Open Journal of Fluid Dynamics, 2025, 15(1), 19-32
https://www.scirp.org/journal/ojfd
ISSN Online: 2165-3860
ISSN Print: 2165-3852

Numerical Method of Measurement of the Corrosion Rate in the Flow of a Fluid in a Smooth Tube: A Case Study of Atmospheric Distillation of Crude Oil

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How to cite this paper: Fall, N., Diop, D., Ndiaye, M., Talla, K., Adannou, H.A. and Beye, A.C. (2025) Numerical Method of Measurement of the Corrosion Rate in the Flow of a Fluid in a Smooth Tube: A Case Study of Atmospheric Distillation of Crude Oil. *Open Journal of Fluid Dynamics*, **15**, 19-32.
https://doi.org/10.4236/ojfd.2025.151002

Received: June 21, 2024
Accepted: February 17, 2025
Published: February 20, 2025

Abstract

The atmospheric distillation column is a vertical cylinder, approximately 50 meters high and 8 meters in diameter. Once the crude oil is vaporized, it is injected into this column. Throughout the column, vaporized crude oil carries properties such as moisture and corrosivity, thereby diffusing the chemical factors of corrosion throughout the column walls. This study aims to utilize the physicochemical properties of vaporized crude oil and its upward flow motion to quantify corrosion induced by atmospheric distillation. The objective of this article is to characterize this specific flow and to measure corrosion within the atmospheric distillation column. This study is conducted by modelling the flow using dimensionless numbers and programming the characteristic equations of this flow in a specific geometry and under physicochemical conditions. The results indicate that the regime of this flow is a critical turbulent flow regime. However, induced flow corrosion increases significantly due to turbulence.

Keywords

Corrosion, Crude Oil, Dimensionless Numbers, Flow, Materials

1. Introduction

Fluid mechanics is the field of physics that studies and characterizes the motion of fluids. In her study approach, she often uses dimensionless numbers to interpret certain flows and the physicochemical properties of the fluid that can affect the environments in which these flows are studied. The flow in question in this study is an advective and diffusive flow of crude oil in the atmospheric distillation column. However, the crude oil, once vaporized and injected into the column, makes an upward movement. In this article, we will see how to characterize the flow of oil in the atmospheric distillation column and quantify the corrosion rate as a function of the dimensionless numbers characteristic of the flow and its properties.

Some researchers show that the behaviour of flow-induced corrosion is distributed differently in the bends, caused by changes in flow directions and velocities. A high flow velocity can destroy not only the protective layer but also the surface of the metal [1] [2].

The Reynolds and Schmidt numbers give the dependence between the fluid velocity and the limit current under laminar and turbulent flow conditions. The application of dimensional analysis and dimensionless groups in mass transfer measurements is decisive in obtaining quantitative information on induced flow corrosion [3]. By experimentally determining the Sherwood number, the relationship between the Reynolds number and the Sherwood number can be used to estimate the corrosion rate [3]. The flow rate has a great influence on the corrosion behaviour of steel [4]. It is widely proven that the membrane caused by corrosion on metals can prevent the proliferation of corrosion but it must be preconditioned. During pickling corrosion, the protective membrane formed by Fe_3O_4 is destroyed by the high flow velocity and the protective effect is thus lost [5].

The velocity of the fluid is one of the predominant factors that influence the corrosion rate. Often, severe rates of corrosion are found in places where turbulence is significant [6]. It's clearly seen that increasing velocity in tubes near the shell inlet at the point of 356 mm causes corrosion to occur [7]. It is proved that severe corrosion mainly occurs near the elbow wall outlet due to the bend angle, velocity, dimensions, and crude oil origin [8]. The studies of [9] [10] state that for Reynolds numbers less than 2000, the shear forces of the fluid are low, which cannot destroy the protective layer on the metal; when the Reynolds number is greater than 2000, the shear forces accelerate the transport of corrosion factor reagents in the convective flow and therefore these reagents carry the protective layer on the surface of the metal, this can even scrape the metal on the surface, accelerating the corrosiveness of the fluid. High Reynolds values in natural gases accelerate widespread corrosion but can also generate localized corrosion [11] [12]. The absence of turbulence affects the corrosion mechanisms and their uniformity [13].

