Experimental investigation into influence of oil-in-water emulsions flow on permeability of porous bed

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ABSTRACT

Emulsions are interesting dispersed systems that are necessary for a number of technological processes. Their flow through porous structures have many applications in the field of chemical engineering. Enhanced Oil Recovery (EOR) techniques, soil remediation and various treatment methods of oily wastewater are good examples of emulsion flow in porous structure. The phenomenon of dispersed system flow through porous media is not easy to describe, mainly because of rheological behavior of emulsions and porous structure properties. During two phase flow of oil and water through porous bed it is possible to observe the interception of oil to porous structure, as well as filtration of oil in pores. In this study, we tried to examine the influence of the fraction size as well as migration process history on permeability of porous bed.

Keywords: porous bed permeability, emulsions, oil-in-water, multiphase flow

1. INTRODUCTION

Flow of emulsified systems through porous media is very important topic for chemical industry. In processes such as oil extraction, soil remediation with usage of surfactants and wastewater treatment on coalescent filters occurs emulsions flow through porous structure
Soil remediation with usage of biodegradable emulsion can be a typical example of multiphase fluid migration in porous bed (Young-Chul L. 2007). Understanding of transport of emulsion inside porous bed can allow companies to reduce cost connected with contamination removal from soil (Crawford et al. 1997). Also, knowledge in flow of different fluids through porous structure have application in areas such as geomechanics, hydrogeology, and reservoir engineering (Wang, H. F 2000).

In Enhanced Oil Recovery (EOR) techniques, better understanding of emulsion flow through porous media is needed to develop practical improvement in processes based on emulsion flooding mechanisms (Moradi et al. 2014). In this process, the oil-in-water (O/W) or water-in-oil (W/O) emulsions are formed and flow through the porous structure of soil. It is especially important in heavy oil recovery, where emulsified solvent flooding has been shown to be efficient technique (Kumar et al. 2012).

Darcy’s law was the first one that explains flow through porous structure. Moreover, it is one of the elementary equations that characterize flow of fluid through porous media. For emulsions with concentration of dispersed phase up to 50%, the relationship between pressure drop and flow rate is linear, which means that the equation (1) can be used. This law can also be applied to explain flow through porous bed induced by a pump. In such case, the driving force will be the pressure difference $\Delta p$ between the pressure produced by pump and the atmospheric pressure (Heinemann 2005).

Also, for porous structure having determined length and diameter it is possible to determine the permeability coefficient according to the extended Darcy’s law. Permeability coefficient is a measure of the ability of a porous material to allow fluids to pass through it. The Darcy’s law for the presented situation can be described as (1):

$$Q_v = k \frac{A \Delta p}{\mu l}$$

where: $Q_v$ – volumetric flow rate, $m^3/s$,

$k$ – the permeability coefficient for certain porous structure, $m^2$,

$l$ – the distance of flow, m

$\Delta p$ – pressure difference, Pa

$A$ – surface of cross-section of bed, $m^2$

$\mu$ – dynamic viscosity of liquid, $Pa\cdot s$

However, in case of emulsions with concentration higher than 50%, the dependence of pressure drop and flow rate is not linear, which suggest their non-Newtonian behavior, and usually in a case of emulsions show their shear-thinning behavior. This phenomenon has been confirmed with a series of experiments and explained as a result of interaction between droplets caused by the forces of attraction and repulsion (Guillen et al. 2012, Cobos et al. 2009, Soo and Radke 1986). Also, in most practical cases, the oil droplets are not significantly smaller than pores, and even larger, which means that their presence in deposit
cannot be neglected. In this case it is necessary to consider how other emulsion properties such as droplets sizes, viscosity, and density influence the flow (Cai et al. 2012).

Multiphase flow through porous structure is more complex than one phase flow. Until now many mathematical models, both for homogenous and heterogeneous flow, were created (Schramm 1992; Cortis A. Ghezzehei A. 2007; Idorenyin E. and Shirif E. 2012).

