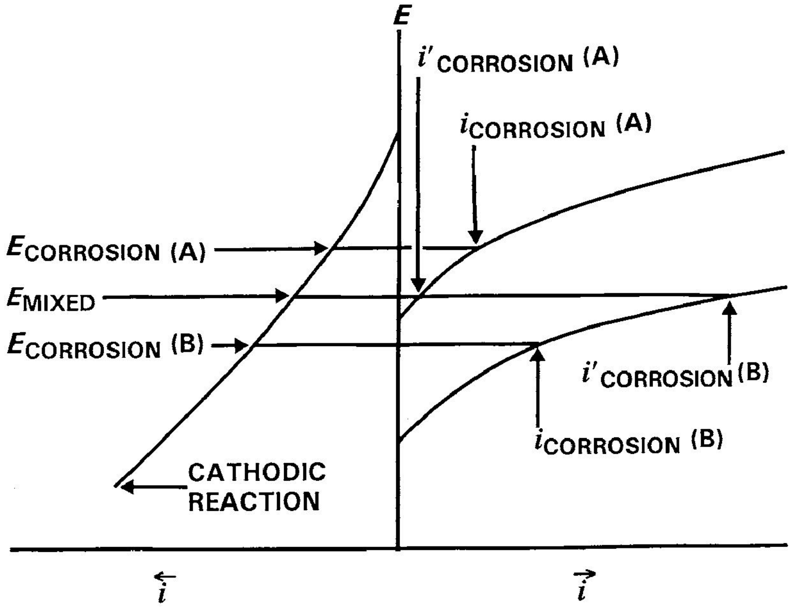
Chapter Two

Galvanic Corrosion

2.1 Introduction

Galvanic corrosion , resulting from a metal contacting another material in a corrosive medium is one of the most common types of corrosion [7]. It is also called dissimilar metal corrosion or wrongly electrolysis and refers to corrosion damage induced when two dissimilar materials are coupled in a corrosive electrolyte. In a bimetallic couple the less noble material becomes the anode and tends to corrode at an accelerated rates [8] .The more noble metal suffers less than if it were isolated in the same medium .The increased attack on the less noble metal is called galvanic stimulation as in Fig (2.1).

The combination of metals producing the effect is a bimetallic couple . The effect can be very intense and is potent cause of the premature failure of the less noble metal . It does not correlate quantitatively either with difference between the standard electrode potential of a pair of metals (E° first metal) – (E° second metal) or with difference between the corrosion potential that each would have separately in the same environment [9].



Figure(2.1) Current distribution on metal A(more noble) and B(less noble) in a corroding bimetallic system If the metals are insulated their corrosion potentials are Ecorrosion (A) and Ecorrosion (B) and their corrosion currents are I corrosion (A) and Icorrosion (B).If connected , they acquire a common potential E mixed and the anodic current on A falls to I corrosion (A) and(B) [9]

2.2 Theory of Galvanic Corrosion

The galvanic couple between dissimilar metals can be treated by application of mixed potential theory [2,6] .Consider a galvanic couple between a corroding and an inert metal. If a piece of platinum is coupled to zinc corroding in an air-free acid solution, vigorous hydrogen evolution occurs on the platinum surface and the rate of hydrogen evolution on the zinc sample is decreased. Also, the corrosion rate of zinc is greater when coupled to platinum. The electrochemical characteristics of this system are schematically illustrated in Fig. 2-2 [6].

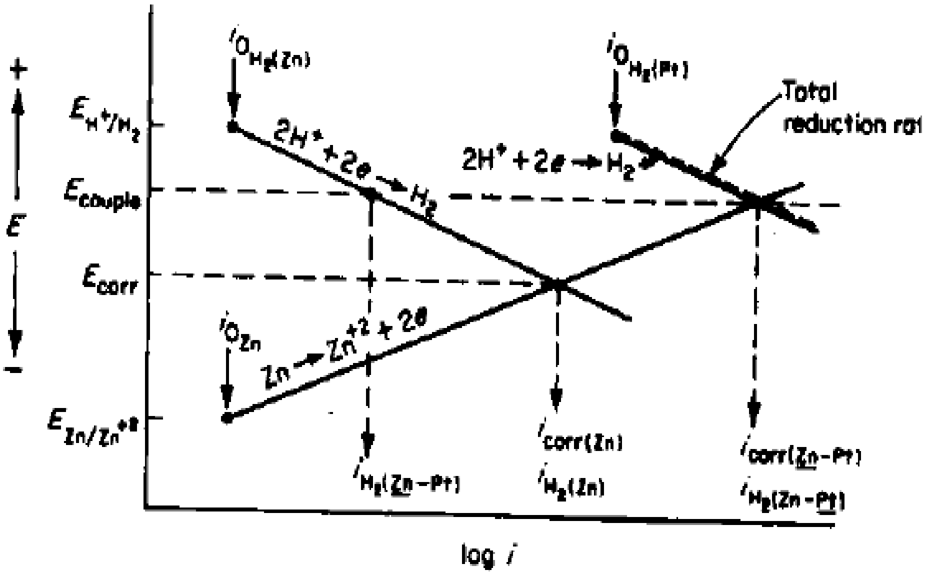


Figure (2.2) Effect of galvanically coupling zinc to platinum[2]

The corrosion rate of zinc in an air-free acid is determined by the interaction between the polarization curves corresponding to the hydrogen evolution and zinc-dissolution reaction, yielding a corrosion rate equal to i_{corr}(Zn) .When equal areas of platinum and zinc are coupled، the total rate of hydrogen evolution is equal to the sum of the rates of this reaction on both the zinc and platinum surfaces. Since the hydrogen ion exchange current density is very high on platinum and very low on zinc, the total rate of hydrogen evolution is effectively equal to the rate of hydrogen evolution on the platinum surface, as shown in Fig.3-2 which shows that coupling zinc to platinum shifts the mixed potential from Ecorr. to Ecouple, increases corrosion rate from Icorr to Icorr(zn-pt) and increases the rate of hydrogen evolution on the zinc from I_{H2}(Zn) to I_{H2}(zn-pt) .The rate of hydrogen ion reduction on the platinum is $I_{H2(Zn-pt)}$ As mentioned above, the increase in corrosion rate of zinc observed when this metal is coupled to platinum is the result of the higher exchange current density for hydrogen evolution on platinum surface. It is not due to the noble reversible potential of the platinum-platinum-ion electrode as frequently stated in the literature. To illustrate this point, consider the relative positions of platinum and gold in the emf and galvanic series.The reversible potential of the gold electrode is more positive than that of platinum in the emf series, as where in most galvanic series tabulations the position of the platinum is below gold. The effect of coupling zinc to gold and to platinum is compared. As mentioned before, the exchange of current density for the rate of hydrogen reaction on the zinc metal surface is very low, and as a consequence the rate of hydrogen evolved in a galvanic couple can be assumed to be almost equal to the rate of hydrogen evolution on either gold or platinum .

If equal areas of gold and zinc are coupled, the corrosion rate increase is less than that observed if equal areas of platinum and zinc are coupled. The reason why gold produces a less severe galvanic effect is not related to its reversible potential but rather to the fact that it has a lower hydrogen exchange current density than platinum [10,11].

A couple between a corroding and an inert material represents the simplest example of galvanic corrosion. A couple between two corroding metals may also be examined by application of mixed potential principles, as shown in Fig.2-3.

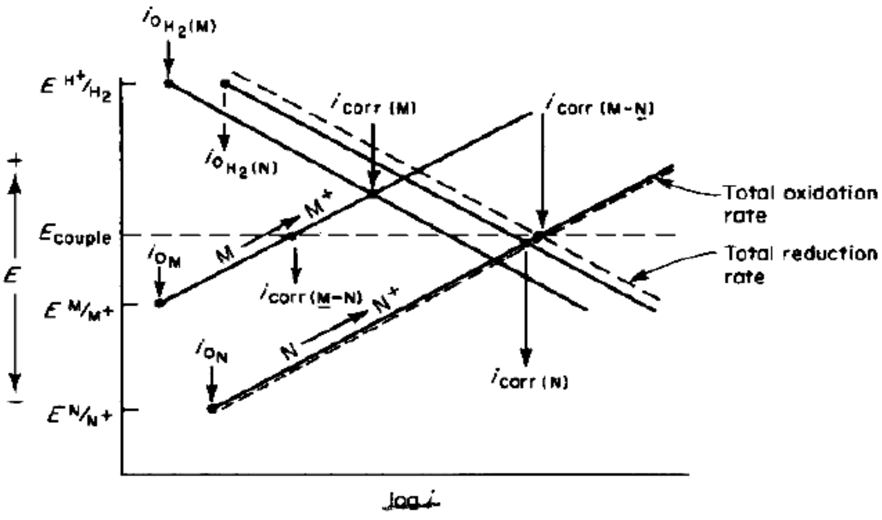


Figure (2.3)Galvanic couple between two corroding metals[2]

The figure shows the corrosion rate of two metals before and after coupling. Metal M has a relatively noble corrosion potential and a low corrosion rate icorr(M),while metal N corrodes at a high rate i_{corr} (N)at an active corrosion potential. If equal areas of these two metals are coupld, the resultant mixed potential of this system occurs at the point where the total oxidation rate equals total reduction rate. The rates of the individual partial processes are determined by the mixed potential. As shown in Fig.2-3, coupling equal areas of these two metals decreases the corrosion rate of metal M to $i_{corr(M-N)}$ and increases the corrosion rate of metal N to $i_{corr(M-N)}$[10]

The relative areas of the two electrodes in a galvanic couple also influence galvanic behavior. Figure 2.4 illustrates the effect of cathode area on the behavior of a galvanic couple of zinc and platinum. Current rather than current density is used in this figure. If a piece of zinc 1 cm^2 in area is exposed to the acid solution, it will corrode at a rate equal to i_A . Note that since 1 cm2 of zinc is considered, current and current density i_A are equal.

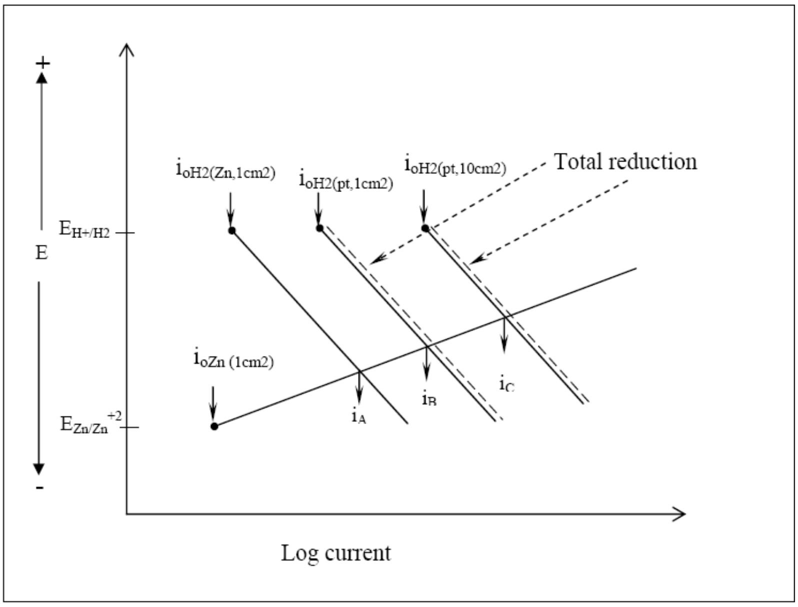


Figure (2.4) Effect of cathode – anode area ratio on galvanic corrosion of zinc-platinum couples[11]

If this zinc specimen is coupled to a platinum electrode of 1 cm area, the zinc corrosion rate is equal to i_B. Again, since electrodes with 1 cm² areas are used, current and current density are equal. However, if a platinum electrode with an area of 10 cm² and its behavior in terms of current is plotted, it has an exchange current i_o, which is 10 times greater than 1 cm² of an electrode. Thus, increasing the area of an electrode increases its exchange current density, which is directly proportional to specimen area. This is illustrated in Fig.2-4. As shown the corrosion rate of the couple is increased as the area of platinum is increased. As the size of the cathode in a galvanic couple is increased, the corrosion rate of the anode is increased. If the relative area of the anode electrode in a galvanic couple is increased, its overall corrosion rate is reduced [11].

So the situation often arises where: (a) components of several different metals are in electrical contact and/or (b) more than one cathodic reactant is present. In these circumstances, several anodic and/or cathodic processes may take place simultaneously: the corroding system is then called a polyelectrode

Because the current density i, and hence the current I, at any given electrode an a function of the potential it follows that, for a given potential, the total anodic current of polyelectrode system is the sum of the corresponding anodic currents of the individual electrodes. If the total area of the system is S, made up of fractions f_A and f_B for the various components A, B, . . ,then the anodic current from the jth component A is [4,6] :

$$I_a^{system} = \sum_j I_a^j = S \sum_j f^j i_a^j \quad \cdots \quad \textbf{(2.1)}$$

Similarly, the total cathodic current is:

$$I_c^{system} = \sum_j I_c^j = S \sum_j f^j i_c^j \quad \cdots \quad \textbf{(2.2)}$$

At the corrosion potential adopted by the polyelectrode, the total anodic and cathodic currents are equal, so that: [4,6]

$$\sum_j f^j i_a^j = \sum_j f^j \left| i_c^j \right| \quad \cdots \quad \textbf{(2.3)}$$

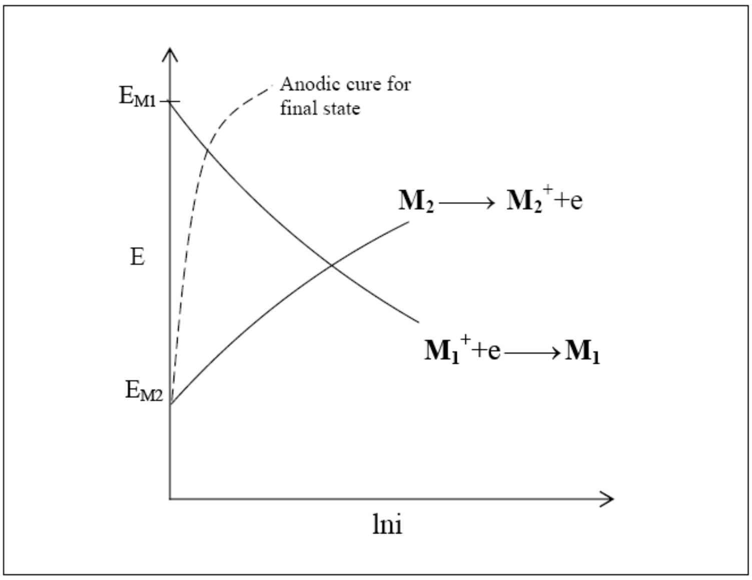
where the current densities on the various components are those corresponding to $E = E_{corr}$ It should be noted that the anodic and cathodic current densities on particular component might be very different that is, attack of a component is intensified if it is connected to large cathode. The combination of large cathode/small anode is all to frequently encountered in corrosion processes. This conclusion regarding the intensifying effect of large cathode/small anode upon corrosion rate is a general one that is elegantly formulated by Equation (3.5) [6]

$$\frac{i_a^B}{i_c^N} = \frac{f^N}{f^B}\left[\frac{\left|i_c^N\right|}{i_a^N} - 1\right] + \left[\frac{\left|i_c^N\right|}{i_a^N}\right] \qquad \text{... } \mathbf{(2.4)}$$

For instance [20] if a metal is placed in an aqueous solution containing cations of a more noble metal, i.e. one which is above it in the electrochemical series, then it will displace the more noble ions from solution and itself dissolves. Such a spontaneous reaction is called galvanic displacement and is presented in Fig (2.5) Displacement continues until the baser metal is with a "flash" porous coating of the more noble one, possibly1 μm or so in thickness, where upon further reaction substantially ceases. Iron dipped into a copper solution rapidly develops a flash coating of copper, whilst copper dipped into silver nitrate acquires a black deposit of finely divided silver within seconds. The structures of these coatings correspond closely to these obtained at high i/i_L values. They are therefore frequently non-adherent or only loosely so. In these instances the reaction is soon over but, when two different solid metals are in contact with one another, the consequences can be more disastrous. For a noble [9,45] metal N and a base metal B immersed in a corrodent, the corrosion of the resulting polyelectrode can be represented by Equation(3.5) given previously. If the cathodic process takes place readily on the noble metal, i.e. the term in brackets is positive, a small area of B connected to a large one of N($f^B << f^N$) results in an intense attack of B such might occur. For example, if a small area of steel or cast iron, in electrical contact with a much larger area of bronze, were immersed in seawater, the cathodic reactant dissolves oxygen. Or again, if aluminum rivets were used in a steel structure exposed to weather, the rivets would corrode preferentially whenever the structure got wet. Both are examples of galvanic attack (bimetallic corrosion). The intensification of attack of the baser metal depends on:

a. The relative area (f^N/f^B) and

b. The relative electrochemical activities of the metals concerned.



Figure(2.5) Galvanic Displacement [2]

2.3 Factors Affecting Galvanic Corrosion [12]

1. Electrode Potentials

The standard electrode potential of a metal in a solution of its ions gives a rough guide to the position of that metal in a galvanic series. In practice however usually concerned with alloys rather than pure metals, and in environments that do not contain the metal ions. To check the best method of obtaining a "galvanic series" of potentials is to actually measure these potentials in the environment under consideration.

2. Reaction Kinetics

Electrode potential data will indicate whether or not galvanic corrosion can occur. The reaction kinetic data indicate how quickly corrosion can take place. The metal dissolution kinetics give information on the rate of the anodic reaction in the corrosion cell; the oxygen reduction or hydrogen evolution over potential on the metals or alloys involved, or both, give information on the rate of cathodic reactions and whether they will occur on one or both materials.

3. Area Ratio

One of the most important parameters in galvanic corrosion is the "area ratio" a high cathode to anode ratio usually resulting in rapid corrosion or high anode to cathode ratio giving low or no corrosion. Distribution of the area is obviously important as is surface shape and condition. The number of galvanic cells in a given system is also important,

4. Mass Transport

Depending on the particular system being considered, one, two, or all of the three forms of mass transport, migration, diffusion, and convective can play an important role in galvanic corrosion.

5. Bulk Solution Environment

Included in this group of factors are the solution temperature, volume, height above the couple, and the flow rate across the surface. All these can affect whether or not galvanic corrosion will occur to any great extent and play an important role in galvanic corrosion.

6. Bulk Solution Properties

This group of factors is one of the most important; the oxygen level‘ and pH. The corrosivity of the solution determines whether corrosion can occur, and the conductivity determines the geometric extent to which it can occur.

7. Alloy Composition

The composition of an alloy affects galvanic corrosion by directly affecting the alloys corrosion resistance. In addition the constituents affect the corrosion potential and the kinetics of the cathodic processes involved; minor constituents can play an important role in this respect.

8. Protective Film Characteristics

The characteristics of the protective film, which exists on most metals and alloys, are important in determining whether or not galvanic corrosion will occur and what form it will take, for example, general or localized, in a particular environment. In particular the potential dependence, pH dependence, and resistance to various solution constituents are important.

2.4 Factors Influencing Corrosion

a) Oxidizing Agents [4]

In some corrosion processes, such as the dissolution of zinc in hydrochloric acid, hydrogen may evolve as a gas while in others, such as the relatively slow solution of copper in sodium chloride, the removal of hydrogen, which must occur so that corrosion may proceed, is effected by a reaction between hydrogen and some oxidizing chemicals such as oxygen to form water. Because of the high rates of corrosion that usually accompany hydrogen evolution , metals are rarely used in solution from which they evolve hydrogen at an appreciable rate as a result , most of the corrosion observed in practice occurs under conditions in which the oxidation of hydrogen to form water is a necessary part of the corrosion process . For this reason, oxidizing agents are often powerful accelerators of corrosion , and in many cases the oxidizing power of a solution is its most important single property in so far as corrosion is concerned .

$$4H^{+} + O_2 + 4e^- \longrightarrow 2H\,O_2 \qquad \ldots(2.5)$$

Oxidizing agents that accelerate the corrosion of some materials may also retard corrosion of others through the formation on their surface of oxides or layers of adsorbed oxygen, which make them more resistant to chemical attack this property of chromium is responsible for the principal corrosion resisting characteristics of the stainless steels [4] .

b) Temperature [13]

Temperature increases corrosion rates. This is due to a combination of factors first, the common effect of temperature on the reaction kinetics themselves and higher diffusion rate of many corrosive by-product at increased temperature. This latter action delivers these by-products to the surface more efficiently. Occasionally, the corrosion rates in a system will decrease with increasing temperature

c) Solution PH

An electrode reaction which involves the production or consumption of hydrogen ions will exhibit a reversible single potential which varies with hydrogen ion concentration , and so with pH .Thus, applying Nernst equation (2.) to hydrogen electrode yields[6]

$$E_{H/H} = E^{o}_{H/H^{+}} - \ln \frac{RT}{2F} \ln \frac{PH_2}{[H^{+}]^{2}} \qquad \ldots(2.6)$$

The accepted method of defining acidity is by means of a term called PH. It is a scale from 0 to 14 and is defined as follows [12]:

$$PH = -\log [H^{+}] \qquad \ldots (2.7)$$

so that :

$$E_{H/H^{+}} = -0.059pH + 0.029P_{H2} \qquad \ldots (2.8)$$

$$E_{H/H^{+}} = -0.059\ pH \qquad \ldots (2.9)$$

for P_{H2} =1 atmosphere at 25 C.

The relationship between pH and corrosion rates tends to follow one of three general patterns [4]:

1. Acid- soluble metals such as iron have a relationship as shown in Figure 2.1. In the middle pH range (~4 to 10) , the corrosion rate is controlled by the rate of transport of oxidizer (usually dissolved oxygen) to the metal surface . Iron is weakly amphoteric. At very high temperatures such as those encountered in boilers, the corrosion rate increases with increasing basicity as shown by the dashed line .

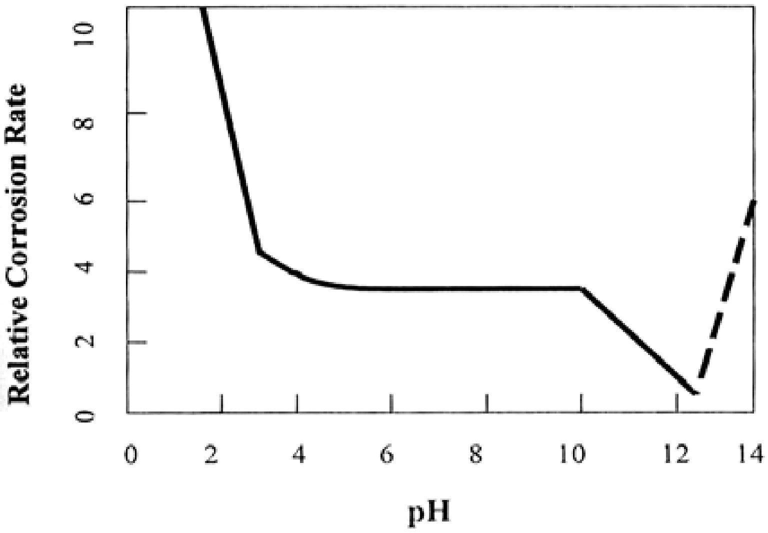


Figure2.6: Effect of pH on corrosion rate of iron[14].

