PAPER • **OPEN ACCESS**

Experimental study on viscous fingering in Hele-Shaw cell under acoustic impact

To cite this article: E A Marfin *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **927** 012027

Experimental study on viscous fingering in Hele-Shaw cell under acoustic impact

E A Marfin[1,2], S V Garaeva[2] and A A Abdrashitov[1]
[1] Institute of Power Engineering and Advanced Technologies, FRC Kazan Scientific Center, Russian Academy of Sciences, 2/31 Lobachevsky Street, Kazan, Russia
[2] Kazan Federal University, Institute of Physics, 16a Kremlyovskaya Street, Kazan, Russia

E-mail: marfin_ea@mail.ru

Abstract. Viscous fingering shaped as curvature of the fluid displacement fronts are usually formed in porous media and Hele-Shaw cell when a liquid with a high viscosity is displaced by a liquid with a lower viscosity. Such interfacial instability is undesirable in many displacement processes, and mainly in oil production. We present the results of physical modeling of the displacement of viscous oil by air in Hele-Shaw cell. As a method of suppressing undesirable interphase instability, the effect of elastic vibrations on the process is proposed. The experiment was performed in stationary conditions and under acoustic action on the displacement process. In the absence of superimposed vibrations, the growth rate of viscous finger is 2.15 times higher than the speed of liquid flow at the cell border. The imposition of acoustic oscillations can both accelerate and slow down the growth rate of viscous fingers depending on their frequency. The paper discusses the peculiarities of the development of viscous fingering. The results are compared with the calculated data.

1. Introduction

In Russia, oil production is not efficient enough. The average oil recovery factor is about 30%. In most fields, produced oil is heavily waterlogged. The main reason for this situation seems to be the fact that oil is extracted from a porous reservoir by displacing it with water, which is a less viscous liquid than oil. From a physical point of view, this process can be described as the Saffman-Taylor instability [1]. With this displacement, the interphase between the two liquids is deformed with formation of folds. These folds do not grow at the same rate, forming viscous fingers. Such "fingers" of water in the reservoir, reaching the producing wells, form a breakthrough, which significantly increases the water content of the extracted oil. At the same time, areas of immobile oil that are not involved in filtration are formed in the reservoir itself, surrounded by water. The solution to the problem, according to oilmen, lies in the use of various gels instead of water. The gels are more viscous liquids than oil. However, this approach has significant environmental risks related to possible contamination of groundwater and surrounding areas.

A large number of papers have been devoted to the simulation of Saffman-Taylor instability. The development of computer technology has allowed us to expand the field of solving problems with moving borders. The paper [2] studies the stability of a system with two propagating fronts in a Hele-Shaw cell, where the viscosity increases monotonously from the eigenvalue to the viscosity of the external liquid. The critical parameter is the ratio of viscosities of liquids. The minimum value, below which the system is stable at any flow rate, is determined. It is proposed to use the stability criterion for choosing the viscosity of a displacing liquid in relation to the problem of pumping liquid into an oil well. In the paper [3], the authors identified three flow modes that characterize the development of viscous fingers and the conditions for their fusion. In the paper [4], the process of formation and growth of viscous fingers in inhomogeneous porous media is numerically investigated.

Various ways of suppressing undesirable instability are suggested. Thus, the paper [5] proposes a gradual reduction in the pore size of a porous medium. In the work [6], the inhomogeneity of the permeability was studied. In this study, three different models of inhomogeneity are considered: an exponential decrease in permeability in the transverse direction, an exponential decrease and an increase in the longitudinal direction. In the paper [7], the influence of cracks in a porous medium on the formation and growth of viscous fingers were studied. In many works, for example, in [8-10], the displacement of oil by various liquids with non-Newtonian properties is studied. In the paper [11], the influence of perturbations of the initial interface of liquids in the Hele-Shaw cell is investigated. The authors show that the period and amplitude of these perturbations affect the growth rate of viscous fingers.

The presented brief overview of the state in the field of Saffman-Taylor instability shows that various groups of scientists have been actively studying this phenomenon in various manifestations. At the same time, studies on the management of such instability by external acoustic treatment, as well as similar results, have not been found in the world literature. The main idea of this paper is that the phenomenon of Saffman-Taylor instability, often observed in the Hele-Shaw cell, can be influenced by the exposure to elastic oscillations. Moreover, the field experience of acoustic treatment of the reservoir indicates an increase in oil production and a decrease in water cut [12-13].

