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**NUMERICAL AND EXPERIMENTAL STUDY OF FLUSHING PROCESS IN
A HORIZONTAL PIPE USING MISCIBLE FLUIDS**

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Abstract. *The displacement of a fluid by another fluid is commonly used to clean oil and gas pipelines that may be subject to problems such as hydrate blockage and corrosion. This type of operation is called Flushing. Typical applications include: pre-commissioning, where saline water is removed to prevent corrosion; commissioning and shutdown operations, where the pipeline fluid is replaced by a safe medium to prevent the formation of hydrates; and decommissioning, where the pipeline fluid is replaced to allow safe disconnection. Optimization of the flushing process, considering the time and volume of fluid spent, requires knowledge about the characteristics of the flow so that the process is enhanced from an economic point of view. In this scenario, this work presents a numerical and experimental study of flushing of fresh water by a viscous fluid. The viscous fluid was a mixture of water and glycerol with viscosities of 3.5cP and 8.5cP. The flow loop consisted of a straight tube of 8.15 m in length and 26 mm in internal diameter, built at Multiphase Flows Research Center - Nuem, at Federal Technological University of Paraná - UTFPR. Time series of the mixture mass concentration were recorded at two different points, 5.135 m and 5.35 m, using resistive sensors. Pressure drop between two points, 2.015 m and 5.335 m, was also recorded. For the experiments with the injection fluid of 3.5cP, the superficial velocities tested were 0.2, 0.3, 0.4, 0.5 and 1 m/s, while for the injected fluid of 8.5 cP, the superficial velocities tested were 0.2, 0.5 and 1 m/s. The instruments were connected to a data acquisition system and were monitored through an interface developed in LabVIEW. The flushing efficiency was analyzed in relation to the viscosity ratios, the behavior of the pseudo-interface between the fluids, as well as the volume of fluid injected necessary to clean the pipe. Numerical simulations were performed using Ansys CFX®. A good agreement with the experimental data was observed.*

Keywords: *Multiphase Flow, Flushing, Liquid-liquid Displacement, Miscible Fluids, Numerical Simulation.*

1. INTRODUCTION

Flushing processes used to clean remaining fluids from oil and gas pipelines have been studied over the past years. The characterization of the flow with regard to the difference in viscosities was addressed by some authors. Xu et al. (2011) and (2016) studied the displacement of water by oil in low sections of pipes. They proposed a model to predict the conditions for the onset of water displacement by oil flow from a horizontal section followed by an upward inclined section. They also analyzed the influence of viscosities and densities in the flow. Alba et al. (2013) and Etrati et al. (2018) experimentally investigated the displacement of two miscible fluids, observing the effect of the density ratio on the pseudo-interface instability, the conditions for backflow and the flow displacement efficiency. Schumann et al. (2014) investigated the displacement of oil by tap water concerning the frontal velocity propagation as well as buoyancy and gravitational forces acting in the flow direction. Leuchtenberger et al. (2021) performed a comprehensive analysis on how the displacement of a viscous liquid by a less viscous one occurs in different pipe segments, varying the injection velocity.

They suggested a dimensionless group to analyze optimal values for the cleansing time in relation to the flow configuration.

When dealing with miscible fluids, it is important to observe what some works report about the behavior of these flows. Taghavi and Frigaard (2013) studied the flow of miscible fluids in tubes with different inclinations and almost horizontal, using a more viscous fluid to push another less viscous and with different densities. They observed that the region where the mixing length is found (that is, the interface where the presence of the two fluids is observed) can be larger or smaller depending on the ratio between the densities. They also correlated the influence of viscous force, inertial force and gravity with Reynolds number (Re) and Froude number (Fr). Alba et al (2013) reported that the smaller the density ratio differences between the two fluids in the pipe, the better the displacement process, as this region (interface or mixing length) becomes smaller (i.e., less stratified). They also reported that the smaller this region, the more efficient the cleaning process will be.

Regarding numerical simulation of this kind of flow, turbulence and mixing are key phenomena that must be properly addressed by the model so that the result is physically representative. Abraham et al. (2008) suggested adapting a turbulence model for internal flows, modifying some constants, with the intention of expanding the range of the transition value of the Reynolds number (Re) to be between 2300 and 4000. This range delimits the region where the flow transitions from laminar regime to fully turbulent. The purpose of this modification is to better describe this transition region and adequately resolve runoff. This region is commonly found when it comes to the mixing site between two miscible fluids (viscous fluid pushing a less viscous fluid). It is noteworthy that there are few studies about transition regime and how this region is formed

The onset of instabilities in the flow initiates the phase dragging process and increase the shear stresses between the two fluids, consequently leading the formation of a fluid plug that pushes the fluid downstream, as experimentally described by Xu et al. (2011).

Still talking about transition regions, Hankzes apud Van Eeden (2021) reported that stratification effects are no longer observed for multiphase flow in a horizontal pipe for $Fr > 3.9$.

As reported above, flushing optimization processes have been analyzed in several ways. Although these analyses focus mainly on the behavioral aspects of the flow, they also bring important information such as the influence of the fluid properties and optimal viscosity ratios and measurements of the mixing interface length, allowing the development of models capable of predicting the optimal conditions for an efficient flushing with a low economic cost.