2. Amphoteric metals such as aluminum and zinc have a relationship as shown in Figure .2.2. These metals dissolve rapidly in either acidic or basic solutions .

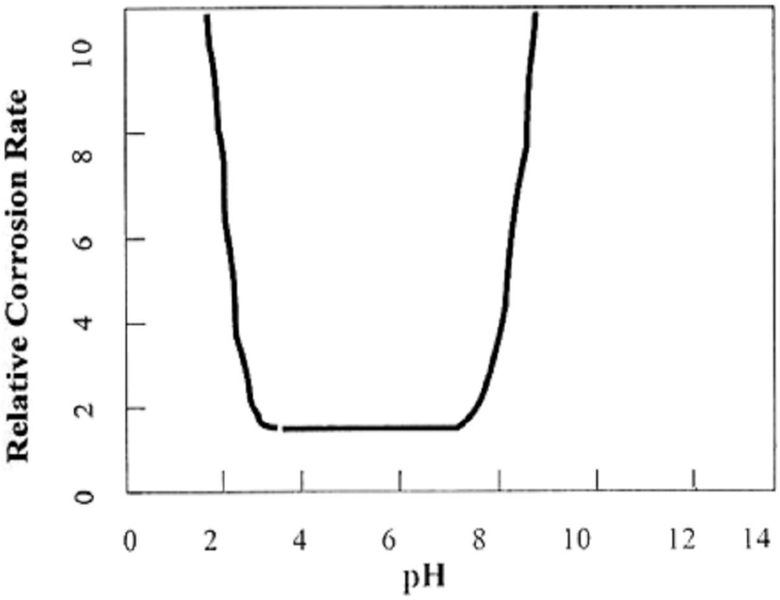


Figure 2.7 :Effect of pH on the corrosion rate of amphoteric metals (aluminum and zinc) [4]

3. Noble metals such as gold and platinum are not appreciably affected by pH as shown in Figure 2.3.

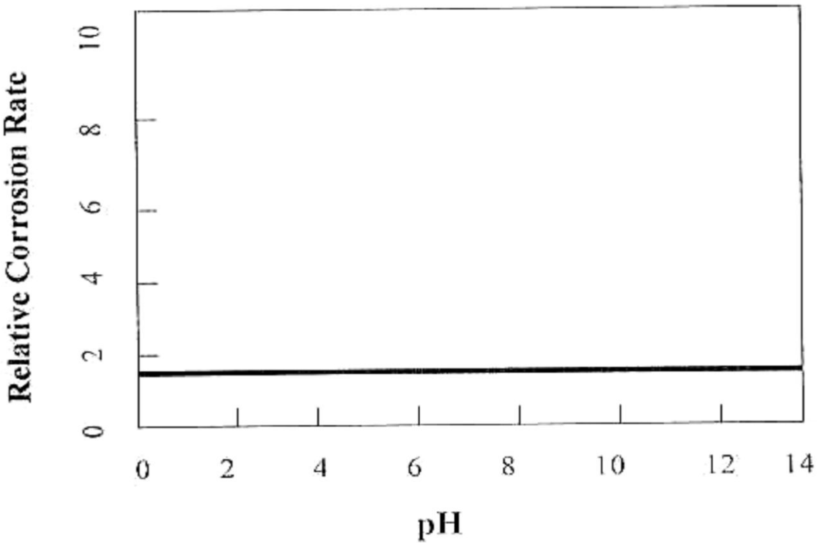


Figure 2.8: Effect of PH on the corrosion rate of noble metals [4].

d) Effect of Salt Content and Chloride Ion

Chlorides have probably received most consideration in relation to their effect on corrosion. The effect of sodium chloride concentration on the corrosion of iron in air saturated water at room temperature was found to increase the corrosion rate. The corrosion rate in air saturated water at room temperature was found to increase reaching maximum at about 3% NaCl (seawater concentration), and then decreases, the value falling below that of distilled water when saturation is reached (26 % NaCl). To understand this behavior, oxygen solubility in water decreases continuously with sodium chloride concentration, explaining the falling off of corrosion rate at higher sodium chloride concentration. The initial rise appears to be related to a change to 3.5%, and the corrosion potential becomes more negative with increase of sodium chloride solution in the protective nature of the barrier rust film that forms on the corroding metal. On the other hand chlorides increase the electrical conductivity of the water so that the flow of corrosion currents will be facilitated [14,15].

2.5 Polarization

When the metals are not in equilibrium with a solution of their ions , the electrode potential differs from the equilibrium potential by an amount known as the polarization . Other terms having equivalent meaning are overvoltage and overpotential . The symbol commonly used is η [14]. Potential resuls from the effect of current flow, measured with respect to zero flow (reversible) potential, i.e., the counter emf caused by the products formed or concentration changes in the electrolyte. When current flows to or from an electrode, it is no longer at equilibrium.

The measured potential of such an electrode is altered to an extent that depends on the magnitude of the external current and its direction. The direction of potential change always opposes the shift from equilibrium and hence opposes the flow of current or is of galvanic origin [16].

2.5.1 Activation Polarization

Polarization refers to an electrochemical process, which is controlled by the reaction sequence at the metal-electrolyte interface or stated in another way the reaction at the electrode requires activation energy in order to go. Activation polarization is usually the controlling factor during corrosion in media containing a high concentration of active species (e.g., concentrated acids). This is easily illustrated by considering hydrogen evolution reaction on zinc.

2.5.2 Resistance Polarization

Solutions of electrolytes generally have a rather poor conductivity compared to metals, particularly for dilute solutions. In corrosion system paints are often compounds forming this or other films of insulating materials, which can only conduct by way of traces of water dissolved in the coating. Corrosion processes usually consist of two or more essentially independent reactions .If the solution has a high electric resistance, this will give rise to a potential difference between the anodic and cathodic sites which is known as "Resistance Polarization " [14,17].

2.5.3 Combined Polarization

Both activation and concentration polarization usually occur at an electrode. At low reaction rates activation polarization usually controls, while at higher reaction rates concentration polarization becomes controlling. The total polarization of an electrode is the sum of the contribution of activation polarization and concentration polarization [18,14]:

$$\eta_t=\eta_A+\eta_C \qquad \text{... (2.10)}$$

During reduction process such as hydrogen evolution or oxygen reduction, concentration polarization is important as the reduction rate approaches the limiting diffusion current density. The overall reaction for activation process is given by [18]:

$$\eta_{red} = -\beta_c \log \frac{i}{i_o} + \frac{2.303RT}{nF} \log\left(1 - \frac{i}{i_l}\right) \quad \ldots (2.11)$$

2. 6 Inhibitors

2. 6.1 Definition

An inhibitor is a substance, which retards or slows down rate of chemical reaction. Thus, a corrosion inhibitor is a substance which, when added to an environment, decreases the rate of attack by the environment on a metal.

Corrosion inhibitors are usually added in small amounts to acids, cooling waters, steam, and other environments, either continuously or intermittently to prevent serious corrosion .The efficiency of an inhibitor is thus expressed by the following equation:

Inhibitor efficiency (%) = 100 ($CR_{uninhibited} - CR_{inhibited}$) / $CR_{uninhibited}$).

where $CR_{uninhibited}$ is the corrosion rate of the uninhibited system, and $CR_{inhibited}$ is the corrosion rate of the inhibited system[19,20].

2. 6.2 Classification of Corrosion Inhibitors [21]

Inhibitors have been classified differently as follows:

1. Passivating inhibitors.
2. Organic inhibitors.
3. Precipitation inhibitors.
4. Volatile corrosion inhibitors.
5. Cathodic inhibitors.
6. Anodic inhibitors.

7. Mixed inhibitors.

2. 6.3 Inhibitor Mechanisms

Inhibition usually results from one or more of three general mechanisms. In the first, the inhibitor molecule is adsorbed on the metal surface by the process of chemisorptions, forming a thin protective film either by itself or in conjunction with metallic ions. Some inhibitors merely cause a metal to form its own protective film of metal oxides, thereby increasing its resistance, this is the second mechanism. In the third, the inhibitor changes the characteristics of the environment either by producing protective properties or inactivating an aggressive constituent so that it does not corrode the material[22,23].

2.6.4Behavior of Inhibitors

Inhibitors may have different effects with respect to whether the anode, cathode, or both receive the direct impact of the inhibitor. Therefore, they can be classified according to their behavior to anodic, cathodic, and mixed inhibitors[24].

2. 6.4.1 Anodic Inhibitors

Anodic inhibitors which cause a large shift in the corrosion potential are called passivating inhibitors. They are also called dangerous inhibitors because, if used in insufficient concentrations, they cause pitting and sometimes increase in corrosion rate. With careful dosage control, however, passivsating inhibitors are frequently used because they are very effective in sufficient quantities. Oxidizing passivators such as sodium chromate and sodium nitrite do not require oxygen and are easily reduced themselves, i.e. they are good cathode depolarizers. They cause passivity by speeding up the corrosion reaction to the extent that the anodes are polarized to a passive potential adsorption of the inhibitor on anodic areas also plays a part in the process because it decreases the current (or corrosion rate) required for the anode to reach the critical passive potential [24].

Anodic inhibitors are safe to use only in cases where the corrosion rate is controlled wholly by the anodic reaction. The current density arising on the part of the electrode which for any reason has remained in the active state will then still be the same in the electrolyte [25].

2.6.4.2 Cathodic Inhibitors

Cathodic inhibitors reduce corrosion by retarding individual stages of the cathode reaction: ionization of oxygen, diffusion of oxygen to the cathode, and discharge of hydrogen ions, which naturally cannot lead to local corrosion.

In the presence of such cathodic inhibitors as calcium bicarbonate or calcium phosphate, a considerable part of the electrode remains inert with regard to the cathodic process, and this reduces the corrosion current sharply

Cathodic inhibitors are completely safe, since they never lead to local corrosion, and hence to an increased corrosion intensity. Cathodic inhibitors also present no danger when they are added to an electrolyte in small quantities. However, cathodic inhibitors are less effective in protecting metals against corrosion than anodic inhibitors. On the other hand, because of their favorable properties they are often used in practice [26, 27].

2.6.4.3 Mixed Inhibitors

Mixed inhibitors retard the corrosion processes of both electrodes, and have advantages over inhibitors which retard either the anodic or cathodic process.

Frequently, a simulation retardation of both electrode processes by inhibitors can completely exclude any harmful effects of purely anodic inhibitors, leading for partial passivation of the metal to an increase in the corrosion intensity. For this to be the case, the reduction of the corrosion current due to the retardation of the cathodic reaction must be equal to the difference between the current density i_2 after addition of the inhibitor and the current density i_1 before addition, multiplied by the area F_{a2} of the electrode which remains in the active state in the presence of the retarder, i.e. : $(i_2-i_1)\ F_{a2}$ [28]. Mixed inhibitors are less dangerous than pure anodic inhibitors, and in a number of cases they may not increase the corrosion intensity. For a predominant retardation of the cathodic process their properties approximate those of cathodic inhibitors, that is, they begin to be cathodic.

2.7 Literature Review on Galvanic Corrosion

Copson [29] studied the galvanic action between steel coupled to nickel in tap water, with 3 to 1 area ratio of Ni/ Fe and found that the galvanic corrosion of steel was appreciable. The addition of 300 ppm of sodium chromate to the water effectively made the steel more noble and inhibited corrosion.

Wranglen et al.[30] investigated the difference between the galvanic corrosion rates of high and low carbon steel in acid solutions and concluded that the engineers should not depend only on the galvanic series in the selection of their materials of construction, Tsujino et al.[31] studied the galvanic corrosion of steel coupled to noble metals (Pt, Cu, 304 stainless steel), in sodium chloride solution and found that the local currents on the steel depend on the area ratio of the steel to the cathodic metal and these currents are not related to the concentration of sodium chloride in neutral solutions.

Fangteng et al.[32] presented a theoretical approach for galvanic corrosion allowing for cathode dissolution, and found that the cathode of the couple is also corroded at the galvanic corrosion potential where the corrosion is controlled by the rate of oxygen diffusion to the electrode surfaces and the cathode dissolution in a galvanic system leads to a decrease in the galvanic current and it has been shown that the current density through the anode is independent of the area ratio of the electrodes, providing that the ratio of cathode to anode area is large and the free corrosion potential of the alloys is similar

Pryor [51] investigated the galvanic corrosion of Al/steel couple in chloride containing solution and found that aluminum completely protects steel cathodically within the pH range 0-14, and the galvanic current and the corrosion rate of aluminum are at a minimum in the nearly neutral pH range.

Morris and Smyrl [33] have calculated the Galvanic currents and potentials on heterogeneous electrode surfaces comprising random configurations of coplanar anodes and cathodes, for the purpose of investigating system behavior on different electrode geometries. The electrochemical transport equations were solved in the absence of mass transfer effects with a three-dimensional application of the finite element method. The galvanic currents and potentials so calculated were investigated for similarities linking behavior on different electrode geometries. It has been found that for a wide range of system parameters galvanic currents scale with the active perimeter separating anodic and cathodic regions on the electrode surface. Moreover, this effect enables the accurate prediction of galvanic current for an arbitrarily complex electrode surface geometry.

Perboni and Rocchini [34] studied the influence of some primary aliphatic amines on the anodic dissolution of iron in a 1N HCl solution which has been investigated , mostly at the temperature of 25 ^{0}C. Some measurements have also been made to determine the activation heat in a 1N HCl solution between 25 and 65 ^{0}C .The result obtained at 25 ^{0}C has confirmed data to the effect that the inhibiting efficiency of a polar compound increases with the number of carbon atoms . For the inhibitors examined , adsorption is governed by the Freundlich isotherm for 1- aminobutane , some tests were repeated in an uninhibited solution to determine whether the behavior of the samples showed any variations as a result of prolonged use . Colorimetric and electrochemical results both showed that in a 1 M HCl the corrosion rate of the samples was the same , within the limits of experimental error and remained fairly constant .

Sorkhabi1, et al. [35] studied the inhibition of steel corrosion in hydrochloric acid solution by juice of prunus cerasus, two electrochemical measurements were used to evaluate the inhibition efficiencies, linear polarization and electrochemical impedance spectroscopy. This inhibitor contains different organic compounds such as proteins, organic acids (such as ascorbic acid), vitamins, lipids, carbohydrates, pigments, and some inorganic ions .Some of these organic compounds have been used as organic corrosion inhibitors for metals. The aim of that study was to investigate the inhibition effect of prunus cerasus juice as a cheap, raw and non-toxic corrosion inhibitor on steel corrosion in hydrochloric acid. Results obtained from both electrochemical methods showed that the prunus cerasus juice acts as an inhibitor for corrosion of steel in hydrochloric acid media. Corrosion inhibition action of prunus cerasus juice increased as its concentration increases. Inhibition of steel in HCl solution by prunus cerasus juice is attributed to adsorption of the phytochemical compounds in this juice. The authors reasoned the reduction of corrosion inhibition efficiencies by increasing the temperature, may be due to thermal degradation of its organic content especially degradation of anthocyanine pigments.

Arora, et al. [36] studied the corrosion inhibition of aluminium by capparis decidua in acidic media (HCl and H_2SO_4 solutions) by using weight loss tests and electrochemical technique. Organic compounds containing nitrogen have been found to function as very effective corrosion inhibitors. The efficiency of these compounds as corrosion inhibitors can be attributed to the number of mobile electron pair present, the orbital character of free electrons and electron density around the nitrogen atoms. In this study, the inhibitive effects have been evaluated of ethanolic extract of fruit, stem bark and root bark of capparis decidua. This inhibitor has better inhibition efficiencies in HCl solution than in H_2SO_4 solution.

The inhibition efficiency (IE %) calculated from the mass loss measurement for hydrochloric acid and sulphuric acid in the presence of the inhibitor are given in tables. It is observed that the inhibition efficiency increases with increase in the concentration of inhibitor and decreases with increases in acid strength. The corrosion rate decreases with increases in concentration of inhibitor. The maximum effeciency was obtained in low acid concentration.

From this study, the following conclusions can be drawn:

1. The rate of corrosion of mild steel and aluminum in hydrochloric acid and sulphuric acid is a function of the concentration of capparis decidua.
2. The inhibition increases with increased additive concentration.
3. Capparis decidua ethanolic extract is a corrosion inhibitor and can replace toxic chemicals.

Atul Kumar [37] studied the effect of sodium lauryl sulfate (SLS), a surfactant on corrosion of mild steel in 1 M hydrochloric acid by using three techniques: weight loss, electrochemical polarization and metallurgical research microscopy. Results obtained reveal that SLS is agood inhibitor and shows very good corrosion inhibition efficiency (IE). And he found that the (IE) of SLS increases with increase in concentration of this inhibitor, and from weight loss measurements he found the influence of temperature on IE of SLS at various concentrations .The IE increases with temperature up to 35ºC and after that it decreases at higher temperature due to desorption of inhibitor. Corrosion inhibition of mild steel in 1M HCl solutions by SLS is under anodic control, this is revealed by electrochemical polarization result.

Mansfeld [38] studied the relationship between galvanic current and dissolution rates in aerated 3.5%NaCl, he found that the galvanic current cannot be accurate measure of dissolution rates, since dissolution rates from the galvanic current are smaller than the true dissolution rates.

Chapter Three

Experimental Work

3.1 Introduction

The present chapter illustrates the experimental work as well as the laboratory design of galvanic corrosion inhibitor system.

Experimental work was carried out to determine the free corrosion rate of single carbon steel , stainless steel , tin, and cadmium specimens under static conditions in the presence and absence of dimethylaminoethanol as corrosion inhibitor of concentrations 177.2, 354, 531.6 and 708.8 ppm . The area ratio of (Ac\Aa) coupled metal specimens was 1, 0.75, 0.5, and 0.25. Corrosion potential, weight loss, galvanic current, and galvanic potential difference were determined in solutions of 0.1N NaCl .

The experimental work was divided into three main parts:

1. Measuring the corrosion potential of different single metals (carbon steel, stainless steel , tin, and cadmium) in solutions of PH values 0, 1, 2, and 3. The area of each specimen was equal to $A=16.24*10^{-4} m^2$under the conditions $T=40\ {}^0C$, and t=2h.
2. Weight loss measurements of single metals (free corrosion) to determine the average corrosion rate and corrosion potential under static and in the presence of dimethyl amino ethanol inhibitor .
3. Measuring the potential difference and current simultaneously in galvanic corrosion under the conditions, $T=40^0C$ and t=2 h between coupled specimens, i.e., carbon steel –stainless steel, carbon steel – cadmium , and stainless steel – cadmium in acidified NaCl solutions of pH values= 0,1and different concentrations of inhibitor .

3.2 Solvents Used

These were used to clean the metal specimens.

1. Acetone**:** C_3H_6O of concentration ≅ 99% supplied by FLUKA.
2. Ethanol**:** C_2H_6OH of concentration ≅ 99% supplied by FLUKA.

3.3 The Electrolyte

1. Distilled water for preparing the solution
2. The corrosive solution used in this work was 0.1 NaCl solution. It was acidified using annular hydrochloric acid HCl of concentration 36%, which has a molecular weight of 36.64 g/gmol and density of 1.17 gm/cm^3.The concentrated acid was diluted by distilled water to obtain the required PH , and normality of 0.1 N NaCl. Preparation of 0.1 molar NaCl was made by weighing 5.85 NaCl for each liter of distilled water.
3. The inhibitor used was dimethylaminoethanol

3.4 Instruments

1. **PH-meter:** A digital pH-meter, type EXTECH, was used to measure and monitor the PH of the working solution during the test run. The pH-meter was calibrated using buffer solutions of pH 4, 7, and 9.
2. **Multi –**meter : A digital Multi –meter (1Ω) resistor was used to measure the current passing through the galvanic corrosion cell.
3. **Zero Impedance Ammeter**
4. **Water bath:** Water bath with a temperature of 40^{0}C, type Greenfield, NR, Oldham, Voltage=200/20, and power = 1000 Watt.

5. **Electronic Balance:** High accuracy digital balance with 4 decimal points of type (METTLER AE260) was used for weight loss determinations. The balance had 0.1 mg accuracy.
6. **Desiccators**
7. **Holders**
8. **Beakers (0.5 and 1 liters).**
9. **Greene cell type.**

3.5 Accessories

1. Different beakers
2. Hooks
3. Stand
5. Pipette
6. Cylinders 10 milliliter, & 5 milliliter.
7. connections Wire.
8. Epoxy warmish.
9. Thermometer.

3.6 Materials of Electrodes

The materials specifications of electrode specimens used are given below in Tables 3.1, & 3.2, analyzed by the Specialized Institute of Engineering Industries. They were used as working electrodes for weight loss measurements with a length of 4 cm. , width 2 cm and thickness 0.02cm. The chemical composition of carbon steel and stainless steel are given in Tables 3.1& 3.2 below.

Table 3.1: Chemical Composition of Carbon Steel 37

C, %	Si, %	Mn, %	P,%	V, %	Fe, %
0.0666	**0.0119**	**0.249**	**0.0056**	**0.0019**	**99.66**

Table 3.2: Chemical Composition of Stainless Steel 304

Ni, %	Cr, %	Cu, %	Mn, %	Si, %	Fe, %
8.865	**12.1**	**0.0498**	**1.846**	**0.832**	**Remaining**

and pure Cd and Sn.

3.7 Corrosion Inhibitor [40]:

Nitrogen-containing compound was used in the present work as corrosion inhibitor. The specifications and some physical properties are shown below in Table (3.3).

Table (3.3): Some Physical Properties of Inhibitor Used in Present Work: -

Inhibitor	Formula	MW	m.p (^oC)	b.p (^oC)	Density ($^{g/L}$)
Dimethylaminoethanol	$C_4H_{11}NO$	89.14	98.5	134-136	0.886

ADE are used as corrosion inhibitors; ADE is a common inhibitor for Cd, C.S, St.St, and Sn in different environments. Many inhibitors are also used as is an effective corrosion inhibitor in acidified aqueous chloride solutions. It is a toxic organic compound, sparingly soluble in water, soluble in alcohol, color is yellow, has odor like the odor of fish and its structure is $(CH_3)_2\,N\,CH_2\,CH_2\,OH$.

3.8 Preparation of Solutions

The solution PH is always determined by using digital PH meter type EXTECH. It is adjusted using pure hydrochloric acid (HCl) of Mw =36.65 and density =1.17 g/cm^3, in presence of annular NaCl salt and distilled water as shown in Table4.4.

Table 3.4: Preparation of solution PH 0,1,2,3 in 0.1 N NaCl

PH	HCl(ml)	NaCl, (g/l)	H_2O (L)	NaCl M
0	109	5.8	1	0.1
1	11	5.8	1	0.1
2	1	5.8	1	0.1
3	0.1	5.8	1	0.1

A volume of HCl was added drop by drop l with measuring the change in PH by digital PH meter until the required PH was reached as shown in Table 3.4.

