Evaluation of electroosmotic pumping effect in microporous media flow

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Abstract: In this paper, the electroosmotic flow (EO) in desiccant powders of micro porous is investigated regarding to the flow rate caused by the electroosmosis and the gravity. In particular, the coupling effect of electroosmosis and dehumidification in the flow is studied. It is noticeable that the actual electroosmosis pumping force maintains at a certain rate (10µL/min for the designed system). It is interpreted that the actual voltage from bench power is kept constant which exerts same effect of electric field on the desiccant particles. And during this stage the resistance inside the channel deceases with the rate of water entering into the electroosmosis pumping section which is affected by the capacity of dehumidification of the desiccant particles. Moreover, the mass flow rate by the effect of electroosmosis pumping can be achieved at 0.746 $gm^{-2}m^{-1}$ under 5V DC supply. These experimental results in this study provide useful instructions of electroosmosis performance for designing the micro porous channel in such as filtering the compounds of drug delivery, particle purification and liquid separation applications etc.

Keywords: Microporous Flow, Electroosmosis pumping

1. Introduction

The phenomena of electroosmotically driving flow, which were firstly observed by Reuss in 1809 when doing an experimental investigation on porous clay have currently been widely studied and analyzed in many subject areas such as electrochemistry, physics and vascular plant biology. The theory of electroosmotic flow (EOF) has been applied to various fields in pharmaceutical and chemical industries, and also civil engineering including mine tailing water prevention and waste sludge treatment. Many experimental and numerical investigations of EO driving fluid flow in porous media with normal size particles have been carried out over the past decades(Coelho et al., 1996; Kozak and Davis, 1989a, b; Rathore and Horváth, 1997; Wang and Chen, 2007), and the studies of natural electroosmosis phenomena and the inspired bionic or biomimetics design applications have also been carried out and reported (Yan Y.Y., 2007; Yan, 2004, 2007; Zu Y.Q. and Yan Y.Y., 2006). and the application the EO theory to the practice such as drag reduction in machinery and dehumidification of solid desiccant in HVAC (Li B. and Yan Y.Y., 2011). Fluid flow in micro porous media also has significant scientific and practical importance in many areas. In petroleum mining industrial, carbon dioxide is captured and made us of repelling the raw oil under earth (Ghesmat et al., 2011; Javaheri et al., 2010). In hydrogen storage, the particle diameters in the porous hydrogen storage alloys are 1–20 µm. Better knowledge about the fluid flow characteristics and improved heat and mass transfer models for microporous media are very important for the development of CO_2, hydrogen storage and other related technologies. There have been a number of studies on the phenomenon of fluid flow through micro porous media. Scheidegger (1974) introduced the physics of flow in porous media and gave a detailed review of the pioneering theories and investigations. In recent years, the theory of transport through microporous media has been studied extensively by various researchers, such as Kast and Hohenthanner (Kast and Hohenthanner, 2000; Miguel, 2007) . A number of studies have found that for the same porous media the permeability with gases is larger than with liquids and the permeability differs with different gases. In this paper, the EOF theory has been applied to regenerate micro solid desiccant particles by regarding desiccant structure as micro-channels. And an applying electric field will be placed between the desiccants membrane. So the de-ioned water absorbed by desiccant can be pumped out in a certain rate. In spite of plenty of studies related to the fluid flow in porous media, the flow mechanisms in micro porous media still need to be investigated further. There are not adequate papers that investigate the dehumidification application involved in micro porous media flow. Besides that, there are little reports that cover the coupling effect between the absorption behaviour of solid desiccant particles and electroosmosis pumping effect. Thus, the aim of the present study is to examine the effect of electroosmosis pumping force on fluid flow in the micro porous media.

