Effective Interfacial Tension And Geometrical Parameters Relationship For The Description Of Oil Leakages From Submarine Pipelines

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The increase in petroleum exploration from shallow and deep marine waters raised the possibility of an oil leakage due to a pipeline rupture. In this case, the water penetrates into the damage pipe section, expulsing the remaining oil (phase inversion phenomenon). When a fluid drags the other one during an immiscible flow, the concept of effective interfacial tension should be used rather than the static interfacial tension. In the present study, the effective interfacial tension was related to the geometrical parameters of leakages by advective migration from ruptured submarine oil pipelines. The obtained results produced an empirical model which provides adequate values for the effective interfacial tension as a function of five geometrical characteristics of the hole. Results show that leakage flow obtained using the proposed empirical correlation to estimate the effective interfacial tension presented very good agreement with experimental values.

1. Introduction

In the case of submarine leakages, an accurate quantification of the released oil is important to forecast the potential environmental impact and correctly define actions to soften the damages and clean up the oil spill.

During a submarine leakage in a ruptured pipeline, the oil is expulsed from it while the water penetrates into the damage pipeline section through the same hole. This situation produces a dynamic interface between these two immiscible fluids. In this context, it is important to carry out experiments of the water-oil interface stability to evaluate the factors that leads to the phase inversion phenomenon. It happens when a less dense and more viscous phase (oil) penetrates into a denser less viscous one (water). This situation produces geometrical patterns similar to fingers (viscous fingering phenomenon) which may give important information about submarine leakages (Xu, 1998).

In a leakage involving two immiscible fluids (*e.g.* water and oil), experimental values of the static interfacial tension between fluids can not be applied to adequately describe the dynamic interface. Hence, when a fluid drags the other one during an immiscible flow, the concept of effective interfacial tension must be introduced (Ayub and Bentsen,

1999). Dragging happens because the no slip boundary condition at the hole wall result in a momentum transfer through the liquid interface.
In the present study, the effective interfacial tension was related to the geometrical parameters of leakages from ruptured submarine oil pipelines by advective migration. The obtained results produced an empirical model which provides adequate values for the effective interfacial tension as a function of five geometrical factors. The mentioned model makes part of a simulation program which correctly describes the leakage experimentally observed (Quadri *et al.*, 2004).

2. Experimental Procedures

An experimental apparatus was constructed to simulate and study real oil leakages by advective migration from ruptured submarine pipelines (Figure 1). The apparatus is composed by two connected glass pipes with an inner diameter of 10cm. One of the glass pipes is 80cm length and the other one is 40cm length. A circular acrylic slab with a central circular or rectangular hole (Figure 2) was positioned between the pipes to allow the fluid flow from a pipe to the other one.

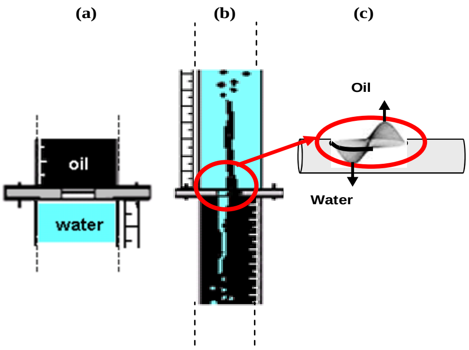

Figure 1. Detailed scheme of the experimental apparatus: a) Initial condition with a plane interface; b) Perturbed interface after a rotation of 180° of the apparatus; c) real horizontal situation simulated with the experiments.

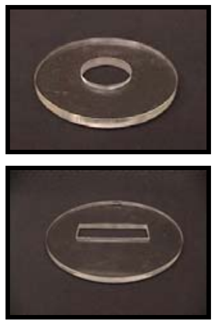

Figure 2. Acrylic circular slab with central circular and rectangular hole area of 12.57cm^2.

