CATALOGUE EOR CHIPS

PERMEABILITY DETERMINATION

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Revision History

Revision	Date (yyyy-mm-dd)	Editor	Revision Description
01	2023-05-31	Rudy Lagraauw	Initial document
02	2023-06-20	Rudy Lagraauw	Adjusted to comments PJK and IR
03	2023-07-26	Rudy Lagraauw	Finalization report

1 INDEX

2 INTRODUCTION

This document describes experiments in which the permeabilities of the Micronit Enhanced Oil Recovery (EOR) microfluidic chips are determined. In our webstore, we sell three types of EOR chips in which the pore structure is different: physical rock, random network, and uniform network. The three types are depicted below. For all chips, the depth of the channels and pores is 20 µm.

2.1 PHYSICAL ROCK (ITEM NUMBER 02976)

The physical rock EOR chip has a pore structure that resembles a randomized physical rock structure.

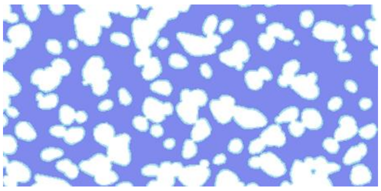

Figure 1: The physical rock EOR chip (left) and a zoom-in of its pore structure (right)

2.2 RANDOM NETWORK (ITEM NUMBER 02977)

The random network EOR chip contains a pore structure that consists of randomized channels of varying width and connections with neighboring channels.

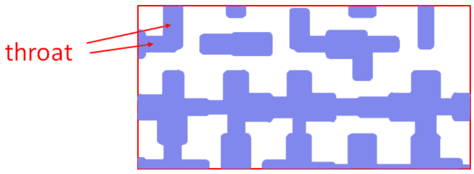

Figure 2: The random network EOR chip (left) and a zoom-in of its pore structure (right)

There channel widths can either be 50, 70, 90, 110 or 130 µm and each channel width occurs approximately equally often (respectively 1429, 1438, 1412, 1412 and 1531 times).

2.3 UNIFORM NETWORK (ITEM NUMBER 02978)

The pore structure in the uniform network chip contains a pattern of pores and throats.

Figure 3: The uniform network EOR chip (left) and a zoom-in of its pore structure (right)

The widths of the throats are 50 µm and the pores have a diameter of 90 µm and have a pitch of 200 µm.

3 METHOD AND EXPERIMENTAL SETUP

3.1 INTRODUCTION

Oklahoma State University, in Stillwater USA has in collaboration with Micronit, established a semi-analytical method to determine the permeability of EOR chips. A paper[1] was published on this method and the reader is kindly requested to infer this document to understand how the method works.

Similar to the paper's method, flow rates of 50, 75, 100, 125, 150 and 175 µL/min were applied the experiments reported in this document.

3.2 EXPERIMENTAL SETUP

A setup was built in accordance with the description in the Oklahoma paper. A photograph of the setup is shown below.

