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TRANSIENT UPWARD INJECTION OF LIQUID IN IMMISCIBLE LIQUID

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Abstract. *The flow of immiscible fluids has applications in several areas of science and engineering. In the petroleum industry, for example, it is found in the displacement of drilling mud and in the cementing of wells. More specifically, in deep and ultra deep water operations, problems with hydrate formation and corrosion are common in petroleum production and one way to avoid them is through the injection of oil to withdraw water in pipelines. This paper aims to study the transient displacement of water by kerosene in a pipeline. Therefore, it was assumed that the kerosene-water transport is governed by the Unidimensional Advection-Diffusion Equation and that the process can be characterized by two main parameters: the average front velocity of the injected liquid and the macroscopic diffusion coefficient. Simulated profiles of kerosene concentration and a computational code based on the inverse analysis were used to recover these characteristic parameters. The difficulty of measuring the macroscopic diffusion coefficient in liquid-liquid flows and the growth of oil operations in deep water motivate this study. The results of the estimates were satisfactory and sensitive to the expected parameters range and the tool presented low errors and quick solution.*

Keywords: *Oil-water flow, front propagation in liquids, macroscopic diffusion, inverse analysis, parameter estimation.*

1. INTRODUCTION

In many processes it is necessary to remove one liquid by injecting another. Among others, our motivation comes from applications in oil and gas companies, such as drilling mud removal, cement displacement in oil wells or the restart of pipeline flows of waxy crude oils. For these scenarios, flow and rheological behavior are important. Other scenarios are related to the removal of water from pipelines to prevent hydrate formation in deepwater production lines or corrosion. The source of water may be the leftover in the pipeline after running water tests or the accumulated water during operation or shutdown. Both methanol and oil can be used to displace and inhibit any accumulation of water in the lines. Another situation is the oil spill during subsea intervention. Before disconnecting the duct, water is injected through the service line to remove oil from the line. The removal of all residual oil is crucial to meet the requirements of operating standards. In all cases, the minimum injected fluid flow rate required for the accumulated fluid displacement has a significant impact on the requirements of umbilicals, pumps, and storage tanks.

Several authors have investigated the two-phase flow of oil and water and Ismail *et al.* (2015) present an extensive review. However, studies on liquid drainage with another liquid are still rare. Cagney *et al.* (2006) studied the water withdrawal through the injection of methanol in a complex geometry. Xu *et al.* (2011) studied experimentally the water initially trapped in a lower horizontal section of an oil pipeline and then drained with oil. Xu *et al.* (2016) used a commercial CFD code in a similar geometry. Schümann *et al.* (2013) studied experimentally the water withdrawal by the injection of oil and vice versa in a geometry similar to Cagney *et al.* (2006). Schumann *et al.* (2014) used a commercial code in a similar study, but with horizontal and inclined downward test sections. Kazemihatami (2013) and Folde (2017) used the Schumann *et al.* (2014) approach, but with a geometry similar to Cagney *et al.* (2006) and the authors used another commercial code. Suguimoto *et al.* (2016) also studied draining water by injecting kerosene and vice versa, but in a vertical test section. All of these authors measured the concentration of fluids during the withdrawal process and their profiles showed a diffusive flow characteristic.

Although there is a rich bibliography in this area of two-phase flow, most of the studies analyze the behavior of the injected fluid front and the macroscopic diffusion coefficient in miscible liquids in the limit of high Péclet number. At such a flow, molecular diffusion occurs at high time scales, and an "interfacial pseudo-tension" between the fluids can be considered (Taghavi *et al.*, 2009; Alba *et al.*, 2012, 2013). Taghavi *et al.* (2009) studied the flow of two miscible fluids at the viscous limit in tubes with a model based on the lubrication theory. According to the authors, the non-slip condition on the walls, the homogeneity of the velocity and the shear stress at the interface are standard for miscible fluids. Studies of immiscible liquids are rare due to interfacial tension and wettability. Hasnain and Alba (2017) studied the displacement flows in sloped pipes with the same approach as Taghavi *et al.* (2009), but for immiscible liquids.

