



THE INFLUENCE OF REYNOLDS NUMBER AND TEMPERATURE ON THE MASS TRANSFER COEFFICIENT OF THE CORRODING PIPE

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ABSTRACT

Corrosion of carbon steel pipe in aerated 0.1N NaCl solution under isothermal turbulent flow conditions (Reynolds number= 15000-113000 and temperature of 30-60°C) is investigated by weight loss method. The effect of Reynolds number and temperature on corrosion rates is experimentally studied and discussed.

Corrosion mechanism is analyzed as a mass transfer operation and the corrosion rate is expressed in terms of mass transfer dimensionless groups (Sh and St) and in terms of usual corrosion units. The results of corrosion rates are compared with many proposed models particularly those based on the concept of analogy among mass, heat, and momentum transport by determining experimental friction factor. The capability of these models to express corrosion rates over the investigated range of Re and temperature is examined and discussed. Many of these correlations are adopted to estimate corrosion rates for the considered system.

It is found that Reynolds number increases the corrosion rate depending on temperature. Temperature increases the corrosion rate for high and moderate values of Reynolds number. At low Reynolds number the effect of temperature depends on oxygen solubility, oxygen molecular diffusivity, and Reynolds number (or eddy diffusion).

Generally, Von Karman and Prandtl-Taylor analogies (based on the experimental friction factor) show good agreement with experimental mass transfer results while Chilton-Colburn analogy exhibits reasonable agreement at low Reynolds number and some overestimation at high Reynolds number.

الخلاصة

تم إجراء اختبارات التآكل على أنبوب من الفولاذ الكربوني في محلول كلوريد الصوديوم (0.1 عياري) الحاوي على أوكسجين الجو الذائب تحت ظروف الجريان المضطرب بسرعات ودرجات حرارة مختلفة (عدد رينولد 15000 إلى 113000 ودرجة حرارة من 30°C إلى 60°C) باستخدام طريقة فقدان الوزن. تمت دراسة مختبرية ومناقشة تأثير عدد رينولد (أو السرعة) ودرجة الحرارة على معدل التآكل وتأثير.

تم تحليل عملية التآكل كعملية انتقال كتلة ووضعت علاقات تجريبية وضعية لحساب معدل التآكل تحت ظروف مختلفة. وقد تم مقارنة النتائج العملية مع عدة علاقات موضوعة للتعبير عن انتقال الكتلة بين الجدار والمائع وخاصة العلاقات المبنية عن التشابه في ميكانيكية الانتقال بين الكتلة والحرارة والزخم لمعرفة إمكانية

حساب معدل التآكل باستخدام هذه العلاقات. وقد تم اعتماد بعض هذه العلاقات للتعبير عن معدل التآكل للنظام المذكور.

دلت النتائج على ان زيادة عدد رينولد تؤدي الى زيادة معدل التآكل لكل درجات الحرارة وكذلك تأثير عدد رينولد على معدل التآكل يتغير بتغير درجة الحرارة والزمن.

زيادة درجة الحرارة تؤدي الى زيادة معدل التآكل لقيم عدد رينولد المتوسطة والعالية أما عند قيم عدد رينولد الواطئة فان تأثير درجة الحرارة على معدل التآكل يعتمد على قيمة عدد رينولد.

أبدت علاقات (Prandtl-Taylor) و (Von Karman) توافقا جيدا مع النتائج العملية لكل قيم عدد رينولد. كذلك أبدت علاقة (Chilton-Colburn) توافقا مع النتائج العملية عند قيم عدد رينولد المنخفضة واعطت نتائج عالية نسبيا عند قيم عدد رينولد العالية.

KEY WORDS

Corrosion, mass transfer, turbulent flow, analogy

INTRODUCTION

The analogy among mass, heat, and momentum transfer has led to successful methods regarding the mass or heat transport interactions with fluid flow, since the behavior of three transport processes is similar in many ways. Most of experimental studies showed that there is a relation exists between mass (or heat) transfer and skin friction. A thorough knowledge of relationship would allow prediction of rate of mass (or heat) transfer from friction loss data [Knudsen and Katz 1958, Shreir 1994]. The analogy between momentum and heat transfer is best defined by Reynolds theory. According to this theory, the movement of heat (or mass) between a surface and a fluid follows the same laws as the movement of momentum between the surface and fluid, whether by conduction or convection. If Reynolds theory is correct, and if, in fact, mass (or heat) and momentum transfer follow the same laws, it will be possible to predict rates of mass (or heat) transfer from rate of momentum transfer and to predict temperature or concentration profiles from velocity profiles [Knudsen and Katz 1958]. Over the years there were many proposed correlations based on the concept of analogy among heat, mass, and momentum transport. **Table (1)** lists many analogy correlations.