To carry out the experiments, the longest pipe was filled with distilled water containing a sodium chloride mass fraction of 3.0% to simulate the sea water salinity. After that, the shortest pipe was filled with soybean oil (Figure 1.a). This vegetable oil was used because its physical properties and their behavior are similar to many mineral oils.
Just after a rotation of 180^o of the experimental apparatus, the oil phase, positioned below the water phase (Figure 1.b), starts to leak from its reservoir (shortest glass pipe) by the advective migration phenomenon (viscous fingering – penetration of a phase into the other one). The situation presented in Figure 1.b simulates real leakages by the advective migration phenomenon from ruptured submarine pipelines, considering a hole positioned on its superior surface, according to Figure 1.c.

3. Results and Discussion

The experiments were carried out considering all possible combinations of the different values used for the five geometrical parameters taken in to account in the study. Table 1 presents these values, which combination provided a number of 183 experimental tests.

Table 1. Values of the geometrical parameters used in the experimental tests.

Equivalent Radius (cm)	***Wall Thickness (cm)***	***Hole Plane Inclination (rad)***	***Perimeter Ratio***	***Presence of Grooves***
1.0 1.5 2.0	0.4 0.8 1.2	0.2618 0.7854 1.3090 1.5708	1.00 1.13 1.30 1.52 1.88	YES (1) NO (2)

Each of the 183 experiments was carried out three times to guarantee the reproducibility, except for the cases in which two oil fingers appeared in the system. In this case, the experiments were carried out more than three times to check the repetitiveness of this behavior. *A priori*, this behavior does not follow any pattern that could exactly define the conditions for these fingers appearance during oil leakages by advective migration.

Figures 3 and 4 illustrate the effect of the appearance of two oil fingers on the leakage kinetics. The appearance of more than one finger tends to reduce the leakage velocity when compared to the same situation in which only one finger was produced. It was also verified that the cases in which two fingers appears are related to the rectangular geometry. Moreover, the greater the perimeter for a specific hole area, the greater the possibility of appearance of two or more oil fingers.

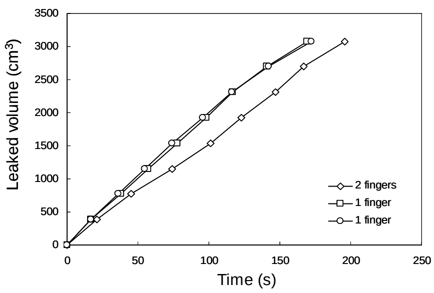

Figure 3. Leakage tests using a rectangular hole (4.60 X 1.53cm^2) with a wall thickness of 0.8cm and no grooves.

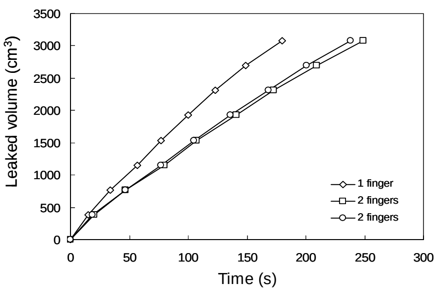

Figure 4. Leakage tests using a rectangular hole (6.00 X 1.18cm^2) with a wall thickness of 0.8cm and no grooves.

Figure 5 presents a snapshot of the two oil fingers produced during the experiment presented in Figure 3. According to Figure 5, the two oil fingers observed presented a very similar size and shape. These two oil fingers were produced in the beginning of the leakage and maintained throughout the experiment.

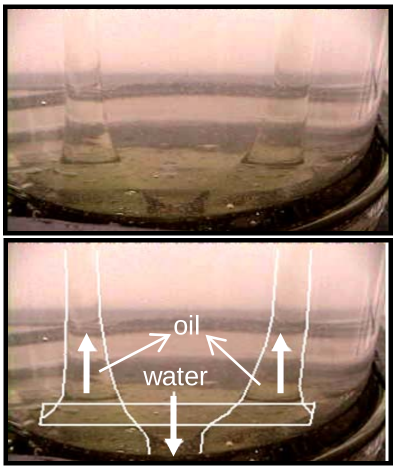

Figure 5. Formation of two similar oil fingers during leakage tests using a rectangular hole (4.60 X 1.53cm^2) with a wall thickness of 0.8cm, no inclination and no grooves.

