

Kinematical description of the spontaneous imbibition processes

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Abstract: A set of experiments of spontaneous imbibition for water displacing oil or a mixture of water and glycerine displacing oil, on flat and rectangular Hele-Shaw cells, is reported. Visualization of the imbibition process allowed the knowledge of the evolution of three basic kinematical variables: the active oil area, the interfacial length and the mean velocity of displacement. A derived kinematical variable, the active area equivalent length, is shown to be well suited for the kinematical description of spontaneous imbibition processes, since its normalized values become lumped to a narrow experimental band when two time scales are defined and used, looking for a self-similar behavior. The dimensionless active area equivalent length is found to be lumped to a narrow time gap, for a potential function with two time scales. This function is found to be appropriate for further description by a fractal approach.

Key-Words: Spontaneous imbibition, Hele-Shaw cells, Oil recovery, Interfacial tension, Sweep efficiency.

1 Introduction

Studies about fluid dynamics in capillary media started with pioneer works by Gauss, Laplace and Young, almost two centuries ago. Among capillary phenomena, imbibition processes have an important position, due to the practical applications where they play a relevant role (see Table 1). *Imbibition* is defined as the process where a wetting fluid penetrates into a porous media, displacing the fluid that occupied the space. When an external force is applied (e.g. pressure gradient) to promote the displacement, the process is called *forced imbibition*. Otherwise, in the absence of external forces, the *spontaneous imbibition* is defined as the process when the fluid penetrates the capillary media due solely to the potential generated by the wettability difference at the solid wall with respect to the contacting fluids. Frequently, the studies on imbibition processes are focussed on forced imbibition and assume that the spontaneous phenomena can be described as a particular case of the former [2], [1]. One of the consequences of this perception is a lack of knowledge on how the complex fluid-fluid and solid-fluid interactions control the spontaneous flow dynamics.

Due to the inherent limitations to visualize the flow patterns in porous rock samples, Hele-Shaw cells are frequently used as an experimental analog to the porous media [3]. A simplified system like this has

enormous advantages when one wishes to observe the very basics of the capillary displacement: all the resistances to the movement of the system are reduced to the interaction between the fluids and the surfaces. Hence, we expect to obtain some information about the real importance of the contribution of surface tension and contact angle, or even the line tension, to the dynamics of displacement.

In a previous work [4], a methodology to perform experiments for a viscous fluid spontaneous displacement by another one in a Hele-Shaw cell is developed. This methodology stresses on the statistical repeatability of the experiments. In other words, despite of the random nature of the displacement, there are characteristic features of the flow system which are preserved. The authors also report that the process occurs in two or three stages, characterized by a mean displacement velocity depending on the interface position in the cell. In order to obtain more information about these stages and searching for the influence of entrance effects, we performed experiments in longer cells. Also, some improvements on the cleaning procedure were introduced, in order to obtain increased chemical uniformity of the surface. Moreover, a 9-set of further experiments were done, where the wetting fluid was modified, increasing its viscosity in order to get a better performance and statistical repeatability. We report here new observations on the behavior of

Oil recovery	Displacement of one liquid by another.
Paper processes	Ink penetration in paper, absorbing materials.
Food industry	Coking, wine filtration.
Biologic sciences	Fluid transport in plants, water penetration in seeds, medical applications.
Surface chemistry	Measure of contact angles, drops spreading on surfaces, surface coating.
Textile industry	Water-proofing.
Construction	Water penetration on concrete.

Table 1: Some processes where imbibition is the most important phenomena.

the displacement of two fluids by spontaneous imbibition.

2 Experiments

2.1 Apparatus

The Hele-Shaw cells used in this work were made up from a single commercial window glass sheet, in order to diminish the influence of the variations due to the manufacturing process. The glass sheet was divided into pieces 20 cm width and 40 cm length (nominal size), and subjected to a careful cleaning process before each experiment [5, 4]. This process starts with a bath in a potassium hydroxide-alcohol solution that removes all organic compounds and actually renew the surface by removing the very superficial layer of glass. Next step was a washing down with hydrochloric acid that removes the remaining impurities and provides chemical uniformity to the surface. Finally, the glass pieces were rinsed with deionized water, and the remaining water film was displaced from the surface with a nitrogen jet. If a water film over the surface showed discontinuities at the rinsing end, the cleaning process was repeated.