Mass transfer theory can be applied to estimate corrosion rates for systems that are, (i) under diffusion control, (ii) not exhibiting passivity phenomena.

The geometry of a system, i.e., flat plates, stirrers, pipes, etc. have a large effect in determining the influence of Reynolds number on corrosion rate.

In many corrosion problems, there is strong evidence that the rate of uniform corrosion is controlled by the rate of mass transfer. This is true whether the corrosion fluid remains static or in fast motion with respect to the metal surface. However, molecular diffusion is not the only factor which influences the rate of corrosion. In addition, in turbulent fluids, the rate of transport of eddy diffusion appears to participate in the control of the over-all transfer rate. It is well known that the rate-controlling step in most natural water corrosion processes is the cathodic half reaction of oxygen reduction [Mahato et al. 19980, Atia 1996, Moreira et. al. 2004, Cheng and Steward 2004].

The aim of this work is to study the influence of Reynolds number and temperature on the mass transfer coefficient and corrosion rate for commercial steel pipe in 0.1N NaCl solution under fully developed turbulent flow conditions. It is aimed also to analyze the corrosion process as a mass transfer operation to investigate to what extent the diffusion controlled corrosion process can obey



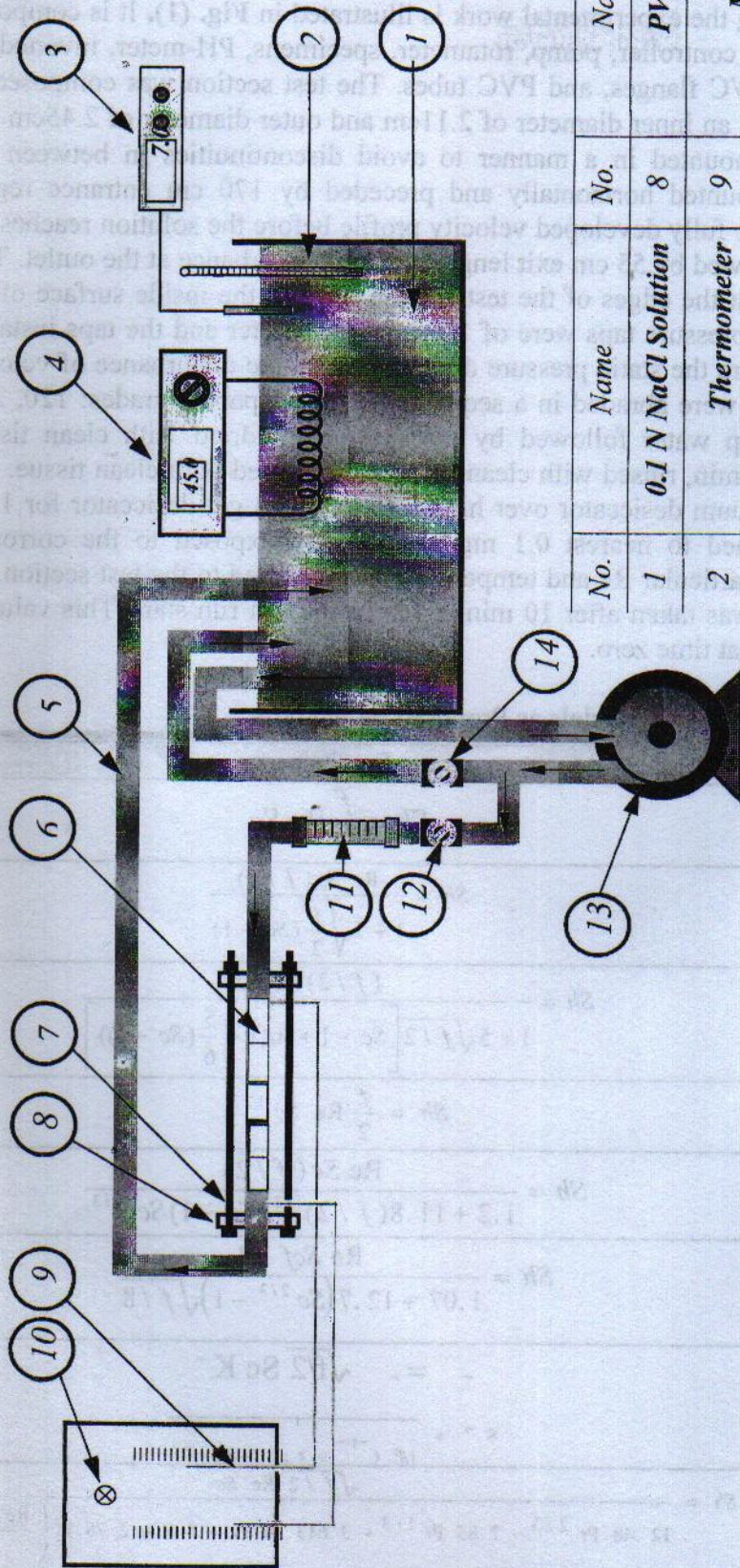
mass transfer models, particularly those based on the concept of valid analogy among momentum, heat, and mass transfer processes by determining experimental friction factor.