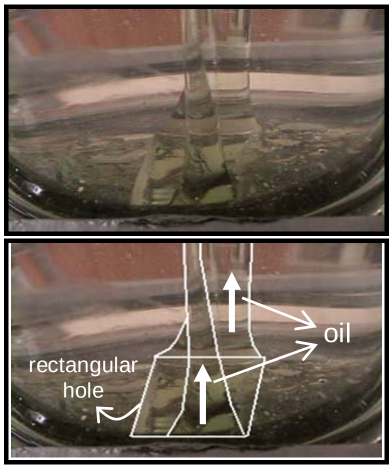

Figure 6. Formation of two different oil fingers during leakage tests using a rectangular hole (6.14 X 2.05cm^2) with a wall thickness of 1.2cm, no inclination and no grooves.

On the other hand, using a slab with a rectangular hole with an area of 6.14 X 2.05cm^2, wall thickness of 1.20cm, no inclination and no grooves, the two oil fingers observed did not presented the same size and shape (Figure 6). In this case, one of the oil fingers was greater than the other one. In the experiment presented in Figure 6, there is a tendency to produce two oil fingers in the beginning of the leakage. However, during the leakage, this formation becomes unstable and the two oil fingers connect to each other producing only one oil finger. According to experimental observations, the greater the rectangular hole, the more unstable are the oil fingers produced.

Experiments carried out using slabs with circular holes and grooves on its internal walls showed that the presence of these irregularities does not affect the base area distribution of the water and oil fingers. Besides, the oil finger base area showed to be slightly greater than the water finger base area, as in the case of circular holes with smooth internal walls.

As observed in the cases considering circular holes, the presence of grooves on the internal walls of the rectangular holes does not affect significantly the leakage flow by advective migration phenomenon in the most of the studied cases. However, when slabs with small circular holes (R_h=*1.0cm*) were tested, the presence of grooves is a determining factor for the occurrence of the leakage.

A statistical analysis was accomplished to determine an empirical relation capable to correctly describe the system behavior. This analysis permitted to determine the variables significance and, through a residue evaluation between experimental and calculated values, verify whether no considered factors could be acting on the system and particularly on the leakage velocity.

Constructing a Pareto's chart (Figure 7), it was possible to evaluate the relative importance of each of the five geometrical parameters used to characterize the hole.

From the five geometrical parameters tested, the presence or absence of grooves on the hole wall presented the poorest importance.
Figure 8 shows how the effective interfacial tension and the hole radius define the leakage flow according to an appropriate phenomenological model developed in a previous work (QUADRI *et al.*, 2004).

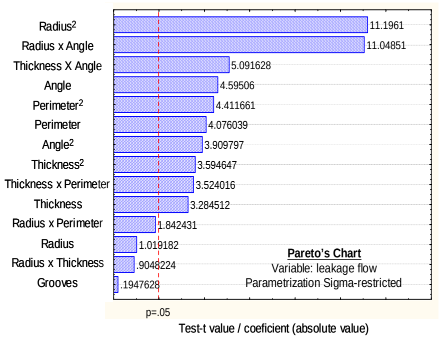

Figure 7. Results of the significance test considering p=0.05 for the five geometrical parameters considered, including their interactions up to the second order.

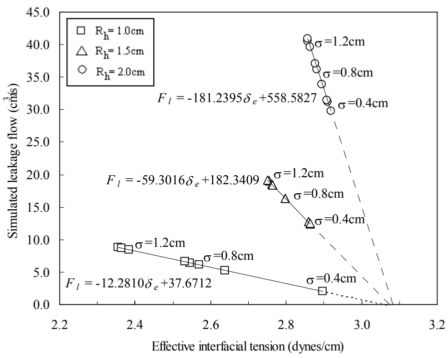

Figure 8. Leakage obtained from the phenomenological model as a function of the effective interfacial tension, considering three different hole radius.