However, this study aims to study the nature of the oil flow in the atmospheric distillation column but also to quantify the corrosion rate by dimensionless numbers.

The rest of this article is divided into three parts. Firstly, in this study, we will define the materials and methods used, then present and discuss the results obtained and finally summarize them and give perspectives on the attenuation of the critical turbulent flow regime in order to possibly reduce the corrosion rate in the column.

2. Material and Method

2.1. Material

In this study, we want to measure the dimensionless numbers characteristic of this flow and the corrosion rate by computer programming using the software Jupiter (Python). This software is a web-based, interactive computing notebook environment. It edits and runs human-readable documents while describing the data analysis. This study is made by modelling the flow using dimensionless numbers and programming the characteristic equations of this flow within a particular geometry. To do this, we vary the Reynolds and Peclet numbers according to the velocity parameter U of the fluid. The Sherwood number is studied as a function of the mass transfer coefficient parameter K. The Schmidt number is constant for this study. The corrosion rate is measured by the Sherwood number, which varies with the Reynolds number. Experimentally, the order of the velocity of the vaporized fluid is between 0.1 to 2 $\text{m}\cdot\text{s}^{-1}$, and the order of the mass transfer coefficient is between 0.1 to 1 $\text{m}\cdot\text{s}^{-1}$.

2.2. Method

Our study system, as shown in **Figure 1**, involves a fluid, specifically vaporized crude oil, moving within a pipe that is 50 meters high and 8 meters in diameter. The velocity of the fluid adjacent to the wall is zero. Viscous forces make the fluid slow down as it approaches the walls upon entering the pipe. Consequently, a velocity gradient is established in the boundary layer. The thickness of this boundary layer increases as the fluid progresses through the pipe, near a distance denoted as L_h, referred to as the hydrodynamic entrance length. Typically, for a pipe, L_h is approximately 70 times the diameter [14]. This scenario results in a parabolic velocity profile.

Advection refers to the transport of properties such as humidity, temperature, pollution, or corrosivity by a fluid during its movement. Diffusion, on the other hand, involves the migration of sometimes corrosive chemical species into a liquid or gaseous medium.

In the absence of detachment, advection occurs in the general direction imposed by the conditions at infinity along the current line, deviating only slightly from the geometry of the obstacle. Under these conditions, a representative timescale for the advective transport of momentum over the distance L_h can be expressed as follows [16]:

$$T_a = \frac{L_h}{U_\infty} \tag{1}$$

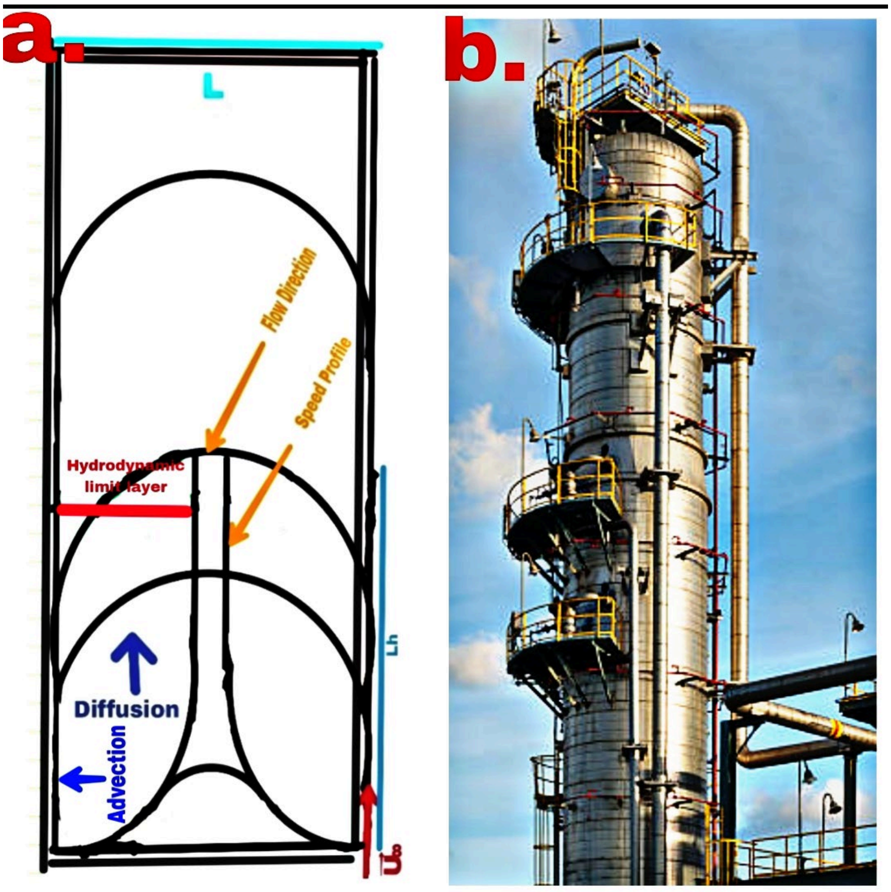

Figure 1. (a) Representation of the flow within the atmospheric distillation column. (b) Atmospheric distillation column of crude oil [15].

where U_∞ is the flow velocity, T_a is the advection timescale, L_h is the hydrodynamic entrance length.

The presence of a fixed obstacle in a flow of viscous fluid results in a deficit or "well" of momentum for the moving medium. This condition imposed on the wall diffuses beyond the entire field with a diffusivity that is essentially the kinematic viscosity ν of the fluid. If we denote by δ the orthogonal transverse distance to the wall (the thickness of the hydrodynamic boundary layer) characteristic of this diffusion at the fluid edge of this obstacle, then for a distance equal to the hydrodynamic entry distance L_h, the timescale corresponding to the diffusive transfer of momentum is given by [16]:

$$T_d \approx \frac{\delta^2}{\nu} \tag{2}$$

Advection and diffusion occur on the same time scale, which is given in [16]:

$$\frac{\delta}{L_h} \approx \sqrt{\frac{\nu}{U_\infty \cdot L_h}} \tag{3}$$

With the described phenomenology, it can be demonstrated that the relative thickness decreases as the characteristic Reynolds number of the flow increases.

$\frac{\delta}{L_h}$ decreases as $R_e^{\frac{-1}{2}}$, where

$$Re = \frac{U_\infty \cdot L_h}{\nu} \tag{4}$$

This represents a novel interpretation of the Reynolds number as a dimensionless variable comparing diffusive and advective transport times occurring over the same distance [16]. Previous studies have demonstrated the importance of the relationship between the Reynolds, Sherwood, Peclet, and Schmidt numbers. Even when vaporized, crude oil is continually emulsified with water. For aqueous electrolytes, the kinematic viscosity is approximately $\nu \approx 10^{-6}\ \text{m}^2 \cdot \text{s}^{-1}$ and the mass diffusion coefficient is approximately $D \approx 10^{-9}\ \text{m}^2 \cdot \text{s}^{-1}$ [14]. The distillation column diameter is approximatively $L = 8$ m.

Consequently, the dimensionless variables relevant to this study can be expressed as follows:

$$Sc = \frac{\nu}{D} = 10^3 \tag{5}$$

$$Re = \frac{U \cdot L}{\upsilon} = 8 \times 10^6 \cdot U \tag{6}$$

$$Sh = \frac{K \cdot L}{D} = 8 \times 10^9 \cdot K \tag{7}$$

$$Pe = Re \cdot Sc = 8 \times 10^9 \cdot U \tag{8}$$

The constant flow parameters are given in **Table 1**:

Table 1. Constant flow parameters.

Constant flow parameter	Schmidt number	Mass coefficient diffusivity	Kinematic viscosity
Symbol	Sc	D ($\text{m}^2 \cdot \text{s}^{-1}$)	ν ($\text{m}^2 \cdot \text{s}^{-1}$)
Value	1000	10^{-9}	10^{-6}

Hydrodynamic mass transfers are treated by presenting corrosion rates in terms of dimensionless parameters. The number of variables involved in mass transfer problems is quite large. The Reynolds and Schmidt numbers provide the dependence between velocity and limit current under laminar and turbulent conditions. Utilizing dimensional and dimensionless variable analyses in mass transfer measurements is highly beneficial for obtaining information on induced flow corrosion control [3]. The corrosion rate can be predicted without testing if certain parameters are known. For example, for flow in a smooth tube, the correlation is [3].

$$Sh = 0.023 \cdot Re^{0.8} \cdot Sc^{0.33} \tag{9}$$

But, for this study $Sc = 10^3$, Equation (8) can be rewritten as follows:

$$Sh = 0.2247 \cdot Re^{0.8} \tag{10}$$

The Sherwood number quantifies the evolution of corrosion; indeed, the corrosion rate evolves by half compared to the Sherwood number as a function of the Reynolds number [3].