EXPERIMENTAL WORK

The dynamic system for performing the experimental work is illustrated in Fig. (1). It is composed of: electrolyte reservoir, heater and controller, pump, rotameter, specimens, PH-meter, inverted U-tube manometer, control valves, PVC flanges, and PVC tubes. The test section was composed of nine cylindrical specimens each has an inner diameter of 2.11cm and outer diameter of 2.45cm and 3cm long. The specimens were mounted in a manner to avoid discontinuities in between the specimens. The test section is mounted horizontally and preceded by 170 cm entrance region (i.e., L/d=80) of PVC tube to ensure fully developed velocity profile before the solution reaches the specimens. The test section is followed by 55 cm exit length to avoid disturbance at the outlet. Two static pressure taps were installed at the edges of the test section flash to the inside surface of the extension PVC pipe. The holes of pressure taps were of 1.5 mm in diameter and the taps installed flash to the inside surface to measure the static pressure drop and avoid the disturbance of velocity profile. Prior to use the specimens were abraded in a sequence of emery papers grades: 120, 200, 320, 400, and 600, washed by tap water followed by distilled water, dried with clean tissue, immersed in analar methanol for 5 min, rinsed with clean acetone, and dried with clean tissue. The specimens then were stored in vacuum desiccator over high activity silica gel desiccator for 1.5 h before use, then they were weighed to nearest 0.1 mg and directly exposed to the corrosion environment. The solution with a particular Re and temperature was pumped to the test section and the pressure drop across the later was taken after 10 minutes from the test run start. This value of pressure drop was considered to be at time zero.

Table (1) Analogy Models as Proposed by Authors

Author	Formula
Reynolds Analogy [Reynolds 1874]	$Sh = \frac{f}{2} Re Sc$
Prandtl -Taylor Analogy [Knudson and Katz 1958]	$Sh = \frac{Re Sc (f/2)}{1 + 5 \sqrt{\frac{f}{2}} (Sc - 1)}$
Von Karman Analogy [Karman 1939]	$Sh = \frac{(f/2) Re Sc}{1 + 5 \sqrt{f/2} \left[Sc - 1 + \ln \left(1 + \frac{5}{6} (Sc - 1) \right) \right]}$
Chilton and Colburn Analogy [Chilton and Colburn 1934]	$Sh = \frac{f}{2} Re Sc^{1/3}$
Deissler Analogy [Deissler 1952]	$Sh = \frac{Re Sc (f/2)}{1.2 + 11.8 (f/2)^{1/2} (Sc - 1) Sc^{-1/3}}$
Petukhov Analogy [Petukhov 1970]	$Sh = \frac{Re Sc f / 8}{1.07 + 12.7 (Sc^{2/3} - 1) \sqrt{f/8}}$
Mizushina Analogy [Mizushina 1977]	$Sh = \frac{\sqrt{f/2} Sc K^+}{K^+ = \frac{1}{\int_0^1 \left(\frac{1}{\epsilon} + \frac{\epsilon}{\nu} \right) dy}}$
Sandall et. al. Analogy [Sandall et. al 1980]	$Sh = \frac{\sqrt{f/2} Re Sc}{12.48 Pr^{2/3} - 7.85 Pr^{1/3} + 3.613 \ln Pr + 5.8 + 2.78 \ln \left(\frac{Re \sqrt{f/2}}{90} \right)}$