To add a small contribution to the two-phase flow literature, the present study aims to investigate the removal of a heavier liquid (water) by injecting a lighter liquid (kerosene) into a vertical test section. This problem consists of tracking

the interface between the two immiscible liquids along the tube. Initially flat, the buoyancy causes liquid exchange due to mass conservation, and to understand the behavior of the interface it is necessary to predict macroscopic diffusion. Macroscopic diffusion occurs when small volumes of fluid have local motions in regions of distinct concentration and it is strongly related to the density difference of the fluids, their viscosities and the front propagation velocity (Debacq *et al.*, 2001, 2003; Séon *et al.*, 2007). The macroscopic diffusion coefficient is significantly greater than the molecular one. For miscible liquids it is in the range of $\alpha = 10^{-4}$ - $10^{-3} \text{ m}^2\text{s}^{-1}$ (Seon *et al.*, 2004) and it is difficult to measure it because of its binary property (Canedo, 2000), while molecular diffusion presents values five orders of magnitude smaller.

To the best of the authors' knowledge, there are no studies on macroscopic diffusion estimation using inverse analysis methodology. In addition, most of the methods for macroscopic diffusion analysis are for tracer particles (Taylor, 1953, 1954; Hart, 2013; Hart *et al.*, 2016; Hawkins *et al.*, 2016) and for miscible liquids (Taghavi *et al.*, 2009; Alba *et al.*, 2012, 2013; Debacq *et al.*, 2001, 2003; Séon *et al.*, 2007). In this study, a simplified model (one-dimensional) for the front propagation and diffusion of a liquid (kerosene) that displaces another immiscible liquid (water) into a circular cross-section tube has been developed. For this purpose, the authors used a numerical code that solves the One-Dimensional Advection-Diffusion Equation for the concentration of injected fluid. The concentration profiles of the fluid injected along the length of the tube at several times were recorded. Applying an inverse analysis on the concentration profiles the mean front velocities and the diffusion coefficients were recovered.

2. THEORETICAL MODEL, NUMERICAL SIMULATIONS AND PARAMETER ESTIMATION

The Figure 1 shows the problem schematically. The test section was initially filled with liquid 1 and it was waited for its stagnation. Then the liquid 2 was injected ($\rho_2 < \rho_1$ and $\mu_2 = \mu_1$) at the bottom of the pipe at a constant volumetric flow rate. Due to the incompressibility of the liquids, as the fluid 2 (kerosene) is injected, the fluid 1 (water) must leave the tube at the same flow rate. However, buoyancy deforms the interface between the two liquids and two traveling fronts can be identified. In this model there is only water ahead of the leading front and only kerosene behind the trailing front front. Between these two fronts, the kerosene flows into the core as droplets of different sizes and shapes and the water flows downward like a thin film near the wall. The leading and the trailing fronts velocities are V_2^+ and V_2^- , respectively. The distance between these two fronts is called the elongation length (L) and tends to be approximately constant (Alba *et al.*, 2012). This scenario is similar to one-dimensional diffusion, but for two liquids, and the diffusion coefficient between these two fluids must be known to solve this problem.