Consequently, the corrosion rate can be evaluated as follows:

$$C = 0.11235 \cdot Re^{0.8} \tag{11}$$

Figure 2 summarizes the methodology used to characterize the fluid flow and to measure the corrosion rate in the flow of the fluid in the atmospheric distillation column.

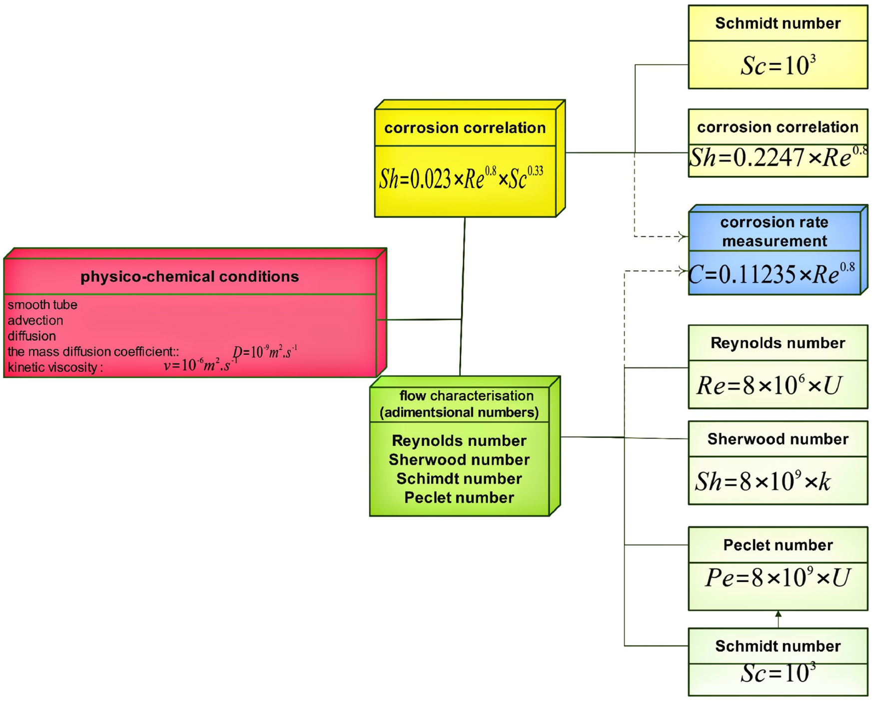

Figure 2. Diagram of the method of characterizing the fluid flow and measuring corrosion rate.

3. Results and Discussions

3.1. Results

3.1.1. Flow Characterization by Dimensionless Numbers

Equation (6) shows in **Figure 3** that the Reynolds number increases significantly and in proportion to the flow velocity. This translates into a critical or even a supercritical regime in this study.

Equation (7) indicates in **Figure 4** that the Sherwood number varies significantly and in proportion to the mass transfer coefficient.

Equation (8) shows through **Figure 5** that the Peclet number increases with the fluid velocity.

The Schmidt number is a dimensionless number representing the ratio between momentum diffusivity ν (or kinematic viscosity) and mass diffusivity D. It is employed to characterize the flow of fluids where viscosity and material transfer occur simultaneously. For this study, its value is 1000.