No.	Name	No.	Name
1	0.1 N NaCl Solution	8	PVC Flanges
2	Thermometer	9	Inverted Manometer
3	PH Meter	10	Venting Valve
4	Heater & Controller	11	Rotameter
5	Connection Pipes	12	Test section Valve
6	Specimens	13	Centerfugal Pump
7	Fixation Screw	14	By Pass Valve

Fig.(1) Experimental Apparatus

As the corrosion proceeds there was a continuous formation of corrosion products with time and hence continuous increase in pressure drop and friction factor. Therefore the values of pressure drop were recorded at different time intervals during the test period (including time zero) to obtain friction factor variation with time. The test duration was 6 h.

After exposure to the corrosion environment the specimen was washed by tap water then brushed by smooth brush under running tap water to remove part of corrosion products. Then the outer surface of specimen is insulated by teflon tape and the specimen was immersed in 20% warm hydrochloric acid containing organic inhibitor (hexamine) for 1.5 minutes. After that the specimen was washed by tap water, distilled water, dried with clean tissue, kept in dissector for 1.5 h, and then weighed. Blank tests showed no appreciable weight loss caused by the cleaning inhibited acidic solution.

RESULTS AND DISCUSSION

Friction Factor

Over the years, friction factor has received a wide attention from authors. Numerous studies have been performed to study factors influencing friction factor under different conditions, e.g., isothermal and heat transfer conditions [Colburn 1933, Mody 1944, Smith and Epstein 1957, Knudson and Katz 1958, Petukhov 1970] and roughness conditions [Mody 1944, Knudson and Katz 1958]. Most of these studies have showed that the main two variables influencing friction factor (f) were Re and surface roughness. The variation of friction factor with Re at time zero (clean surface) is presented in Fig.(2) as compared with other correlations (the effect of time on the friction factor will be considered in a other paper). It is obvious that f agrees with that of Knudson and Katz for commercial pipes. It can be noted that the experimental friction factor exhibits some deviation from smooth pipe behavior correlations, i.e., Nikuradse [1932] and Drew [1932], because these correlations are proposed for very smooth wall.

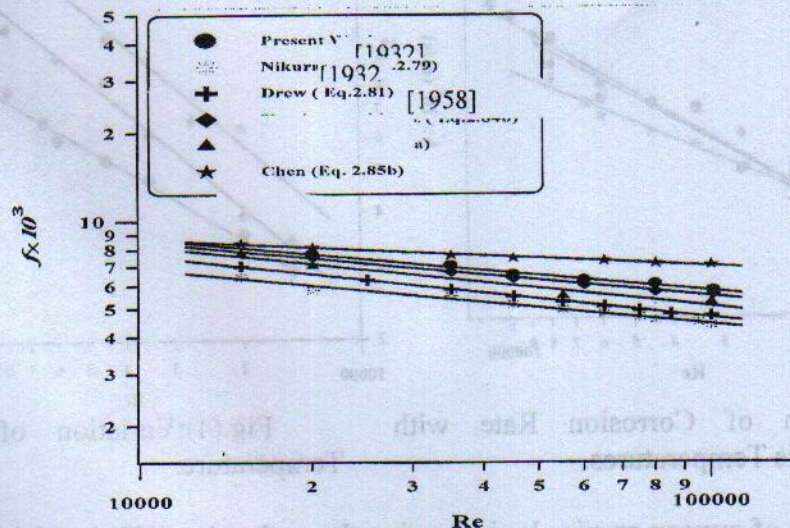


Fig. (2) Variation of Experimental Friction Factor as Compared with other Correlations .

CORROSION RATE

Effect of Reynolds Number

Fig. (3) shows the variation of corrosion rate with Re at three temperatures. It is evident that at a particular temperature the corrosion rate increases with Re . Since the corrosion of iron in aerated

water is a mass transfer controlled process, therefore increasing Re (or velocity) will increase the amount of oxygen arriving to the surface and hence the corrosion rate is increased. Increasing Re leads to decrease the thickness of diffusion layer that represents the main resistance to oxygen transport.