Once cleaned, the glass pieces were assembled as Hele-Shaw cells. The gap was set by using calibrated nylon fibers at the lateral long sides sealed with epoxic resin, in order to get a narrow slit, with inlet and outlet in the shorter sides. The cell inside was filled up with a commercial oil, Soltrol 170 by Phillips Petroleum, ($\mu = 3.8 \times 10^{-3}$ Pa s, $\rho = 0.7735$ g/cm³ @ 25°) colored with Merck Red Oil BDA (0.2 grams per liter), to enhance contrast between the phases.

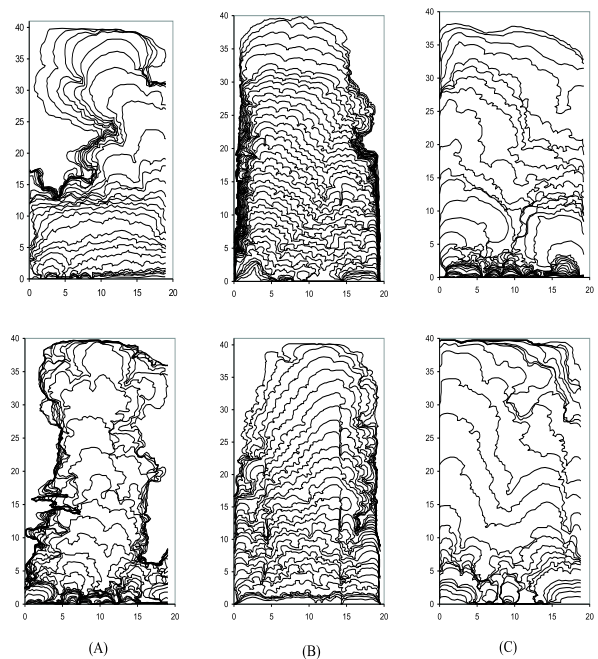


Figure 1: Evolution of the advancing front in a horizontal Hele-Shaw cell, where oil is displaced spontaneously by twice-distilled water. Two experiments for each gap value: (A) 0.015 cm, (B) 0.030 cm and (C) 0.040 cm. The flow proceeds from bottom to top in the Figure. The time intervals are not the same for all curves.

The cell filled with oil was placed horizontally inside a temperature-controlled bath. Then, twice-distilled water (or a glycerol-water solution) was approached to the oil at the inlet, feeding in a certain way to avoid pressure gradients. All the process was recorded in videotape.

A total of 27 experiments were performed in three Hele-Shaw cells, one cell was prepared and assembled for each experiment and then disassembled and cleaned for further experiments. In order to assess the gap influence on the process, three gap values were set: 0.015 cm, 0.030 cm and 0.040 cm and to appraise statistic repeatability, experiments were repeated at least once for each gap value in each cell.

It is known that a viscosity ratio between water and oil (around 1:4) promotes a very unstable interface [6], so a mixture of 64% weight of glycerine and twice-distilled water ($\mu = 12.3 \times 10^{-3}$ Pa s) as wetting fluid was used in order to get a more stable interface. Nine of the 27 experiments were done with this wetting fluid for 0.015 cm and 0.030 cm gap values.