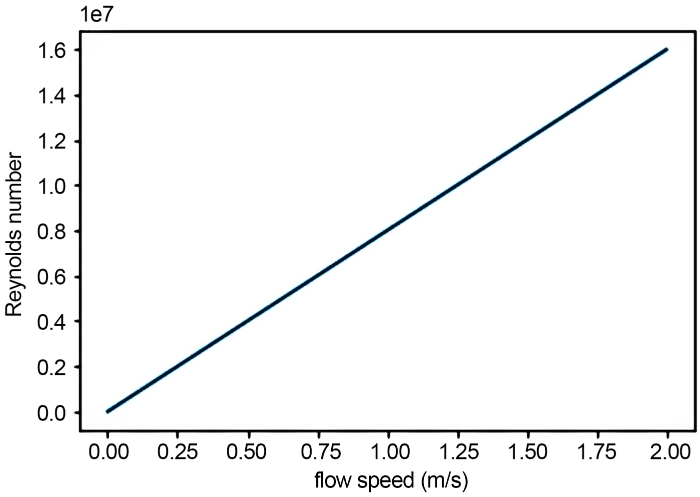

Figure 3. Evolution of the Reynolds number as a function of fluid velocity.

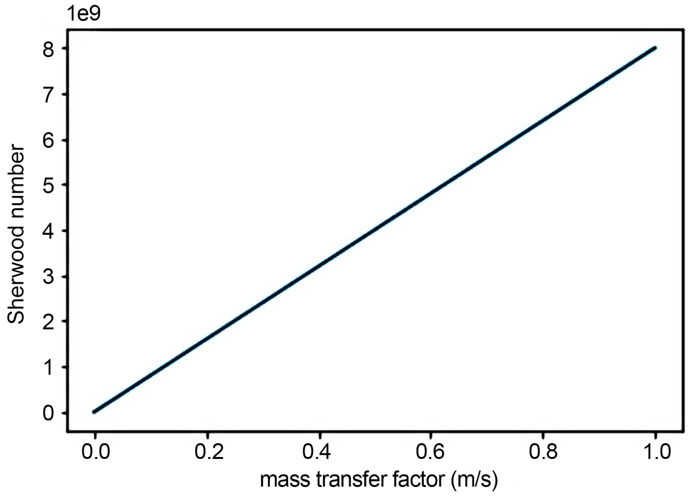

Figure 4. Evolution of the Sherwood number as a function of the mass transfer coefficient within the atmospheric distillation column.

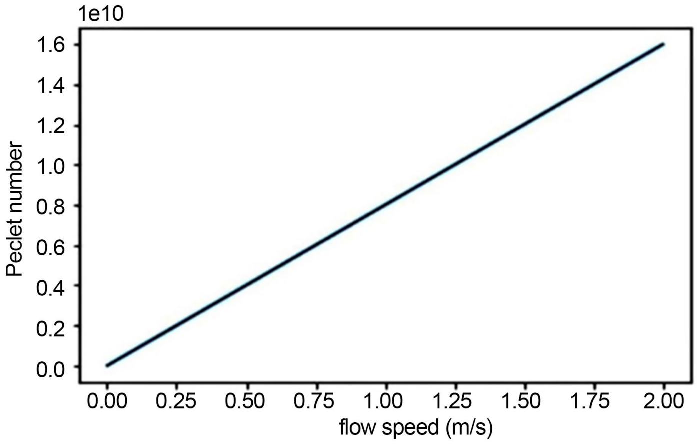

Figure 5. Evolution of the Peclet number as a function of the fluid velocity within the atmospheric distillation column.

3.1.2. Corrosion Rate Measurement

Equation (10) shows, in **Figure 6**, the evolution of the Sherwood number which translates the ions transport from the electrolytes to the metal and Equation (11) models the measurement of corrosion rate using dimensionless numbers in convective and diffusive flow within the atmospheric distillation column, and it shows at **Figure 7** that corrosion increases significantly under critical and supercritical regimes.