2. METHODS

In this work two miscible fluids were used: a mixture of tap water and glycerin with two different concentrations resulting in viscosities of 3.5 cP e 8.5cP, and tap water at 20°C. The experiments were performed in a horizontal flow loop (as shown in Figure 1) of 8.15-m long and 26-mm ID built at in the Multiphase Flows Research Center - NUEM, of the Federal Technological University of Paraná – UTFPR. One camera positioned 5.8 m distant from the pipe inlet captured images of the flow.

The time series of the mass concentration of the mixture was measured as well as the pressure drop in a segment of the pipe. For the mass fraction signals, two resistive sensors were used at positions 5.135 m and 5.35 m from the inlet. The pressure drop was measured between two points in the test section located at 2.015 m and 5.335 m from the inlet. For the tests with the injection fluid with a viscosity of 3.5cP, the tested velocities were 0.2, 0.3, 0.4, 0.5 and 1 m/s, while for the injected fluid with a viscosity of 8.5 cP, the velocities were 0.2, 0.5 and 1 m/s. The instruments were connected to a data acquisition system and recorded through an interface developed in LabVIEW.

This system was used to monitor parameters such as injection factor (volume of fluid injected over pipe volume) versus time, injection velocity and to estimate the position of the displacement fluid interface (considering plug flow).

With the signal of the resistive sensors, it was possible to monitor the front velocity of flushing propagation and local concentration.

To describe the flow, we use the relations for Reynolds number (Eq. 4), Froude number (Eq. 5) and injection factor:

$$Re = \frac{\rho_{injection} U_{injection} D}{\mu_{injection}}, \quad (1)$$

$$Fr = U_{injection} \left(gD \left(1 - \frac{\rho_{lighter}}{\rho_{heavier}} \right) \right)^{-0.5}, \quad (2)$$

$$\phi = \frac{Vol_{injected}}{Vol_{pipe}} = \Delta t * \frac{U_{injection}}{L_{pipe}}, \quad (3)$$

where $\rho_{injection}$ is the mass density of the fluid injected into the tube, $\mu_{injection}$ is the viscosity of the fluid injected, $U_{injection}$ is the average injection velocity, D is tube inner diameter, $\rho_{lighter}$ is the density of the lightest fluid, $\rho_{heavier}$ is the density of the heaviest fluid, g is gravity, $Vol_{injected}$ is the volume of fluid injected into the pipe, Vol_{pipe} is the volume of the pipe, L_{pipe} is the length of the pipe and Δt is the cleaning time.

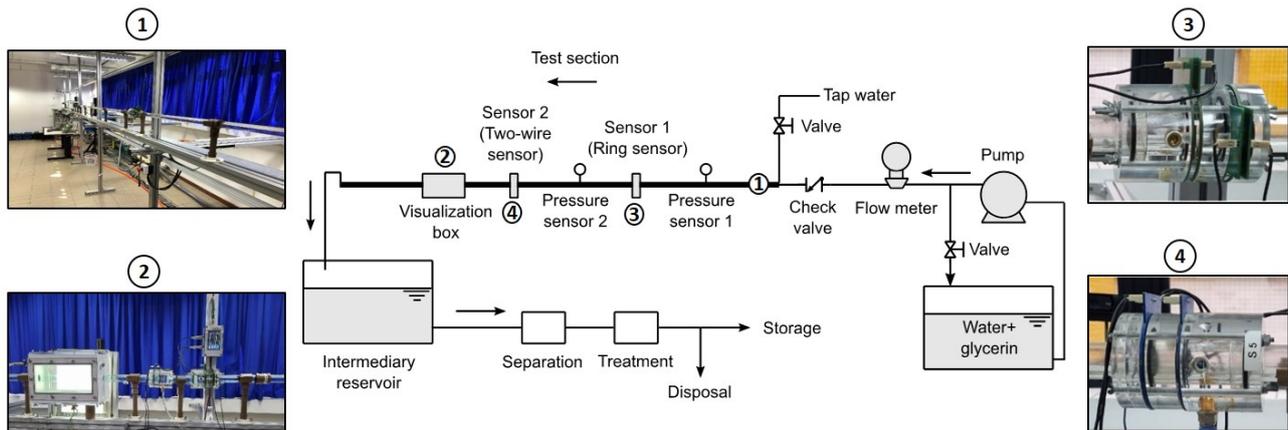


Figure 1: Experimental loop scheme of the flow loop and its respective instruments: 1) Mean pipe; 2) Visualization section; 3) Ring sensor; 4) Two-wire sensor.

Table 1 shows the test matrix used to perform the experiments, as well as the properties of each fluid, the calculated values for Re number (Re) (Eq.1) and Froude number (Fr) (Eq. 2), the injection factor (Eq. 3) and the concentration of the fluid injected.

Table 1: Test Matrix used for the experimental Performed

Test	Injection velocity (m/s)	Fr	Re	Concentration	Time (s)	ϕ
1	1	5.6	3493	50 vol% glycerin + 50 vol% water (8.5 cP, 1140 kg/m ³)	20	2.5
2	0.5	2.8	1764		35	2.1
3	0.2	1.2	726		50	1.2
4	1	6.9	8120	33 vol% glycerin + 67 vol% water (3.5 ~ 4cP, 1089 kg/m ³)	20	2.5
5	0.5	3.4	4063		41	2.5
6	0.4	2.7	3249		51	2.5
7	0.3	2.1	2446		58	2.1
8	0.2	1.4	1649		102	2.5

These injection velocities were selected in order to have a wide range of Fr and Re numbers. As it will be discussed in the next sections, the flow behaves differently depending on these parameters, which directly affects the flushing performance.