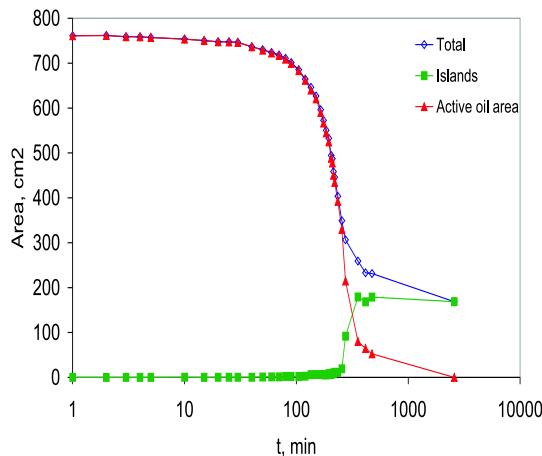


Figure 2: Values for total area (\diamond), islands area (\blacksquare) and active oil area (\blacktriangle) as they changes with time for a gap value of 0.015 cm

3 Analysis and Results

From the recorded videotapes, series of photographs were selected at specific times, each one digitalized and recovered as a set of points. Figure 1 shows the summary of six experiments performed on the same cell with three gap values: 0.015 cm, 0.030 cm and 0.040 cm.

3.1 Behavior of basic kinematical variables

When water penetrates the cell, some parts of the oil phase may be trapped and left behind the water advancing front. We called this oil globules *islands* and observed that they do not further contribute to the imbibition process. Also, we called *active oil area* to the oil placed between the outlet and the water advancing front, in order to make a difference from the islands of oil. Figure 2 shows the total oil area splitted in its two contributions: the active oil area and the islands area.

From the digitalized images it is possible to measure the active oil area as a function of time, so we can define a mean velocity of displacement as

$$V_i = \frac{A_{i+1} - A_i}{(t_{i+1} - t_i)W} \quad (1)$$

where A_i is the active oil area at time t_i , and W is the inlet width. V_i is a measure of the mean oil recovery rate.

In Figure 3 a plot of mean velocity against time can be observed. It is apparent in this figure that the mean velocity increases up to a maximum around

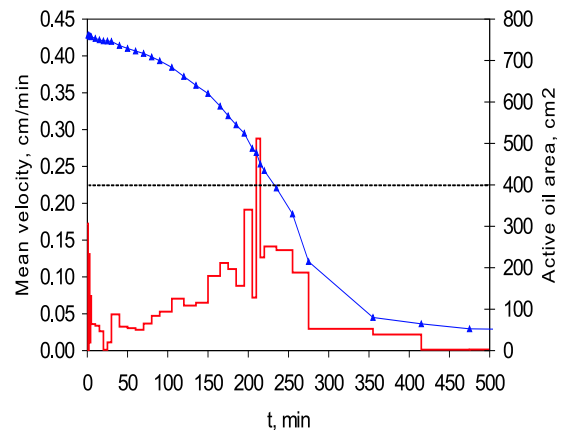


Figure 3: Mean velocity (stairs-like line) and active oil area (\blacktriangle) against time for a gap value of 0.015 cm.

$t = 210$ min (for this particular experiment) and then decreases up to the end of experiment. It should be pointed out that the maximum occurs when active oil area is around half the initial quantity (~ 400 cm²). Also in Figure 3, a plot of active oil area as a function of time shows a continuous decrease with an inflexion point. The locus of this point is close to the maximum mean velocity. The same behavior was observed in most of the experiments for all gap values.

Another important feature is the behavior of the interfacial length as compared to the mean velocity, as shown in Figure 4, where a maximum of interfacial length can be observed, lagging from the mean velocity maximum.

3.2 Active area equivalent length

One derived kinematic variable of singular importance for spontaneous imbibition is the ratio of the active oil area to the interfacial length

$$(L_{21})_i \equiv \frac{A_i}{L_i} \quad (2)$$

where A_i is the active oil area and L_i is the interfacial length at time t_i . This variable may be called the *active area equivalent length*. The geometric meaning of this variable can be assessed by thinking of the interfacial length as being stretched parallel to the inlet. Then, the active area is obtained as the area of the rectangle given by the product of the interfacial length times the active area equivalent length (see Figure 5)

Figure 6(A) is a plot of the evolution of the active area equivalent length for the whole set of experiments. Experiments lasted different times even