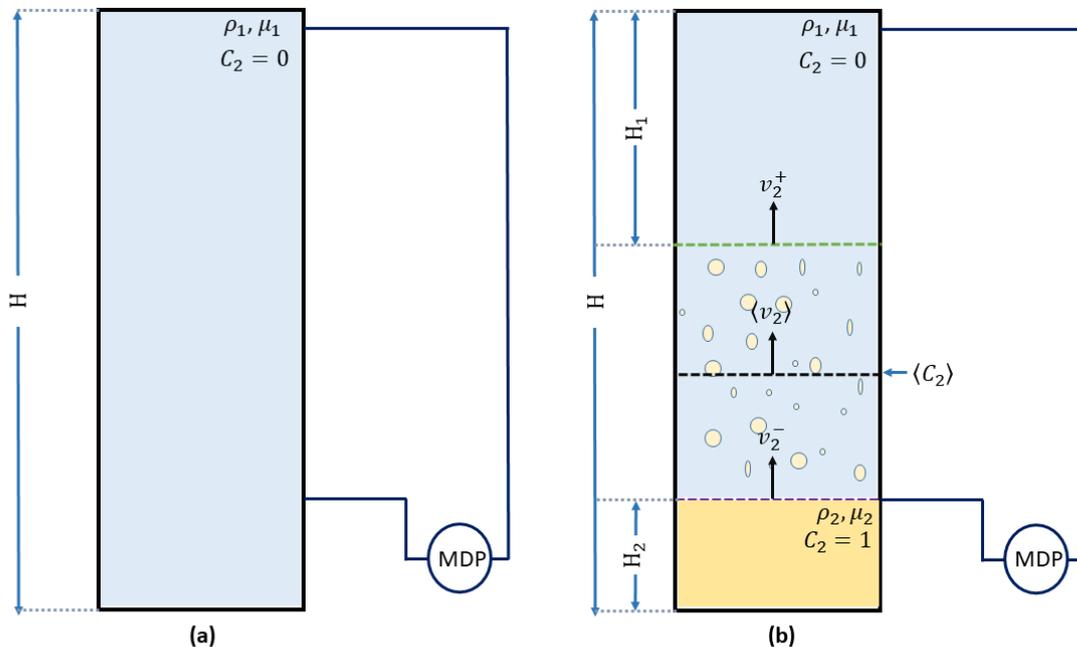


Figure 1: Schematic drawing of upward injection of fluid 2 (kerosene) in fluid 1 (water). In (a) we have the initial setting, prior to the injection's start. In (b) we have the setting for an injection time t_i , in this time the tubing is partially filled by the fluid 2. The interface shape is merely illustrative.

The research of Sugimoto *et al.* (2016) is an important reference to understand the authors' considerations in the previous paragraph. Sugimoto *et al.* (2016) studied the displacement of water through the injection of kerosene in a

vertical test section. The kerosene concentration was measured at a fixed point along the test section ($x = 3.4 \text{ m}$). The velocity range of injected kerosene was 0.2 to 0.65 m/s , which corresponds to the turbulent regime. The duct was 26.0 mm i.d and the properties of the fluids are shown in the Table 1. The Suguimoto's data can be used as measured data for an inverse analysis, and Figure 2 shows that the measured kerosene profile is similar to a diffusion process expressed by:

$$\frac{\partial \langle C_2(x, t) \rangle}{\partial t} = \alpha \frac{\partial^2 \langle C_2(x, t) \rangle}{\partial x^2} - \langle V_2 \rangle \frac{\partial \langle C_2(x, t) \rangle}{\partial x}. \quad (1)$$

where $\langle C_2(x, t) \rangle$ is the mean concentration of injected fluid (or holdup of injected fluid), α is the macroscopic diffusion coefficient, $\langle V_2 \rangle$ is the mean front velocity, x is the longitudinal space coordinate and t is time.