These equations typically predict changes in deposit permeability or changes in the structure of emulsions as a function of time. The basic assumption of the homogenous models is that the emulsion is a continuous single – phase liquid, so its microscopic features are unimportant in describing the physical properties of the liquid or the bulk flow characteristic. The interactions between the droplets in the emulsions and the solid surface are also ignored. However, especially in oil recovery processes, modeling of emulsion flow through porous media is developing area of interest (Renena V. et al 2014).

On the other hand, there exist examples that are based on implementation of the mathematical models for improvement in heavy oil recovery (Qiu F. and Mamora D. 2010) The good example of heterogeneous model that include filtration equations was presented by Soo and Radke (Soo and Radke 1986). In case of multiphase flow, the driving force is created not only due to pressure difference $\Delta p$ but also due to capillary differential pressure $p_c$. The existence of capillary forces have significant effect on fluid flow in porous structure, and was also modeled (Guillen et al. 2012).

During emulsion flow through porous media filtration phenomena of oil phase can be observed. It happens when the emulsion droplets have similar size to pores (Mendez 1999). The filtration theory is still developed and has a great meaning for Enhanced Oil Recovery techniques (Iryna I. et al. 2016). Van der Waals forces also play vital role in such flow and they lead to connection of the oil droplets to porous media and effect in reduction of bed permeability (Buret et al. 2010). Interception of oil to porous structure is another mechanism that occurs during emulsion flow process, and leads to reduce of free space size in structure. This mechanism can be explained by the capture of droplet in porous structure, due to its interception to porous bed walls. When pores are either blocked or significantly reduced by retained drops, emulsion flow takes place along the adjacent space that left (Torok et al. 2006). Moreover, when O/W emulsion is introduced into (or forms in) the porous structure, firstly it flows to more permeable zones. After blocking of those zones, emulsion flows into less-permeable sectors, which results in the more effective distribution of emulsion inside the porous structure. This phenomenon is recognized as the “straining mechanism” (Cobos et al. 2009, Wang and Dong 2011).

The emulsions presents certain droplet size distribution with an average value that represents dispersion. The droplet size depends on a few factors such as type of oil, compounds present in the continuous phase, interphase properties of emulsions, type of emulsifier (used or naturally present), flow rate, and properties of the bed. The correlation between droplet size and pores size influences the emulsion flow through porous media, which has been experimentally confirmed (Alvarado et al. 2011).

The analysis of literature shows that emulsion flow through porous structure is a complex issue which is important to investigate because of the use of this process in many industrial fields. The aim of presented experiments were to investigate the influence of porous bed fraction, and flow of different media, on permeability of porous structure.
2. MATERIALS AND METHODS

The measurement equipment that was used in experiments is shown in Fig. 1. It consisted of six elements: 1. container with liquid 2. pressure indicator 3. signal converter 4. peristaltic pump 5. pipe with microspheres 6. volumetric flow indicator at outflow section.

![Figure 1](image)

**Figure 1.** Equipment used in experiments: 1-container with liquid, 2-pressure indicator, 3-signal converter, 4-peristaltic pump, 5-pipe with microspheres, 6-outflow section with flow indicator.

In the experiments we used the peristaltic pump type 372C produced by ELPIN-PLUS manufacturer. It was calibrated before measurements to obtain its characteristics. The signal converter PT-5261M was connected with pressure indicator MD-5270, which scale was in bar. The pipe was made from stainless steel and it had length of 0.5 m. The diameter of this pipe was 0.05 m. The following materials were used: microspheres with diameter 90±150 µm, 100±200 µm and 200±300 µm. Porosity of such beds was equal $\varphi = 0.34$. The used liquids were: edible oil with viscosity of 60 mPa·s in ambient temperature and density of 865 kg/m$^3$, tap water and emulsifier Rokacet obtained from PCC Rokita S.A. Glass microspheres were used instead of sand or soil, since this material have strictly determined porosity and grain diameter. Edible sunflower oil was used instead of crude oil because of its safety. The experiments were carried in ambient temperature of 25 °C. The emulsion was prepared as following: oil, water and emulsifier were mixed together to obtain dispersed system with certain concentration. Emulsification process was conducted with usage of high speed hand automatic mixer. Mixing time was three minutes. The oil in water emulsion with concentration of 20% O/W was prepared. Fig. 2 presents photograph of prepared emulsion with 40x magnification.