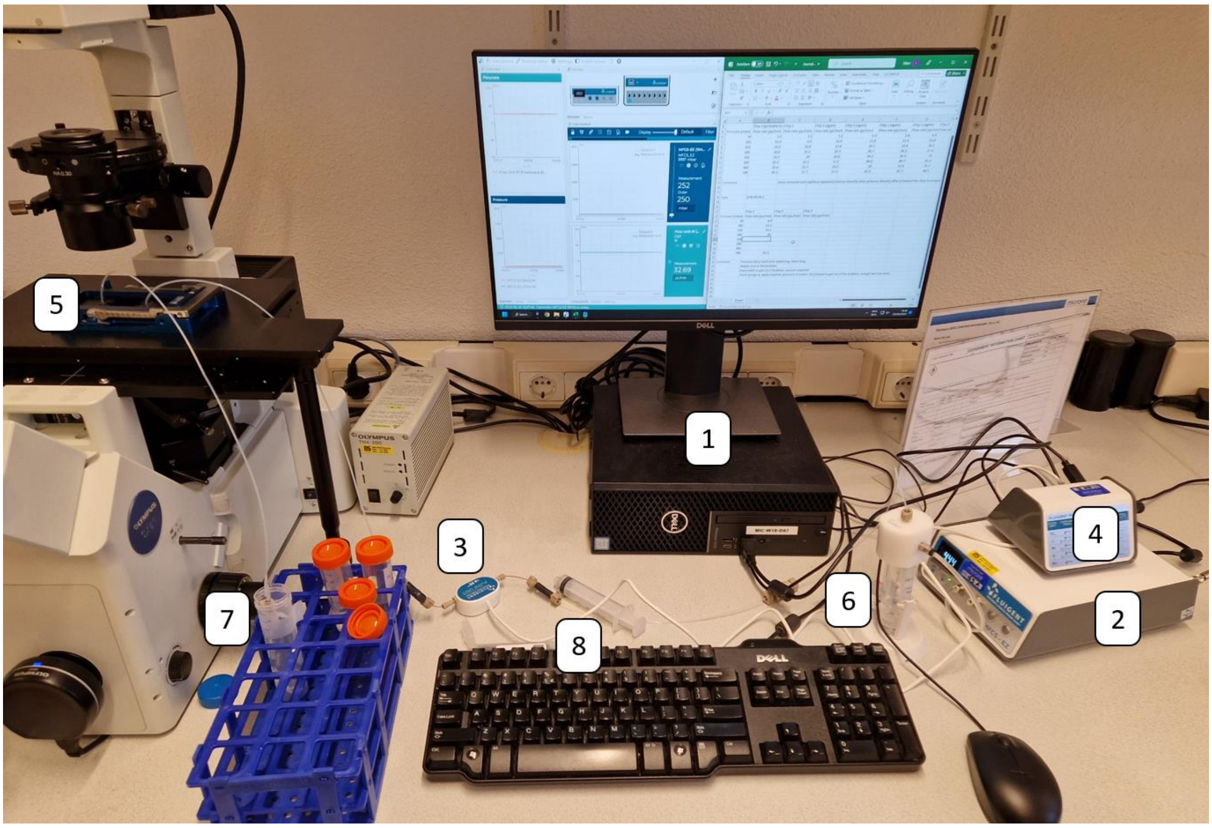

Figure 4: The setup used to determine the permeability of the Micronit EOR chips

1 Pradhan, S., Shaik, I., Lagraauw, R., & Bikkina, P. K. (2019). A semi-experimental procedure for the estimation of permeability of microfluidic pore network. MethodsX, 6, 704–713. https://doi.org/10.1016/j.mex.2019.03.025

Setup requirements:

- 1. Laptop or desktop PC with the Fluigent OXYGEN software
- 2. Fluigent pump (MFCS-EZ)
- 3. Fluigent flow sensor unit (M)
- 4. Fluigent Flowboard
- 5. Micronit Fluidic Connect Pro with inserts for fluidic slides
- 6. Tube with DI water with connector for the Fluigent
- 7. Outlet tube
- 8. Syringe (to manually apply vacuum at the outlet)
- Tubings:
    - O.D. 1/16” and I.D. 0.5 mm (several tens of centimeters to connect all parts)
    - Two capillaries (for connection to the flow sensor)
    - Silicon tubing (ID ~1/16”) to replace the chip for the zero measurement
- EOR chips

3.3 METHOD ADJUSTMENTS

The outlet tubing has a potential non-negligible resistance, yet in the paper it seems to be not taken into account when measuring the pressure drop in the system (zero measurement). In our experiments, the outlet tubing is taken into account (see Chapter 4.1).