2. Experiment

A series of experimental studies was conducted on the displacement of oil by air in the Hele-Shaw cell. A Hele-Shaw cell is a device consisting of two closely located parallel plates containing a thin layer of viscous liquid, which is mainly used to simulate the flow of a liquid in a porous medium. To avoid the influence of gravity, the model was placed horizontally.

2.1. Materials

The viscous phase in the experiment was mineral oil of the I-20A brand (GOST 20799-88). The rheological properties of the oil were measured using a vibration viscometer SV-10 (A&D). The experiment was conducted in room conditions at a temperature of 23 ° C. At this temperature, the oil had a density of 0.860 g/cm^3, viscosity - 45.4 mPa·s, and the surface tension coefficient - 0.1472 N/m.

2.2. Experimental setup

For laboratory research, an experimental stand was created, which included the actual Hele-Shaw cells and a reservoir model, a liquid supply system and pressure measurement system, a lighting and video recording system, and a system for generating elastic oscillations. Hele-Shaw cells are made of two organic glasses with a thickness of 4 mm and a size of 200x100 mm. The gap between the glasses is 0.8 mm. On the sides, the cell is hermetically closed, and the inlet and outlet are connected through a slotted hole with pipes that supply liquids. The liquid supply system is based on syringe pump. The system for keeping a record of liquid displacement process in the cell is based on a digital video camera and a smartphone which provides video recording with a resolution of 1920 x 1080 pixels. The semi-transparent horizontal surface, on which the Hele-Shaw cell is placed, and the panel with LED illumination placed under it provide a contrasting image of the observed process. Acoustic treatment was carried out by means of created emitters from piezoelectric rings, working and back plates. Four emitters were placed under the Hele-Shaw cell and used to influence the displacement process with sound. The AKIP-3408/2 electric oscillator was used as the master generator. Measurement of the pressure difference at the cell boundaries is performed using a digital pressure sensor indicating the pressure. The experimental setup is shown in figure 1.

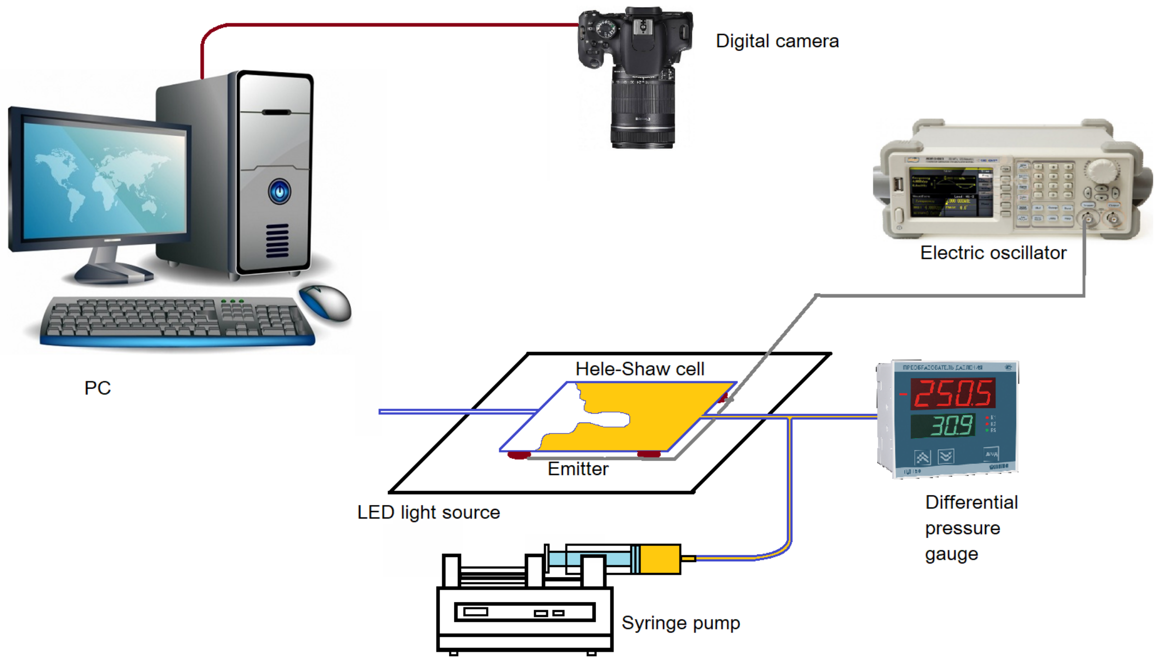

Figure 1. Experimental setup.