The mass transfer coefficient is estimated from the in weight of specimen using the following Fig. (4) shows the variation of mass transfer coefficient with Re at the three bulk temperatures. It is clear that k increases with increasing Re for all Sc values. The increase in k with Re is due to the fact that, as Re increases the convective mass transport of O_2 will increase, i.e., mass transfer by eddy diffusion (ϵ_D) due to the increased turbulence. Increasing turbulence leads to decrease the thickness of viscous sub-layer and the diffusion layer that represents the main resistance to momentum and mass transport respectively, hence the O_2 concentration gradient at the surface will be increased leading to increase k . Increasing k with Re leads, consequently, to increase Sh over the whole range of temperature as shown Fig. (5). The variation of Stanton number with Re is shown in Fig. (6). The trend is in accordance with usual behavior of St_d with Re [Mezushina 1971, Deissles 1952, Gay et. al. 1976, Berger and Hau 1977, Nesic et al. 1995].

Effect of Temperature

Observing Fig.(3) show that at low Re , the corrosion rate at $45^\circ C$ is nearly equal that at $30^\circ C$. Above Re of 35000 the corrosion rate increases with temperature rise. This behavior can be explained as follows: increasing temperature leads to change two variables that act in a conflicting way. Firstly, increasing temperature accelerates the reaction rate

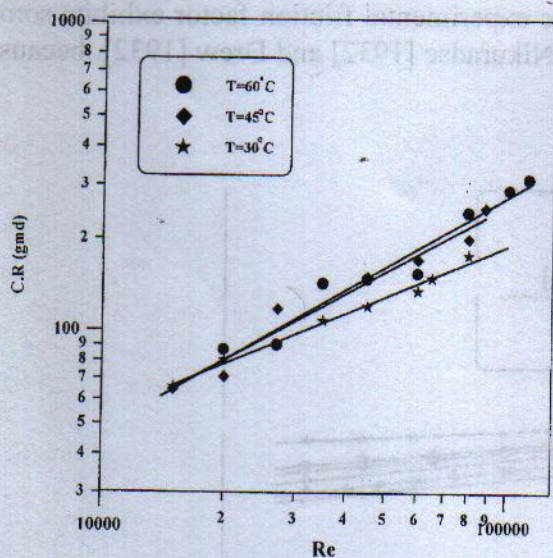


Fig.(3): Variation of Corrosion Rate with Re at Various Temperatures.

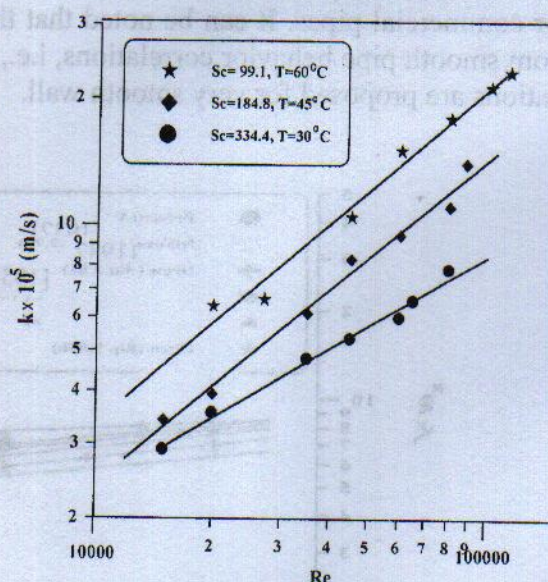


Fig.(4): Variation of $k Re$ at Various Temperature.

and diffusion rate of oxygen species by increasing the molecular diffusion coefficient. Secondly, as the temperature increases the oxygen solubility decreases [Sheir 1994]. Third factor will play an important role in determining the corrosion rate is Re (or velocity). The increase in Re enhances the eddy diffusion of O_2 from the bulk of solution to the metal surface which increases O_2 transport to the metal surface leading to higher corrosion rate