The emulsion had addition 2% of Rokacet emulsifier. It was also tested that it is stable system with stability time of more than 24 hours. The viscosity of fluid emulsion was also checked. Emulsion viscosity varies with its concentration, this is reason why this parameter was checked with rheometer. The viscosity of prepared 20% O/W emulsion was 0.15 mPa·s.

During next step the certain amount of porous bed with previously mentioned parameters was placed into the pipe and then the main part of experiment began. Firstly we leached the bed with plain tap water, then with emulsion and at the end with the water again.
Figure 2. Microscopic picture of emulsion

Figure 3. The frequency of occurrence of microspheres with different diameter for 90±150 μm porous bed

Since in experiments we used three types of microspheres with diameter 90±150 μm, 100±200 μm and 200±300 μm, we decided to investigate the frequency of occurrence of microspheres with certain diameters in them. It allowed us to better analyze the mechanisms of emulsion flow and elution from porous media. In Fig. 3 we present the frequency of occurrence of certain diameter of microspheres in 90±150 μm porous bed.
Figure 4. The frequency of occurrence of microspheres with different diameter for 100–200 µm porous bed

Figure 5. The frequency of occurrence of microspheres with different diameter for 200–300 µm porous bed
As it can be seen from Fig. 3 the most frequent particle size was 90÷93 µm, 96÷99 µm and 123÷126 µm. It can be also observed that in the bed there were more smaller particles – it means from 90 to 126 µm than bigger – from 126 to 150 µm. The range in this case is rather homogenous - there are no particles with shear of more than 8% from total.

As it can be seen from Fig. 4 the most frequent particle size was 100÷105 µm and 110÷115 µm. It can be also noticed that in the bed there were less bigger microspheres - it means from 160 to 195 µm than smaller – from 100 to 155 µm. The frequency of occurrence varies with the maximum share of microspheres with certain size of 10% and minimum of 2%.

The eluted liquid containing emulsion was collected in bakers with the 100 ml capacity in order to perform further analysis. The leaching process was stopped when the steady state was obtained, in other words when obtained pressure was stable. The water and emulsion was pumped with the same flow rate $6.5 \cdot 10^{-6} \text{ m}^3/\text{s}$ during the entire process.

As it can be seen from Fig. 5, in microspheres in range 200÷300, the most frequent particle size was 200÷205 µm. It can be also observed that in the bed generally the smaller the particles were, the less frequent they occurred. The range in this case is rather not homogenous - some particles have 2% frequency, the biggest fraction have 14% occurrence frequency.

3. RESULTS AND DISCUSSION

During experimental tests it was possible to measure the pressure at the inlet to the bed and the flow rate at the outlet of it. The results of experiments are showed in the form of charts where the inlet pressure $\Delta p$ and outlet flow rate $Q_v$ versus time are presented – Fig. 6 and Fig. 7.

The experiments started with tap water pumped through porous bed. In this step it was possible to observe that the steady state was reached quickly, and the pressure as well as flow rate at outlet did not varied significantly. For the first step regarding water flow, to conduct calculations according to equation (1) we took the pressure difference $\Delta p$ and volumetric flow rate $Q_v$ from Fig. 6 and Fig. 7 presented later in this article, and we assumed density of liquid equal to $\rho = 997.29 \text{ kg/m}^3$. The permeability coefficient calculated for the porous bed fraction of 200÷300 µm equaled to $3.27 \cdot 10^{-11} \text{ m}^2$, when for fraction of 100÷200 µm had the value of $2.02 \cdot 10^{-11} \text{ m}^2$, and for the finest fraction 90÷150 µm was just $1.33 \cdot 10^{-11} \text{ m}^2$. It means that permeability for medium fraction 100÷200 µm equaled to 61.9%, of permeability reached for the biggest fraction 200÷300 µm. The permeability of bed with the smallest particles 90÷150 µm equaled to 40,6% of the value obtained for the 200÷300 µm fraction.