It is advised by the writers to apply a vacuum to the outlet before filling the chip, in order to prevent bubble capture. Instead, they apply a high pressure that sequentially gives a flow rate high enough to drag any generated bubbles along towards the outlet. At Micronit, this approach did work for the Uniform Network EOR chip (the chip used in the paper), but failed for the Physical Rock and Random Network chips. Hence, a vacuum was applied to the outlet manually with a syringe and almost simultaneously a high pressure was applied: in the majority of times this approach got rid of all bubbles in the system. For uniformity, a vacuum was also applied in the Uniform Network experiments.

In the paper, the permeability is measured for each flow rate. Here, we plot the measured pressures against the set flow rates, which should be a linear relation, and then determine the permeability from the slope of the linear fit.

4 PERMEABILITY DETERMINATION

4.1 ZERO MEASUREMENT

Integral part of the method is to determine the pressure drop in the system when the chips is not inserted. To accomplish this, the tubing that were connected to the in- and outlet of the chip were connected with a piece of silicone tubing (see image blow). As mentioned before, in contrast to the Oklahoma University approach, here we include the outlet tubing in determining the pressure drop over the system without EOR chip.

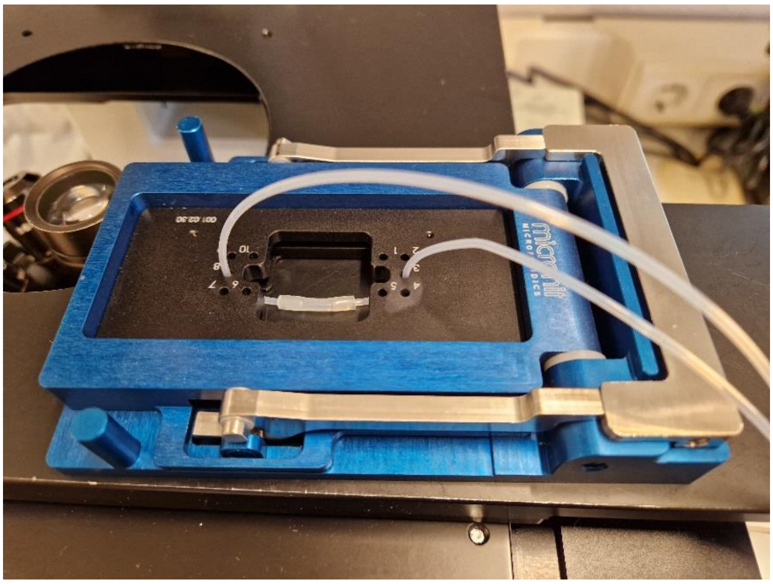

Figure 5: In the zero measurement, the EOR chips has been replaced by a piece of silicon tubing with a neglicible resistance

The internal diameter of the tubing is large so it is assumed that the resistance it adds is negligible. The pressure drop ($P_{without\ chip}$) was measured at the set flow rates (three times). The results are depicted in the graph:

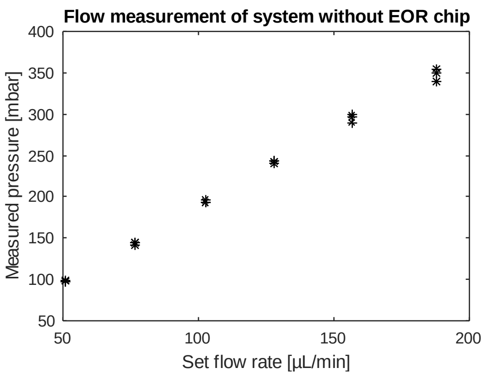

Figure 6: The measured pressure drop over the system without EOR chip plotted against the set flow rate

4.2 MEASUREMENT WITH EOR CHIP

Consequently, for each EOR chip the pressure drop is measured at the set flow rates.