2. Method

When the electrohydrodynamics is considered, it is necessary to address the electrophoresis and the Electroosmosis simultaneously.(Bruus H. et al., 2004) Electrophoresis is the movement of a charged surface relative to a stationary liquid induced by an applied electric field. However, Electroosmosis is the movement of liquid relative to a stationary charged surface induced by an applied electric field. Hence, if the force of the electrophoresis is blocked or balanced by the opposite force from the filter which blocks the desiccant particles moving outside, only the water will be removed by the electroosmotic performance. As depicted in Figure 1, a spherical particle of charge Z_e moves in a low-conductivity liquid with viscosity η under the influence of an applied electrical field E. The motion becomes stationary at the velocity u_{ep}, when the Stokes drag force F_{drag} balances the electrical driving force F_{el}. Then the F_{drag} will be balanced by the opposite force F_{filter} = - F_{drag} from the fixed filter, the F_{el} force will be balanced by the liquid movement which means the F_{el} = - F_{eo} exerted on the liquid to make them flow eventually. Given the assumption that the particles are kept stationary inside the container, the flow rate cause by the electroosmosis can be obtained indirectly by measuring the pressure difference and working areas.

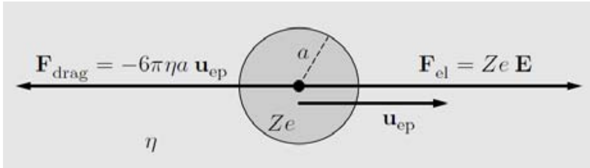


Fig. 1: Forces exerted on the particles by electric field(Bruus H., 2008)

In addition, for EO flow, it is mostly influenced by several forces such as gravity, hydraulic pressure, viscosity, temperature driven force and EO but the hydrostatic pressure and electro-osmotic force are dominant factors. Therefore, the total flow rate is determined by the sum of EO effects and hydraulic pressure. It has also been proved that due to the low Re number, for a steady state flow, the hydraulic flow rate can be expressed as:

$$Q_{hyd} = \frac{\Delta p_{hyd}}{R_{hyd}} \quad (1)$$

where Δp_{hyd} is the pressure drop and R_{hyd} is the hydraulic resistance. Moreover, for a pure EO driven flow, due to the limit of thin Debye layers, the flow rate can be expressed as:

$$Q_{eo} = \mu_{eo}\frac{\Delta\phi_{eo}}{L}A = \mu_{eo}\phi_{eo}(R_{elec}\lambda_{elec})^{-1} \quad (2)$$

where μ_{eo} is the electro-osmotic mobility, L is the length of EO channel and ΔΦeo is the electrical potential drop and A is the channel cross section area. R_{elec} is the electrical resistance and λ_{elec} is the electrical conductivity. If there is EOF, the electro-osmotic pressure force must balance or exceed the hydraulic counter pressure force. Then total flow rate combining both hydraulic and electro-osmotic flow is (Brask A. et al., 2005):

$$Q = \frac{\Delta P_{eo} - \Delta P_{hyd}}{R_{hyd}} \quad (3)$$

In the experiment, it is assumed that the channels are formed by the uniformed round-shaped particles with radius a, the number of channels is N and all the channels were assumed as cylindrical; the total flow rate in the experiment should be calculated as:

$$Q_{eo,N} = NQ_{eo} = N\frac{\pi a^2 \varepsilon\zeta}{\eta L}\Delta\phi \quad (4)$$

where ζ is the zeta potential of specific particles, ε is electric permittivity. Then, the pressure caused by the electroosmosis is calculated as:

$$p_{eo,N} = p_{eo} = N\frac{8\varepsilon\zeta}{a^2}\Delta\phi \quad (5)$$

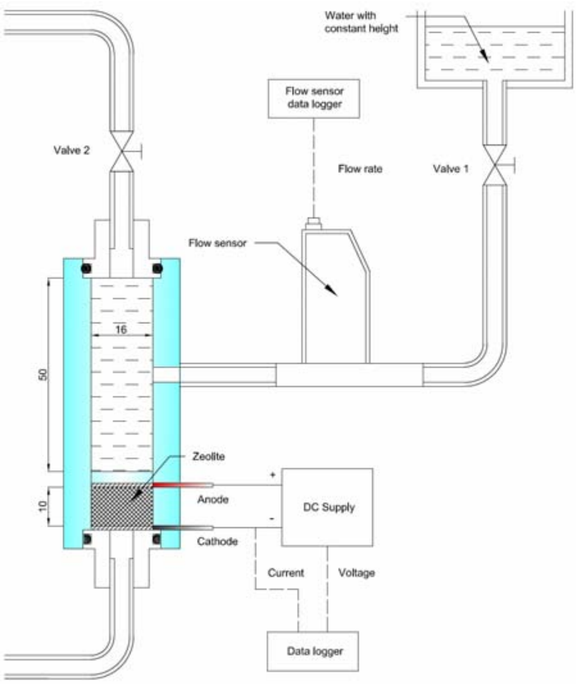


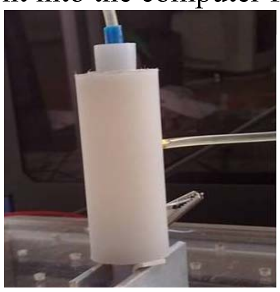
Fig. 2: Schematic of electroosmosis pumping flow rate testing plan