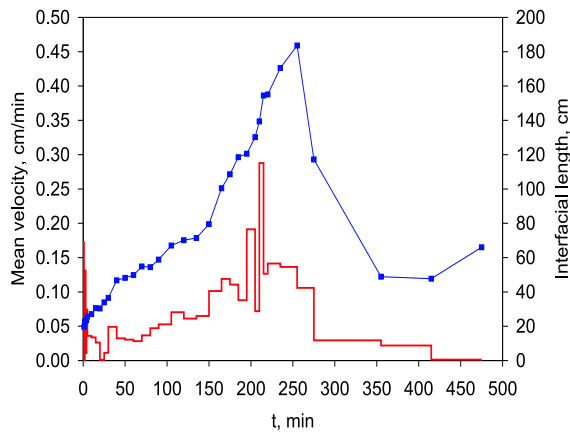


Figure 4: Mean velocity (stairs-like line) and interface length (■) against time for a gap value of 0.015 cm.

for the same gap value. Thus, the total experiment time varies in one order of magnitude, from 100 min to 1000 min, showing a wide spread even in a logarithmic time scale. In this figure symbols of the same color are used for same gap and wetting fluid.

The tendency showed by the data on Figure 6(A) strongly suggest the possibility of a normalization of the active area equivalent length, looking for a self-similar behavior [7]. To achieve this statement, we define a dimensionless active area equivalent length $\xi(t)$,

$$\xi(t) \equiv \frac{L_{21}}{L_{21_0}} \quad (3)$$

where L_{21_0} is the value for L_{21} at $t = 1$ min, when some interfacial length has been developed. A first time scale $t_{1/2}$ was defined as the time when the active area equivalent length gets its middle value, say when $\xi(t_{1/2}) = 0.50$ and assumes an exponential relationship between the dimensionless variables

$$\xi(t) = \left(\frac{t}{t_{1/2}} \right)^\alpha \quad (4)$$

Adjusting the values of exponent α we obtain a series of displaced curves, as shown in Figure 6(B). It is apparent that the behavior is well described for short times, since experiments become lumped in a narrow zone. When another time scale is defined, as $t_{1/4}$, for $\xi(t_{1/4}) = 0.25$, another exponent is gotten

$$\xi(t) = \left(\frac{t}{t_{1/4}} \right)^\beta \quad (5)$$

Adjusting the values of β the displaced curves shown in Figure 6(C) are obtained. This now is well suited

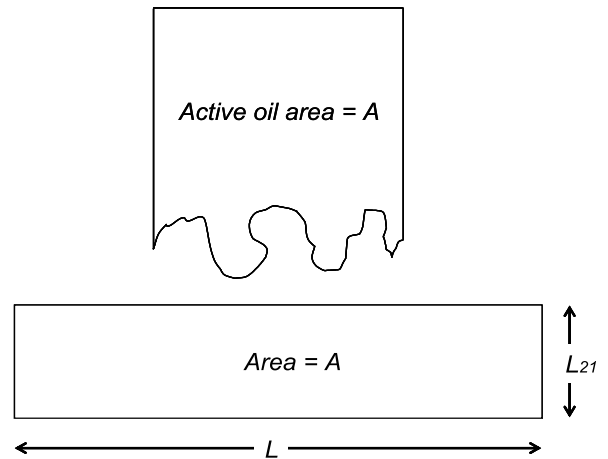


Figure 5: Geometrical description of the active area equivalent length. The curved line at the top figure represents an interface of length L .

for long times. Finally, we built up a multiplicative relationship between equations (4) and (5) and propose the scaled function

$$\xi(t) = \frac{1}{A} t^{1/\gamma} \quad (6)$$

where

$$A = \left(t_{1/2}^\alpha t_{1/4}^\beta \right)^{1/2}$$

and

$$\gamma = \frac{2}{\alpha + \beta}$$

The application of equation (6) results in a better lumping of the $\xi(t)$ values, as shown in Figure 6(D). It is important to remark that these numerical values are appropriate regardless the wetting fluid is twice-distilled water or a water-glycerine mixture.

Equation (6) can be arranged as a similar expression to a random walk as a function of time [8], [9],

$$t(\xi) = A\xi^\gamma \quad (7)$$

where the exponent γ plays the role of the fractal dimension.