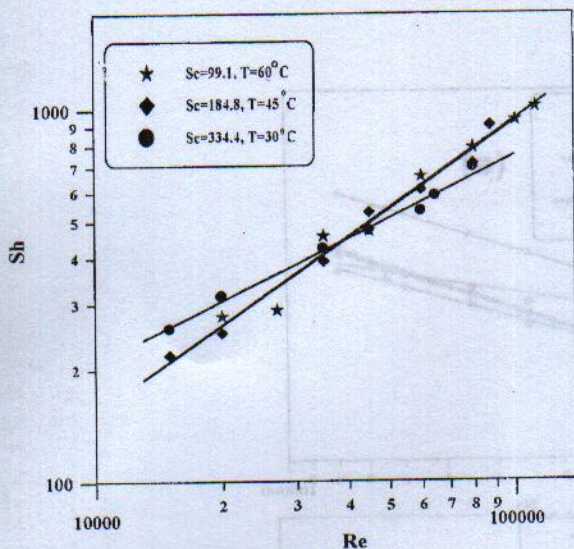


Fig.(5):Variation of Sh with Re at Various Temperatures

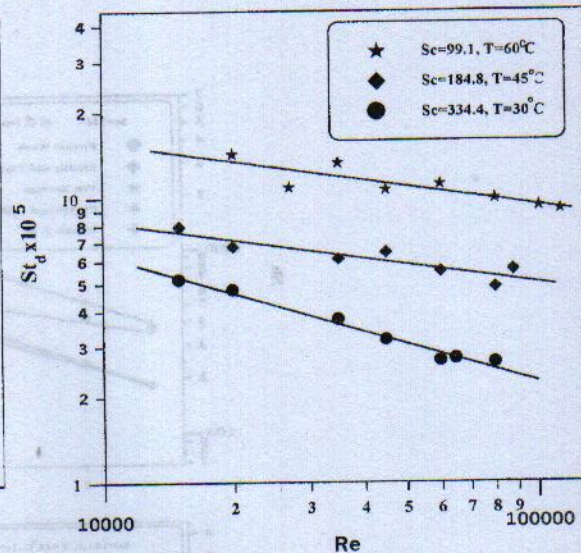


Fig.(6): Variation of St_d with Re at Various Temperatures.

Strictly speaking, the combined effect of three variables, namely, oxygen solubility, oxygen molecular diffusivity, and solution velocity (or eddy diffusion), will determine the trend of corrosion rate with increasing temperature.

Best fitting of the experimental results gives the following correlations:

$$Sh = 5.588 Re^{0.534} \quad C.C = 0.97 \quad T = 30^\circ C \quad 15000 < Re < 80000 \quad (1a)$$

$$Sh = 0.1739 Re^{0.739} \quad C.C = 0.99 \quad T = 45^\circ C \quad 15000 < Re < 88000 \quad (1b)$$

$$Sh = 2.799 Re^{0.8} \quad C.C = 0.97 \quad T = 60^\circ C \quad 20000 < Re < 113000 \quad (1c)$$

Eqs. (1) indicate that the Re dependence of Sh varies with temperature.

The results revealed some scattering of data. Also it showed that the position of the specimen in the test section, has no influence on its corrosion rate i.e., no entrance effect of mass transfer was noticed, that is in harmony with previous observations [Mahato et al 1980]. This may be ascribed to the formed corrosion product which may disturb the uniformity of active sites and the oxygen amount near the surface by increasing the turbulence. Experimental results showed that the effect of temperature on k is higher than on i_L as i_L is affected by oxygen concentration which decreases with temperature.

Comparison with the Proposed Models

The comparison of experimental results with the proposed correlations particularly those which are based on the concept of analogies among momentum, heat, and mass transfer serves to investigate the capability of analogy models to predict the corrosion rate and to find whether these models give reasonable results or may deviate. The experimental mass transfer results were compared with other proposed correlations, such as Prandtl and Taylor [1921], Von Karman [1939], Chilton and Colburn [1934], and Mahato et. al. [1980]. Graphical comparison is shown in Figs.(7).