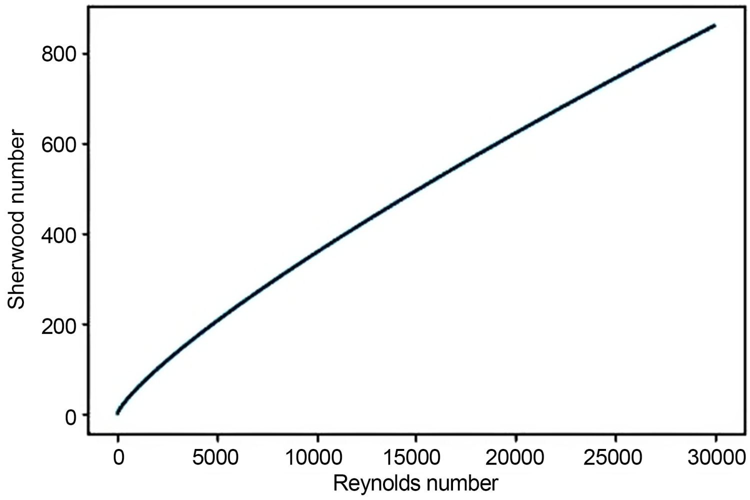

Figure 6. Evolution of the Sherwood number as a function of the Reynolds number within the atmospheric distillation column.

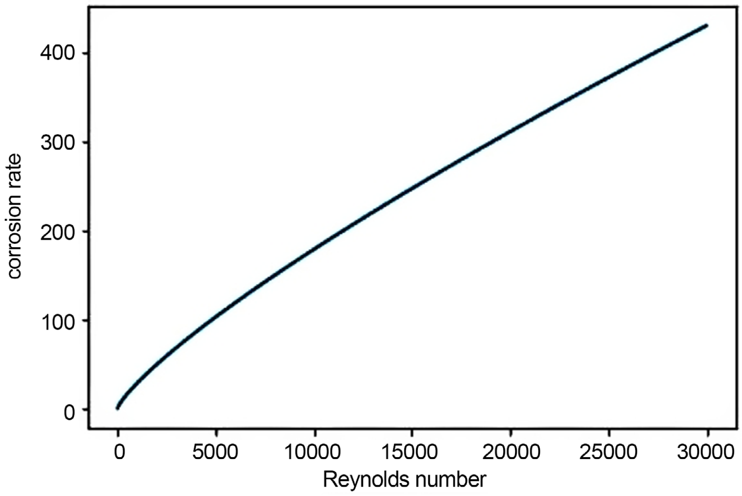

Figure 7. Evolution of the corrosion rate as a function of the Reynolds number within the atmospheric distillation column.

3.2. Discussions

3.2.1. Flow Characterization by Dimensionless Numbers

Figure 3 illustrates that the Reynolds number increases significantly with flow velocity, indicating a critical flow regime. This velocity is attained when the transition point, which moves upstream during the subcritical regime, reaches the detachment point. The value of this critical Reynolds number varies considerably across different experimental studies, ranging between (10^5 and 10^6), owing to the high sensitivity of the flow to boundary conditions (such as turbulent intensity of the incident flow, elongation ratio and ends of the cylinder, blocking coefficient, roughness of the cylinder). The critical regime is distinguished by the turbulent transition of the boundary layer before detachment [16].

The Sherwood number is a dimensionless parameter used to characterize mass transfer between a fluid and an interface. **Figure 4** illustrates an increase in the Sherwood number, indicating that a significant quantity of corrosive crude oil particles is deposited on the cylinder walls.

The Peclet number is a dimensionless parameter representing the ratio of forced convection transport to diffusion transport. **Figure 5** demonstrates a substantial increase in the Peclet number, indicating a low mass diffusivity compared to the convective transport of corrosive particles in contact with the cylinder walls.

The Schmidt number is a dimensionless quantity representing the ratio of momentum diffusivity ν (or kinematic viscosity) to mass diffusivity D. It is utilized to characterize fluids where viscosity and material transfer occur concurrently. In this study, the Schmidt number has a value of 1000. This implies that dynamic (or kinematic) viscosity is significantly more influential than mass diffusivity within the cylinder.

3.2.2. Corrosion Rate Measurement

This numerical study of corrosion measurement is carried out by using existing correlations on the quantification of corrosion. This correlation is made on a cylinder geometry where a fluid with physicochemical characteristics flows. This measurement is thus only valid for perfectly cylindrical columns, and the fluid in question has a known flow speed and is dissipated by convection and advection substances (corrosion factors) during its upward movement. This constitutes the limitations of this study.

Figure 6 and **Figure 7** show that critical turbulence regimes are favourable to corrosion proliferation. However, these regimes are characterized by large Reynolds numbers, but also high flow velocity.