4 Conclusion

A derived kinematical variable, called here the active area equivalent length, is defined and found to be well suited for the search for a self-similar behavior in spontaneous imbibition processes in a Hele-Shaw cell. It is found that the normalized values of the active area equivalent length become lumped to a narrow experimental band when two time scales are defined

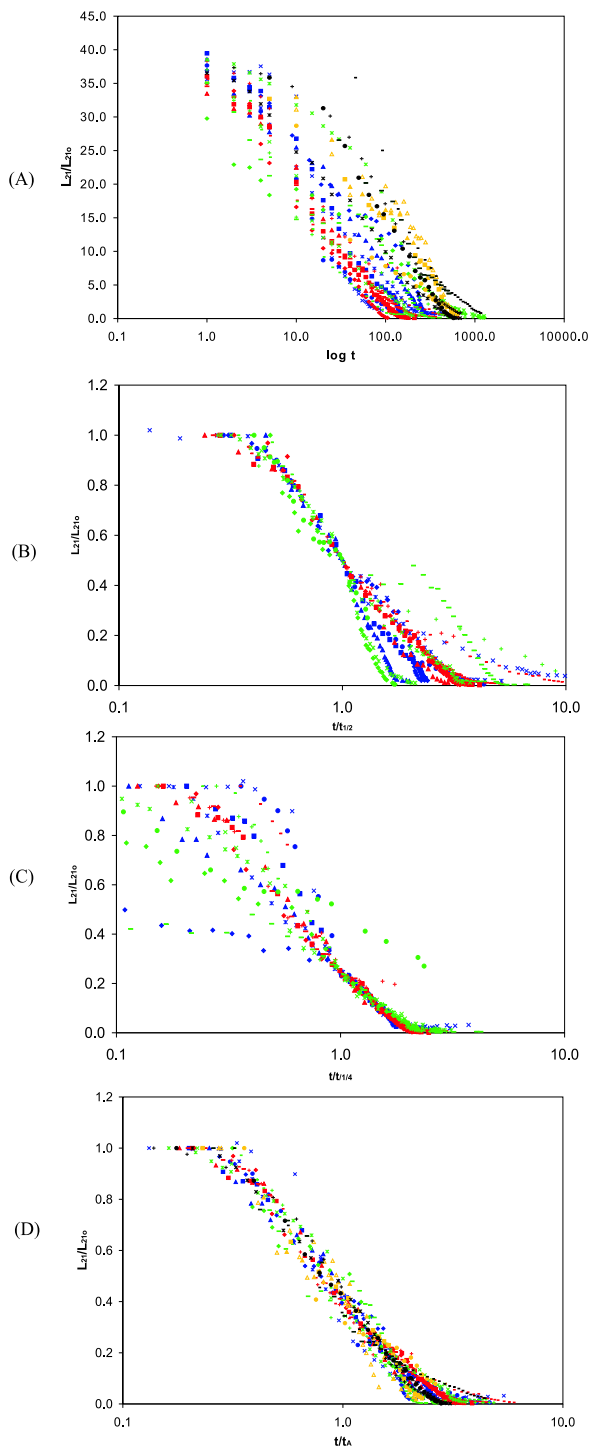


Figure 6: Lumping of L_{21} data by normalization, using the initial value L_{210} as the characteristic length. (A) Raw data, (B) $\xi(t_{1/2})$, (C) $\xi(t_{1/4})$ and (D) Equation (6).

and used to built up two potential functions. While the first time scale renders an appropriate lumping for short times, a second time scale shows to be appropriate for long times. Then a dimensionless active area equivalent length is proposed as the product of both potential functions, giving a lumping on most of the experimental time, except for the end of the experiments. This new function is found to be appropriate for a further description by a fractal approach.

Acknowledgements: The authors highly acknowledge the Consejo Nacional de Ciencia y Tecnología (CONACyT), Mexico, for financial support through 176240 Scholarship for one of them (RL) and Grant 50379/2005. The authors are also deeply obliged to the Physics of Liquids Team, Physics Department, at the Universidad Autónoma Metropolitana Iztapalapa, by allowing a place to perform the experiments.

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