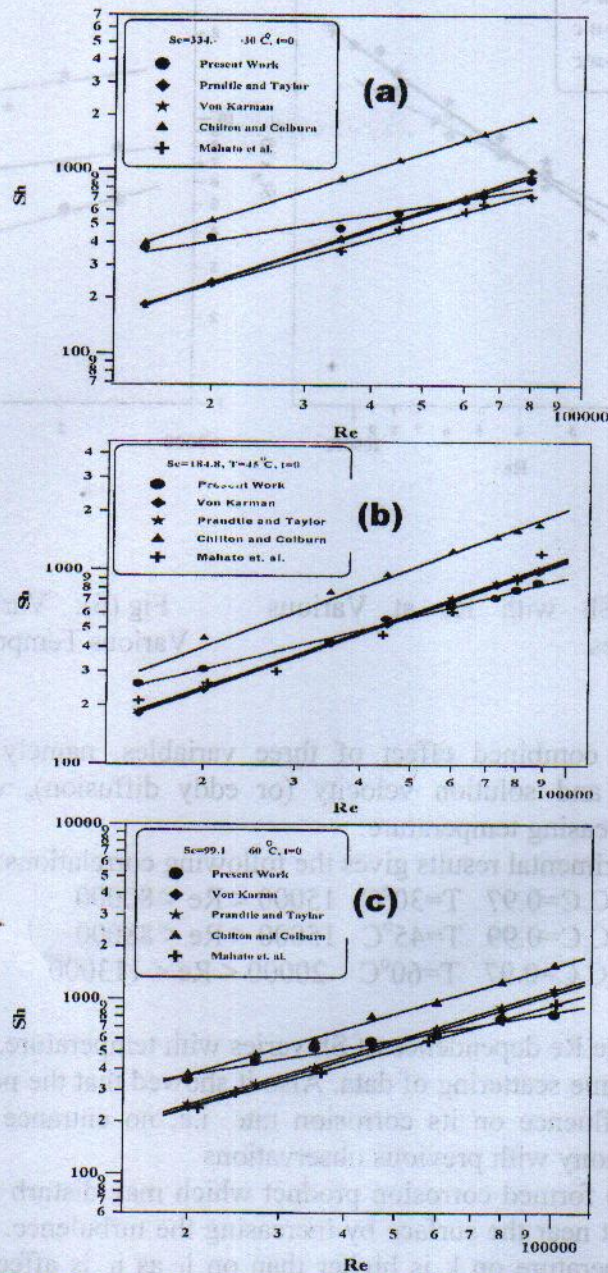


Fig. (7) Comparison of Experimental Sh with Analogies.

Portraying the present results are within the limits of these correlations. The analogies considered in the comparison are all based on the experimental friction factor. Generally, the experimental results for corrosion rates show good agreement with Von Karman and Prandtl-Taylor analogies. Reasonable agreement with Chilton-Colburn analogy is also observed at low Re .

It can be deduced that the corrosion process, even when controlled by diffusion, is not always simply related to mass transfer. This can be attributed mainly to two reasons: (i) the change of O_2 concentration with temperature rise. This is why the temperature rise leads to appreciable change in the dependence of Sh on Re , (ii) the role of solution electrical conductivity in influencing the corrosion rate at certain conditions. Results of corrosion of carbon steel in sea water (high electrical conductivity) and in ordinary distilled water (low electrical conductivity) under the same conditions of Re and temperature of present work [Slaiman and Hasan] showed that the corrosion rates to be different by about $\pm 20\%$ from that in 0.1N NaCl. Certainly the difference in corrosion rates among



the three solutions is ascribed to the difference in electrical conductivity. Accordingly the electrical conductivity of the solution must be accounted for.

CONCLUSIONS

From present investigated system the following points can be concluded:

- 1- Increasing Re increases the corrosion rate for the investigated range of temperature. In addition the dependence of corrosion rate on Re varies with temperature.
- 2- Increasing the temperature increases the corrosion rate for the entire range of Re except at low Re where the effect of temperature varies with Re (or velocity).
- 3- Corrosion rate, even when controlled by mass transfer, is not simply obeying mass transfer correlations but it can be predicted with reasonable accuracy from experimental friction factor and physical properties of solution.
- 4- Generally, the experimental results of corrosion rates show good agreement with Von Karman and Prandtl-Taylor analogies. Reasonable agreement with Chilton-Colburn analogy is also observed at low Re .

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NOMENCLATURE

C	Concentration, mole/m ³ .
C _b	Bulk concentration, mole/m ³ .
C _s	Surface concentration, mole/m ³ .
d	Pipe diameter, m.
F	Faradays constant (96487 Columb/equivalent)
f	Friction factor.
i	Current density, A/m ² .
i _L	Limiting current density, A/m ² .
k	Mass Transfer Coefficient, m/s.
K ⁺	Dimensionless mass transfer coefficient= k/u^* .
k _T	Thermal Conductivity, w/m.°C
Pr	Prandtl number = $\mu C_p/k_T$
Re	Reynolds number= $\rho du/\mu$
Sc	Scmhidt number= $\mu/\rho D$
Sh	Sherwood number= kd/D .
St _d	Stanton number= k/u
u	Velocity, m/s
u [*]	Friction velocity, m/s
Δp	Pressure drop, N/m ² .
μ	Viscosity, kg/m.s ² .
ν	Kinematic viscosity , m ² /s.

ABBREVIATION

C.C Correlation Coefficient