2.1 Computational modeling

Simulations were performed using Ansys CFX solver. The Multicomponent Single Phase Flow Model was used, which solves Navier-Stokes equation for the bulk flow, as well the continuity equation and diffusive transport equation for each diluted phase.

The dimensions of the experimental test section were replicated in the numerical domain. To simplify the geometry and to reduce the number of elements of the mesh, the geometry was considered axisymmetric.

The simulated domain is of 8.15-m long and 26-mm. The mesh has 4758432 elements and 4987800 nodes.

As boundary conditions, as input condition (INLET), the reported injection velocities were used (0.2 to 1 m/s) and at the exit (OUTLET) the Mass and Momentum option was used as Average Static Pressure, as Relative Pressure equal to zero and Pressure Profile Blend equal to 0.05. In the symmetry region of the domain, the Symmetry option was used. The simulation was carried out considering transient regime.

The working fluids were the same as in the experiments (mixture of glycerin and water washing tap water) and were solved considering as miscible fluids. In order to better model the turbulence, the SST-Gamma Theta model was used for the cases where $Re < 2000$. This transition model was originally developed to predict the onset of turbulence for boundary layer flows (e.g., airfoils). Although it has been applied with some success for internal flows (e.g., flow in pipes), the model used for the simulation in this work was modified according to Abraham et al. (2008) to change the range of transition to turbulent flow. With the modification, the Re of transition matches the one for flow in circular pipe.

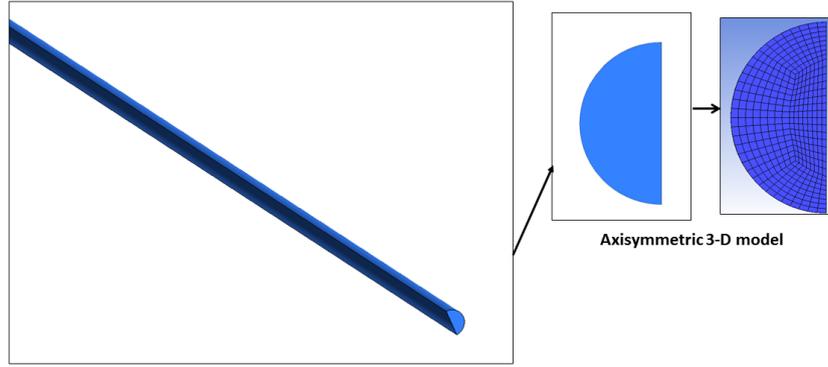


Figura 2: Axisymmetric 3D geometry used in the simulations, with details of the discretization of the domain used (computational mesh).

2.1.1 Mathematical modeling

The assumptions for the model are: two miscible fluids, there is no chemical reaction between the fluids and isothermal flow. Furthermore, it is assumed that the fluids involved have constant properties and are considered as Newtonian fluids, as well as their mixture.

For the turbulence modeling, the Reynolds concept of averages (BATCHELOR, 1967) and the Boussinesq hypothesis (WILCOX, 2006) are assumed. The system resulting from this approach is commonly referred to as RANS, which stands for Reynolds-Averaged Navier-Stokes equations.

A single-phase and isothermal flow can be modeled by the equations of continuity and balance of momentum, in addition to a transport equation for the mass fraction of one of the fluids that dilutes in the main fluid, presented respectively below:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0, \quad (4)$$

$$\frac{\partial \rho \vec{V}}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \mu_{eff} \cdot \nabla^2 \vec{V}, \quad (5)$$

$$\frac{\partial (\rho \varphi)}{\partial t} + \nabla \cdot (\rho \vec{V} \varphi) = \nabla \cdot \left[\left(\rho D_\phi + \frac{\mu_t}{Sc_t} \right) \nabla \varphi \right] + S_\varphi, \quad (6)$$

In Eq. 6, Φ refers to the concentration of the fluid that is injected, where $\varphi = \Phi/\rho$ is the concentration per unit mass, S_φ is the volumetric source term and D_ϕ is the kinematic diffusivity for the scalar. The term Sc_t which is the Schmidt turbulence number and μ_t refers to the turbulent viscosity.

For both equations, ρ is the specific mass of the fluid, t is the time, p is the pressure, \vec{V} is the Reynolds mean velocity vector, and μ_{ff} is the effective viscosity of the fluid. By definition, the effective viscosity is composed of the sum of molecular viscosity, μ and turbulent viscosity, μ_t , i.e.. $\mu_{ff} = \mu + \mu_t$ (POPE, 2000).

3. RESULTS

3.1 Experimental Results

In the experiments, fresh water is displaced by a mixture of glycerin and water with two different concentrations, which results in viscosities of 3.5 cP (Figure 3) and 8.5 cP (Figure 4). The mixture was injected at different velocities. For the best efficiency of the cleaning process, one must have the flow as less stratified as possible, that is, with the appearance of a plug flow pattern. For that, one can relate the flow pattern with Reynolds number (Eq. 1) and Froude number (Eq. 2). It is important to note that in this work both fluids are Newtonian fluids and a lighter and less dense fluid is being displaced by a heavier and denser one.