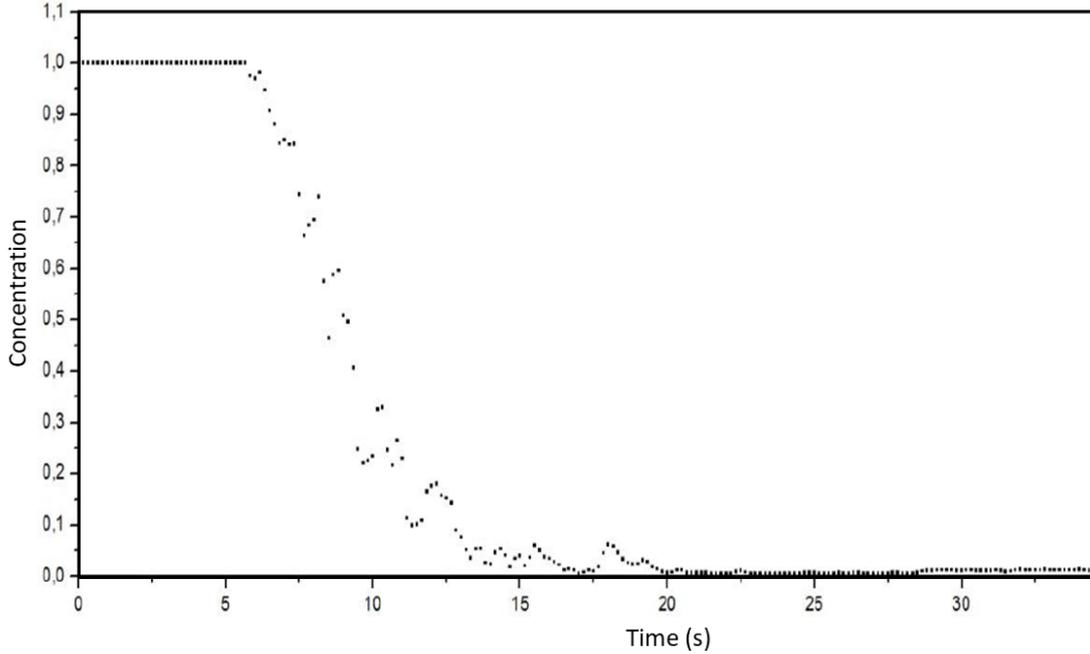


Figure 2: Measured kerosene concentration profile at $x = 3.4 \text{ m}$ from the bottom through time for injection velocity of 0.45 m/s . Source: Suguimoto *et al.* (2016).

Table 1: Fluids Physical Properties. Source: Suguimoto *et al.* (2016).

Fluid	Density [kg/m^3]	Dynamic Viscosity [N.s/m^2]	Surface Tension [N/m^2]
Water	998	0.001	0.019
Kerosene	793	0.0011	0.019

As there were insufficient concentration profile data in the work of Suguimoto *et al.* (2016) to establish an inverse analysis, the authors used a numerical procedure to solve Eq. (1): a finite difference method of high order for spatial discretization with a fourth-order Runge-Kutta method for time integration. The mean front velocity $\langle V_2 \rangle$ was computed using the Drift Flux model proposed by Zuber and Findlay (1965).

$$\langle V_2 \rangle = C_o \langle V_{inj} \rangle + V_\infty \quad (2)$$

where $\langle V_{inj} \rangle$ is the mean velocity of the injected fluid, C_o is the distribution coefficient and V_∞ is the rate of rise and it measures the rate of advance of a single droplet/bubble in a stagnant liquid. There is an extensive literature for distribution parameters and drift velocity, and in this work we used $C_o = 1.2$ as proposed by Nickin *et al.* (1962) and:

$$V_\infty = 1.18 \left[\frac{g\sigma}{\rho_1} \right]^{0.25} \quad (3)$$

The numerical results were presented in the form of mean concentration profiles of injected fluid through space for macroscopic diffusion bands typical of liquid-liquid miscible flow ($\alpha = 10^{-4} - 10^{-3} \text{ m}^2/\text{s}$) in various measurement

times (which simulate the presence of sensors). Then a code was developed to estimate the mean front velocity and the macroscopic diffusion coefficient by inverse analysis. The inverse analysis uses measured data and a physical model to infer the characteristic parameters values. Parameter estimation by inverse analysis is a well-established field in thermal sciences for heat conduction problems (Ozisik, 2000; Cui *et al.*, 2015, 2016, 2017; Singh *et al.*, 2017), for example, but the authors have realized that it is also a very useful tool for fluid mechanics.