3.9 Cleaning of Specimen

In this work, a specimen of C.S –St.St– Sn – Cd with dimensions of 4 cm length , 2 cm width, and 0.02 cm thickness, exposing a surface area to corrosive media. were abraded in sequence using emery papers and finally of grade number zero.Specimens were cleaned by washing with tap water followed by distilled water, dried with clean tissue, immersed in ethanol for 5 minutes and rinsed with clean acetone and dried with clean tissue The specimens were then stored in a desiccators over highly active silica gel for half hour before use, and then they were weighed accurately and directly exposed to the corrosion environment of PH values of 0,1,2, and 3 , then placed in water bath at 40 C^{o} as shown in Fig 3.1 . Before each run, specimens of (C.S. –St.St – Sn – Cd) . After the exposure to the corrosion environment, the specimen was washed by tap water then brushed by smooth brush under running tap water to remove non-adherent corrosion products. After that the specimen was washed by tap water, distilled water, dried with clean tissue, and kept in desiccators for half hour, and then accurately weighed . Each run was repeated twice in solutions of PH 0,1,2,&3 . The above procedure was repeated for each run in absence and presence of inhibitor.

3.10 Measuring the Electrode Potential:

The electrode potential for metals used (carbon steel , stainless steel , cadmium , tin) was measured. Each specimen was cleaned as mentioned above, then placed in Greene cell to measure the electrode potential in solutions of different PH values of (0, 1, 2, 3). Standard reference electrode, i.e., Saturated Calomel Electrode, E =0.2416 V SHE, salt bridge of Lugging Capillary Tip was placed near the specimen at about 2 mm to avoid (IR) drop to record the change of electrode potential, i.e., corrosion potential, that occurred versus time which at about 1hr started be to stable. The temperature used in the experimental work is 40 ^{0}C [13]

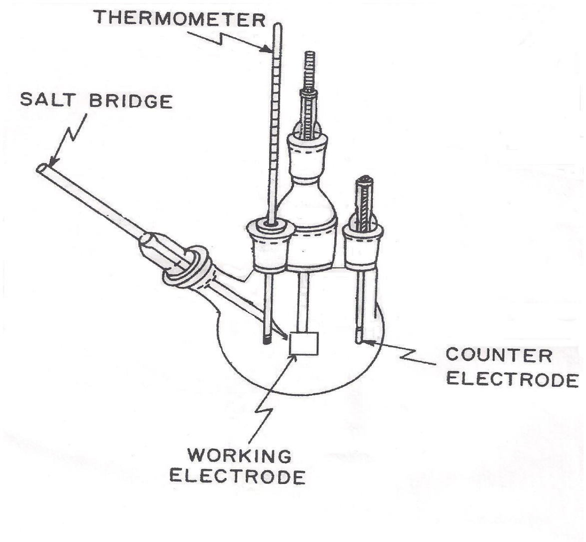


Fig.(3.1) Green cell system

3.11 Weight Loss Measurement:

Weight loss technique is the widely used method for measuring the corrosion rate. The corrosion of (C.S, St.St.,Sn,Cd in acidified 0.1N NaCl solutions was studied in absence and presence of inhibitor under static conditions. A typical procedure is as follows: a specimen of known surface area and mass is exposed to the test corrosive solution for a fixed period of time. The loss of a metal as a result of corrosion is then determined from the loss of mass in specimen after removal of corrosion products or other deposits from the metal. Mass loss values are usually recorded together with the exposed surface area of the specimen and the period of the test.

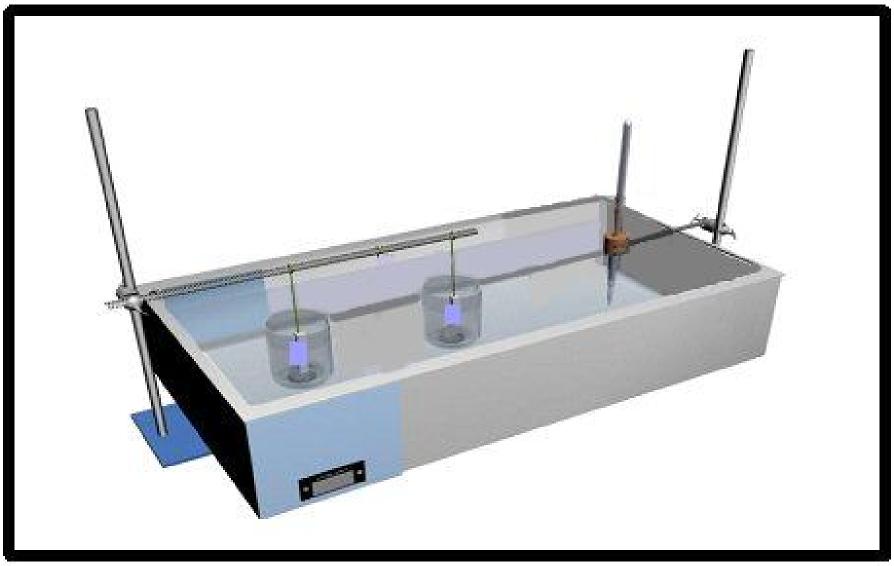


Fig.(3.2) Weight loss system

3.12 Measuring the Current , Potential and Corrosion Rate of Coupled Metals in Galvanic Corrosion

The dimensions of metal specimens were equal to 4 cm length, 2 cm width , &0.02 thickness . They were cut from carbon steel, stainless steel, cadmium, and tin in order to use them in the weight loss experiments. Then the heater controller in the bath was set to the required temperature of 40 ^{0}C to achieve thermal equilibrium before starting the experimental run. The experiment was carried out with 0.1 N NaCl in absence of inhibitor and with (0.1772 ,0.3544 ,0.5316, 0.7088) g/l added as an inhibitor at the following area ratios AR= (1 , 0.75 , 0.5 , & 0.25) .

At a certain value of (AR) the specimen was immersed in the solution, and then the current was read every 5 minute for 2 h by using multimeter as a multirange ammeter with low resistance which depends on the principle of zero ammeter impedance. The weight loss was measured after this period (2h) by using digital balance of 0.1 mg accuracy type (METTLER AE260) to calculate the corrosion rate

The experiments were repeated for different values of (AR) and concentration of ADE inhibitor using two different pH solutions 0 and 1 . All previous experiments were duplicated using different metal couples, i.e., C.S./St.St, Cd/St.St, C.S /Cd. Use of the same apparatus as for above experiments but with the multi -meter as a voltmeter to measure the potential difference which was monitored every 5 minutes for 2 h using multi -range voltmeter .

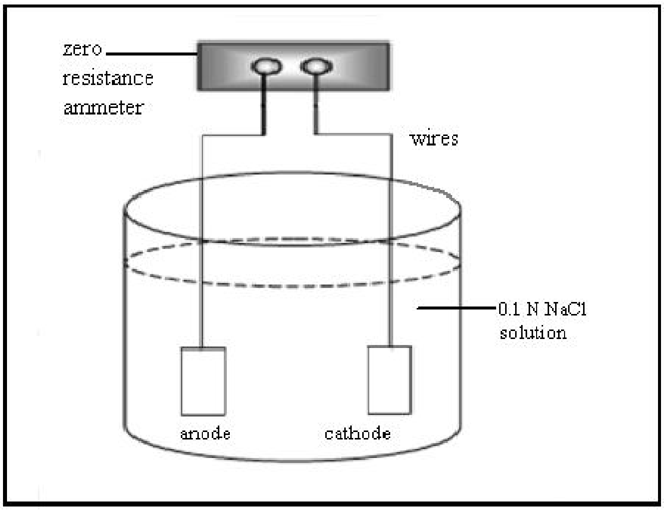


Fig.(3.3) Galvanic corrosion system

Chapter Four

Results

4.1 Introduction

As mentioned in chapter one , the aim of the present work is to investigate the mechanism of galvanic corrosion using coupled metals and also the mechanism of its inhibition under the influence of various factors and compare these results with their counterparts obtained from the weight loss in the single state .All above experiments were carried out in aerated 0.1N NaCl with a variable solution PH values of 0,1 ,2, and 3, concentration of inhibitor 0.1772,0.3544,0.5316,0.7088 g/l, i.e., 177.2, 354.4, 531.6, and 708.8 ppm , and different area ratios of metal specimens 1, 0.75, 0.5, and 0.25 . Three operating conditions were taken into account during these experiments: inhibitor concentration, different solution PH values, and different area ratios of the cathode to anode.

4.2CorrosionPotentialMeasurements

The values of steady state corrosion potential were measured from the experimental runs, with variation of electrode potential with time at zero current conditions. To measure the corrosion potential ($E_{corr.}$) Greene cell was used with Saturated Calomel Electrode (SCE) using salt bridge of the same solution ending with capillary tip placed at a distance 2mm from the metal sample which was 2cm below the solution/air interface and 2cm from the bottom of the flask. Multi-meter was used to measure the corrosion potential which became stable after approximately 30 min.

Air bubbles in salt bridge should be removed in order to obtain stable and correct reading. The experimental run was continued for two hours showing steady state potentials for each metal having different values in each solution depending on PH value.

The metal surface was cleaned before measuring the potential because any oxide layer may affect the measurement which is dependent on type of solution and metal. There is no passivation to metal surface because the solution is rich in Cl^- ions and the salts of all metals[10] are completely soluble in such acidic solutions. The following tables show the values of corrosion potential vs. time for each metal in solutions of different PH values.

Table (4.1): Corrosion potential of carbon steel vs. SCE under the following conditions: PH= (0,1,2,3) , T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2 h.

Time(min)	Corrosion Potential (v)			
	PH (0)	PH(1)	PH(2)	PH(3)
0	-0.465	-0.534	-0.573	-0.715
20	-0.450	-0.530	-0.593	-0.729
40	-0.464	-0.527	-0.593	-0.727
60	-0.464	-0.527	-0.593	-0.727
80	-0.464	-0.527	-0.593	-0.727
100	-0.464	-0.527	-0.593	-0.727
120	-0.464	-0.527	-0.593	-0.727

Table (4.2): Corrosion potential of stainless steel vs.SCE under the following conditions: PH= (0,1,2,3) , T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2 h.

Time(min)	Corrosion Potential (v)			
	PH (0)	PH(1)	PH(2)	PH(3)
0	-0.479	-0.545	-0.605	-0.707
20	-0.483	-0.538	-0.591	-0.723
40	-0.484	-0.535	-0.585	-0.723
60	-0.484	-0.535	-0.585	-0.723
80	-0.484	-0.535	-0.585	-0.723
100	-0.484	-0.535	-0.585	-0.723
120	-0.484	-0.535	-0.585	-0.723

***Table (4.3)*:** Corrosion potential of cadmium vs. SCE under the following conditions: PH= (0,1,2,3) , T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2 h.

Time(min)	Corrosion Potential (v)			
	PH (0)	PH(1)	PH(2)	PH(3)
0	-0.830	-0.735	-0.772	-0.777
20	-0.831	-0.770	-0.781	-0.781
40	-0.832	-0.772	-0.781	-0.781
60	-0.832	-0.772	-0.781	-0.781
80	-0.832	-0.772	-0.781	-0.781
100	-0.832	-0.772	-0.781	-0.781
120	-0.832	-0.772	-0.781	-0.781

Table (4.4): Corrosion potential of tin vs. SCE under the following conditions:

PH= (0,1,2,3) , T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2 h.

Time(min)	Corrosion Potential (v)			
	PH (0)	PH(1)	PH(2)	PH(3)
0	-0.566	-0.509	-0.514	-0.505
20	-0.565	-0.512	-0.519	-0.508
40	-0.567	-0.518	-0.520	-0.508
60	-0.567	-0.518	-0.520	-0.508
80	-0.567	-0.518	-0.520	-0.508
100	-0.567	-0.518	-0.520	-0.508
120	-0.567	-0.518	-0.520	-0.508

4.3 Weight Loss of Individual Metals

As shown in chapter four , specimens of 4cm in length , 2cm in width and 0.02 cm in thickness ,were cut from carbon steel , stainless steel , cadmium , and tin .Tables 5.5 to 5.8 show the weight loss results , corrosion rate in gmd ,mm/y , & mpy and inhibitor efficiency for the corrosion of above metals .

When adding different concentrations of inhibitor for the different metals at different PH values, the metals have different rates of corrosion for each concentration. The corrosion rate of tin is very much lower than the corrosion rates of Cd, C.S, & St.St. The PH is very effective factor in the weight loss and corrosion rate experiments. When added inhibitor started to diffuse to metal surface, corrosion rate of anode after some minutes decreased and the corrosion potential moved in the more negative direction. For example at concentration of 177.2, 354.4, 531.6, & 708.8 ppm, Δw of each metal decreased compared with Δw before inhibitor addition. The efficiency of inhibition of Cd reached about 98% at 708.8 ppm in solution of PH=3 at $T=40\ {}^0C$ in 0.1N NaCl solution after, $A=16.24*10^{-4}m^2$, t=2 h.

Table (4.5): Effect of inhibitor (Dimethal amino ethanol) concentration on corrosion rate (by weight loss) of carbon steel in 0.1N NaCl solution at T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2 h.

& ρ=7.87 g/cm³

PH	C(ppm)	ΔW (g)	CR (gmd)	CR(mm/y)	CR(mpy)	*η*%
0	0	0.0073	54	2.5044	98.600	-
	177.2	0.0041	30.3	1.40527	55.3257	47
	354.4	0.0051	37.8	1.75311	69.0200	31.65
	531.6	0.00315	23.4	1.0852	42.726	56
	708.8	0.0024	17.7	0.8209	32.318	67
1	0	0.0775	57.4	26.6213	1048.08	-
	177.2	0.00375	27.8	1.28932	50.7608	47
	354.4	0.0035	25.9	1.2012	47.29	51.8
	531.6	0.00615	45.6	2.1148	83.262	92
	708.8	0.0013	9.6	0.4452	17.5289	81.9
2	0	0.0078	57.8	2.6806	105.53	-
	177.2	0.0026	19.25	0.8927	35.149	53
	354.4	0.0041	30.3	1.40527	55.3257	37
	531.6	0.004	29.6	1.37280	54.0475	89
	708.8	0.0016	11.8	0.54726	21.545	71.8
3	0	0.0053	39.2	1.8180	71.576	-
	177.2	0.00495	36.7	1.70209	67.0116	6.7
	354.4	0.00205	15.18	0.70402	27.7176	52
	531.6	0.00165	12.2	0.56581	22.2763	68
	708.8	0.00076	5.6	0.25972	10.225	85.6

Table (4.6): Effect of inhibitor (Dimethal amino ethanol) concentration on corrosion rate (by weight loss) of stainless steel in 0.1N NaCl solution at T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2h.

& ρ=7.87 g/cm³

PH	C(ppm)	ΔW(g)	CR(gmd)	CR(mm/y)	CR(mpy)	η%
0	0	0.0045	33.3	1.5444	60.8035	-
	177.2	0.00257	19.03	0.88258	34.7474	44.5
	354.4	0.001235	9.14	0.4239	16.689	73
	531.6	0.0222	164.5	7.6267	300.26	100
	708.8	0.00115	8.5	0.39421	39.370	74
1	0	0.0034	25.18	1.16781	45.9769	-
	177.2	0.05395	39.96	18.517	729.0199	0
	354.4	0.0032	23.7	1.0991	43.274	40.8
	531.6	0.0045	33.4	1.54904	60.986	15
	708.8	0.00195	14.4	0.6678	26.293	63
2	0	0.0052	38.5	1.78557	70.298	0
	177.2	0.00663	49.2	2.28182	89.835	73
	354.4	0.0024	17.8	0.82554	32.5015	56.3
	531.6	0.00415	30.7	1.42382	56.0560	20
	708.8	0.00115	8.5	0.3942	15.5204	77.8
3	0	0.0033	24.5	1.13627	44.535	-
	177.2	0.00354	26.3	1.21975	48.0219	28.2
	354.4	0.003	22.3	1.03424	40.7182	31.7
	531.6	0.0015	11.2	0.51944	20.450	69
	708.8	0.000725	5.3	0.2458	9.6774	85

Table (4.7): Effect of inhibitor (Dimethal amino ethanol) concentration on corrosion rate (by weight loss) of Cadmium in 0.1N NaCl solution at T=40 ^{0}C, A=16.24*10^{4}m^2 , t=2h & ρ=8.65 g/cm³.

PH	C(ppm)	ΔW(g)	CR(gmd)	CR(mm/y)	CR(mpy)	*η*%
0	0	0.0057	42.3	1.7849	70.2721	-
	177.2	0.0051	37.8	1.59502	62.7964	10.5
	354.4	0.00175	12.9	0.5443	21.430	69
	531.6	0.0032	23.7	1.00005	39.3723	43
	708.8	0.0018	13.7	0.57809	22.7595	67
1	0	0.01	74	3.1225	122.934	-
	177.2	0.0022	16.2	0.68358	26.9127	67.7
	354.4	0.00265	19.6	0.82770	32.5611	61.7
	531.6	0.0075	55.6	2.34612	92.3672	25
	708.8	0.00175	12.9	0.54433	21.4305	82.5
2	0	0.0078	57.8	2.4389	96.0220	-
	177.2	0.0022	16.2	0.68358	26.912	71
	354.4	0.003	22.3	0.94098	37.0465	61
	531.6	0.001	7.4	0.31225	12.2934	87
	708.8	0.0004	2.96	0.12490	4.91739	94
3	0	0.0056	41.48	1.7503	68.909	-
	177.2	0.0075	55.6	2.34612	92.3672	60.8
	354.4	0.00405	30	1.26589	49.838	57.2
	531.6	0.0035	25.9	1.09289	43.0271	80
	708.8	0.0025	1.8	0.07595	2.99030	98

Table (4.8): Effect of inhibitor (Dimethal amino ethanol) concentration on corrosion rate (by weight loss) of Tin in 0.1N NaCl solution at T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2h & ρ=7.30 g/cm³.

PH	C(ppm)	ΔW(g)	CR(gmd)	CR(mm/y)	CR(mpy)	*η*%
0	0	0.0055	40.7	2.035	80.1181	-
	177.2	0.00295	21.8	1.09	42.9133	52.7
	354.4	0.0016	11.8	0.59	23.228	38.18
	531.6	0.0035	25.9	1.295	2.09842	36.3
	708.8	0.0016	11.8	0.59	23.228	70.9
1	0	0.007	51.85	2.5925	102.066	-
	177.2	0.0675	50	25	984.25	10.6
	354.4	0.00225	16.6	0.83	32.677	70
	531.6	0.0041	30.3	1.515	59.645	45.3
	708.8	0.0016	11.8	0.59	23.228	78.7
2	0	0.00715	52.9	2.645	104.1338	-
	177.2	0.0022	19.29	0.9645	37.9724	30
	354.4	0.002	14.8	0.74	29.1338	71.8
	531.6	0.004	29.6	1.48	58.2677	43
	708.8	0.0007	5.1	0.255	10.039	90
3	0	0.0119	88.14	4.407	173.503	-
	177.2	0.00315	23.3	1.165	45.8661	37
	354.4	0.00225	16.7	0.835	32.8740	55
	531.6	0.0035	25.9	1.295	2.09842	74
	708.8	0.00012	0.89	0.0445	1.75196	89

4.4 Galvanic Coupling

The galvanic coupling experiments were conducted according to the following conditions: solutions PH of 0,&1 , three metals (St.St, C.S, & Cd) of (AR=1 ,0.75 , 0.5 ,& 0.25),and dimethalaminoethanol as inhibitor at concentrations of 0, 177.2 , 354.4 ,521.6 , &708.8 ppm at 40 ^{0}C, to measure the potential difference and galvanic current between two metals against time for 120minutes , experiments were carried in 0.1 N NaCl.

When metals are coupled, the corrosion rates are different on each member of the couple and dependent on the following factors:

1. Area ratio.
2. Type of metal.
3. PH of solution.

In the galvanic series of experiments, the current due to coupling and the galvanic potential difference were measured versus time for a period of two hours. Steady state condition was realized after approximately 30 minutes. When area ratio increased the coupling current with time depends on this area and type of metal coupling. For example when the couple C.S/Cd was used the galvanic current was different for each area ratio with maximum value of current when area ratio was 4/3.The inhibitor decreased the current due to coupling to become 100 times less than that without inhibitor.

Table (4.9): Effect of area ratio AR , and solution PH on galvanic current density (µA/cm^2) and potential difference for the metal couple(4 cmC.S/4 cmSt.St) in air-saturated 0.1N NaCl solution T=40 ^{0}C, A=16.24*10^{-4}m^2 , t=2h and ρc.s=7.87 g/cm^3, ρst.st=7.87 g/cm^3.