Figures 3 and 4 show the behavior of the flow between two miscible fluids where it is possible to observe the stratified or plugged aspect of the interface formed for each of the velocities and each viscosity.

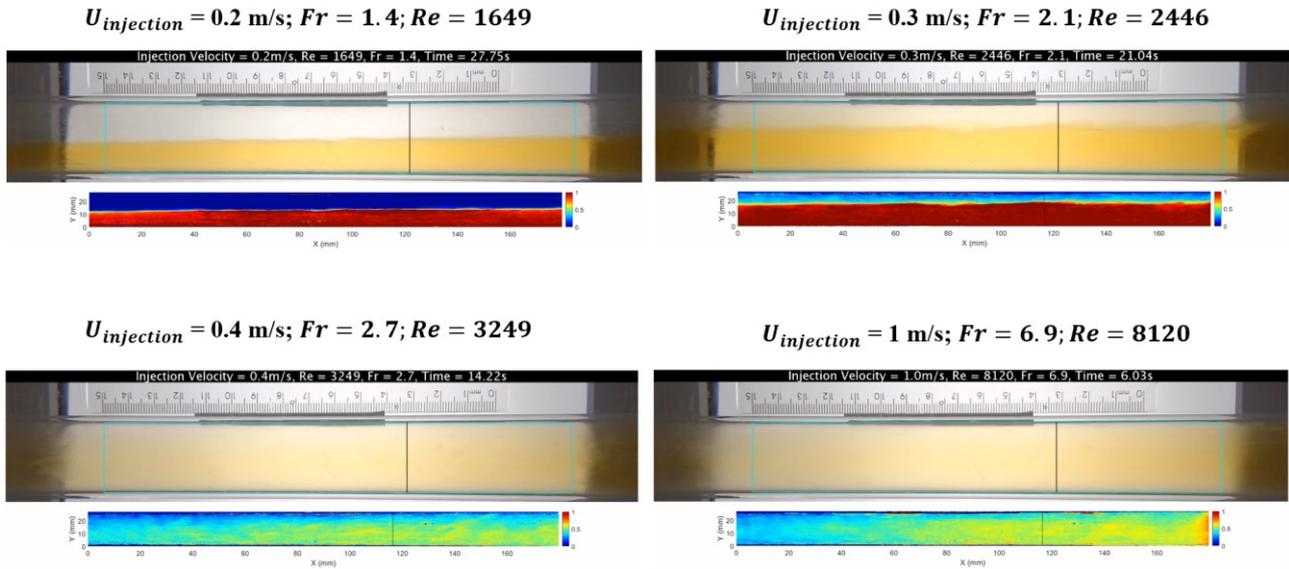


Figure 3: Behavior of the flow in the flushing process, using water as the fluid to be cleaned, and the concentration of glycerin and water as the cleaning fluid for 3.5 cP. The post-processing shows the growth in the height of the water and glycerin concentration column as a function of the length of the pipe.

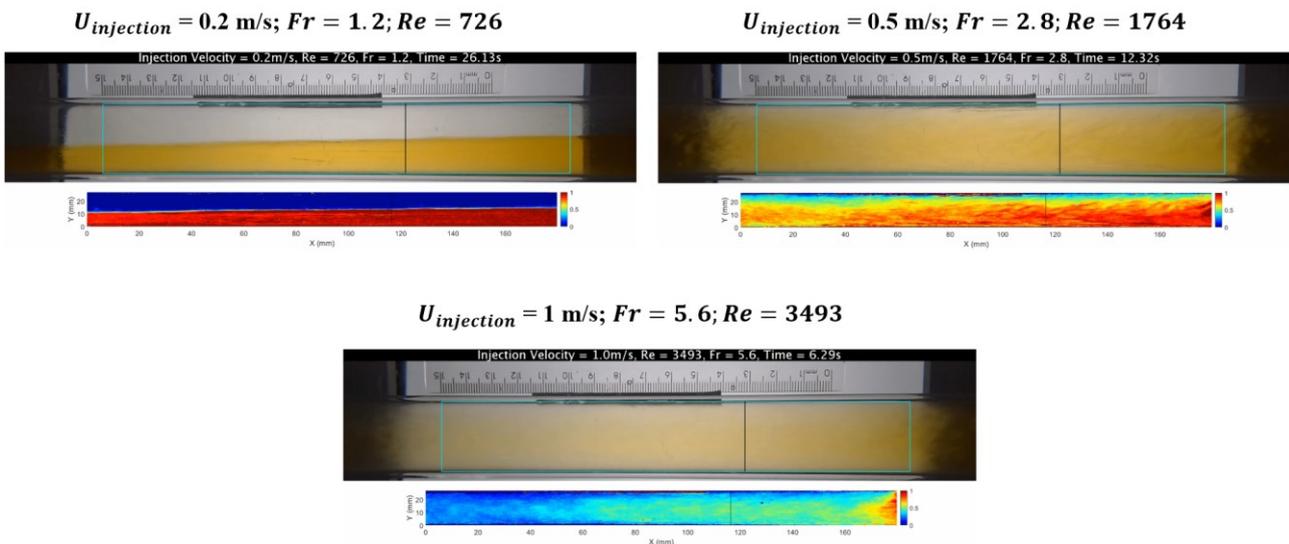


Figure 4: Behavior of the flow in the flushing process, using water as the fluid to be cleaned, and the mixture of glycerin and water (orange color) as the cleaning fluid for 8.5 cP. The post-processing shows the growth in the height of the water and glycerin concentration column (mass fraction) as a function of the length of the pipe