To solve the inverse problem of the concentration profiles and to obtain the diffusion coefficient and the average front velocity, the Levenberg-Marquardt method was chose. (Ozisik, 2000; Zhang *et al.*, 2017; Singh *et al.*, 2017). Like the Gauss-Newton algorithm, the Levenberg-Marquardt method is used to solve nonlinear least squares problems, with the advantage of better treatment of divergences.

3. RESULTS AND DISCUSSION

In order to analyze the behavior of the fluid front and the diffusion of the injected phase the authors established two cases: displacement flow (I) without drift and (II) with drift between phases. The goals were to certify if (a) the code is able to recover the diffusion coefficient and the kerosene average front velocity; (b) to establish the range of possible values to be recovered and (c) to confirm if such an interval is suitable for experimental interests.

Based on Figure 2 extracted from Suguimoto *et al.* (2016), the authors proposed two similar cases to verify the accuracy of the numerical solution for direct and inverse problems. The Figures 3 and 4 show the simulated and recovered concentration profiles. In both images the red curve represents simulated data and the blue curve represents the data recovered with the estimated parameters. In addition, three reference curves were plotted for the kerosene mean front velocity (green), kerosene trailing front velocity (yellow) and injection velocity (black). These three extra curves are important to understand the difference between flow with and without slip between phases. Without slippage, as shown in Figure 3 (when both liquids have the same densities) the average front velocity travels with the same velocity of injection. Figure 4, on the other hand, shows a change between the mean velocity (green curve) and the injection velocity (black curve) because the buoyancy between the phases accelerates the lighter liquid (kerosene). But this effect does not change the flow diffusion and the same diffusion coefficient is recovered in both cases.

According to Suguimoto *et al.* (2016) the time required to remove all water from the test section until the measuring position $x = 3.4 \text{ m}$ with $\langle V_{inj} \rangle = 0.45 \text{ m/s}$ was $t = 6.5 \text{ s}$. In our comparative cases, in the same period, the trailing front is at $x = 2.4 \text{ m}$ (Figure 3) and $x = 3.5 \text{ m}$ (Figure 4). For this velocity the flow is turbulent and strongly dominated by the buoyancy, therefore, to consider the existence of drift between phases is crucial to the problem. The work of Debacq *et al.* (2003) showed that the diffusion coefficient remains constant for low Atwood number (between $10^{-4} < At < 10^{-2}$) and grows with the increase of this dimensionless ($At > 10^{-2}$). For the showed cases, there is a high value of Atwood, of the order of $At = 10^{-1}$.