C.S Δw=0.004g	C.S-St.St pH=0 without inhibitor Zero resistance Ammeter AR 4/4	St.St Δw=0.0010g
gmd=29.629		gmd=7.4074
mm/y=1.37418		mm/y=0.3435
mpy=54.1016		mpy=13.5246
I=118.346 µA/cm^2		I=29.587 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.73	-0.354
20	0.45	-0.374
40	0.38	-0.390
60	0.38	-0.390
80	0.38	-0.390
100	0.38	-0.390
120	0.38	-0.390

Table (4.10): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (3 cmC.S /4 cmSt.St) in air-saturated 0.1N solution, t=2h, T=40 ^{0}C, A(c.s) =16.24*10^{-4}cm^2 , A(st.st) =12.2*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=7.87 g/cm^3

C.S Δw=0.0019g	C.S-St.St pH=0 without inhibitor Zero resistance Ammeter AR 4/3	St.St Δw=0.0015g
gmd=14.0740		gmd=14.6370
mm/y=0.6527		mm/y= 0.678844
mpy=25.6981		mpy=26.726
I=56.215 µA/cm^2		I=58.464 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	2.08	-0.368
20	1.85	-0.392
40	1.40	-0.396
60	1.40	-0.396
80	1.40	-0.396
100	1.40	-0.396
120	1.40	-0.396

Table (4.11):): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/2 cm St.St) in air-saturated 0.1N NaCl solution, t=2h, T=40^oC, A(c.s) =16.24*10^{-4}cm^2 , A(st.st) =8.16*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=7.87 g/cm^3

C.S Δw=0.0015g	C.S-St.St pH=0 without inhibitor Zero resistance Ammeter AR 4/2	St.St Δw=0.0016g
gmd=11.112		gmd=23.357
mm/y=0.51535		mm/y= 1.08329
mpy=20.289		mpy=42.649
I=44.384 $\mu A/cm^2$		I=93.294 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	0.73	-0.114
20	0.33	-0.145
40	0.29	-0.160
60	0.29	-0.160
80	0.29	-0.160
100	0.29	-0.160
120	0.29	-0.160

Table (4.12): Effect of area ratio AR , PH solution on galvanic curre0nt density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/1cm St.St) in air-saturated 0.1N NaCl solution, t=2h, T=40^oC, A(c.s) =16.24*10^{-4}cm^2 , A(st.st) =4.12*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=7.87 g/cm^3

C.S Δw=0.001g	C.S-St.St pH=0 without inhibitor Zero resistance Ammeter AR 4/1	St.St Δw=0.0018g
gmd=7.4074		gmd=52.0231
mm/y=0.3435		mm/y= 2.4127
mpy=13.52		mpy=94.9906
I=29.587 $\mu A/cm^2$		I=207.79 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	1.40	-0.101
20	1.11	-0.090
40	0.89	-0.082
60	0.89	-0.082
80	0.89	-0.082
100	0.89	-0.082
120	0.89	-0.082

Table (4.13):): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/4 cm Cd) in air saturated 0.1N NaCl solution, t=2h, T=40^{o}C, A(c.s) =16.24*10^{-4}cm^2 , A(cd) =16.24*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0052g	C.S-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/4	Cd Δw=0.0029g
gmd=38.518		gmd=21.481
mm/y=1.7864		mm/y=0.90642
mpy=70.3312		mpy=35.6859
I=153.85 μA/cm^2		I= 42.747 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	12.14	-0.303
20	11.93	-0.322
40	11.27	-0.330
60	11.27	-0.330
80	11.27	-0.330
100	11.27	-0.330
120	11.27	-0.330

Table (4.14): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/3 cm Cd) in air-saturated 0.1N NaCl solution, t=2h ,T=40^{o}C, A(c.s) =16.24*10^{-4}cm^2 , A(cd) =12.2*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0097g	C.S-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/3	Cd Δw=0.0041g
gmd=71.851		gmd=40.0078
mm/y=3.3323		mm/y= 1.68819
mpy=131.19		mpy=66.464
I=100 μA/cm^2		I=79.614 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	14.45	-0.296
20	14.14	-0.315
40	13.77	-0.327
60	13.77	-0.327
80	13.77	-0.327
100	13.77	-0.327
120	13.77	-0.327

Table (4.15): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/2 cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40^{o}C, A(c.s) =16.24*10^{-4}cm^2 , A(cd) =8.16*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0025g	C.S-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/2	Cd Δw=0.0012g
gmd= 18.518		gmd=17.5182
mm/y=0.8588		mm/y= 0.73920
mpy=33.8125		mpy=29.1027
I=73.966 μA/cm^2		I= 34.861 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	12.09	-0.309
20	11.70	-0.327
40	11.52	-0.333
60	11.52	-0.333
80	11.52	-0.333
100	11.52	-0.333
120	11.52	-0.333

Table (4.16): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/1 cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40^{o}C, A(c.s) =16.24*10^{-4}cm^2 , A(cd) =4.12*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0037g	C.S-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/1	Cd Δw=0.0002g
gmd= 27.407		gmd=5.78034
mm/y=1.2710		mm/y= 0.24391
mpy=50.0432		mpy=9.600277
I=109.471 μA/cm^2		I=11.503 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	13.82	-0.293
20	13.24	-0.325
40	13.10	-0.325
60	13.10	-0.325
80	13.10	-0.325
100	13.10	-0.325
120	13.10	-0.325

Table (4.17): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^{2}) and potential difference for the metal couple (4 cm St.St/4 cm Cd) in air-saturated 0.1N NaCl solution, t=2h,T=40^{o}C, A(st.st) =16.24*10^{-4}cm^{2} , A(cd) =16.24*10^{-4}cm^{2}, and ρst.st=7.87 g/cm^{3}, ρcd=8.65 g/cm^{3}

St.St Δw=0.00481g	St.St-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/4	Cd Δw=0.000301g
gmd= 35.695		gmd=22.316
mm/y=1.6554		mm/y= 0.94165
mpy=65.1766		mpy=37.0731
I= 142.57 µA/cm^{2}		I=44.409 µA/cm^{2}
Tim(min)	I(mA)	E(volt)
0	11.25	-0.307
20	10.82	-0.325
40	10.22	-0.335
60	10.22	-0.335
80	10.22	-0.335
100	10.22	-0.335
120	10.22	-0.335

Table (4.18): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^{2}) and potential difference for the metal couple (4 cm St.St/3 cm Cd) in air-saturated 0.1N NaCl solution, t=2h ,T=40 ^{o}C, A(st.st) =16.24*10^{-4}cm^{2} , A(cd) =12.2*10^{-4}cm^{2}, and ρst.st=7.87 g/cm^{3}, ρcd=8.65 g/cm^{3}

St.St Δw=0.00948g	St.St-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/3	Cd Δw=0.00531g
gmd=70.256		gmd=39.365
mm/y=3.2583		mm/y= 1.6610
mpy=128.282		mpy=65.396
I= 280.62 µA/cm^{2}		I= 78.337µA/cm^{2}
Tim(min)	I(mA)	E(volt)
0	14.40	-0.296
20	14.06	-0.315
40	13.60	-0.330
60	13.60	-0.330
80	13.60	-0.330
100	13.60	-0.330
120	13.60	-0.330

Table (4.19): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cm St.St/2 cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^{o}C, A(st.st) =16.24*10^{-4}cm^2 , A(cd) =8.16*10^{-4}cm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3

St.St Δw=0.0025g	St.St-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/2	Cd Δw=0.0012 g
gmd= 18.518		gmd=17.5182
mm/y=0.8588		mm/y= 0.73920
mpy=33.8125		mpy=29.1027
I=73.9666 µA/cm^2		I=34.8616µA/cm^2
Tim(min)	I(mA)	E(volt)
0	12.10	-0.311
20	11.75	-0.332
40	11.50	-0.347
60	11.50	-0.347
80	11.50	-0.347
100	11.50	-0.347
120	11.50	-0.347

Table (4.20): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cm St.St/1 cm Cd) in air-saturated 0.1N NaCl solution, t=2h ,T=40 ^{o}C, A(st.st) =16.24*10-4 cm^2 , A(cd) =4.12*10-4cm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3

St.St Δw=0.00138g	St.St-Cd pH=0 without inhibitor Zero resistance Ammeter AR 4/1	Cd Δw=0.00085g
gmd=10.256		gmd=6.3651
mm/y=0.4756		mm/y= 0.2685
mpy=18.7267		mpy=10.5742
I=40.9653 µA/cm^2		I= 12.666µA/cm^2
Tim(min)	I(mA)	E(volt)
0	12.82	-0.290
20	12.24	-0.312
40	12.08	-0.328
60	12.08	-0.328
80	12.08	-0.328
100	12.08	-0.328
120	12.08	-0.328

Table (4.21): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/4 cm St.St) in air-saturated 0.1N NaCl solution, t=2h,T=40^{o}C, A(c.s) =16.24*10^{-4}cm^2,A(st.st) =16.24*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=7.87 g/cm^3

C.S Δw= 0.00432g	C.S-St.St pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/4	St.St Δw=0.00337
gmd= 32		gmd=25
mm/y=1.4841		mm/y= 1.1594
mpy=58.429		mpy=45.648
I= 127.816μA/cm^2		I= 99.856μA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.71	-0.307
20	0.49	-0.322
40	0.28	-0.335
60	0.28	-0.335
80	0.28	-0.335
100	0.28	-0.335
120	0.28	-0.335

Table (4.22): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple 4 cm C.S/3 cm St.St) in air-saturated 0.1N NaCl solution, t=2h ,T=40^{o}C, A(c.s) =16.24*10^{-4}cm^2,A(st.st) =12.2*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=7.87 g/cm^3

C.S Δw=0.000703g	C.S-St.St pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/3	St.St Δw=0.000786
gmd= 5.2145		gmd=5.8231
mm/y=1.90329		mm/y= 0.27006
mpy=74.932		mpy=10.6325
I= 20.828 μA/cm^2		I= 23.259μA/cm^2
Tim(min)	I(mA)	E(volt)
0	2.23	-0.270
20	2.15	-0.295
40	1.10	-0.300
60	1.10	-0.300
80	1.10	-0.300
100	1.10	-0.300
120	1.10	-0.300

Table (4.23): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/2 cm St.St) in air-saturated 0.1N NaCl solution, t=2h ,T=40 ^{o}C , A(c.s) =16.24*10^{-4}cm² , A(st.st) =8.16*10^{-4}cm², and ρc.s=7.87 g/cm³, ρst.st=7.87 g/cm³

C.S Δw=0.00434g	C.S-St.St pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/2	St.St Δw=0.01016
gmd=32.154		gmd=75.321
mm/y=1.49125		mm/y= 3.4932
mpy=58.710		mpy=137.530
I= 128.432 μA/cm^2		I=300.85 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.29	-0.220
20	0.15	-0.239
40	0.12	-0.345
60	0.12	-0.345
80	0.12	-0.345
100	0.12	-0.345
120	0.12	-0.345

Table (4.24): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/1 cm St.St) in air-saturated 0.1N NaCl solution, t=2h T=40 ^{o}C, A(c.s) =16.24*10^{-4}cm² , A(st.st) =4.12*10^{-4}cm², and ρc.s=7.87 g/cm³, ρst.st=7.87 g/cm³

C.S Δw=0.00069g	C.S-St.St pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/1	St.St Δw=0.00165 g
gmd= 5.124		gmd=12.245
mm/y=0.2376		mm/y= 0.5679
mpy=9.3560		mpy=22.358
I= 20.466 μA/cm^2		I=48.909 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.22	-0.215
20	0.15	-0.246
40	0.10	-0.258
60	0.10	-0.258
80	0.10	-0.258
100	0.10	-0.258
120	0.10	-0.258

Table (4.25): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/4 cm Cd) in air-saturated 0.1N NaCl solution, t=2h,T=$40^{o}C$, A(c.s) =$16.24*10^{-4} cm^2$, A(cd) =$16.24*10^{-4} cm^2$, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0017g	C.S-Cd pH=0 With 708.8 ppm inhibitor Zero resistance Ammeter AR 4/4	Cd Δw=0.0114g
gmd= 12.5461		gmd=84.445
mm/y=0.5818		mm/y=3.5632
mpy=22.908		mpy=140.2834
I=50.1126 $\mu A/cm^2$		I=168.13 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	0.14	-0.391
20	0.07	-0.405
40	0.02	-0.413
60	0.02	-0.413
80	0.02	-0.413
100	0.02	-0.413
120	0.02	-0.413

Table (4.26): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/3 cm Cd) in air-saturated 0.1N NaCl solution, t=2h and T=$40^{o}C$, A(c.s) =$16.24*10^{-4} cm^2$, A(cd) =$12.2*10^{-4} cm^2$, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0047g	C.S-Cd pH=0 With 708.8 ppm inhibitor Zero resistance Ammeter AR 4/3	Cd Δw=0.0005g
gmd= 34.814		gmd=4.87900
mm/y=1.61462		mm/y= 0.20587
mpy=63.5679		mpy=8.10539
I=139.056 $\mu A/cm^2$		I=9.7145 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	0.11	-0.372
20	0.06	-0.390
40	0.01	-0.394
60	0.01	-0.394
80	0.01	-0.394
100	0.01	-0.394
120	0.01	-0.394

Table (4.27): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cm C.S/2 cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40^{o}C, A(c.s) =16.24*10^{-4}cm^2 , A(cd) =8.16*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0029g	C.S-Cd pH=0 With 708.8 ppm inhibitor Zero resistance Ammeter AR 4/2	Cd Δw=0.0017g
gmd=21.4814		gmd=12.5925
mm/y=0.9962		mm/y=0.53135
mpy=39.2235		mpy=20.9196
I=85.802 µA/cm^2		I=25.072 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.47	-0.360
20	0.20	-0.348
40	0.14	-0.348
60	0.14	-0.348
80	0.14	-0.348
100	0.14	-0.348
120	0.14	-0.348

Table (4.28): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cm C.S/1 cm Cd) in air-saturated 0.1N NaCl solution, t=2h ,T=40^{o}C , A(c.s) =16.24*10^{-4}cm^2 , A(cd) =4.12*10-4cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3

C.S Δw=0.0028g	C.S-Cd pH=0 With 708.8ppm inhibitor Zero resistance Ammeter AR 4/1	Cd Δw=0.0004g
gmd=20.7407		gmd=11.5606
mm/y=0.9619		mm/y=0.48782
mpy=37.8710		mpy=19.2055
I=82.844 µA/cm^2		I=23.018 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.32	-0.344
20	0.25	-0.359
40	0.13	-0.364
60	0.13	-0.364
80	0.13	-0.364
100	0.13	-0.364
120	0.13	-0.364

Table (4.29): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm StSt/4 cm Cd) in air-saturated 0.1N NaCl solution, t=2h ,T=40^{o}C , A(st.st) =$16.24*10^{-4}cm^2$, A(cd) =$16.24*10^{-4}cm^2$, and ρst.st=7.87 g/cm³, ρcd=8.65 g/cm³

St.St Δw=0.00339g	St.St-Cd pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/4	Cd Δw=0.00312 g
gmd=25.147		gmd=23.156
mm/y=1.1662		mm/y=0.9771
mpy=45.916		mpy=38.468
I= 100.44 $\mu A/cm^2$		I=46.105 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	1.12	-0.233
20	0.80	-0.245
40	0.59	-0.253
60	0.59	-0.253
80	0.59	-0.253
100	0.59	-0.253
120	0.59	-0.253

Table (4.30): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm StSt/3cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40^{o}C, A(st.st) =$16.24*10^{-4}cm^2$, A(cd) =$12.2*10^{-4}cm^2$, and ρst.st=7.87 g/cm³, ρcd=8.65 g/cm³

St.St Δw=0.002258g	St.St-Cd pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/3	Cd Δw=0.00272 g
gmd=19.165		gmd=20.215
mm/y=0.8888		mm/y= 0.8530
mpy=34.99		mpy=33.582
I= 76.550 $\mu A/cm^2$		I=40.2498 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	1.11	-0.230
20	0.84	-0.255
40	0.62	-0.276
60	0.62	-0.276
80	0.62	-0.276
100	0.62	-0.276
120	0.62	-0.276

Table (4.31): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm StSt/2cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40^{o}C , A(st.st) =16.24*10^{-4}cm^2 , A(cd) =8.16*10-Zcm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3

St.St Δw=0.00150g	St.St-Cd pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/2	Cd Δw=0.000135 g
gmd= 11.148		gmd=14.201
mm/y=0.51702		mm/y= 0.59923
mpy=20.355		mpy=23.5918
I= 44.528 μA/cm^2		I=28.275 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.70	-0.421
20	0.53	-0.440
40	0.39	-0.458
60	0.39	-0.458
80	0.39	-0.458
100	0.39	-0.458
120	0.39	-0.458

Table (4.32): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm StSt/1 cm Cd) in air-saturated 0.1N NaCl solution, t=2h ,T=40^{o}C , A(st.st) =16.24*10^{-4}cm^2 , A(cd) =4.12*10^{-4}cm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3.

St.St Δw=0.00273g	St.St-Cd pH=0 With708.8ppm inhibitor Zero resistance Ammeter AR 4/1	Cd Δw=0.0039 g
gmd=20.256		gmd=29.365
mm/y=0.9394		mm/y= 1.2391
mpy=36.986		mpy=48.783
I=80.908 μA/cm^2		I= 58.468μA/cm^2
Tim(min)	I(mA)	E(volt)
0	1.95	-0.475
20	1.65	-0.492
40	1.43	-0.498
60	1.43	-0.498
80	1.43	-0.498
100	1.43	-0.498
120	1.43	-0.498

Table (4.33): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/3cm St.St) in air-saturated 0.1N NaCl solution, t=2h, T=$40^{o}C$, A(c.s) =$16.24*10^{-4}cm^2$,A(st.st) =$16.42*10^{-4}cm^2$, and ρc.s=7.87 g/cm³, ρst.st=7.87 g/cm³.

C.S Δw=0.000521	C.S-St.St pH=1 without inhibitor Zero resistance Ammeter AR 4/4	St.St Δw=0.000831
gmd=4.270		gmd=6.811
mm/y=0.1980		mm/y=0.2874
mpy=7.7967		mpy=11.315
I=17.055 $\mu A/cm^2$		I= 27.0205$\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	0.30	-0.322
20	0.27	-0.330
40	0.22	-0.339
60	0.22	-0.339
80	0.22	-0.339
100	0.22	-0.339
120	0.22	-0.339

Table (4.34): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/3cm St.St) in air-saturated 0.1N NaCl solution, t=2h, T=$40^{o}C$, A(c.s) =$16.24*10^{-4}cm^2$, A(st.st) =$12.2*10^{-4}cm^2$, and ρc.s=7.87 g/cm³, ρst.st=7.87 g/cm³.

C.S Δw=0.0007g	C.S-St.St pH=1 without inhibitor Zero resistance Ammeter AR 4/3	St.St Δw=0.000714 g
gmd=5.18518		gmd=5.8548
mm/y=0.24047		mm/y= 0.2715
mpy=9.4676		mpy=10.6904
I=20.711 $\mu A/cm^2$		I=23.382 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	0.26	-0.203
20	0.17	-0.254
40	0.14	-0.263
60	0.14	-0.263
80	0.14	-0.263
100	0.14	-0.263
120	0.14	-0.263

Table (4.35): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^{2}$) and potential difference for the metal couple (4 cm C.S/2cm St.St) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^{o}C ,A(c.s) =$16.24*10^{-4}cm^{2}$, A(st.st) =$8.16*10^{-4}cm^{2}$, and ρc.s=7.87 g/cm^{3}, ρst.st=7.87 g/cm^{3}.

C.S Δw=0.0013g	C.S-St.St pH=1 without inhibitor Zero resistance Ammeter AR 4/2	St.St Δw=0.0007g
gmd=9.6296		gmd=10.2189
mm/y=0.4466		mm/y= 0.47394
mpy=0.30915		mpy=18.6591
I=38.463 $\mu A/cm^{2}$		I=40.817 $\mu A/cm^{2}$
Tim(min)	I(mA)	E(volt)
0	0.24	-0.319
20	0.16	-0.340
40	0.11	-0.346
60	0.10	-0.346
80	0.10	-0.346
100	0.10	-0.346
120	0.10	-0.346

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Table (4.36): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^{2}$) and potential difference for the metal couple (4 cm C.S/1cm St.St) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^{o}C , A(c.s) =$16.24*10^{-4}cm^{2}$, A(st.st) =$4.12*10^{-4}cm^{2}$, and ρc.s=7.87 g/cm^{3}, ρst.st=7.87 g/cm^{3}.

C.S Δw=0.0008g	C.S-St.St pH=1 without inhibitor Zero resistance Ammeter AR 4/1	St.St Δw=0.0001g
gmd=2.9529		gmd=2.89017
mm/y=0.13695		mm/y= 0.13404
mpy=5.3917		mpy=5.27725
I=11.7944 $\mu A/cm^{2}$		I=11.544 $\mu A/cm^{2}$
Tim(min)	I(mA)	E(volt)
0	0.36	-0.349
20	0.22	-0.398
40	0.14	-0.405
60	0.14	-0.405
80	0.14	-0.405
100	0.14	-0.405
120	0.14	-0.405

Table (4.37): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/4cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^{o}C , A(st.st) =16.24*10^{-4}cm^2 , A(cd) =16.24*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3.

St.St Δw=0.00088g	St.St-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/4	Cd Δw=0.00084 g
gmd= 6.589		gmd=6.235
mm/y=0.30558		mm/y= 0.2630
mpy=12.0310		mpy=10.3580
I= 26.318μA/cm^2		I= 12.4077μA/cm^2
Tim(min)	I(mA)	E(volt)
0	3.22	-0.280
20	3.12	-0.295
40	2.80	-0.333
60	2.80	-0.333
80	2.80	-0.333
100	2.80	-0.333
120	2.80	-0.333

Table (4.38): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4 cm C.S/3cm Cd) in air-saturated 0.1N NaCl solution, t=2h , T=40 ^{o}C , A(st.st) =16.24*10^{-4}cm^2 , A(cd) =12.2*10^{-4}cm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3.

St.St Δw=0.00381g	St.St-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/3	Cd Δw=0.00342 g
gmd=28.253		gmd=25.365
mm/y=1.31033		mm/y= 1.0703
mpy=51.5880		mpy=42.138
I= 112.83 μA/cm^2		I= 50.476μA/cm^2
Tim(min)	I(mA)	E(volt)
0	2.99	-0.240
20	2.76	-0.260
40	2.60	-0.274
60	2.60	-0.276
80	2.60	-0.276
100	2.60	-0.276
120	2.60	-0.276

Table (4.39): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cm C.S/2cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^{o}C , A(st.st) =16.24*10^{-4}cm² , A(cd) =8.16*10^{-4}cm², and ρst.st=7.87 g/cm³, ρcd=8.65 g/cm³.

St.St Δw=0.00216g	St.St-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/2	Cd Δw=0.000246 g
gmd=16.0583		gmd=18.256
mm/y=0.7447		mm/y= 0.7703
mpy=29.321		mpy=30.323
I= 64.140 µA/cm^2		I=36.329 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	1.75	-0.410
20	1.47	-0.425
40	1.39	-0.441
60	1.39	-0.441
80	1.39	-0.441
100	1.39	-0.441
120	1.39	-0.441

Table (4.40): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cm C.S/1cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^{o}C , A(c.s) =16.24*10^{-4}cm² , A(cd) =4.12*10^{-4}cm², and ρst.st=7.87 g/cm³, ρcd=8.65 g/cm³.

St.St Δw=0.00205g	St.St-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/1	Cd Δw=0.00481g
gmd=15.214		gmd=35.652
mm/y=0.70560		mm/y= 1.5043
mpy=27.779		mpy=59.227
I= 60.752 µA/cm^2		I=70.948 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	2.45	-0.480
20	2.29	-0.496
40	1.79	-0.498
60	1.74	-0.498
80	1.74	-0.498
100	1.74	-0.498
120	1.74	-0.498

Table (4.41): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/4cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^oC , A(c.s) =16.24*$10^{-4}cm^2$, A(cd) =16.24*$10^{-4}cm^2$, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3.

C.S Δw=0.00151g	C.S-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/4	Cd Δw=0.00124 g
gmd=11.254		gmd=9.214
mm/y=0.5219		mm/y= 0.3887
mpy=20.549		mpy=15.307
I=44.9516 $\mu A/cm^2$		I=18.336 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	15.04	-0.290
20	14.90	-0.303
40	14.70	-0.312
60	14.69	-0.312
80	14.69	-0.312
100	14.69	-0.312
120	14.69	-0.312

Table (4.42): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/3cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^oC , A(c.s) =16.24*$10^{-4}cm^2$, A(cd) =12.2*$10^{-4}cm^2$, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3.

C.S Δw=0.00203g	C.S-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/3	Cd Δw=0.00205 g
gmd= 15.092		gmd=15.191
mm/y=0.6999		mm/y= 0.6410
mpy=27.556		mpy=25.2365
I= 60.281 $\mu A/cm^2$		I=30.230 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	10.23	-0.295
20	10.09	-0.335
40	9.79	-0.340
60	9.66	-0.340
80	9.66	-0.340
100	9.66	-0.340
120	9.66	-0.340

Table (4.43): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/2cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^oC , A(c.s) =$16.24*10^{-4}cm^2$, A(cd) =$8.16*10^{-4}cm^2$, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3.

C.S Δw=0.00126g	C.S-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/2	Cd Δw=0.0038 g
gmd= 9.407		gmd=28.2778
mm/y=0.4362		mm/y= 1.1932
mpy=17.176		mpy=46.9773
I= 37.574$\mu A/cm^2$		I=56.273$\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	9.41	-0.320
20	9.02	-0.349
40	8.61	-0.366
60	8.60	-0.366
80	8.60	-0.366
100	8.60	-0.366
120	8.60	-0.366

Table (4.44): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cm C.S/1cm Cd) in air-saturated 0.1N NaCl solution, t=2h, T=40 ^oC ,A(c.s) =$16.24*10^{-4}cm^2$, A(cd) =$4.12*10^{-4}cm^2$, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3.