Second stage of experiment started 700s after beginning of the process. During this stage the emulsion was pumped through porous media. The starting moment was noted with the black vertical lines in Fig. 6 and Fig. 7. In Fig. 6 it can be noticed that pressure difference $\Delta p$ growth at the inlet was very rapid. The steady state was observed after longer period of time, than just in case of flow of tap water. The main reason for that is fact that oil droplets of emulsion during flow blocks the paths that exist in porous structure. Because of this phenomena the permeability of bed gradually lowered, until the steady state was observed. It can be noticed that the time for reaching steady state was the longest one in the case of bed with the finest fraction. It means that during emulsion flow through small porous bed fraction
interception phenomenon occurs. In this case the calculated permeability coefficient was $3.21 \times 10^{-11} \text{ m}^2$ for 200÷300 µm fraction and $1.57 \times 10^{-11} \text{ m}^2$ for 100÷200 µm fraction and $5.87 \times 10^{-12} \text{ m}^2$ for 90÷150 µm size. Therefore it can be concluded that permeability of the medium fraction dropped two times when compared to the biggest fraction. On the other hand for the smallest fraction the permeability was around 5.5 times less than for 200÷300 µm fraction.

The last stage started around 1400s after the experiment began. During this stage water was pumped through porous bed. The beginning of this process was marked with the vertical black lines in Fig. 6 and Fig. 7. The rapid increase in pressure difference in the porous bed inlet can be observed at the beginning of this stage. For every flow in relatively short time the new steady state was reached. The permeability for fractions 200÷300 µm, 100÷200 µm, 90÷150 µm were as follows: $2.83 \times 10^{-11} \text{ m}^2$, $1.68 \times 10^{-11} \text{ m}^2$ and $8.32 \times 10^{-12} \text{ m}^2$. Comparing the permeability coefficient reached for the bed with the biggest and medium fraction it can be stated that it was 60% of this amount, while the smallest fraction was 29.4% of the biggest fraction.

![Figure 6](image.png)

**Figure 6.** Pressure drop at the inlet to porous bed versus the time of process

During the analysis of flow of different liquids through the same bed we noticed an interesting fact. The permeability of bed for the water flow after the emulsion flow was smaller, than for the flow of water through the clean bed. For the bed with particle size fraction 200÷300 µm reservoir permeability decreased by about 14%, while for the bed that have fraction of 100÷200 µm decreased by 16%, and for bed size 90÷150 µm dropped by
37%. That means that, after the emulsion flow through the bed droplets of the oil phase not only block the flow paths, but are also trapped in it. It can be also noticed that when the particle size fraction of bed was lower, the blocking intensity was higher. It also leads to a conclusion that the correct analysis of porous structure permeability can be done basing not only on the type of fluid that flows through it, but also on the history of it.

\[ Q_v \text{ [l/min]} \]
\[ t \text{ [s]} \]

**Figure 7.** Flow volume at the porous bed outlet versus the time of process

4. CONCLUSIONS

From experimental results obtained in this research, it can be concluded that porous bed permeability is directly related to particle size fraction. During emulsion flow through porous bed the permeability reduction can be observed, until the steady state was reached. The reason for this is the fact that emulsion droplets intercept to porous structure and therefore they block the paths for medium during flow. Also the time until the steady state was reached is the longest for the smallest fraction.

During the flow of water through porous bed that was previously leached with emulsion it can be observed that steady state was reached relatively quick. However, in this case the pressure drop was bigger than in situation when water flows through fresh porous structure. It leads to a conclusion that oil droplets from emulsion were trapped in the porous structure and this phenomenon causes the fact that during the second flow of water through porous structure the permeability of it was lower. It proves that history of process have significant effect on analysis of liquid flow through porous bed.
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References


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