Figure 3 and 4 show the camera images for the two concentrations used. The difference in the mixing of the phases and consequently in the cleaning efficiency can be clearly seen. The results for the injection fluid of 3.5 cP and lower velocities (0.2 and 0.3 m/s) show a stratified flow pattern, as well as for the 8.5-cP injection fluid (0.2 and 0.5 m/s). For the 3.5-cP fluid and 0.2 m/s, the value of Re is less than 2000 and the flow is laminar, while for 0.3 m/s, $Re > 2000$ and it is the transition from laminar to turbulent just began. However, a stratified behavior can still be seen. For values of $Re > 2300$ (velocities of 0.4, 0.5 and 1 m/s), the flow can be considered transitional with flow characteristics similar to plug flow. For a viscosity of 8.5 cP, the appearance of a plug pattern occurs at a velocity of 1 m/s, with a delayed transitional Reynolds range due to the higher viscosity (ABRAHAM et al. 2008). It shows the behavior of the flow between two miscible fluids and it is possible to observe the stratified or plugged aspect of the interface formed at each velocity for each viscosity.

3.2 CFD Results

Figure 5 shows the evolution of the flow for a viscosity of 3.5 cP for different velocities and at different time steps, in the same way that Figure 6 shows the behavior of the flow for a viscosity of 8.5 cP.

It is important to note that the flow is visualized from the symmetry region of the pipe. This way we can observe the mass fraction of water and glycerin pushing the water mass fraction.

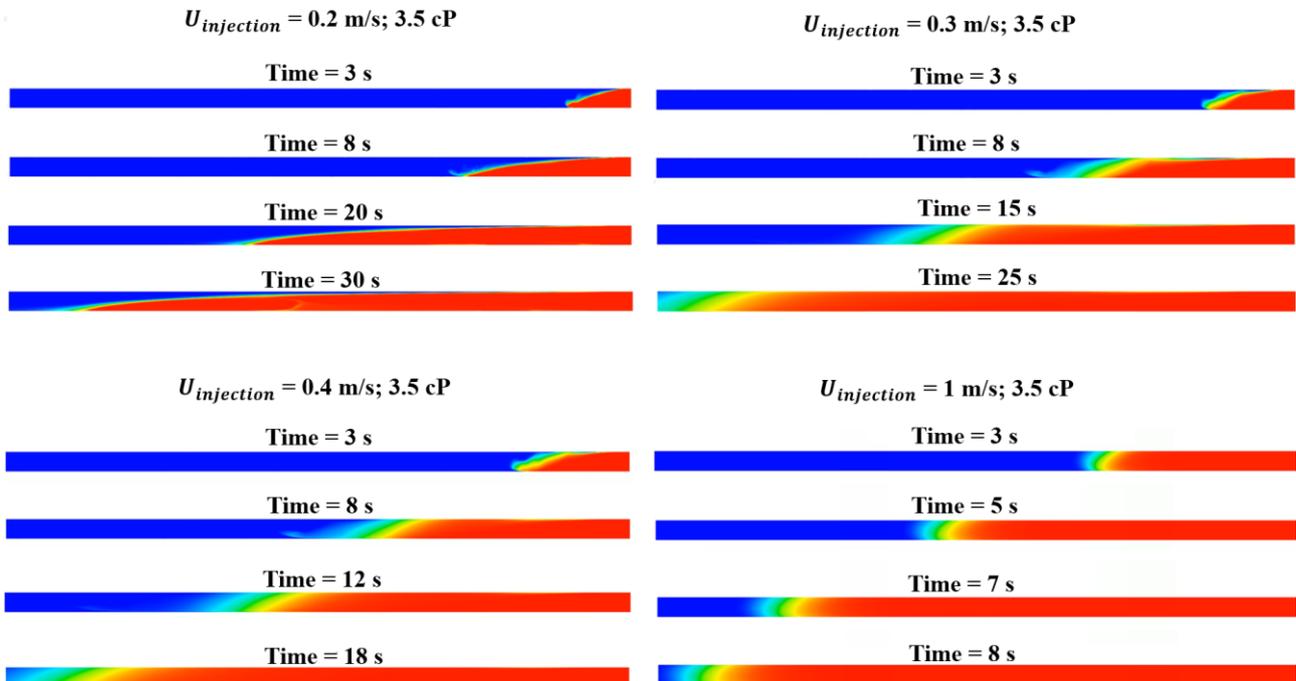


Figure 5: Evolution of flow for each injection velocities with 3.5 cP.