C.S Δw=0.00543g	C.S-Cd pH=1 Without inhibitor Zero resistance Ammeter AR 4/1	Cd Δw=0.00475 g
gmd=40.237		gmd=35.236
mm/y=1.8661		mm/y= 1.4868
mpy=73.469		mpy=58.536
I= 160.717$\mu A/cm^2$		I=70.120 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	13.45	-0.295
20	13.19	-0.321
40	13.16	-0.332
60	13.06	-0.332
80	13.06	-0.332
100	13.06	-0.332
120	13.06	-0.332

Table (4.45): Effect of area ratio AR , and solution PH on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cmC.S/4 cmSt.St) in air-saturated 0.1N NaCl solution: t=2h, T=40^{o}C, A(st.st) =16.24*10^{-4}cm^2 , A(c.s) =16.24*10^{-4}cm^2, and ρst.st=7.87 g/cm^3, ρc.s=8.65 g/cm^3.

St. St Δw=0.001g	St.St -C.S pH=1 with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/3	C.S Δw=0.001g
gmd=7.40		gmd=9.75800
mm/y=0.34320		mm/y=0.45256
mpy=13.5118		mpy=17.817
I=29.557 µA/cm^2		I=38.976 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.82	-0.274
20	0.62	-0.289
40	0.55	-0.289
60	0.55	-0.289
80	0.55	-0.289
100	0.55	-0.289
120	0.55	-0.289

Table (4.46): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (3 cmC.S /4 cmSt.St) in air-saturated 0.1N solution, t=2h ,T=40 ^{o}C, A(st.st) =16.24*10-4 cm^2 , A(c.s) =12.2*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=8.65 g/cm^3.

St. steel Δw=0.001 g	St.St -C.S pH=1 with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/4	Carbon Steel Δw=0.002 g
gmd =7.4		gmd=14.8
mm/y=0.34320		mm/y=0.6864
mpy=13.5118		mpy=27.023
I=29.55 µA/cm^2		I=59.115 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	3.99	-0.275
20	2.31	-0.347
40	0.75	-0.347
60	0.75	-0.347
80	0.75	-0.347
100	0.75	-0.347
120	0.75	-0.347

Table (4.47): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (2cmC.S /4 cmSt.St) in air-saturated 0.1N NaCl solution, t=2h , T=40 ^oC, A(st.st) =16.24*10^{-4}cm^2 , A(c.s) =8.16*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=8.65 g/cm^3.

St. St Δw=0.0111g	St.St-C.S pH=1with 708.8ppm inhibitor Zero resistance Ammeter AR 4/2	C.S Δw=0.0015g
gmd=82.3		gmd=21.8837
mm/y=3.81696		mm/y= 1.01493
mpy=150.274		mpy=39.958
I=328.72 μA/cm^2		I=87.406 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.32	-0.220
20	0.20	-0.235
40	0.14	-0.240
60	0.14	-0.240
80	0.14	-0.240
100	0.14	-0.240
120	0.14	-0.240

Table (4.48): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (1cmC.S /4 cmSt.St) in air-saturated 0.1N NaCl solution, t=2h , T=40 ^oC, A(st.st) =16.24*10^{-4}cm^2 , A(c.s) =4.12*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρst.st=8.65 g/cm^3.

St. St Δw=0.0018g	St.St-C.S pH=1with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/1	C.S Δw=0.0001g
gmd=13.33		gmd=2.889505
mm/y=0.61822		mm/y= 0.13401
mpy=24.339		mpy=5.27603
I=53.24 μA/cm^2		I=11.539 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	0.27	-0.220
20	0.13	-0.245
40	0.12	-0.253
60	0.12	-0.253
80	0.12	-0.253
100	0.12	-0.253
120	0.12	-0.253

Table (4.49): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4cmCd/4 cm C.S) in air-saturated 0.1N NaCl solution, t=2hr , T=40 °C , A(cd) =16.24*10^{-4}cm² , A(c.s) =16.26*10^{-4} cm², and ρc.s=7.87 g/cm³, ρcd=8.65 g/cm³.

Cd Δw=0.0012g	Cd- C.S pH=1with 708.7ppm inhibitor Zero resistance Ammeter AR 4/4	C.S Δw=0.001g
gmd=8.889		gmd=7.407
mm/y=0.3750		mm/y=0.34352
mpy=14.767		mpy=13.5246
I=17.689 $\mu A/cm^2$		I=29.58 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	14.04	-0.280
20	13.90	-0.283
40	13.38	-0.283
60	13.38	-0.283
80	13.38	-0.283
100	13.38	-0.283
120	13.38	-0.283

Table (4.50): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4cmCd/3 cm C.S) in air-saturated 0.1N NaCl solution, t=2h , T=40 °C ,A(cd) =16.24*10^{-4}cm² , A(c.s) =12.2*10^{-4}cm², and ρc.s=7.87 g/cm³, ρcd=8.65 g/cm³.

Cd Δw=0.0020g	Cd-C.S pH=1 with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/3	C.S Δw=0.0015g
gmd=14.814		gmd=14.6370
mm/y=0.6250		mm/y=0.67884
mpy=24.6102		mpy=26.7261
I=29.480 $\mu A/cm^2$		I=58.464 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	9.49	-0.297
20	9.39	-0.310
40	9.19	-0.310
60	9.00	-0.310
80	9.00	-0.310
100	9.00	-0.310
120	9.00	-0.310

Table (4.51): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4cmCd/2 cm C.S) in air-saturated 0.1N NaCl solution, t=2h , T=40 °C A(cd) =16.24*10^{-4}cm^2 , A(c.s) =8.16*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3.

Cd Δw=0.001g	Cd-C.S pH=1 with 708.8 ppm inhibitor in Zero resistance Ammeter AR 4/2	C.S Δw=0.0018g
gmd=7.407		gmd= 26.2773
mm/y= 0.3125		mm/y= 1.21870
mpy=12.305		mpy=47.9806
I=14.740 μA/cm^2		I=104.957 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	8.41	-0.311
20	8.46	-0.320
40	8.30	-0.320
60	8.30	-0.320
80	8.30	-0.320
100	8.30	-0.320
120	8.30	-0.320

Table (4.52): Effect of area ratio AR , PH solution on galvanic current density (μA/cm^2) and potential difference for the metal couple (4cmCd/1 cm C.S) in air-saturated 0.1N NaCl solution, t=2h , T=40 °C, A(cd) =16.24*10^{-4}cm^2 , A(c.s) =4.12*10^{-4}cm^2, and ρc.s=7.87 g/cm^3, ρcd=8.65 g/cm^3.

Cd Δw=0.005g	Cd-C.S pH=1with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/1	C.S Δw=0.0011g
gmd=37.037		gmd=31.7919
mm/y= 1.5628		mm/y= 1.47446
mpy=61.5288		mpy=58.049
I=73.704 μA/cm^2		I=126.98 μA/cm^2
Tim(min)	I(mA)	E(volt)
0	12.47	-0.293
20	12.16	-0.299
40	12.02	-0.299
60	12.02	-0.299
80	12.02	-0.299
100	12.02	-0.299
120	12.02	-0.299

Table (4.53): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cmSt.St/4cmCd) in air-saturated 0.1N NaCl solution, t=2h , T=40 ^{o}C, A(st.st) =16.24*10^{-4}cm^2 , A(cd) =16.24*10^{-4}cm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3.

St. St Δw=0.002g	St.St-Cd pH=1with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/4	Cd Δw=0.008g
gmd=14.8		gmd=59.25
mm/y=0.68640		mm/y= 2.50014
mpy=27.023		mpy=98.4308
I=59.115 µA/cm^2		I=236.66 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	1.19	-0.295
20	0.70	-0.320
40	0.65	-0.320
60	0.65	-0.320
80	0.65	-0.320
100	0.65	-0.320
120	0.65	-0.320

Table (4.54): Effect of area ratio AR , PH solution on galvanic current density (µA/cm^2) and potential difference for the metal couple (4 cmSt.St/3cmCd) in air-saturated 0.1N NaCl solution, t=2h , T=40 ^{o}C, A(st.st) =16.24*10^{-4}cm^2 , A(cd) =12.2*10^{-4}cm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3.

St. St Δw=0.0034g	St.St-Cd pH=1with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/3	Cd Δw=0.0024g
gmd=25.185		gmd=23.4192
mm/y=1.1680		mm/y= 0.98820
mpy=45.986		mpy=38.9058
I=100.59 µA/cm^2		I=9.662 µA/cm^2
Tim(min)	I(mA)	E(volt)
0	1.16	-0.235
20	0.90	-0.249
40	0.65	-0.249
60	0.65	-0.249
80	0.65	-0.249
100	0.65	-0.249
120	0.65	-0.249

Table (4.55): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cmSt.St/2cmCd) in air-saturated 0.1N NaCl solution, t=2h ,T=40 ^oC , A(st.st) =$16.24*10^{-4}cm^2$, A(cd) =$8.16*10^{-4}$ cm^2, and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3.

St. St Δw=0.0014g	St.St-Cd pH=1with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/2	Cd Δw=0.0011g
gmd=10.3708		gmd=16.0583
mm/y=0.4809		mm/y= 0.67760
mpy=18.9363		mpy=26.6775
I=41.423 $\mu A/cm^2$		I=64.140 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	0.75	-0.425
20	0.50	-0.434
40	0.46	-0.439
60	0.46	-0.439
80	0.46	-0.439
100	0.46	-0.439
120	0.46	-0.439

Table (4.56): Effect of area ratio AR , PH solution on galvanic current density ($\mu A/cm^2$) and potential difference for the metal couple (4 cmSt.St/1cmCd) in air-saturated 0.1N NaCl solution, t=2h , T=40 ^oC , A(st.st) =$16.24*10^{-4}cm^2$, A(cd) =$4.12*10^{-4}cm^2$and ρst.st=7.87 g/cm^3, ρcd=8.65 g/cm^3.

St. St Δw=0.0018g	St.St-Cd pH=1with 708.8 ppm inhibitor Zero resistance Ammeter AR 4/1	Cd Δw=0.0011g
gmd=13.34		gmd= 31.7919
mm/y=0.61869		mm/y=1.34150
mpy=24.3579		mpy=52.8152
I=53.283 $\mu A/cm^2$		I=126.98 $\mu A/cm^2$
Tim(min)	I(mA)	E(volt)
0	2.05	-0.482
20	1.63	-0.491
40	1.76	-0.491
60	1.76	-0.491
80	1.76	-0.491
100	1.76	-0.491
120	1.76	-0.491

Chapter Five

Discussion

5.1 Introduction

Corrosion behavior of carbon steel, stainless steel, cadmium ,and tin in 0.1N NaCl solution with and without inhibitor was studied under different conditions of PH values (0, 1, 2, & 3) , temperature 40ºC, different area ratios (1,0.75,0.5, & 0.25), and different inhibitor concentrations of (177.2 , 354.4 , 531.6 , & 708.8) ppm with dimethalaminoethanol as inhibitor under static conditions.

Chapter four introduces a large number of tables. This is because the numbers of variables involved were four types of metals, four area ratios, four solution PH values, and four different concentrations of inhibitors. In discussing the results, the following sections are followed: section 5.2 deals with corrosion potentials, section 5.3 deals with free corrosion and section 5.4 deals with galvanic coupling.

5.2 Corrosion Potentials

The values of corrosion potential of carbon steel ,stainless steel, cadmium and tin in 0.1N NaCl solution in absence of inhibitor and different PH values (0,1,2,&3) are shown in Tables from(5.1 - 5.4). The PH of each solution depends on hydrogen ion concentration as given by Nernst equation. The potential at time zero is high and after a short time it starts to be more negative until it reaches nearly steady state value. The relationship between PH and corrosion rate at PH values of 0,1,2, &3 is nonlinear for all metals which are acid soluble such as iron ,stainless steel ,cadmium ,and tin in the present acidic solutions. Hydrogen evolves as gas, the removal of which must occur so that corrosion may proceed being effected by reaction between hydrogen ion and some oxidizing chemical such as oxygen to form water, because high rates of corrosion that usually accompany hydrogen evolution. The most of corrosion observed in practice occurs under conditions in which the oxidation of hydrogen to form water is the necessary part of corrosion. Oxidation agents are often powerful accelerators of corrosion and in many cases the oxidizing power of solution is most important property insofar as corrosion is concerned. Diffusion and oxidizing agents also affect corrosion of some materials which may also retard corrosion of the others through the formation on their surface of oxide layer. But in solutions of PH (0,1,2,&3) this effect is limited because no passive layer would occur and all oxides dissolve as Cl^- ions at the above PH values which enhance breakdown of such protective layers and are able to destroy them [12].

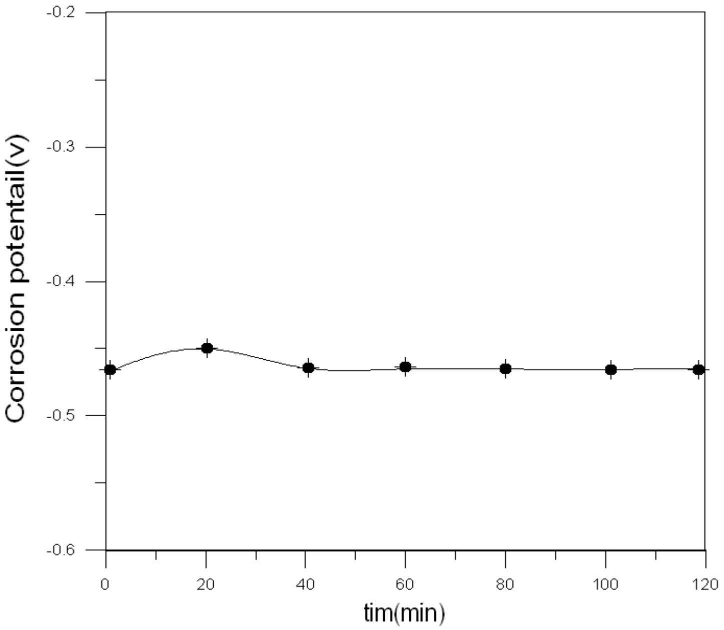

Figure (5.1) Potential vs. time for carbon steel in 0.1N NaCl at T=40 ^{0}C, t=120 min and PH = 0

Figure (5.1) shows that the corrosion potential of carbon steel starts from -0.465V at t=0 min. with reference to Saturated Calomel Electrode (SCE) to become -0.468V at t=11 min. and then begins to decrease until it is stable at t=32 min. to become -0.464V

The potential is stable and it's known as the potential of a corroding metal which is a compromise, or mixed potential of both anodic and cathodic polarization. The stability of carbon steel potential occurs at short time when compared to stainless steel 304, thus the potential from 0 min to 32 min doesnot change very sharply. See Figs. 5.1 & 5.2.

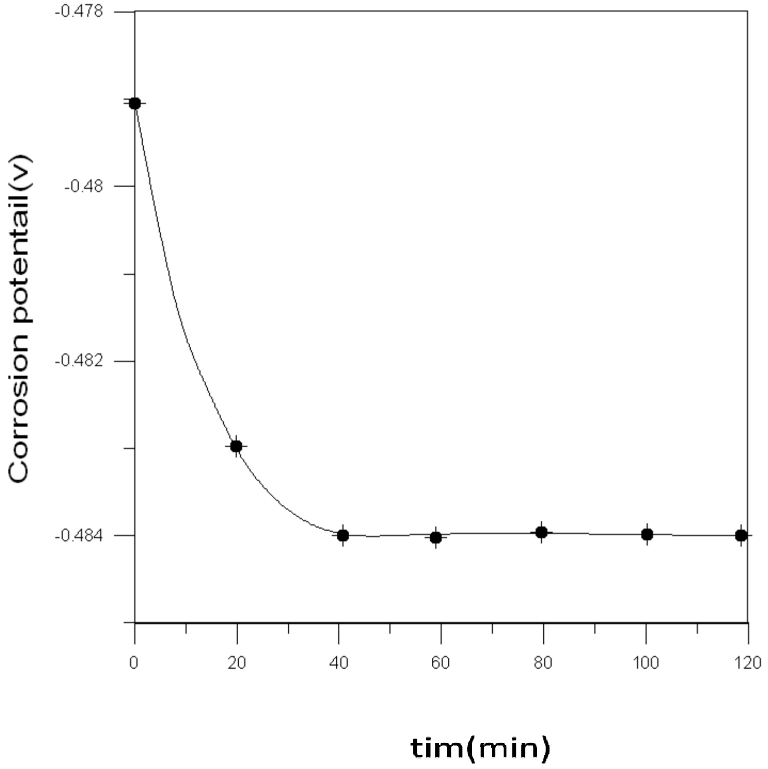

Figure (5.2) Potential vs. time for stainless steel in 0.1N NaCl, T=40 ^{0}C, t=120 min and PH = 0

Figure (5.2) shows the variation in corrosion potential of stainless steel at PH = 0 .The variation in potential with time is not linear during the initial period,i.e., before it became approximately stable after about 40 min .

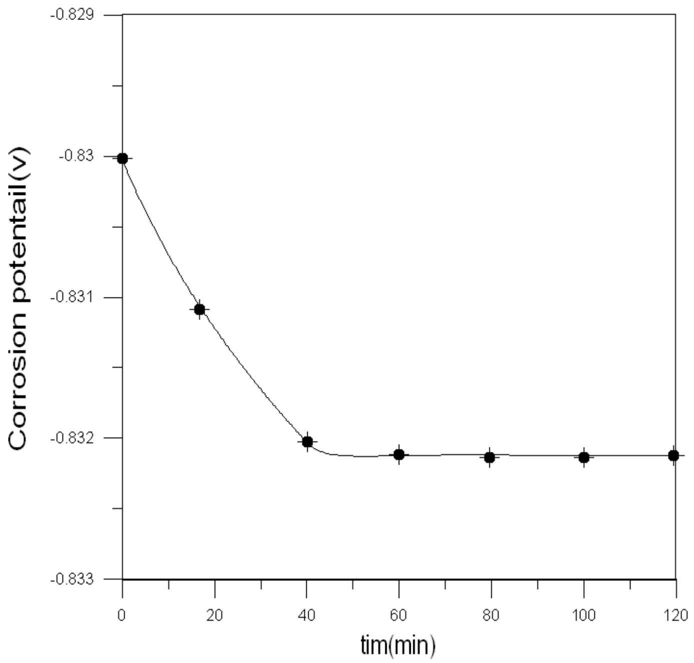

Figure (5.3) Potential vs. time for cadmium in 0.1N NaCl T=40 ^{0}C, t=120 min and PH = 0

Figure (5.3) shows that the corrosion potential of cadmium is stable after a short time of about 40 min.

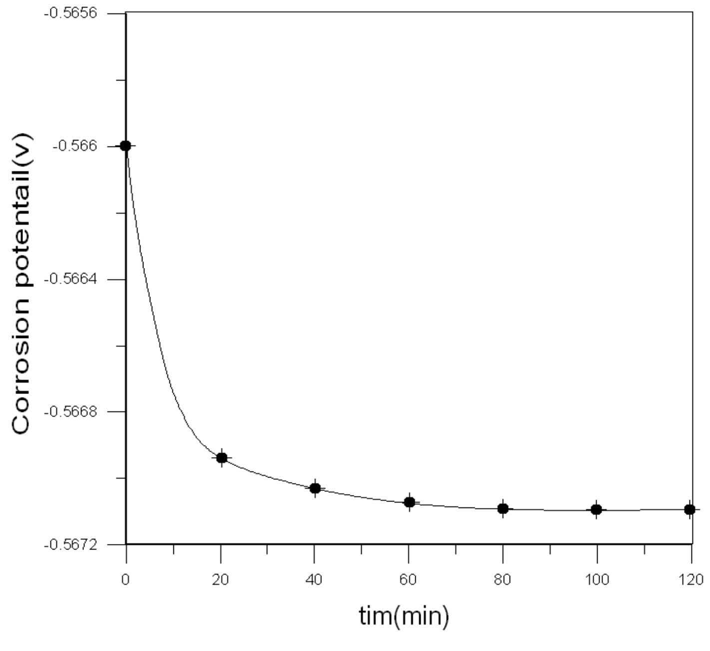

Figure (5.4) Potential vs. time for Tin in 0.1N NaCl T=40 ^{0}C, t=120 min and PH=0

Figure (5.4) indicates that the potential of tin starts from -0.566 V at t=0 and becomes -0.567 V at t=5 min.It begins to be stable after a few minutes to reach -0.567 V.

Tables (4.1) to (4.4) show that the potential decreases as time increases to become stable after sometime. In general acidic conditions dissolve the air-formed oxide films and corrosion potential moves in the more negative direction until it becomes stable with time. Under these conditions the corrosion process is cathodically controlled by the cathodic evolution of hydrogen. Figures 5.5 to 5.8 show the behavior of corrosion potential vs. time, e.g., at PH = 3 which is generally the same trend observed at other investigated PH values. These indicate generally the cathodic control of the corrosion process of these metals.