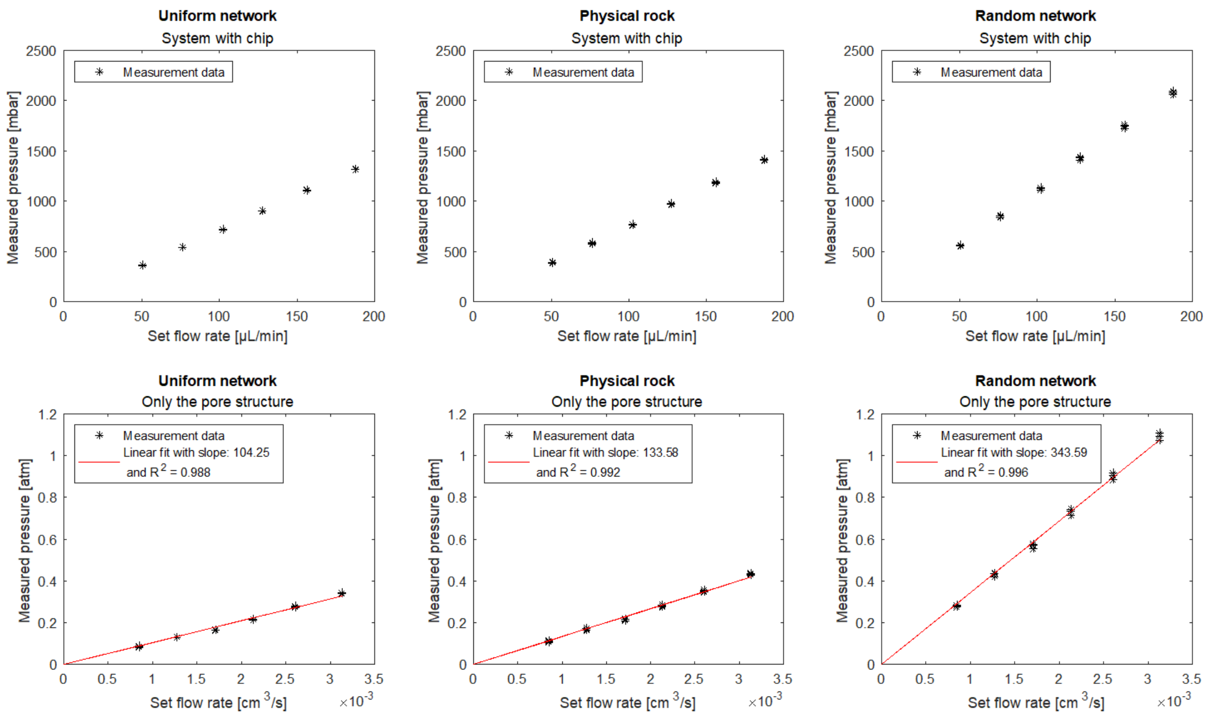

Figure 7: First row of graphs: the measured pressure drop over the system including an EOR chip plotted against the set flow rate. Second row of graphs: the same as the first row of graphs, but now the pressure drop from the system and the estimated pressure drop over the EOR chip its channels are subtracted so that we obtain the pressure drop over the pore structure only

The three graphs in the first row show the measured pressure drop in the system for each chip on each flow rate. A set of three experiments, with three different chips, was performed for each chip type, one after the other. The resulting pressures are however so close that from the image it's hard to distinguish between the separate data points.

4.3 PERMEABILITY DETERMINATION

The three graphs below show the pressure drop over the EOR pore network itself and a linear relation fitted to the data. In these graphs, for each flow rate, the calculated pressure drop over the bifurcating in- and outlet channels (see paper) and $P_{without\ chip}$ (see Figure 6) was subtracted from the pressure drops in the total system (i.e. the graphs above). When subtracting $P_{without\ chip}$, the mean measured pressure value at each flow rate was taken for subtraction.
Notice that the units of the graph have been changed to agree with the calculation that is to follow next.