Ahmed [3] has used the same model to quantify the corrosion rate in Arabic golf water on a modified aluminium alloy. They found that the Sherwood number increased linearly with the Reynolds number, suggesting that the rate of corrosion increases with the increased Reynolds number. In fact, the Sherwood number describes the maximum rate at which the ions are transported from the bulk solution to the metal surface.

We have correlated their results to ours in **Figure 8**. Indeed, in a solution containing electrolytes, corrosion activity is much greater. The red and green curves respectively represent the evolution of the Sherwood number and corrosion in electrolytes, while the blue curve represents the evolution of the Sherwood number as a function of the Reynolds number in the Arabic golf water.

The correlation between the variation of the Sherwood number in the Arabic golf water represented by the curve in blue and the variation of the Sherwood number in an aqueous electrolyte represented by the curve in red and the corrosion C is perfect and is equal to 1.

That means that these three parameters increase proportionally with Re. Indeed, the evolution of the Sherwood number in Arabic golf water is proportional to the variation of the Sherwood number in an aqueous electrolyte. The proportional coefficient is $0.045^{0.33}$, and we have seen previously that the proportionality between the evolution of the Sherwood number and the corrosion rate is 0.5. This indicates that these three equations translate the same phenomenon, namely the transport of ions from the solutions to the metal in question. Hence, the corrosion phenomenon was observed.

For example, with the increasing concentration of Cl^- and the extension of immersion time, the electrochemical noise resistance and charge transfer resistance of P110 steel decrease gradually, and the protective property of the corrosion-product film decreases, which is capable of forming steady pitting corrosion [17].

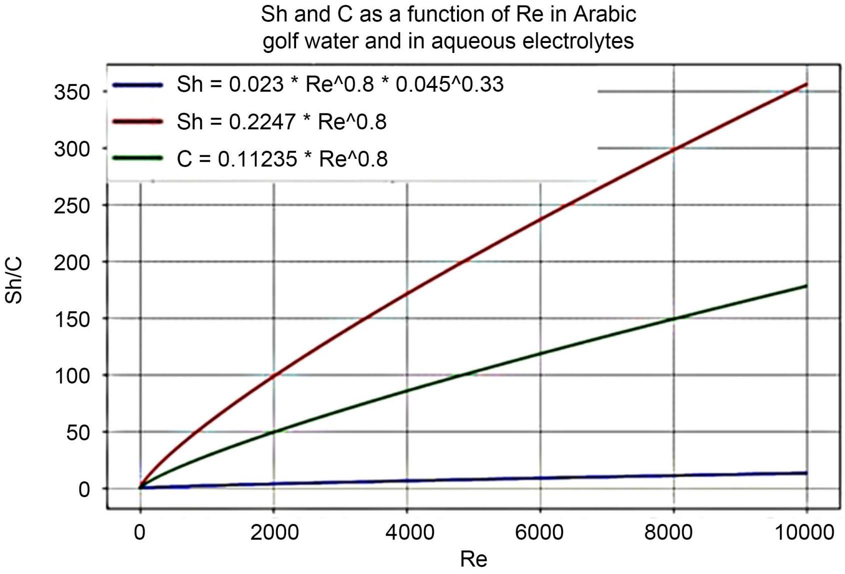

Figure 8. Correlation of evolutions of the Sherwood number and corrosion rates in Arabic golf water and in aqueous electrolytes.

Literature can be used to confirm the results of this study on the effect of turbulence and fluid flow velocity on corrosion progression, as evidenced in this study.

Liu [18] studied the corrosion behaviour of X70 in the water produced in oil fields and found that velocity affects the formation of corrosion product film, with sudden velocity changes leading to transient pressure instability in the pipeline [19]. Martinez [19] investigated the corrosion kinetics of turbulent X52 pipeline steel and observed that turbulence has a considerable impact on the electrochemical processes on the steel surface. The flow rate significantly influences the corrosion behaviour of steel [4]. Hydrodynamic mass transfers are addressed by presenting corrosion rates in terms of dimensionless parameters. The number of variables involved in mass transfer problems is extensive. The Reynolds and Schmidt numbers delineate the dependence between velocity and limit current under laminar and turbulent conditions. Utilizing dimensional and dimensionless variable analyses in mass transfer measurements is highly useful for obtaining information in induced flow corrosion control [3].