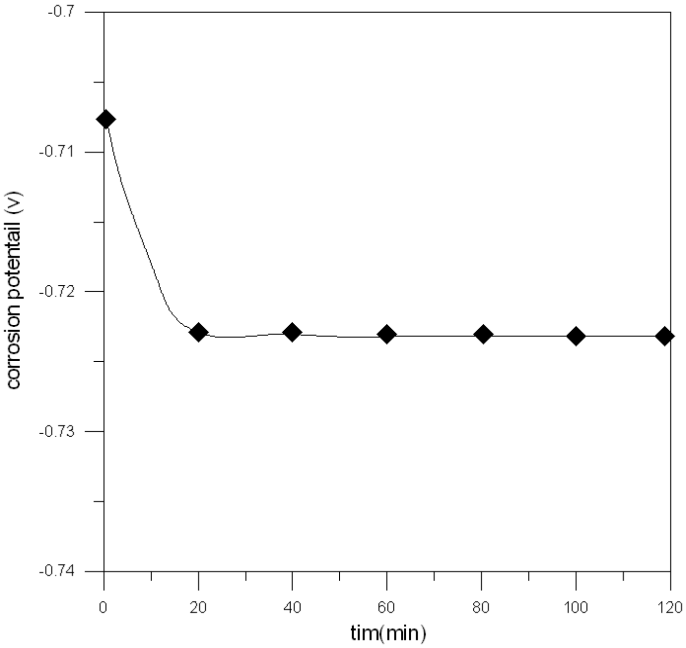

Figure (5.5) Potential vs. time for stainless steel in 0.1N NaCl, T=40Cº, t=120 min and PH = 3

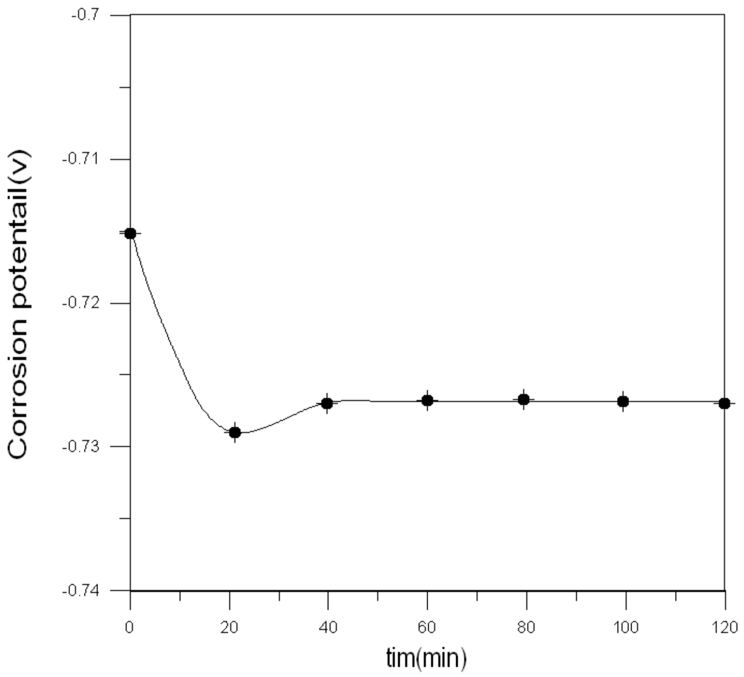

Figure (5.6) Potential vs. time for carbon steel in 0.1N NaCl T=40 ^{0}C,t =120 min and

PH=3

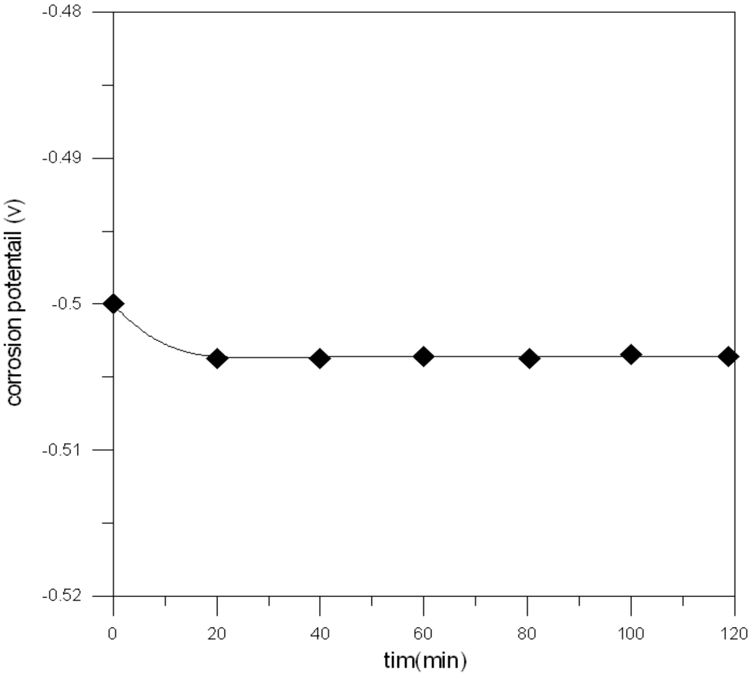

Figure (5.7) Potential vs. time for Tin in 0.1N NaCl T=40 ^{0}C, t=120 min and PH = 3

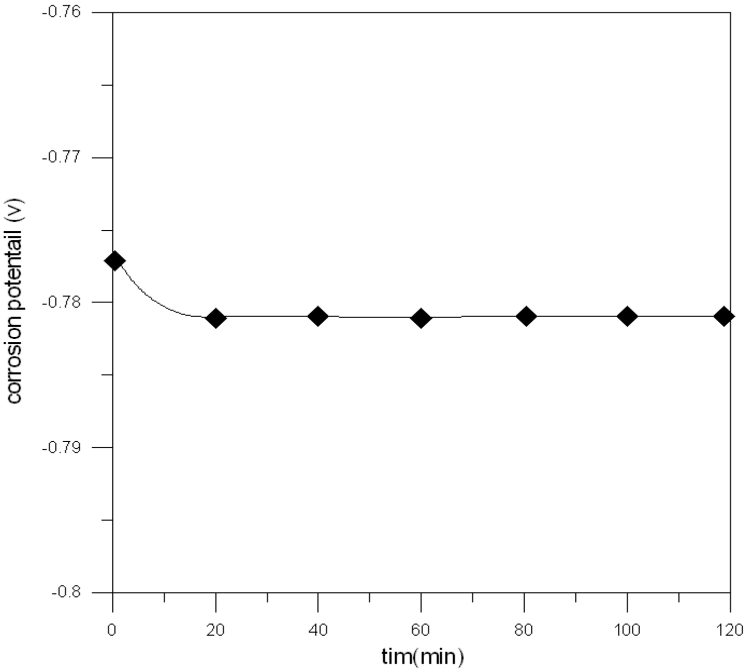

Figure (5.8) Potential vs. time for cadmium in 0.1N NaCl T=40 ^{0}C,t =120 min and PH=3

More dilute acid means less corrosion. In more concentrated acid the reaching of the metal surface is more efficient, hence depolarization in more concentrated acid contributes less to the overall corrosion rate than in dilute acid in which diffusion of oxygen is impeded to a lesser extent.

From tables of corrosion potential shown in chapter four, Tables (4.1) to (4.4), the following table is obtained for all metals at all investigated PH values.

Table (5.1): Effect of PH on the corrosion potential of metals in air saturated 0.1N NaCl solution, T=40 ^{0}C,t =120 min

Corrosion potential $E_{corr.}$(volt)				
PH	**C.S**	**St.St**	**Cd**	**Sn**
0	-0.464	-0.484	-0.832	-0.567
1	-0.527	-0.535	-0.772	-0.518
2	-0.593	-0.585	-0.781	-0.520
3	-0.727	-0.723	-0.781	-0.505

$E_{corr.}$ depends on time of measurement, metal surface roughness, dissolved oxygen, and temperature.

The $E_{corr.}$ for C.S ,St.St ,Cd ,&Sn shows the activity of metals in acidic NaCl solutions for a given PH , and constant temperature .The measured $E_{corr.}$ at PH(0,1,2 &3) is used to distinguish which metal is more active than the others .At PH (0) NaCl solution of a given temperature E_{corr}. depends on the type of metal and thermodynamic conditions for system[12]

Potential (the activity of metal) increases when PH decreases, but this is not for all metals and PH values. From the values of potential shown in chapter four in tables (4.1) to (4.4), it is noticed that the potential is firstly less negative compared with the value at steady state after about 30 min.

Table(5.2): Electrochemical series for four metals in 0.1N NaCl solution without inhibitor, T=40 ^{0}C,t =120 min

PH	Metal	$E_{corr.}$(volt)	Type
0	Cd	-0.832	Anode
	Sn	-0.567	Cathode
	St.St	-0.448	Cathode
	C.S	-0.446	Cathode
1	Cd	-0.772	Anode
	Sn	-0.553	Cathode
	St.St	-0.527	Cathode
	C.S	-0.518	Cathode
2	Cd	-0.781	Anode
	Sn	-0.593	Cathode
	St.St	-0.585	Cathode
	C.S	-0.520	Cathode
3	Cd	-0.781	Anode
	Sn	-0.732	Cathode
	St.St	-0.727	Cathode
	C.S	-0.505	Cathode

Pourbaix Diagrams describe the relationship between equilibrium potential and PH in acid or alkaline solutions. Simillarly they can be used to describe the relation between PH and corrosion potential as presented in Fig. (5.9).

5.3 Corrosion Rate by Weight Loss[13]

The corrosion rate (CR) was obtained by dividing the weight loss of the specimen during a specified time by the area (A) exposed to the corrosive solution as shown in the following equation. The corrosion rate (weight lost) decreases as PH increases as shown in tables of weight loss: st.steel has the lowest corrosion rate which means it has higher resistance for this environment, hence the industrially used metals were chosen with greatly different corrosion rates to study the galvanic corrosion from noticing the data of weight loss in chapter five to obtain the following table without inhibitor:

Table (5.3): Effect of PH (without inhibitor) on the corrosion rate of metals in air air saturated 0.1N NaCl solution T=40 ^{0}C,t =120 min

Corrosion rate (gmd) without inhibitor				
PH	**C.S**	**St.St**	**Cd**	**Sn**
0	54	33.3	42.3	40.7
1	57.4	25.1	74	51.8
2	57.8	38.5	57.8	52.9
3	39.2	24.5	41.48	88.14

Table (5.4): Effect of inhibitor at 177.2 ppm on the corrosion rate of metals in air saturated 0.1N NaCl solution, T=40 ^{0}C,t =120 min

Corrosion rate (gmd) at 177.2 ppm				
PH	**C.S**	**St.St**	**Cd**	**Sn**
0	30.3	19.03	37.8	12.8
1	27.8	39.96	16.2	500
2	19.25	49.2	16.2	19.29
3	36.7	26.3	55.6	23.3

Table (5.5): Effect of inhibitor at 354.4 ppm on the corrosion rate of metals in air saturated 0.1N NaCl solution, T=40 ^{0}C,t =120 min

Corrosion rate (gmd) at 354.4 ppm				
PH	**C.S**	**St.St**	**Cd**	**Sn**
0	37.8	9.14	12.9	11.8
1	25.9	23.7	19.6	16.6
2	30.3	17.8	22.3	14.8
3	15.18	22.3	30	16.7

Table (5.6): Efect of inhibitor at 531.6 ppm on the corrosion rate of metals in air saturated 0.1N NaCl solution, T=40 ^{0}C,t =120 min

Corrosion rate (gmd) at 531.6 ppm				
PH	**C.S**	**St.St**	**Cd**	**Sn**
0	23.4	164.5	23.7	25.9
1	45.6	33.4	55.6	30.3
2	29.6	30.7	7.4	29.6
3	12.2	11.2	25.9	25.9

Table (5.7): Effect of inhibitor at 708.8 ppm on the corrosion rate of metals in air saturated 0.1N NaCl solution, T=40 ^{0}C,t =120 min

Corrosion rate (gmd) at 708.8 ppm				
PH	**C.S**	**St.St**	**Cd**	**Sn**
0	17.7	8.5	13.7	11.8
1	9.6	14.4	12.9	11.8
2	11.8	8.5	2.96	5.1
3	5.6	5.3	1.8	0.89

From comparison between the above tables of corrosion rates (with and without inhibitor) it is noticed that the corrosion rates of metals decrease with increase the inhibitor concentration. This relation is not for all metals as for some metals the corrosion rate increases with increasing the concentration of inhibitor such as stainless steel, but at concentration 708.8 ppm the corrosion rate for all metals decreases compared with the corrosion of metal without inhibitor. Therefore this concentration was used in studying galvanic corrosion.

When the acidity of solution decreases, the rate of corrosion at PH = 1 is 57.4 gmd, but at PH(0) it is (54) gmd,. The same thing for **cadmium** metal at PH(1) the rate of corrosion is (74) gmd while at PH(0) it is (42.3) gmd ,PH(2) is (57.8)gmd , PH(3) is (41.48)gmd . For **stainless steel** gmd rates are generally low at all PH values indicating a higher corrosion resistance in this environment. On the other hand **tin shows** increased rate of corrosion shown in Table (4.8) with increased PH because the salt and oxide of tin are soluble in alkaline solutions.

5.3.1 Inhibitor Concentration

Tables 4.5 to 4.8 show that the corrosion rate in (gmd ,mm/y ,mpy) at different concentrations of inhibitor and the efficiency of inhibition which increases with increasing its concentration leading to a decrease in the total cathodic reaction current , hence inhibitor leads to decrease in the corrosion rate . However in all cases preliminary stage of adsorption of the inhibitor would occurs.

The adsorption theory has fulfilled its purpose by forming on the metal surface adsorption protective layer. Adsorption is generally considered either a physical or chemical, but the efficiency of inhibition is not constant for all metals used experimentally leading to decrease the corrosion rate. However, in all cases, a preliminary stage of adsorption of the inhibitor can be envisaged and to the extent, the adsorption theory has fulfilled its purpose [10].

5.4 Galvanic Coupling [6.10]:

As shown in chapter three, the total anodic current of polyelectrode system is the sum of the corresponding anodic currents of the individual electrodes. If the total area of the system is S, made up of fractions f_A and f_B for the various components A, B, . . ,then the anodic current from the j^{th} component is given by [4,6]

$$I_a^{system} = \sum_j J_a^j = S \sum_j f^j \, i_a^j \qquad \text{... (5.1)}$$

Similarly, the total cathodic current is:

$$I_c^{system} = \sum_j J_c^j = S \sum_j f^j \, i_c^j \qquad \text{... (5.2)}$$

At the corrosion potential adopted by the polyelectrode, the total anodic and cathodic currents are equal, so that:

$$I_{corr}^{system} = I_{a}^{system} = \left|I_{c}^{system}\right| \qquad \ldots (5.3)$$

There is ageneral relation between penetration p(proportional to corrosion rate) of metal having area A_a ,coupled to more noble metal of area A_c where p° is the normal penetration of the metal given by :

$$P = P°(1+ A_c / A_a) \qquad \ldots(5.4)$$

If the area ratio A_c / A_a is large , the increased corrosion caused by coupling can be considerable. Conductivity of electrolyte and geometry of the system enter the problem only on that part of cathode area which is effective when resistance between anode and cathode is not a controlling factor.

The critical distance is greater then the larger potential difference between anode and cathode , all more noble metal accelerate corrosion ,except when surface film acts barrier to diffusion of oxygen or when the metal is a poor catalyst for reduction of oxygen .Increased area of more noble metal also increases corrosion of less noble metal [10].

This theory is not always correct for all coupling because some coupled metals do not obey this equation. Because of the limitation of the emf series for predicting galvanic relation and also because alloys are not included (conditions affecting equilibrium of solid alloy with their environment are not well under stood and the so called galvanic series has been suggested). This series is arrangement of metals and alloys according to their actual measured potential in considered environment.

5.5 Parameters That Affect Galvanic Corrosion

In Tables 4-9 to 4-56, the potential differences and current have been recorded from t=0 to t=120 min as shown in **Figs. 5-12a,b to 23a,b.**

5.5.1 Inhibitor Concentration

In **Figs.5-12a to 5-23a** and Tables 4-9 to 4-56 one can notice that the value of current difference between two metals will be less than the value of current without inhibitor. Increasing inhibitor concentration decreases the value of corrosion rate as shown in **Tables. 4-9 to 4-56** . The potential difference between two metals increases with deceased value of galvanic current.

5.5.2 Area Ratio

Galvanic current increaseS with increasing area ratio (AR). Also the potential difference is increased with increasing area ratio. Area ratio plays an important role in galvanic corrosion as it was found from the results obtained in chapter five. It plays a comprehensive role as shown in **Figs. 5-21a,b to 5-23a,b** and **Tables 4-9 to 4-56** which show that increase in area ratio (A_c/A_a) increases current. Increasing area ratio leads to increase the exposed area to corrosive solution, i.e. the more negative electrode will corrode and the more positive electrode is protected.

5.6 Measuring the Potential and Current Together for Different Coupled Metals

Tables 4-9to 4-56 in chapter four represent results of galvanic potential, which was measured with galvanic current simultaneously as explained in chapter three. With closed circuit a mixed potential results. The potential is increased with increasing inhibitor concentration for C.S & Cd. there was declining in potential curve until stationary phase after about 30 min for all metals. In **Figs. 5-21a to 5-23a** one can notice that the galvanic current in the first few readings, has a fast declining, then it tends to settle down to a steady state phase after about 30 minute The potential values for all coupled metals are increased with decrease in corrosion current. As galvanic current increases the weight loss will be increased .The experimental runs were repeated for different values of (AR) and concentration of inhibitor. All the following experimental runs were duplicated using different metal couplings (C.S/Cd ,C.S/St.St ,St.St/Cd) for different area ratios and different inhibitor concentrations. The potential difference was measured every 5 min up to 2 hours.

5.7 Stainless Steel and Carbon Steel Coupling at PH=0 With &Without Inhibitor

There are two main categories of these experiments:

A -Direct results of current against time for 120 minutes as shown in **Figs.(5.12.a) to Figs(5.13.a) & tables 5.8 & 5.9.**

B - Direct results of voltage difference against time for 120 minutes as shown in **Figs.(5.12.b) to Figs.(5.13.b)**

Table (5.8): Effect of area ratio (without inhibitor) on galv. corrosion current of couple (C.S/St.St) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state

(C.S/St.St) PH=0 without inhibitor		
gmd$_{(C.S)}$ =54 , gmd$_{(St.St)}$=33.3		
AR	**I(mA)**	**E(volt)**
1	0.39	0.390
0.75	0.40	0.396
0.5	0.29	0.160
0.25	0.89	0.028

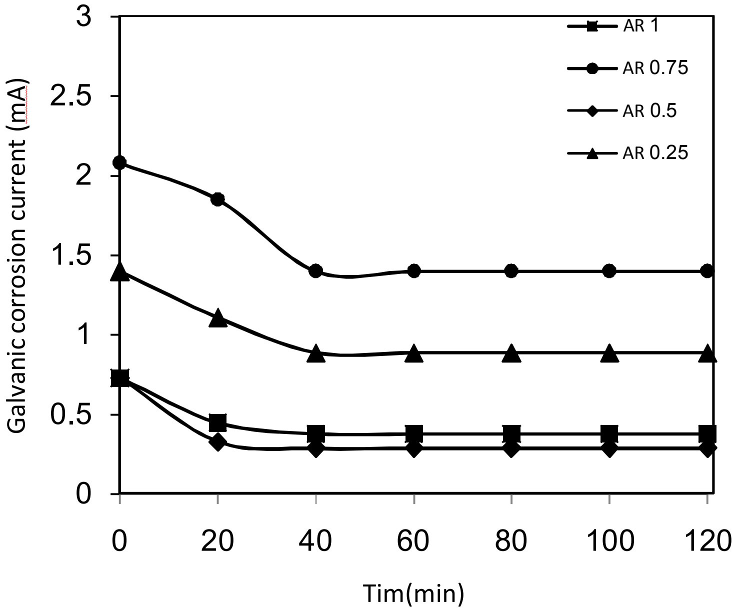

Figure (5.9a) Galv. current vs. time for stainless steel and carbon steel metals in 0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) ,T=40 ^{o}C, t=120m, PH=0 without inhibitor using zero resistance ammeter.

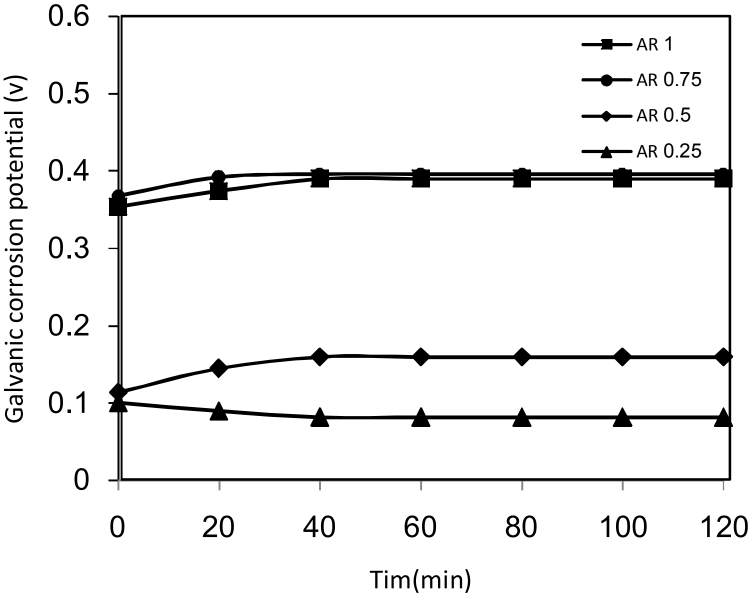

Figure (5.9b) Galv. potential difference vs. time for stainless steel and carbon steel metals in 0.1N NaCl AR(St.St/C.S)=(1,0.75,0.5,0.25), T=40 °C, t=120m, PH=0 without inhibitor

Table (5.9): Effect of inhibitor708.8ppm on galv. corrosion current of couple (C.S/St.St) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state .

(C.S/St.St) PH=0 with708.8ppm		
gmd(C.S) = 17.7 , gmd(St.St)=8.5		
AR	**I(mA)**	**E(volt)**
1	0.28	0.307
0.75	1.10	0.300
0.5	0.12	0.47
0.25	0.10	0.258

From comparing the above data for coupling of carbon steel and stainless steel with and with out inhibitor, it can be noticed that the inhibitor is effective at all area ratios as shown by the following sequence:

0. 5>0.75 ,0.25 (the value of area ratio)

0.28 > 0.12 > 0.1, 0.1 (the value of current)

There is critical area ratio to decrease the value of coupling current of C.S/ St.St

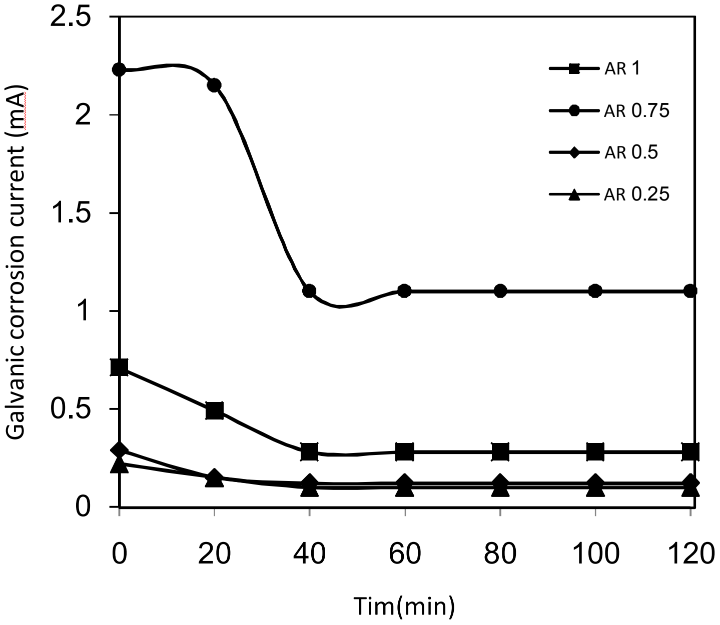

Figure (5-10a) Galv. current vs. time for stainless steel and carbon steel metals in 0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=0 with708.8ppm inhibitor .

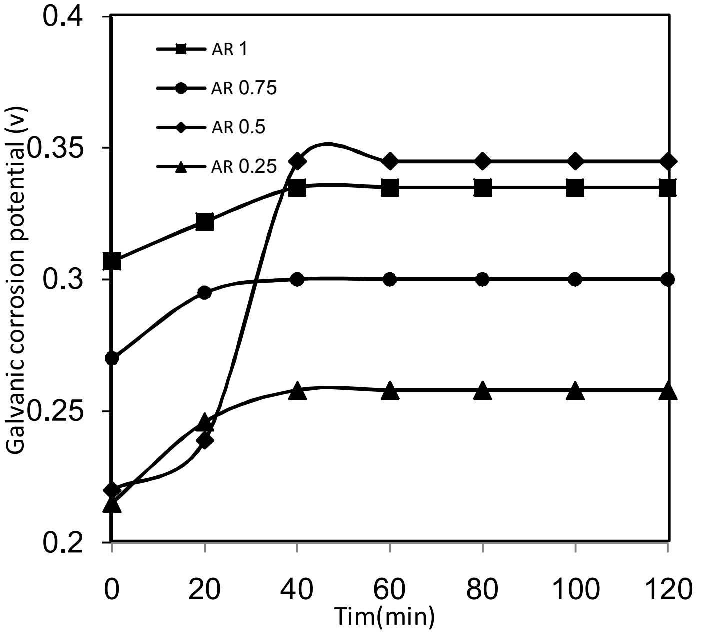

Figure (5-10b) Galv. potential difference vs. time for stainless steel and carbon steel metals in0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) , T=40 ^{0}C,t =120 min, PH=0 with708.8ppm inhibitor

5.8 Cadimum and Carbon Steel Coupling at PH=0 With &Without Inhibitor

There are two main categories of these experiments:

A . Direct results of current against time for 120 minutes as shown in **Figs.(5.14a)to Figs(5.15.a)**

B . Direct results of voltage difference against time for 120 minute as shown in **Figs.(6.14.b) to Figs (6.15.b)** .