From the paper, we learn that the slope of the fitted graphs should follow the following relation:

$$q = \frac{kA}{\mu}\frac{(P_2 - P_1)}{L}$$

Where $(P_2 - P_1)$ is the pressure drop over the network in Pa (hence the y-axis in the three below graphs of Figure 7), L the length of the network (2 cm), A the cross-sectional area of the network (1 cm x 20 µm, or 0.002 cm^2), μ the viscosity of the liquid (0.9321 cP for DI water at 20°C) and k the permeability in Darcy.

The equation can be reoriented to:

$$q = \left(\frac{A}{\mu L}\right) k(P_1 - P_2)$$

When plotting q against $(P_2 - P_1)$, we should get a linear relation in which the slope is equal to $\left(\frac{A}{\mu L}\right) k$. Since we know A, μ and L, we can determine k by measuring the slope of the fits.

We first calculate:

$$\frac{A}{\mu L} = \frac{2 \cdot 10^{-3}\ (cm^2)}{1\ (cP) \cdot 2(cm)} = 0.001073 \frac{cm}{cP}$$

Then we can calculate the permeability for each EOR chip by multiplying the above value with the inverse of the slope (in Figure 6): in the graphs, the measured pressure is plotted against the set flow rate rather than the other way around, hence the inverse of the slopes must be taken of the linear fits.

EOR type	Slope	Permeability (Darcy)
Uniform Network	104.25	8.94
Physical Rock	133.58	6.98
Random Network	343.59	2.71

The determined permeability of the Uniform Network chip deviates from what was found in the paper (6.8 Darcy). A possible cause for the observed difference might be flow sensor calibration related. The sensors used in our experiments require calibration for a specific liquid. In the paper no details on the flow sensor calibration procedure where provided.

4.4 ERROR IN PERMEABILITY

A method of determining the error in the permeability is to find the minimum and maximum slope that the gathered data would allow.

The Fluigent system measures the pressure and there is always some fluctuation; it was determined that the fluctuation was never more than 10 mbar, which translates to about $4.934 \cdot 10^{-3}$ atm. This error is respectively added and subtracted from the data points that would give the maximum and minimum slope when fitting through that point and the origin. The graph below shows the results for the Uniform Network EOR chip.

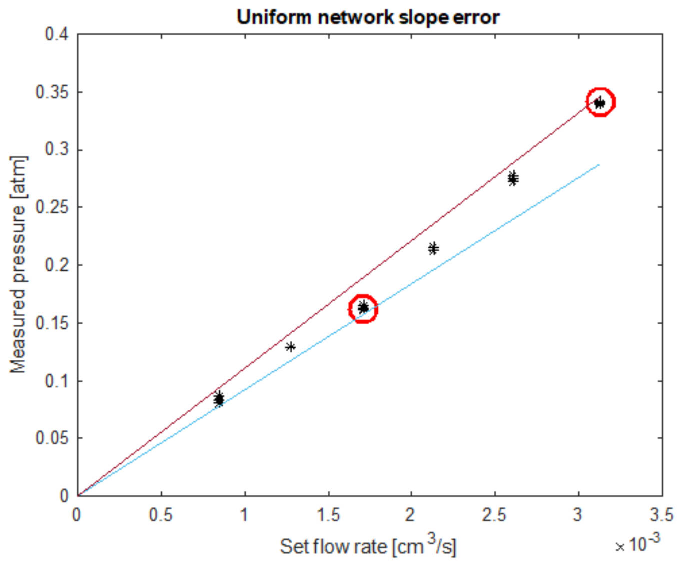

Figure 8: Error determination for the permeability in the uniform network EOR chip

The red circles display the points that would give the minimum and maximum slope. These two linear fits give an indication of the error in the permeability. The maximum slope would give the possible minimum permeability and the minimum slope the possible maximum permeability (the inverse of the slope is used in the calculation). Using this method, we find the following ranges:

EOR type	Permeability (Darcy)
Uniform Network	8.43-10.14
Physical Rock	6.62-7.79
Random Network	2.62-2.94