2.3. Experimental method
The study of the fluid displacement process in Hele-Shaw cell on an experimental installation is based on the processing of a video recording of the experiment. The recorded video file was opened in the VegasPro video processing program from where pictures of Hele-Shaw cell were extracted with the observed border for various moments of time. The pictures also displayed the pressure and recorded the time. Video was recorded at a resolution of 1920x1080 pixels at 30 frames per second. The duration of one experiment was about 1 minute, which corresponds to about 1000 frames.

The tests were divided into two groups: the one without acoustic treatment and the one with acoustic treatment at different frequencies. For each group, three different values of liquid flow rate were set. The experiments were repeated several times for each condition. The purpose of these experiments was to study the effect of superimposed vibrations on the formation of viscous fingers.

The following sequence was used for each test:

1) Filling Hele-Shaw cell with oil.

2) Turning on the video recording; the piston starts moving in the syringe pump at a fixed speed.

3) The process stops when reaching the summit of a viscous finger at Hele-Shaw cell borders. Video recording is over.

4) Repetition of pp. 1-3, including different values of the volumetric velocity.

5) Repetition of pp. 1-4 under conditions of superimposed vibrations.

Subsequent processing of video recordings was carried out on a computer. The graph editor processed footage, where the boundaries of the liquid interface were selected using filters. Then the position of the vertex of the maximum viscous finger was measured for each moment of time.

3. Results and discussion
At the beginning of the experiment, small perturbations of the interface are observed. After about 10 seconds, it is possible to recognize prominent three or four folds that begin to grow forming viscous fingers. Approximately at a distance of 10% of the cell length, there is an accelerated growth of the large "viscous finger", while the growth of others slows down significantly. The average growth rate of the "viscous finger" is more than twice the initial speed of the interface. This result is well described in previous studies, for example, in [1]. Figure 2 shows the change of the liquid interface in time steps of 5 seconds.

When elastic vibrations are applied, the picture of the process endures some changes (see figure 2 b). There is an uneven curvature of the liquid interface. Nevertheless, a single large viscous finger is formed, which grows in the same way as in the absence of superimposed vibrations. As viscous fingers grow, the following feature is manifested. The side surface of the viscous finger also oscillates and side protrusions can appear, which forms a complex shape of the viscous finger. With a certain combination of factors, it is possible to "bud" and grow new fingers from the main one.

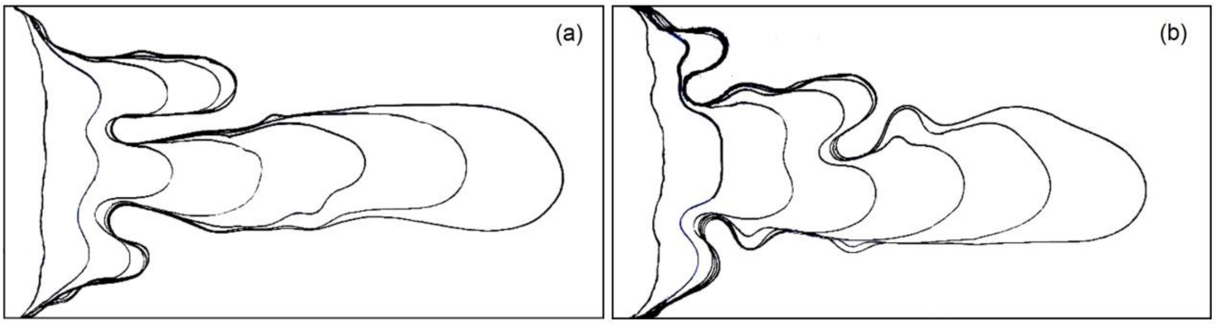

Figure 2. Comparison of the development of viscous fingerings in a Hele-Shaw cell: (a) without acoustic impact, (b) with acoustic impact at a frequency of f = 45 kHz.

Experiments conducted at various frequencies revealed that the growth rate of viscous fingers can vary with the frequency of superimposed oscillations. Figure 3 presents the dependence of the relative growth rate of the viscous finger on the frequency. On the graph, the value of the growth rate of the viscous U_{vf} finger was divided by the rate of fluid displacement from the Hele-Shaw u_x cell. It can be seen that in the absence of acoustic treatment, the growth rate of the viscous finger is approximately 2.18 times greater than the displacement rate. Initially, there is a tendency to increase the growth rate of the viscous finger, with a maximum value at a frequency of 22 kHz. Then the relative speed decreases to a minimum at 45 kHz.