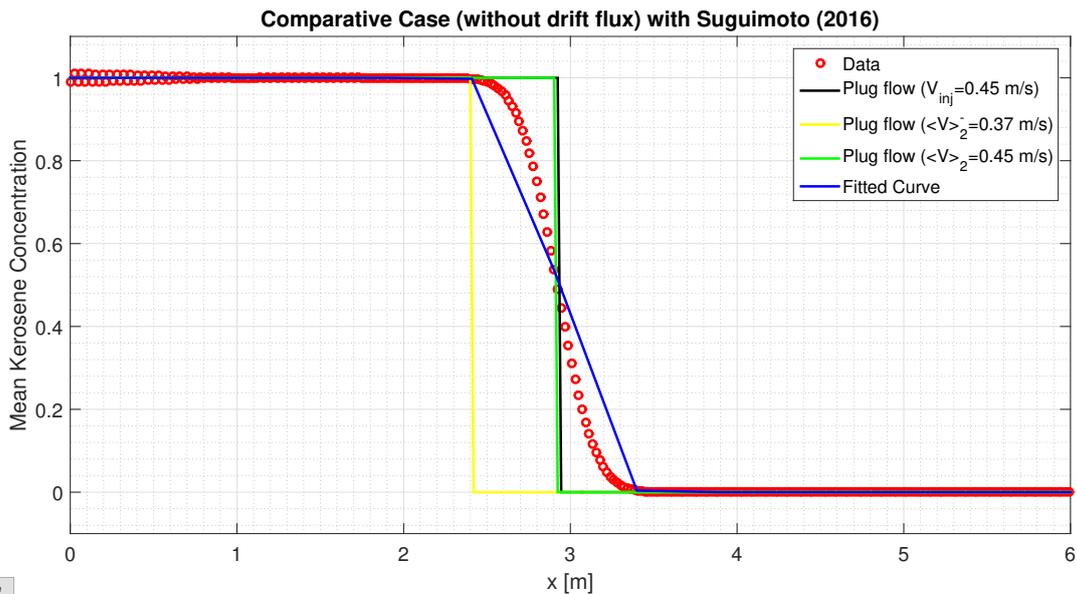


Figure 3: Mean concentration profile simulated and recovered for $V_{inj} = 0.45 \text{ ms}^{-1}$, $\alpha = 2.5 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and $t = 6.5 \text{ s}$. Although the recovered curve does not completely represent the simulated curve, for low velocities and small times, it hits the three relevant points that are: the mean, the leading and trailing fronts.

Figure 5 shows the change in concentration profile for several measurement times versus the similarity variable $\xi = x - \langle V_2 \rangle t$. Since the flow is fully developed in the main direction, the average velocity is a constant and it is possible to

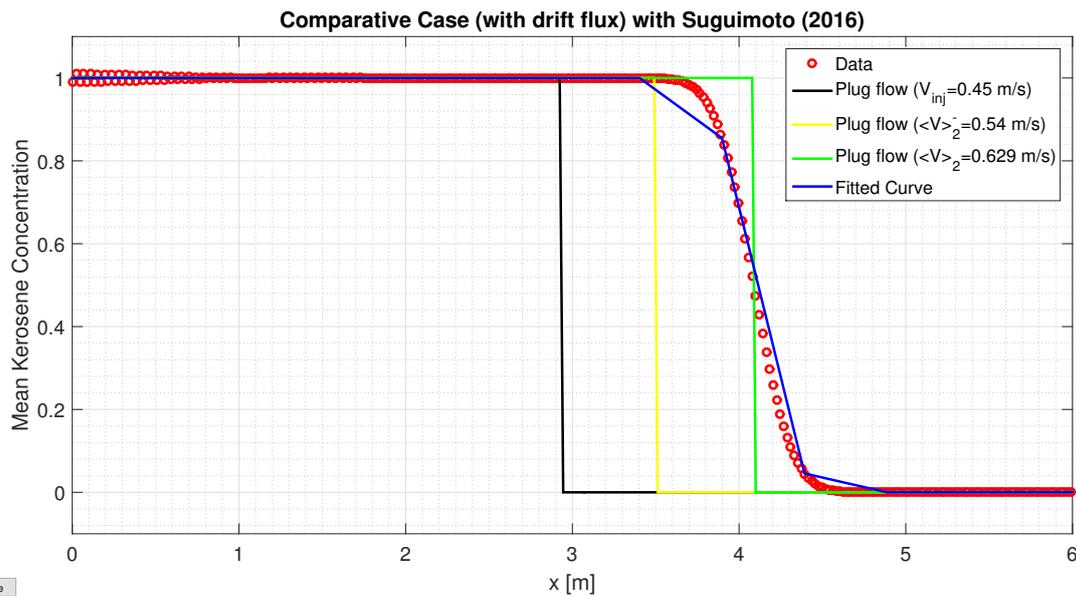


Figure 4: Mean concentration profile simulated and recovered for $V_{inj} = 0.45 \text{ m/s}$, $\alpha = 2.5 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ and $t = 6.5 \text{ s}$.

treat the problem as if it were only diffusive, that is, as time increases the concentration of kerosene spreads through the tube. The existence of a similar variable is very efficient because it becomes possible to recover velocity values with the installation of few measuring points in the pipeline by translating all the curves to the same reference point.