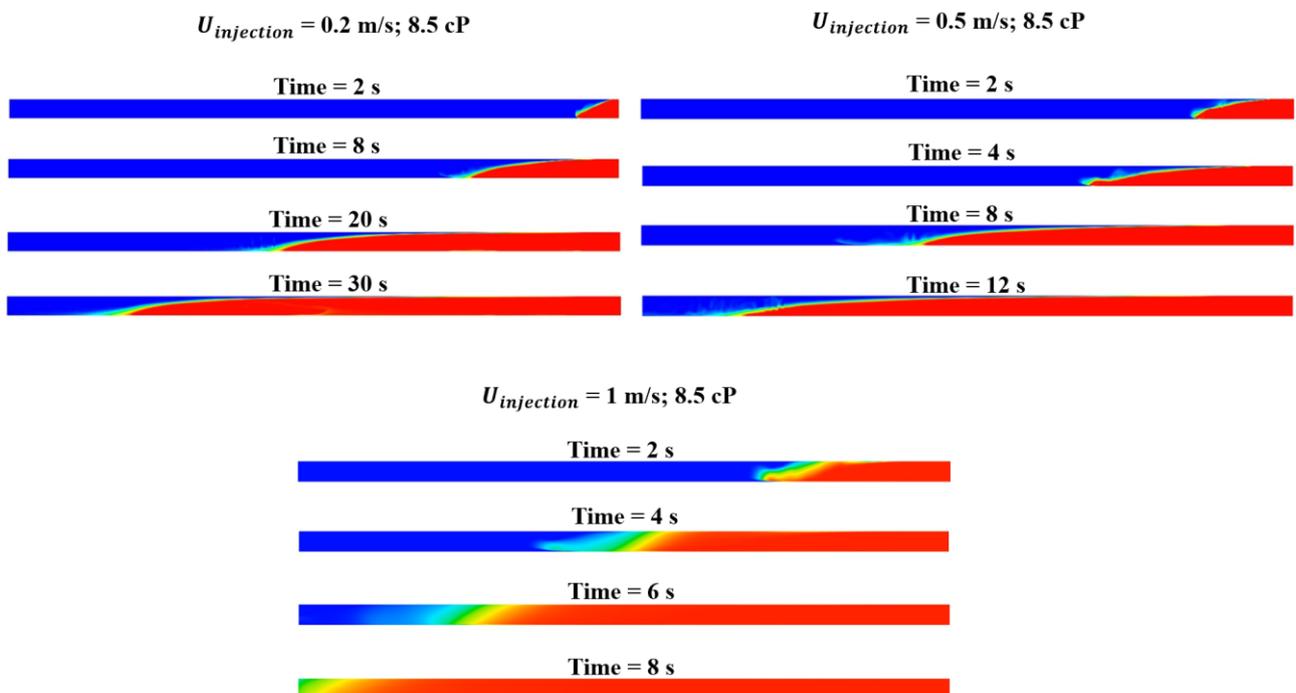


Figure 6: Evolution of flow for each injection velocities with 8.5 cP.

To better visualize the cleaning process over time, Figures 7 and 8 show the evolution of the flushing propagation front for different speeds for the same instant time.

Time = 8 s

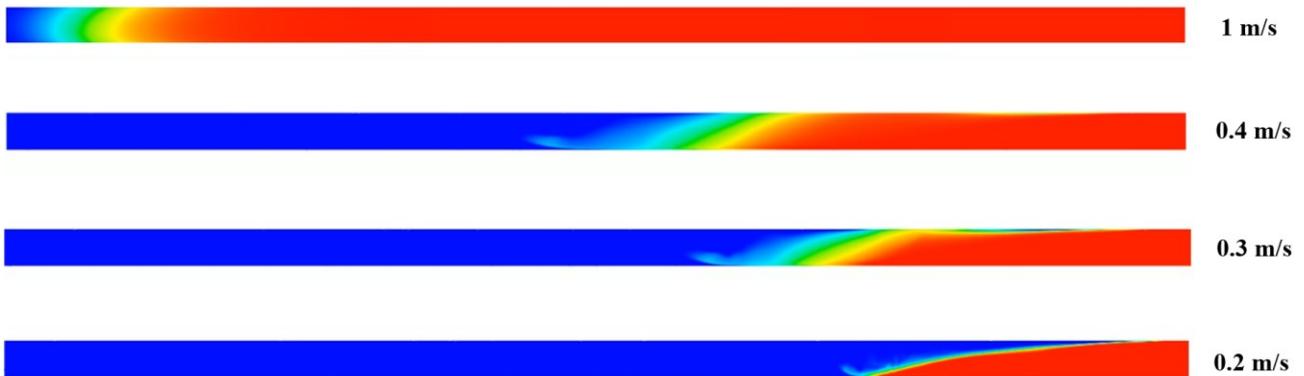


Figure 7: Evolution of the flow for different injection velocities at the same time instant for 3.5 cP.

Time = 8 s

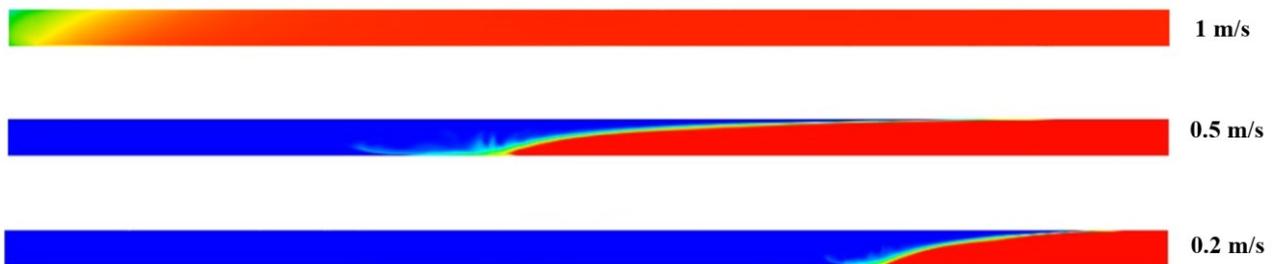


Figure 8: Evolution of the flow for different injection velocities at the same time instant for 8.5 cP.