Table (5.10): Effect of area ratio (without inhibitor) on the corrosion current of couple (C.S/Cd) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min.

(C.S/Cd) PH=0 without inhibitor		
gmd(C.S) = 54, gmd(Cd)=42.3		
AR	**I(mA)**	**E(volt)**
1	11.27	0.330
0.75	13.77	0.327
0.5	11.52	0.333
0.25	13.10	0.325

From table (5.10) it can be seen that both metals are corroding couples acting as cathode and anode simultaneously.

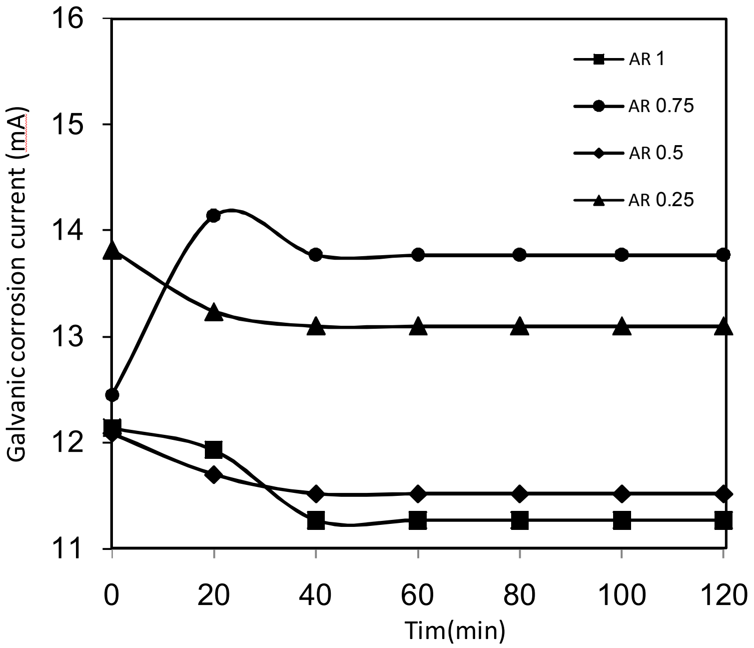

Figure (5.11a) Galv**.** current vs. time for cadmium and carbon steel metals in 0.1N NaCl ,AR(Cd/C.S)=(1, 075,0.5,0.25) ,T=40 ^{o}C, t=120m, PH=0 without inhibitor.

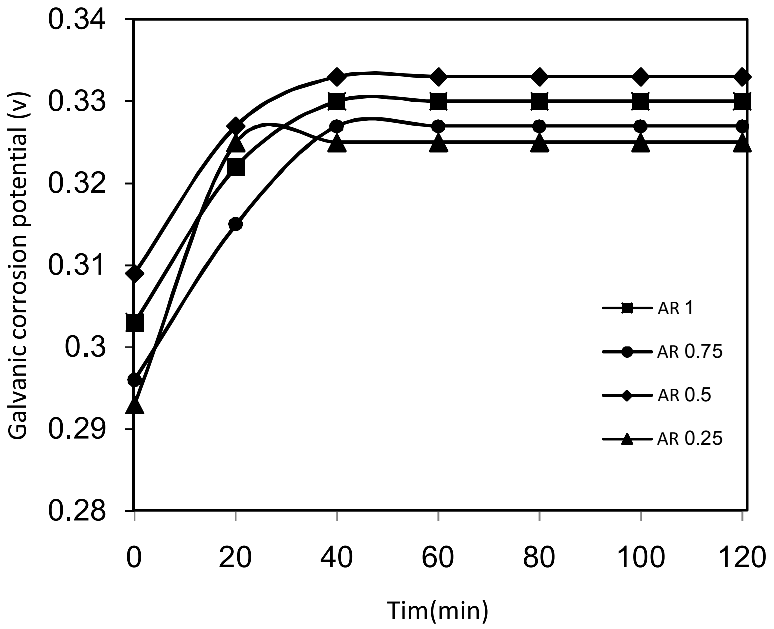

Figure (5.11b) Galv. potential difference vs. time for cadmium and carbon steel couples in 0.1N NaCl AR(Cd/C.S)=(1,0.75,0.5,0.25), T=40 ^{o}C, t=120m, PH=0 without inhibitor.

Table (5.11): Effect of inhibitor,708.8ppm, on the corrosion current of couple (C.S/Cd) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state .

(C.S/Cd) PH=0 with708.8ppm		
gmd(C.S) = 17.7, gmd(Cd)=13.7		
AR	**I(mA)**	**E(volt)**
1	0.02	0.413
0.75	0.01	0.394
0.5	0.14	0.348
0.25	0.13	0.364

From comparing the above data for carbon steel and cadimum with and without inhibitor it can be noticed that the inhibitor is very effective at all area ratios (1, 0.75, 0.5 &0.25) especially at AR 0.75

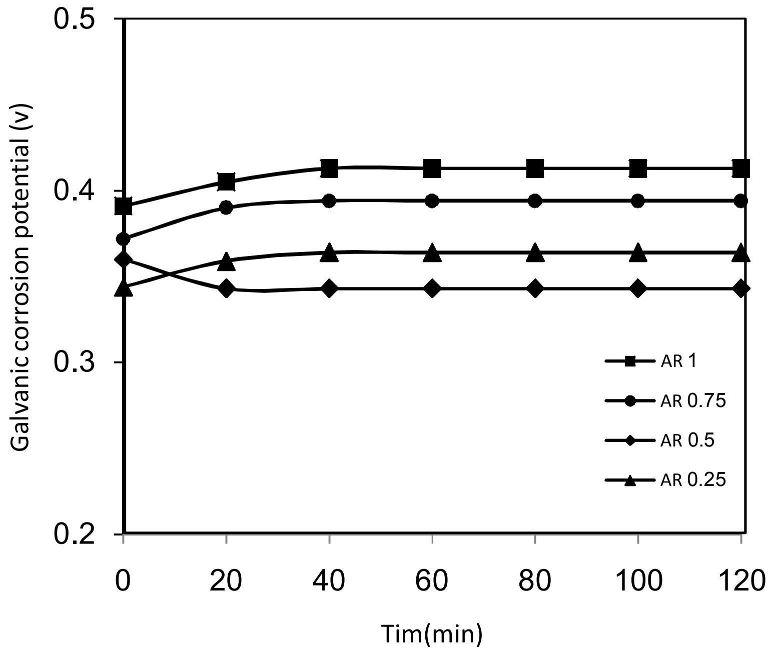

Figure (5.12b) Potential difference vs. time for cadmium and carbon steel couple in 0.1N NaCl ,AR(Cd/C.S)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=0 with708.8ppm inhibitor

5.9 Stainless Steel and Cadmium Coupling at PH=0 With &Without Inhibitor

There are two main categories of these experiments:

A . Direct results of current against time for 120 minutes as shown in **Figs. (5.16.a) to Figs (5.17.a)**

B . Direct results of voltage difference against time for 120 minutes, as shown in **Figs.(5.16.b) to Figs.(5.17.b)**

Table (5.12): Effect of area ratio (without inhibitor) on galv. corrosion current of couple (St.St/Cd) in air saturated 0.1N NaCl solution ,T=40C°,t=120min at steady state

(St.St/Cd) PH=0 without inhibitor		
gmd$_{(St.St)}$ = 33.3, gmd$_{(Cd)}$=42.3		
AR	**I(mA)**	**E(volt)**
1	10.22	0.335
0.75	13.60	0.330
0.5	11.50	0.347
0.25	12.08	0.328

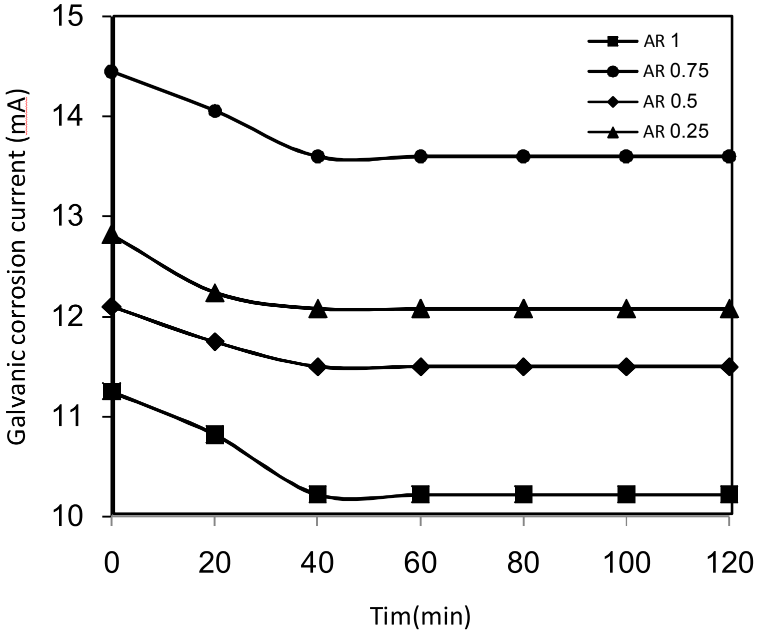

Figure (5.13a) Galv. current vs. time for stainless steel and cadmium metals in 0.1N NaCl ,AR(St.St/Cd)=(1, 075,0.5,0.25) ,T=40 ^{o}C, t=120m, PH=0 without inhibitor.

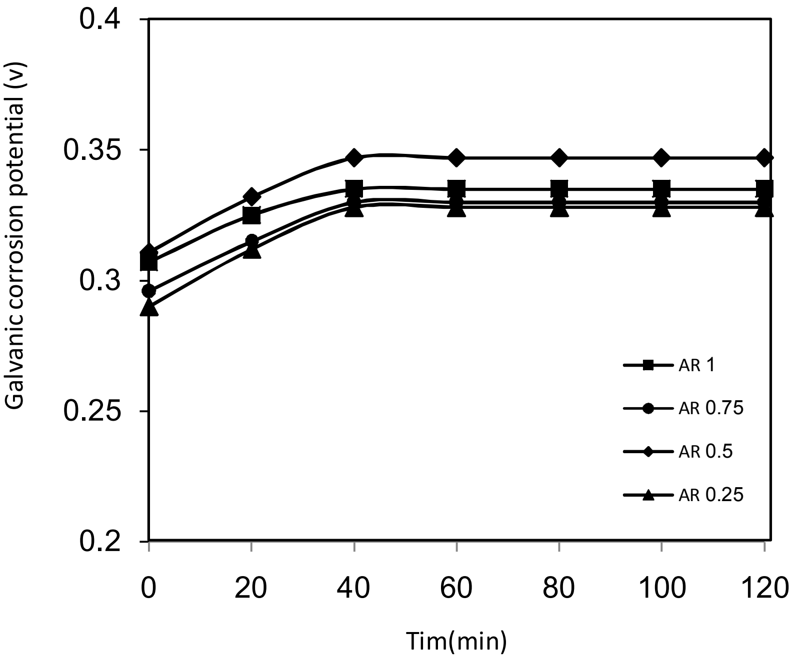

Figure (5.13b) Potential difference vs. time for stainless steel and cadmium couple in 0.1N NaCl ,AR(St.St/Cd)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=0 without inhibitor.

Table (5.13): Effect of inhibitor,708.8ppm, on the corrosion current of couple (St.St/Cd) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state

(St.St/Cd) PH=0 with708.8ppm		
gmd$_{(St.St)}$ = 8.5, gmd$_{(Cd)}$=13.7		
AR	**I(mA)**	**E(volt)**
1	0.59	0.253
0.75	0.62	0.276
0.5	0.39	0.458
0.25	1.43	0.498

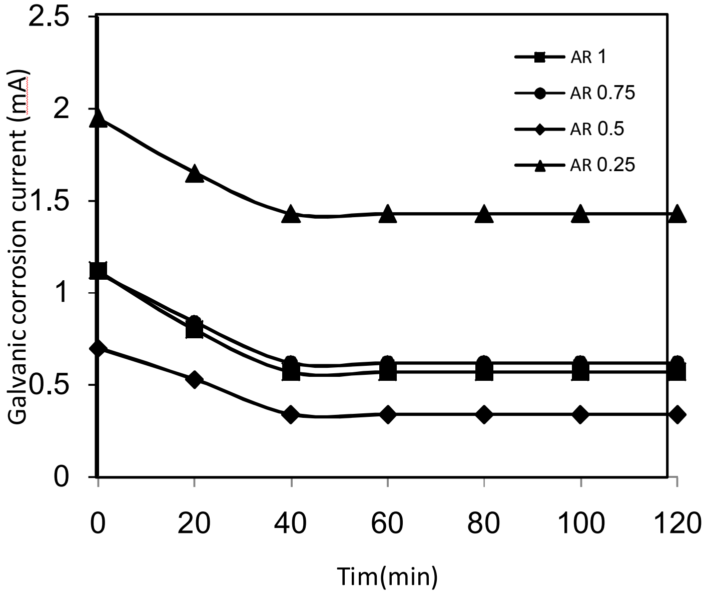

Figure (5.14a) Galv. current vs. time for stainless steel and cadmium metals in 0.1N NaCl ,AR(St.St/Cd)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=0 without inhibitor.

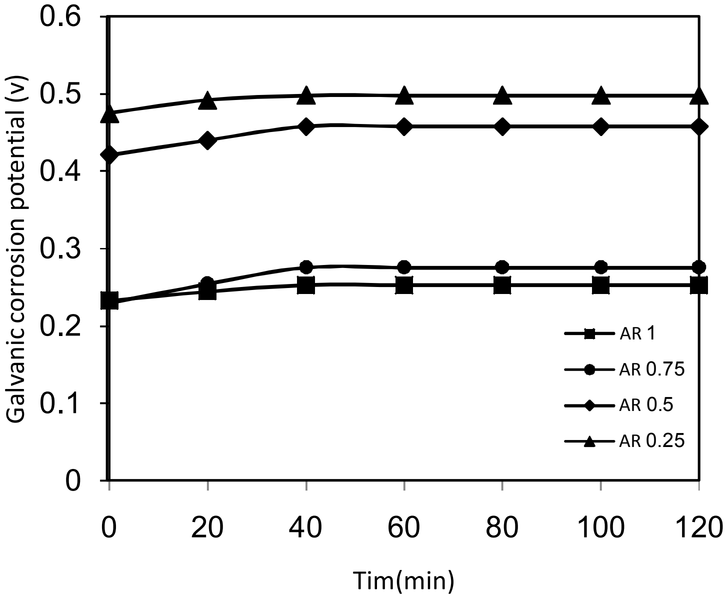

Figure (6.14b) Potential difference vs. time for stainless steel and cadmium couple in 0.1N NaCl ,AR(St.St/Cd) =(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=0 without inhibitor.

5.10 Stainless Steel and Carbon steel Coupling at PH=1 With &Without Inhibitor

There are two main categories of these experiments:

A . Direct results of current against time for 120 minutes as shown in **Figs.(5.18.a) to Figs (5.19.a)**

B . Direct results of voltage difference against time for 120 min as shown in **Figs.(5.18.b) to Figs (5.19.b)**

Table (5.14): Effect of area ratio (without inhibitor) on galv. corrosion current of couple (St.St/C.S) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state

(St.St/C.S) PH=1 without inhibitor		
gmd$_{(St.St)}$ = 25.18, gmd$_{(C.S)}$=57.4		
AR	**I(mA)**	**E(volt)**
1	0.16	0.270
0.75	0.14	0.263
0.5	0.10	0.346
0.25	0.14	0.405

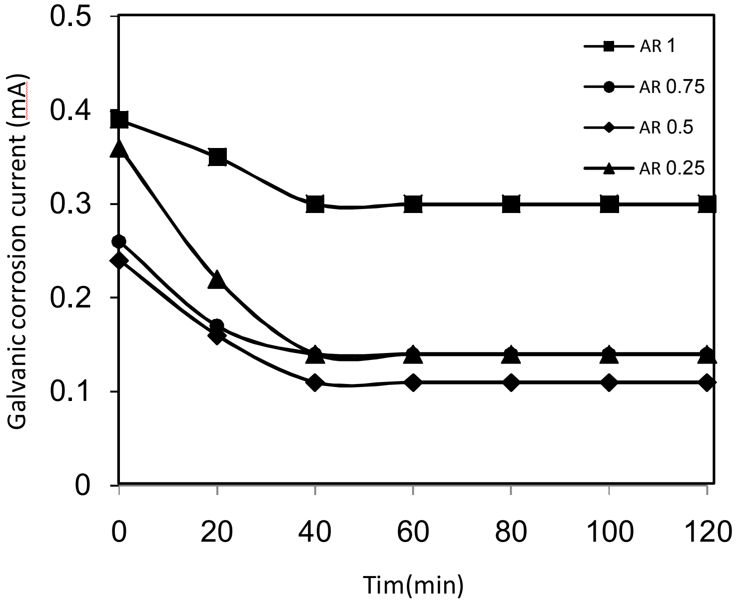

Figure (5.15a) Galv. current vs. time for stainless steel and carbon steel metals in 0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 without inhibitor.

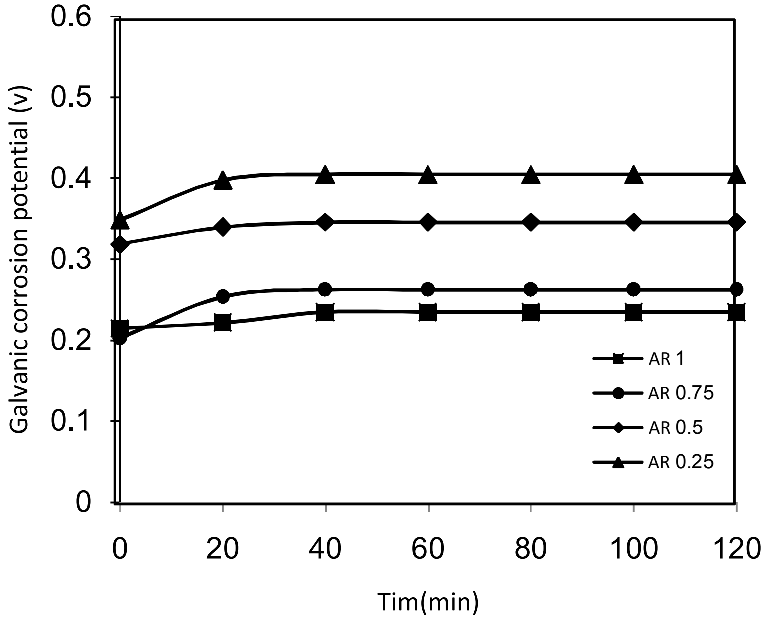

Figure (5.15b) Galv. potential difference vs. time for stainless steel and carbon steel metals in 0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 without inhibitor.

Table (5.15): Effect of inhibitor,708.8ppm,on the corrosion current of couple (St.St/C.S) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min.

(St.St/C.S) PH=1 with708.8ppm		
gmd(St.St) = 14.4, gmd(C.S)=9.6		
AR	**I(mA)**	**E(volt)**
1	0.75	0.347
0.75	0.55	0.289
0.5	0.14	0.240
0.25	0.12	0.253

At PH(1)for coupling C.S/St.St the inhibitor is not very effective, but only at AR= 0.25 the corrosion current decreased from 0.14 to become 0.12 .

So for this couple in 708.8 ppm inhibitor it can be notice dthat the value of I decreased as area ratio decreased as follows:

1< 0.75< 0.5 <0.25 (the value of area ratio)

0.75<0.55 < 0.14< 0.12 (the value of current)

Thus if area ratio becomes small the value of current would become low. This would indicate some protection for carbon steel and stainless steel when inhibitor concentration is 708.8 ppm .

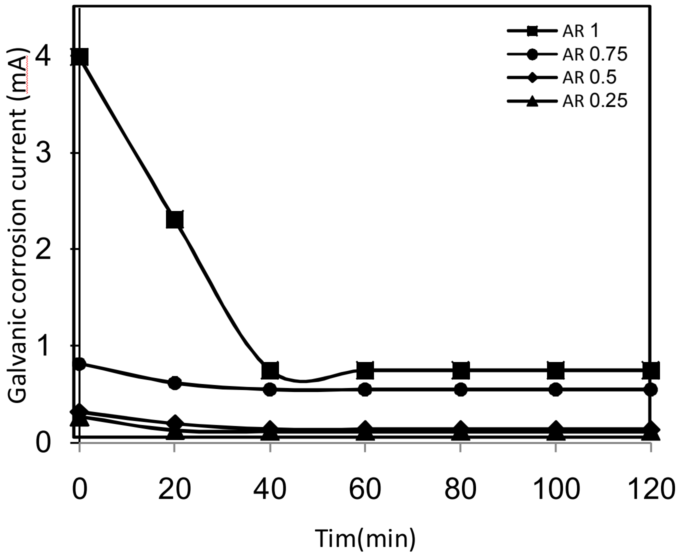

Figure (5.16a) Galv. current vs. time for stainless steel and carbon steel metals in 0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 with708.8ppm inhibitor .

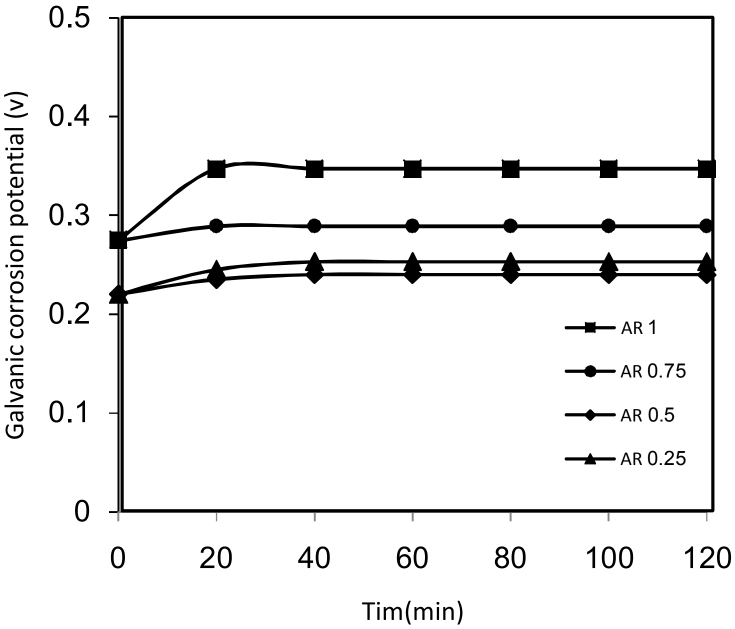

Figure (5.16b) Galv. potential difference vs. time for stainless steel and carbon steel metals in 0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 with708.8ppm

5.11 Cadmium and Stainless Steel Coupling at PH=1 Without & Without Inhibitor

There are two main categories of these experiments:

A . Direct results of current against time for 120 minutes as shown in **Figs.(5.20.a)to Figs.(5.21.a)**

B . Direct results of voltage difference against time for 120 minute as shown in **Figs.(5.20.b) to Figs (5.21.b)**

Table (5.16): Effect of PH (without inhibitor) on the corrosion current of couple (St.St/Cd) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state

(St.St/Cd) PH=1 without inhibitor		
gmd$_{(St.St)}$ =25.18 , gmd$_{(Cd)}$=74		
AR	**I(mA)**	**E(volt)**
0	2.80	0.333
0.75	2.60	0.276
0.5	1.39	0.441
0.25	1.74	0.498

Table 5.16 shows as in other tables that the galvanic current decreases with decreased area ratio.