Figure 6 shows the range of diffusion coefficients in which this research is interested. It demonstrates the ability of the inverse analysis code to capture very small values in the range of $10^{-5} \text{ m}^2/\text{s}$ and large values such as $0.01 \text{ m}^2/\text{s}$. These limits should not be found in actual tests, but have been checked for code limitations. Velocity ranges have also been tested from $V_{inj} = 0.1 \text{ m/s}$ to 2.0 m/s .

Tables 2 and 3 show an error analysis for the parameter estimation interval. In the estimation of both parameters the error increases as their values decrease, but because the diffusion coefficient values are much smaller than the velocity range studied, the code presents larger errors in the estimation of this parameter as the concentration profile approaches a Heaviside function (or step function).

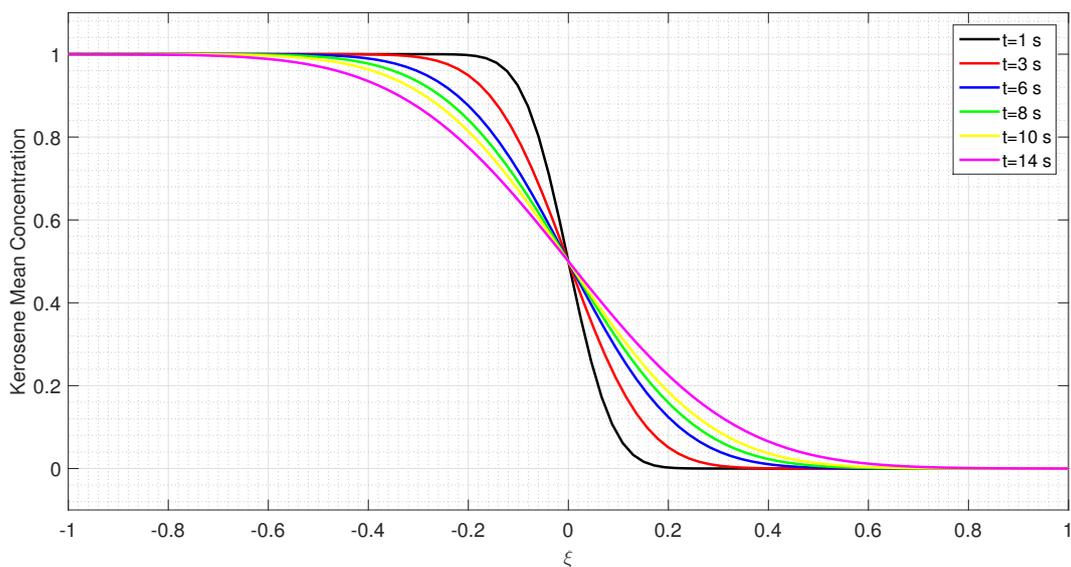


Figure 5: Kerosene mean concentration profile vs. ξ for $\alpha = 2.5 \times 10^{-3}$.