In general, it is possible to observe the formation of the plug flow pattern for cases with high Reynolds (transition from laminar to turbulent). For the viscosity of 3.5 cP, the flow can be considered in the transition from laminar to turbulent regime for the speed 0.3 m/s ($Re = 2446$). It is noted that the stratified aspect can be visualized more clearly for the lowest speed, 0.2 m/s, which has $Fr < 2$. This value is below the value that would result in the beginning of mixing between the phases and, consequently, to the plug flow appearance (indicating a less efficient cleaning in terms of injected volume and time).

When analyzing the effect of viscosity for the two injected fluids, one can note that the formation of the plug pattern happens for higher velocities, as observed in the experimental tests. For example, for 0.4 m/s for 3.5 cP, it can be noticed the plug being formed with better definition than for the case of 0.5 m/s and 8.5 cP, in which the stratified effect is still present (which can also be justified by low Fr number). The latter case would be in the transition region ($Fr = 2.8$), reinforced by Re number still laminar. The justifiable parameter for this is the higher viscosity

Figures 7 and 8 show better the cleaning evolution for the different speeds for the same time. Again, there is a tendency of plug flow for larger Fr and Re numbers, also depending on the viscosity of the fluid that is pushing. For these cases, we can say that the less viscous fluid (3.5 cP) injected as a cleaning fluid is more effective for the removal of the water from the pipe, considering the same injection velocity.

According to the literature (Alba et al. 2018) when $Fr \approx 2.6$, the displaced light fluid layer becomes thin and local mixing occurs at the interface. So $Fr > 2$ is the threshold value for mixing to occur. For lower velocities (0.2 and 0.3 m/s) a stratified flow pattern is present for 3.5 cP, as well for the 8.5 cP (0.2 and 0.5 m/s).

For 8.5 cP the appearance of a plug flow occurs at velocities of 1 m/s with delayed transitional Re due the higher viscosity.

3.3 Results Comparison

This section compares the results of experimental tests and CFD simulations. Figures 9 and 10 compare the mass fraction time series from the experiments against the simulated ones. It is important to highlight that the turbulence model was only used for cases in which the flow regime was transitional or fully turbulent. The more accentuated curves describe the behavior of the cases that have the plug aspect as the dominant factor in the flow. The curves that are smoother refer

to cases that present a stratified aspect at the interface. The CFD model can predict very well the concentration curves and behavior and the cleaning process.