The corrosion rate can be predicted without testing if certain parameters are known. For example, for flow in a smooth tube, the corrosion rate is determined by a correlation linking the Sherwood, Peclet and Reynolds numbers [3]. The Sherwood number quantifies the corrosion evolution. The corrosion rate evolved by half compared to the Sherwood number as a function of the Reynolds number [3]. Flows under critical and supercritical regimes are characterized by high fluid velocity. It is evident that uniform velocity around the tubes occurs within a range of 89 mm - 178 mm before velocity increases in tubes near the shell inlet, becoming non-uniform at the point of 356 mm, where corrosion occurs [7]. Severe corrosion primarily occurs near the elbow wall outlet, involving factors such as elbow material, bend angle, velocity, dimensions, and crude oil origin [8].

Fluid velocity predominantly influences the corrosion rate. Severe corrosion is often found in areas with highly turbulent flow, while areas with minimal turbulence experience little corrosion. For example, variations in corrosion rates were observed in the hottest furnace tubes during the treatment of a particular crude oil. At a temperature of 270˚C, the corrosion rate remained low with a flow rate of 40 tons/day but became considerable with a flow rate of 70 tons/day or higher [6]. Unfortunately, the absolute critical value (which varies with temperature) below which the corrosion rate remains low is not yet known [6].

Product volatility, operating pressure, and steam injections have considerable consequences on fluid velocity [6]. In turbulent flow regimes, a significant increase in metal mass loss is observed with increasing fluid velocity. The rate of erosion-corrosion is influenced by three main factors: the concentration of corrosive substances, the characteristic Reynolds number of the flow, and the duration of the experience [20].

It is well established that the membrane caused by corrosion on metals can inhibit the proliferation of corrosion, but it must be preconditioned. During stripping corrosion, the protective membrane formed by Fe_3O_4 is destroyed by high flow velocity, leading to the loss of its protective effect [5]. The studies of [9] [10] indicate that for Reynolds numbers less than 2000, the shear forces of the fluid are low, which cannot destroy the protective layer on the metal. However, when the Reynolds number exceeds 2000, the shear forces accelerate the transport of corrosion factor reactants in the convective flow, carrying the protective layer on the metal surface, which can even scrape the metal surface, thus accelerating the corrosiveness of the fluid. High Reynolds values in natural gases accelerate widespread corrosion but can also lead to localized corrosion [11] [12]. As described, the formation of holes on the protective layer induced by corrosion on metals occurs when the Reynolds number exceeds 14,000, indicating that the protective layer is destroyed. In this case, the number of holes formed increases considerably compared to cases where low Reynolds numbers are operated. When the protective layer is removed, bare metal is exposed to act as an anode during electrochemical reactions [21] [22]. Small anodic surfaces accelerate the reaction rate of anode dissolution, leading to localized galvanic corrosion and pitting corrosion [5].

The Reynolds number increases with a certain pH value, increasing the corrosion rate. This affects increasing the flow speed, and therefore, turbulence enhances the transport of species to and from the steel surface [23].

4. Conclusions

The primary objective of this article was to characterize the diffusive and advective flow of vaporized crude oil within the atmospheric distillation column while also measuring the corrosion rate using dimensionless variables characteristic of this flow. The flow under investigation in this study is an advective and diffusive flow of crude oil in the atmospheric distillation column. The results of this study indicate that the flow regime observed is a critical regime of turbulent flow. Consequently, induced flow corrosion increases considerably due to turbulence. Under turbulent conditions, the velocity of the fluid impacts the protective membranes of metals, such as Fe_3O_4, leading to an escalation of corrosion.

In the context of control within the atmospheric distillation system, altering the flow regime could be explored as a means to mitigate corrosion damage caused by crude oil refining. Furthermore, optimizing the configuration of tubes utilized in various industries could contribute to reducing induced flow corrosion.

Acknowledgements

N. F. thanks Dahibou fall SOW mathematical and numerical engineer at the Mathematical Department at Cheikh Anta DIOP University of DAKAR-SENEGAL.

Conflicts of Interest

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

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