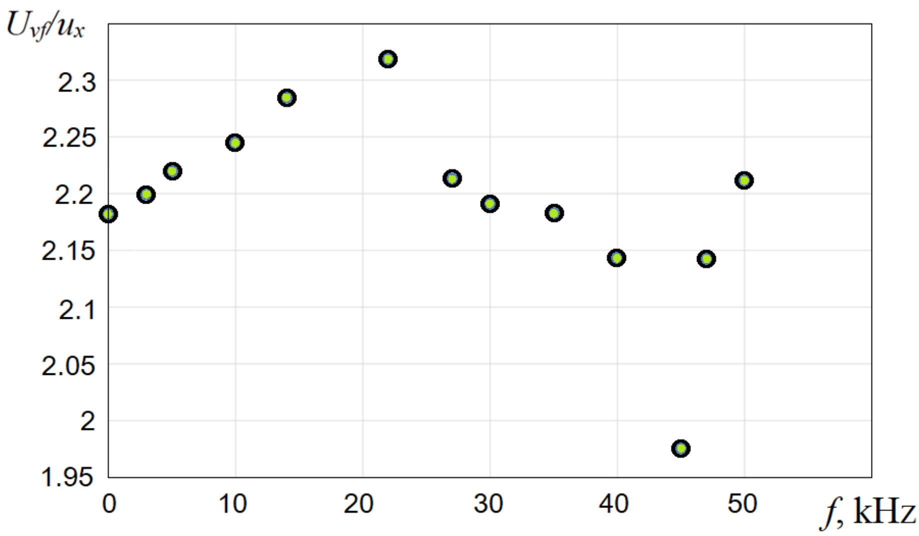

Figure 3. Dependence of the relative growth rate of the viscous finger on the frequency.

As the reason for the change in the growth rate of "viscous fingers", it is most likely that the oil viscosity changes in the field of elastic oscillations. Indeed, the study of oil before and after exposure to ultrasound on a viscometer revealed the effect of reducing its viscosity.

4. Conclusion

The paper studies the influence of acoustic treatment on the formation of viscous fingers in Hele-Shaw cell during the displacement of a viscous liquid. Experiments in stationary conditions confirmed the known data. When the viscous oil is displaced by a less viscous liquid, the initially smooth liquid interface curves, forming several folds that increase in size. Approximately at a distance of 10% of the cell length, there is an accelerated growth of the large "viscous finger", while the growth of others slows down significantly. The average growth rate of a "viscous finger" is more than twice the initial speed of the interface. When elastic vibrations are applied, the picture of the process endures some changes. So, with an increase in frequency to 22 kHz, the average growth rate increases by 6.4%, then decreases to a minimum at 45 kHz and then increases again. The maximum reduction in the speed of the "viscous finger" was 9.6%.

References

[1] Saffman P G and Taylor G I 1958 *Proc. Roy. Soc. London*. A245 **1242** 311
[2] Beeson-Jones T H and Woods A W 2015 *J. Fluid Mech.* **782** 127
[3] Nijjer J S, Hewitt D R and Neufeld J A 2018 *J. Fluid Mech.* **837** 520
[4] Christou K, Radünz W C, Lashore B, de Oliveira F B S and Gomes J L M A 2019 *Adv. Water Resour.* **130** 46
[5] Rabbani H S, Or D, Liu Y, Lai C-Y, Lu N B, Datta S S, Stone H A and Shokri N 2018 *Proc. Natl. Acad. Sci. U. S. A.* **115** 4833
[6] Shoghi M R and Norouzi M 2015 *Rheol. Acta* **54** 973
[7] Kargozarfard Z, Riazi M and Ayatollahi S 2019 *Petrol. Sci.* **16** 105
[8] Eslami A and Taghavi S M 2019 *J. Non-Newton. Fluid.* **264** 25
[9] Norouzi M, Yazdi A A, Birjandi A K 2018 *J. Non-Newton. Fluid.* **260** 109
[10] Shokri H, Kayhani M H and Norouzi M 2019 *J. Eng. Mech.* **145** 04019098
[11] Marfin E A, Garaeva S V, Ermolaev D V 2019 **J**. *Phys. Conf. Ser.* **1158** 032028
[12] Marfin E A, Kravtsov Y I, Abdrashitov A A, Gataullin R N and Galimzyanova A R 2015 *Petrol. Sci. Technol.* **33** 1526
[13] Marfin E A, Kravtsov Ya I, Abdrashitov A A and Gataullin R N 2014 *Georesursy [Georesources]* **57** 14