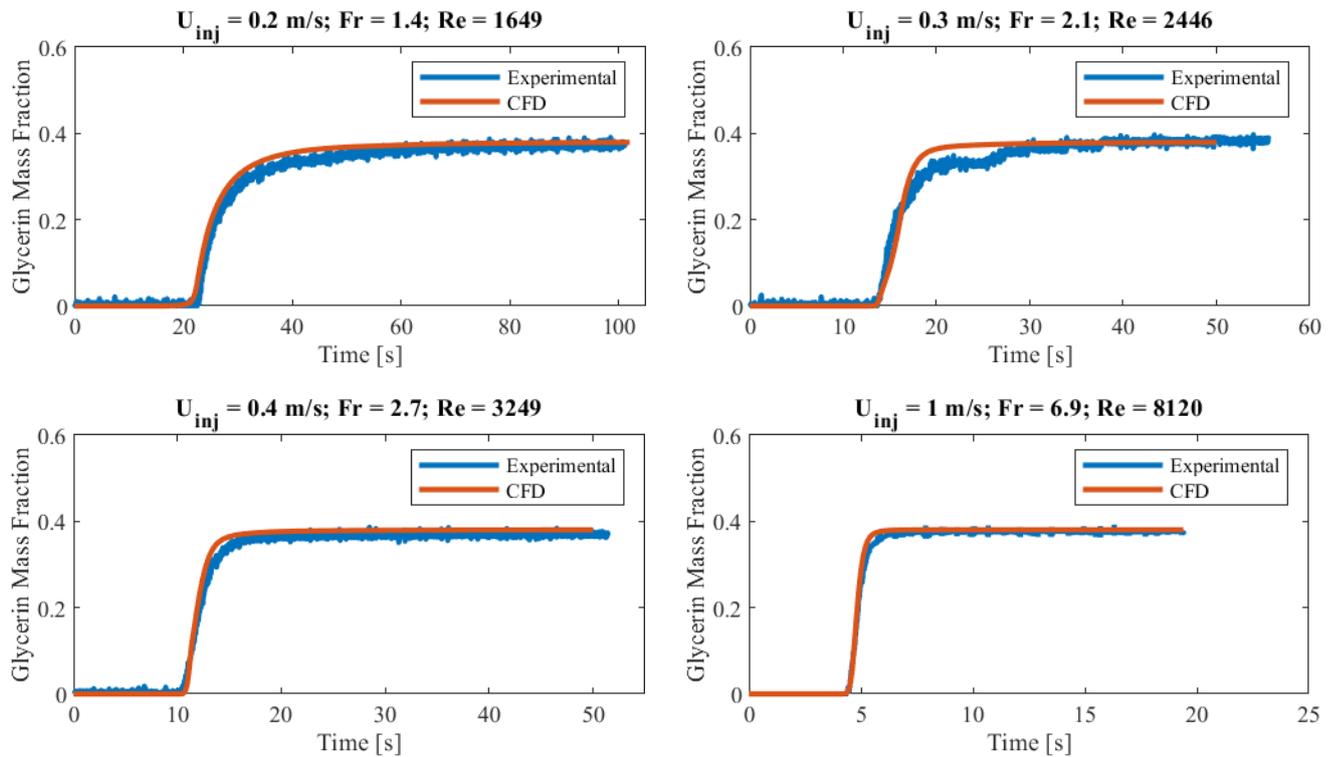
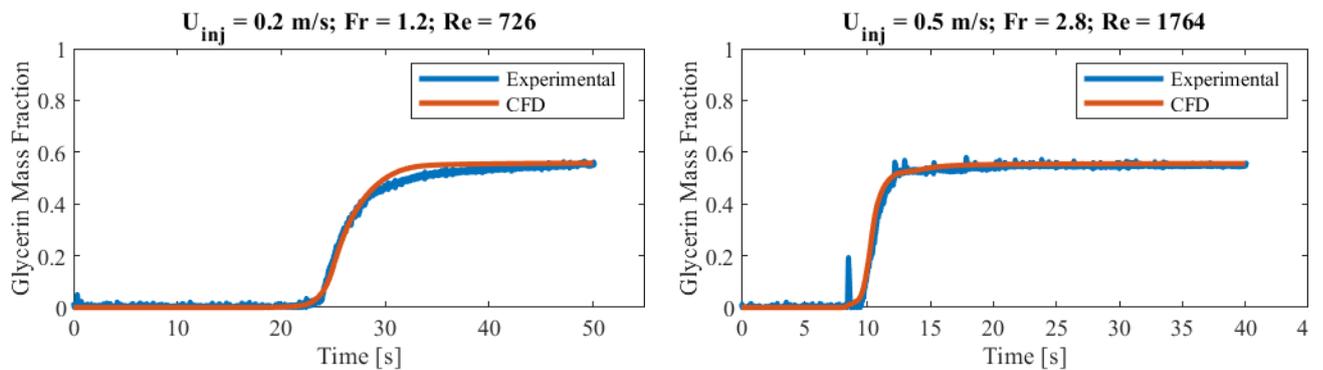


Figure 9: Comparison between experiments and numerical simulations Results for 3.5 cP.



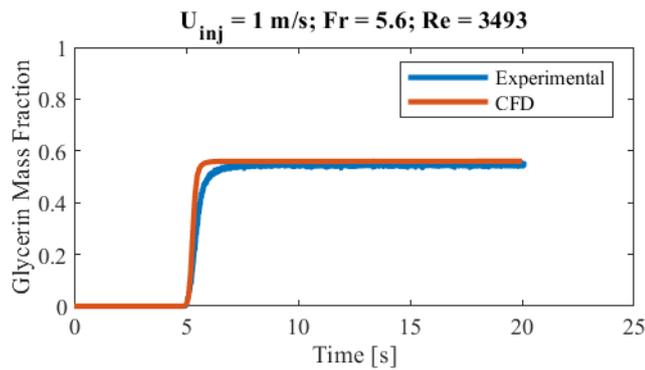


Figure 10: Comparison between experiments and numerical simulations for 8.5 cP.

In general, a good agreement between simulation and experiment was achieved, as can see in Figure 9 and 10. The CFD results have a good agreement with the experimental tests. Flow propagation front was captured very well, as well the stratification aspect for the cases closer to laminar regime and for Fr less than 2. Plug flow pattern occurred when Reynolds number is close to fully turbulent flow.

4. CONCLUSIONS

Fresh water was flushed in a horizontal pipe using viscous fluids (mixture of glycerin and water) with two different viscosities. These viscous fluids were injected at different speeds.

Some trends reported in the literature could be observed and analyzed in practice, such as the case of the beginning of mixing and formation of the plug flow pattern. The effect of using a more viscous or less viscous fluid as a cleaning fluid was also verified. In this work, the best performance occurred with the lowest viscosity washing the fresh water. It should be noted that we have a density difference in the pairs of fluids. When talking about the difference between viscosities during the flushing process, we always have the more viscous fluid performing the cleaning. When we refer to the fluid with less viscous mixture behaving better in cleaning, we refer to the comparison of separate tests, which in this case would be for the less viscous mixture pushing the water.

The literature points to some values for Fr that indicates the beginning of mixing and a subsequent plugging pattern. This value has varied from author to author. In this work, we verified that the value of Froude number for each of the viscosities varies, and that a possible value that would indicate a transition region of Fr , for the beginning of this mixture, presents a different range for more or less viscous fluids. So, more experimental work and computer simulations are still needed to describe how this range for transition Froude number values can vary according to fluids of different viscosities and whether there is a need to define groups of Froude number values for the beginning of mixing for ratios of density and viscosity.

5. ACKNOWLEDGEMENTS

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