The results presented in Figure 8 leads to the following equation for the leakage flow:

$$F_l = 1.3302\,(\pi R_h{}^2)^{1.9417}\,(\delta_0(R_h) - \delta_e) \tag{1}$$

Where δ_0 is a function of the hole radius and correspond to a limit value of the interfacial tension when the flow is zero.

The function δ_0 is calculated by the following quadratic equation, with a correlation coefficient $R^2=1$:

$$\delta_0 = -6.0000\text{x}10^{-5}(\pi R_h{}^2)^2 + 2.4890\text{x}10^{-3}\pi R_h{}^2 + 3.0602 \tag{2}$$

The statistical analysis provided by Figure 7, considering the results presented in Figure 8 and Equations 1 and 2, leads to the following equation capable to calculate the effective interfacial tension as a function of the five geometrical parameters which characterize the hole:

$$\begin{aligned}\delta_e = {} & (36.8633 - 0.0392\,gr - 6.0768\,R_h - 17.002\,R_h{}^2 - 16.8901\,\sigma + 8.5763\,\sigma^2 - \\ & 18.2794\,\varphi + 6.8456\,\varphi^2 - 34.4053\,\tau + 10.6841\,\tau^2 + 1.1693\,R_h\,\sigma + 12.471\,R_h\,\varphi - \\ & 6.8985\,\sigma\,\varphi + 6.0996\,R_h\,\tau + 7.7770\,\sigma\,\tau)/(1.3302\,(\pi R_h{}^2)^{1.9417}) - 6.0000\text{x}10^{-5}\,(\pi R_h{}^2)^2 + \\ & 2.890\text{x}10^{-3}\,\pi\,R_h{}^2 + 3.0602\end{aligned} \tag{3}$$

Where δ_e is the effective interfacial tension (dynes/cm), gr is the presence (1) or absence (2) of groves, R_h is the equivalent hole radius (cm), σ is the hole wall thickness (cm), ϕ is the angle between the hole normal plane and horizontal plane (rad), τ is the ratio between the hole perimeter and the circle perimeter with same area.

The results were analyzed according to a statistical method to postulate and verify the validity of a empirical model which relates the five geometrical parameters tested with the leakage flow and the effective interfacial tension. The normal distribution model was used to evaluate the occurrence of systematic deviations during the obtainment of the experimental values. Results show that the residue between experimental and model leakage flow presents a distribution very close to the normal one. It means that the analysis realized with the five geometrical parameters considered are free of other factors or phenomena that could affect in a systematic way the obtained results.

4. Conclusions

A statistical analysis was accomplished to determine how important are each of the geometrical parameters considered and how their variations affect the leakage. According to the results, the presence of grooves on the hole wall does not affect significantly the leakage. However, if the hole size is sufficiently small, the presence of grooves can be a determining factor for the leakage occurrence.
On the other hand, the hole size and the hole plane angle (related to the horizontal plane) showed to be the most important parameters which affect the leakage. In the first case, the greater the hole size, the faster the leakage. Regarding the hole plane angle, when it is positioned at 45º, higher leakage rates are expected. The increase in the perimeter relative to a certain hole area leads to a reduction in the oil releasing velocity, while the increase in the hole wall thickness raises the leakage rate.
Finally, the evaluation of the residues between experimental and model results of the leakage flow presented a distribution very close to the normal one. It indicates that the analysis accomplished is adequate and free of other factors that could affect in a systematic way the results. In this way, the equation which relates the hole geometrical parameters and the effective interfacial tension is representative. It means that this equation can be used in an appropriate phenomenological model to provide an accurate value for the leaked volume and kinetics aspects of the leakage.

5. References

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