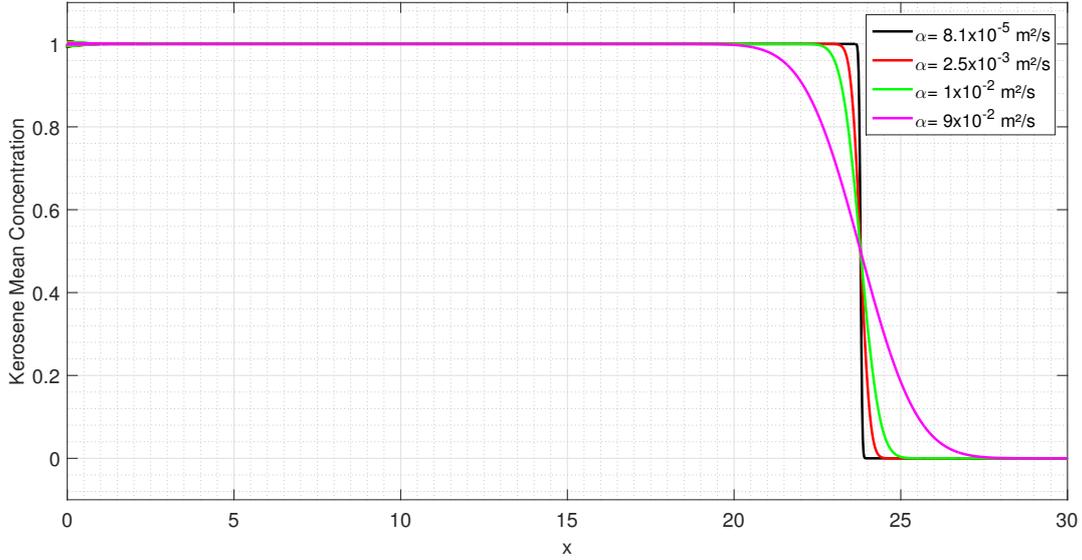


Figure 6: Kerosene mean concentration profile vs x for some values of diffusion coefficient and $\langle V_2 \rangle = 2.38 \text{ m/s}$.

Table 2: Diffusion Coefficient Estimation: Sensibility Analysis

Time [s]	$\langle V_2 \rangle [m \cdot s^{-1}]$	$\alpha_{real} [m^2 \cdot s^{-1}]$	$\alpha_{estimated} [m^2 \cdot s^{-1}]$	Error (%)
10.0	2.38	0.000025	0.00002601	4.04
10.0	2.38	0.000049	0.00004761	2.8367
10.0	2.38	0.000081	0.00007921	2.2099
10.0	2.38	0.0025	0.0025	0.0000
10.0	2.38	0.0036	0.0036	0.0000
10.0	2.38	0.01	0.01	0.0000
10.0	2.38	0.09	0.09	0.0000

Table 3: Mean Velocity Estimation: Sensibility Analysis

Time [s]	$\langle V_2 \rangle_{real} [m \cdot s^{-1}]$	$\langle V_2 \rangle_{estimated} [m \cdot s^{-1}]$	Error (%)	$\alpha_{real} [m^2 \cdot s^{-1}]$
10.0	0.2579	0.2573	0.2326	0.0025
10.0	0.7379	0.7373	0.0813	0.0025
10.0	1.3379	1.3373	0.0345	0.0025
10.0	1.9379	1.9373	0.031	0.0025
10.0	2.5379	2.5373	0.02364	0.0025

4. SUMMARY AND CONCLUSIONS

The authors studied the flow behavior of water withdrawal via kerosene injection in an upward test section. Such a research finds motivation and applications in oil production systems in deep and ultra deep water that encounter problems such as hydrates formation, corrosion and displacement of waxy crude oil in production restart, or onshore/offshore applications such as mud removal and cementing. The proposal modeled the water withdrawal through two parameters: average velocity of the injection front and macroscopic diffusion coefficient. The methodology chosen was the development of a code based on inverse analysis that received data from concentration profiles and retrieved the parameters with the Levenberg-Marquardt algorithm.

The main research conclusions are:

- In diffusive flows, it is possible to characterize the removal of a liquid by immiscible liquid, in this case, the

withdrawal of water by kerosene, by two parameters: mean velocity of the injection front and macroscopic diffusion coefficient.

- The inverse analysis code was able to retrieve very low values of diffusion coefficient (α) of the order of magnitude of $10^{-5} \text{ m}^2/\text{s}$ and very high values as $10^{-2} \text{ m}^2/\text{s}$. This is a safe interval of analysis, since the authors expect to find values of this parameter between $10^{-4} - 10^{-3} \text{ m}^2/\text{s}$. For the injection velocity, the interval was between 0.1 m/s e 2.0 m/s and the code was also able to retrieve the average front velocity values ($\langle V_2 \rangle$).
- The highest errors were for the injection velocity close to the drift velocity (due to the buoyancy) for the initial times, where the flow is not yet fully developed. But for the actual parameters expected, the inverse analysis methodology is a very powerful tool due to its simplicity and accuracy.

5. ACKNOWLEDGEMENTS

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