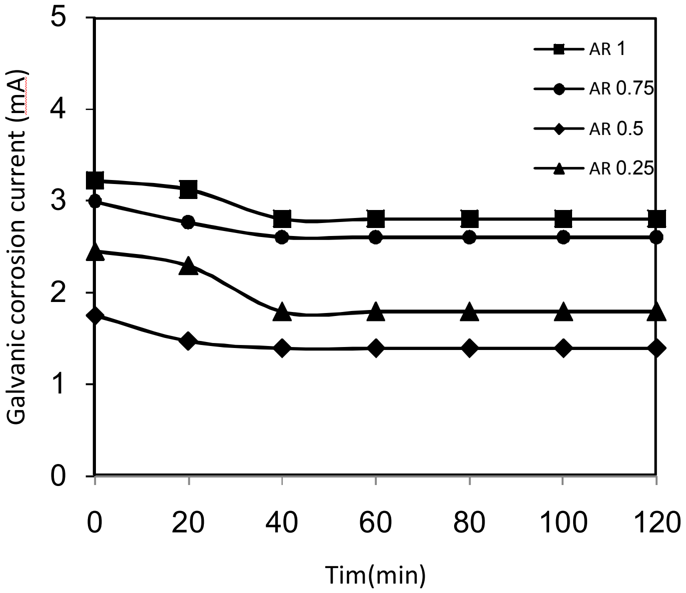

Figure (5.17a) Galv. current vs. time for stainless steel and cadmium metals in 0.1N NaCl ,AR(St.St/C.S)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 without inhibitor.

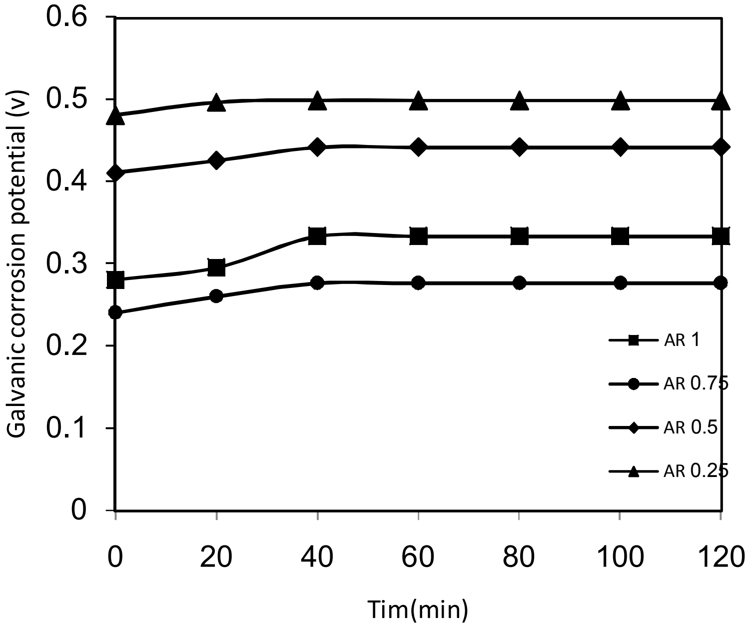

Figure (5.17b) Galv. potential difference vs. time for stainless steel and cadmium metals in 0.1N NaCl ,AR(St.St/Cd)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 without inhibitor

Table (5.17): Effect of inhibitor708.8ppm on the corrosion current of couple (St.St/Cd) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state

(St.St/Cd) PH=1 with708.8ppm		
gmd(St.St) = 14.4, gmd(Cd)=12.9		
AR	**I(mA)**	**E(volt)**
0	0.65	0.320
0.75	0.65	0.249
0.5	0.46	0.439
0.25	1.76	0.491

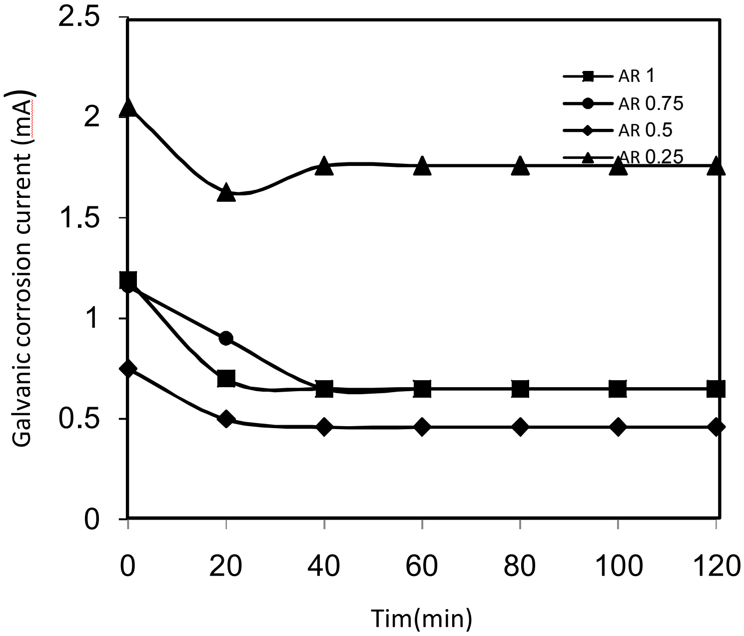

Figure (5.18a) Galv. current vs. time for stainless steel and cadmium metals in 0.1N NaCl ,AR(St.St/Cd)=(1, 075,0.5,0.25) ,T=40 ^{o}C, t=120m, PH=1 with708.8ppm inhibitor.

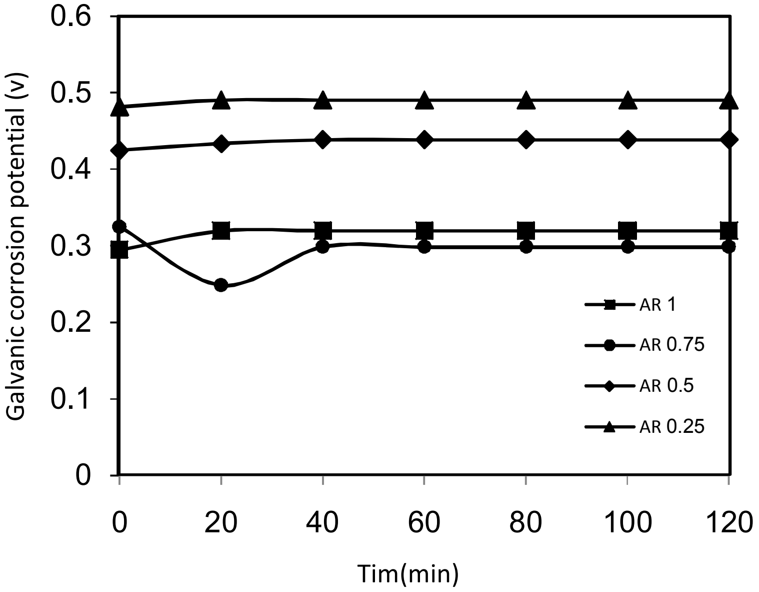

Figure (5.18b) Galv. potential difference vs. time for stainless steel and cadmium metals in 0.1N NaCl ,AR(St.St/Cd)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 with708.8ppm inhibitor

5.12 Cadmium and Carbon Steel Coupling at PH=1 Without & Iithout inhibitor

There are two main categories of these experiments:

A . Direct results of current against time for 120 minutes as shown in **Figs.(5.22a) to Figs.(5.23a)**

B . Direct results of voltage difference against time for 120 minutes, experiments were carried out in aerated 0.1N NaCl under the same conditions of cadmium and carbon steel coupling above, as shown in **Figs.(5. 22b) to Figs.(5.23b)**

Table (5.18): Effect of area ratio (without inhibitor) on the corrosion current of couple (C.S/Cd) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state

(C.S/Cd) PH=1 without inhibitor		
gmd(C.S) = 54, gmd(Cd)=74		
AR	**I(mA)**	**E(volt)**
1	14.69	0.312
0.75	9.66	0.340
0.5	8.60	0.366
0.25	13.06	0.332

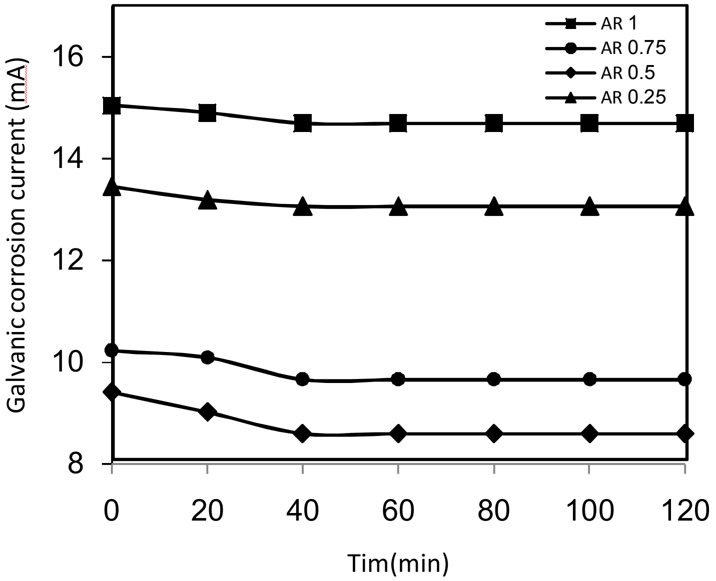

Figure (5.19a) Galv. current vs. time for carbon steel and cadmium metals in 0.1N NaCl ,AR(C.S/Cd)=(1, 075,0.5,0.25) ,T=40 ^{o}C, t=120m, PH=1 without inhibitor .

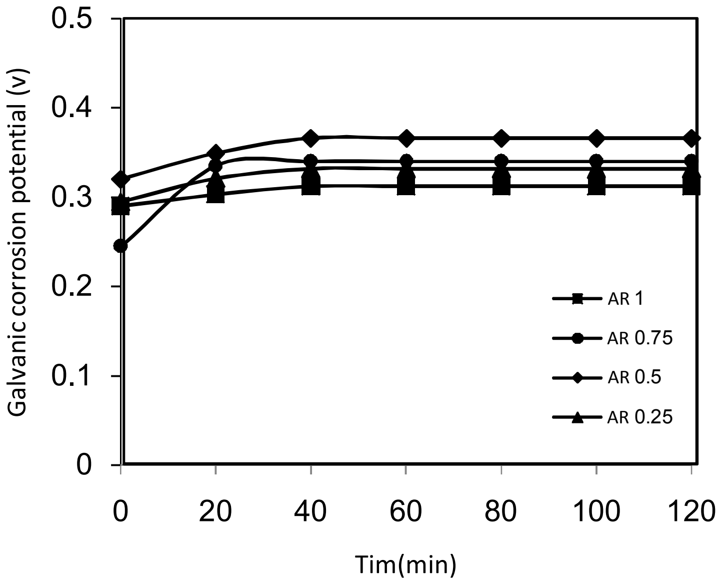

Figure (5.19b) Galv. potential difference vs. time for carbon steel and cadmium metals in 0.1N NaCl ,AR(C.S/Cd)=(1, 075,0.5,0.25) ,T=40 ^{o}C, t=120m, PH=1 without inhibitor .

Table (5.19): Effect of inhibitor,708.8ppm, on the corrosion current of couple (C.S/Cd) in air saturated 0.1N NaCl solution , T=40 ^{0}C,t =120 min at steady state

(C.S/Cd) PH=1 with708.8ppm		
gmd$_{(C.S)}$ = 9.6 , gmd$_{(Cd)}$=12.9		
AR	**I(mA)**	**E(volt)**
1	13.38	0.283
0.75	9.00	0.310
0.5	8.30	0.320
0.25	12.02	0.299

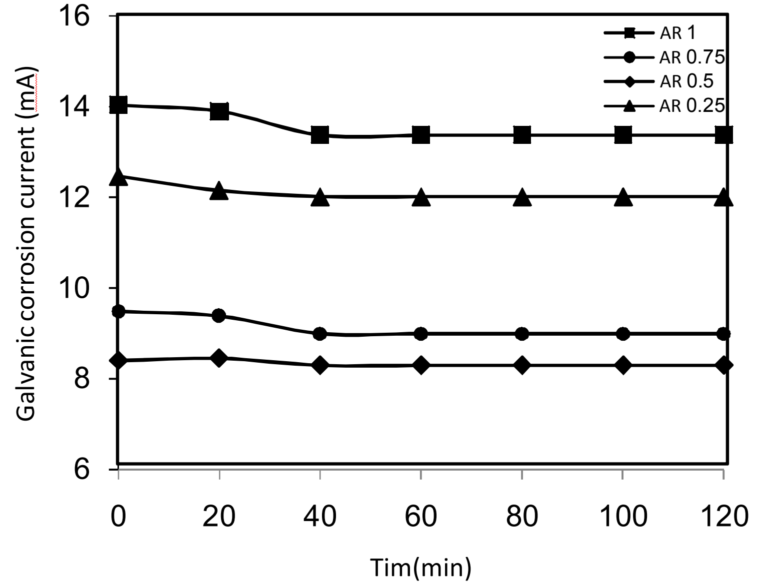

Figure (5.20a) Galv. current vs. time for carbon steel and cadmium metals in 0.1N NaCl ,AR(C.S/Cd)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 with708.8ppm inhibitor.

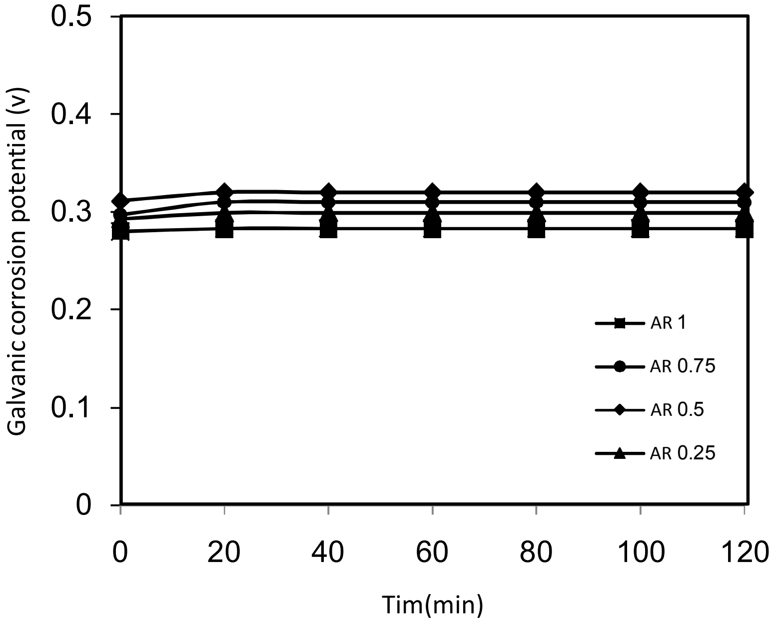

Figure (5.20b) Galv. potential difference vs. time for carbon steel and cadmium metals in 0.1N NaCl ,AR(C.S/Cd)=(1, 075,0.5,0.25) ,T=40 °C, t=120m, PH=1 with708.8ppm inhibitor

For this couple the inhibitor is effective in reducing the rate of corrosion current , e.g., at AR(1) the inhibitor decreases the current from 14.69 to 13.38 and the same thing for other area ratios. It can be seen that the value of gmd in above tables and to back to table (5.2), it is found that (Cd) is anode and (C.S) is cathode

From comparing the above data for carbon steel and cadimum with and without inhibitor it can be noticed that the inhibitor is effective at all area ratios 1,0.75, 0.5, 0.25. The lower coupling current means less corrosion as shown below:

1>0.75 0.5>0.25 (values of area ratio)

13.38> 9>8.30>12.02 (values of current)

There is an area ratio to decrease the value of coupling current of C.S/ Cd a minimum value.

All investigated systems indicate a dissolution current of each member of the various couples showing galvaning corroding couples with partial protection of a member with or without inhibitor.

Chapter Six

Conclusions and Recommendations for Future Work

The present work has been mainly aimed to investigate the mechanism of galvanic corrosion using coupled metals (C.S , St.St ,Cd) . Also the mechanism of its inhibition under the influence of various factors, i.e. , types of metals in contact, metals area ratio, and the type of an inhibitor and its concentration in air-saturated 0.1N NaCl at a variable area ratio, concentration of inhibitor , type of metal and different values of solution PH.

6.1 Conclusions

1- Corrosion potential for all metals as a single phenomenon becomes more negative with time reaching the steady state condition after short initial period of about 30 minutes.

2- The steady state corrosion potentials are sufficiently apart to induce galvanic corrosion on coupling these metals.

3- Stainless steel,carbon steel and tin can act as good cathodes in comparison with cadmium under the present conditions. Cd shows the most negative corrosion potential.

4- For single metal (weight loss) the corrosion of all metals decreases with increasing concentration of inhibitor. The efficiency reaches 98% for cadmium in the presence of 708.8 ppm at PH(3) and 92% in 521.6ppm concentration at PH(1) . It can be noticed the data of Free corrosion of C.S at PH (0) is more than other metals. At all PH values stainless steel suffers the least corrosion. Tin shows the highest corrosion rate among these metals at PH(3) .

5- When the concentration of inhibitor increases to 708.8ppm the inhibitor has different effects on metal couples depending mainly on coupled metals. Galvanic current, and dissoluion corrosion rate change with area ratio , and inhibitor concentration. They decrease with increasing inhibitor concentration in 0.1NNaCl solution , but this is not for all galvanic couples.

6- Each metal coupling should be studied at given PH alone because there is no clear relationship with other couplings or area ratio using this inhibitor .

7- In all cases Cd can protect C.S. at PH(0) for all area ratios at least partially, but the protection is different with other PH values.

6.2 Recommendations for Future Work

The following suggestions are to be considered or to be examined in greater detail for future work:

1- Studying the influence of geometry of sample on galvanic current and galvanic potential difference.

2- Investigating galvanic current and potential difference with longer time and different PH values under different isothermal conditions.

3- C.S and St.St at all PH values (0,1,2,3) work as cathode to cadmium in the coupling experiments between these metals which would require further detailed investigation to benefit from cadmium and its alloys as sacrificial anodes.

4- Investigating the benefit of other types of inhibitors to reduce galvanic corrosion.

5- AR and PH play important role in affecting the galvanic factor (GF) which would suggest simultaneous investigation of their combined influence.

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الخلاصة

لاهمية التاكل الغلفاني ظهرت الحاجة لدراسة تاثير مثبطات التاكل نسبة مساحة الكاثود الى الانود في خلية التاكل الغلفاني ولعدة معادن مهمة صناعيا ولمعرفة كيفية تصرف معدلات التاكل لهذه المعادن وفي هذه التجربة وكخطوة اولية قمنا بقياس جهد التاكل مع الزمن لاربعة معادن مختلفة تم وضعها في اربعة قيم مختلفة من محلول PH الحامضي لمعرفة أي المواد يسلك سلوك الكاثود وايها يسلك سلوك الانود بينما استخدما مبدأ الضغط ن بالوزن كدليل يساعد على معرفة كفاءة المثبط في تقليل معدل التاكل لهذه المعادن (كاربون ستيل ,ستينلس ستيل, كادميوم ,قصدير)في اربع قيم لمحلول PH الحامضي (0,1,2,3) واربع تراكيز مختلفة للمثبط المستخدم في التجربة وهي ppm (531.6,354.4,177.2 and 708.8) خلية التاكل صممت لقياس فرق الجهد والتيار مع الزمن لكل مزدوج من هذه المعادن لقد تم دراسة اربعة عوامل رئيسية مؤثرة على مبدأ التاكل الغلفاني وهي NaCl

1. قيمتان مختلفة للاس الحامضي وهي (0,1) في 0.1 عياري لكلوريد الصوديوم
2. ثلاث انواع من المعادن (كاربون ستيل , ستينلس ستيل , كادميوم)
3. نسبة المساحات (نسبة مساحة الكاثود الى الانود) حيث تم دراسة اربع نسب وهي (1,0.75,0.5,0.25)
4. تركيز واحد لمثبط (Dimethalaminoethanol) ppm (708.8) في درجة حرارة 40 م° و 0.1 عياري لكلوريد الصوديوم

تم دراسة كل من التيار والجهد في معظم الحالات وبالضروف السابقة حيث لوحظ ان معدل التاكل للمواد يقل بزيادة تركيز المثبط الذي يؤدي الى تقليل معدل التاكل بكفاءة تصل الى 98% لمعدن الكادميوم في الاس الحامضي الثالث وبتركيز ppm (708.8)

اجريت التجارب على المزدوج (كاديميوم و كاربون ستيل) , (كاربون ستيل و ستينلس ستيل) , (كادميوم و استينلس ستيل) حيث تم قياس فرق جهديهما والتيار لكل مزدوج ووجد ان قيمة التيار لكل مزدوج تقل مع زيادة تركيز المثبط وان جهد كل منهما يصل الى قيمة الاخر في الاس الحامضي (0) وكذلك الجهد (فعالية المعدن) تزداد مع تقليل قيمة الاس الحامضي (PH) ولكن هذه القاعدة ليست ثابتة لكل المعادن ولكل معدلات المساحة .

وتم معرفة قيمة التيار عندما كانت مقاومة النظام مساوية للصفر ولضروف معينة حيث كانت صغيرة مقارنة بالنتائج المستحصلة , وبصورة عامة اوضحت النتائج ان جهد التاكل يزداد باتجاه السالب بمرور الزمن

شكر وتقدير

اود ان اعبر عن خالص شكري وتقديري وامتناني العميق للمشرف الدكتور قاسم عبد الجبار سليمان لما قدمه لي من توجيهات قيمة ونصائح سديدة طوال فترة انجاز البحث.

اتقدم بالشكر الجزيل الى كادر قسم الهندسة الكيمياوية التدريسي والاداري لاسهامهم في اظهار هذه الاطروحة بالشكل المناسب والى كافة زملائي لمساعتهم بطريقة او باخرى لانجاز هذا العمل

كما اتقدم بالشكر والامتنان الى من ساندني طوال فترة البحث بكل الحب والعطف الى احب من في الوجود ابي وامي وجميع افراد عائلتي

ولا انسى ان اتقدم بفائق الشكر والامتنان الى الاستاذعصام احمد والى زوجي العزيز الذي وقف معي طوال فترة البحث لهم جزيل الشكر والتقدير.

زينب علي زغيلي

تشرين الاول 2009

تثبيط التاكل الكلفاني في محلول كلوريد الصوديوم

رسالة

مقدمه الى كلية الهندسة في جامعة النهرين وهي جزء من متطلبات
نيل درجة ماجستير علوم في الهندسة الكيمياوية

من قبل

زينب علي زغيلي

بكالوريوس علوم في الهندسة الكيمياوية 2006

محرم 1431هـ

تشرين الاول 2009 م