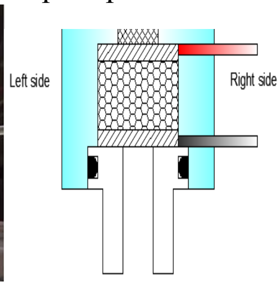
3. Experiment

In order to measure the flow rate Q_{eo} in the desiccant particles, the test rig is set up as depicted in Figure 2. The micro flow sensor is placed between the de-ioned water reservoir and test section which are connected by the PEEK™ tubes with 1/16" ID diameters. The structure of EO pump mainly consists of three parts. There are membrane filters, electrodes and cylinder wall. The self priming bar will be embodied into solid desiccant to absorb water and transfer it to EO process section as show in Figure 3(a). In the EO section, the applied voltage from the electrodes creates EO force to push water molecules downwards to the cathode side. Eventually, the water is collected by a graduated container.

In particular, the material of the self priming bar is porous material such as porous plastic or ceramics showed in Figure 3(b). The diameter of the bar is 8mm. Inside EO pump, the general depth is 12mm and it contains two electrodes with two attached pieces of filter which make the thickness of the particles material 10mm depth. For the electrodes configuration, there are two types to be analyzed. The first type is a ring shape with outside diameter of 16mm, inside diameter of 10mm. The other type of electrode is a steel circular plane with holes inside and the diameter is 16mm. This can be used to compare the influence caused by electrodes.

A bench power supply is connected with the electrodes. It directly produces DC voltage to the meshed electrodes inside ranging from 0V to 35V. The current of the electroosmosis process during the testing is recorded by the data logger. And the flow rate in the tube is recorded by the flow sensor ranging from 0μl/min to 1100μl/min. All the results will be sent into the computer for post-process.





(a) **(b)**

Fig. 3: **(a)** Electroosmosis pump; **(b)** layout inside the pump

4. Results

3.1 Total process of electroosmosis performance

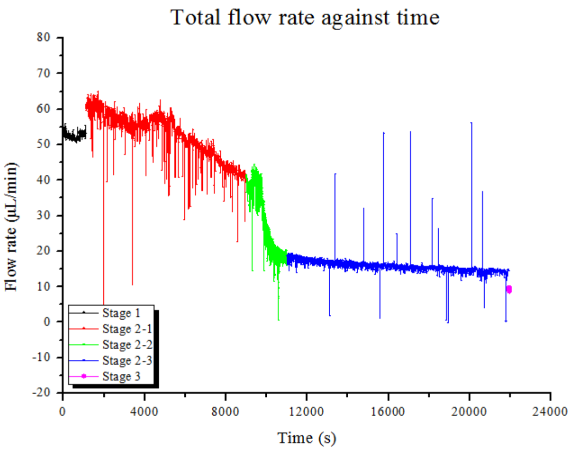


Fig. 4: Flow rate recorded in whole testing

Figure 4 shows the total flow rate during the test. The measured time interval was up to 6 hours to analyse the whole EO process. The process could be generally divided into three parts, represented by red, green and blue lines. In Stage 2-1 the total flow rate reduced gradually and reached Stage 2-2 where a rapid reduction occurred. This is caused by the occurrence of bubbles and the erosion of electrodes. After Stage 2-2, the total flow rate became relatively stable in Stage 2-3. After Stage 2, the total flow rate had a sudden reduction, which means that at the end of 7 hours, EO still had its effectiveness providing 5V voltage. It is very clear that the electrochemical reactions are dominant factors. It not only affect the flow rate in the microchannel but determinate the lifespan of the electrodes. It is foreseen that inert metal or non metallic electrodes will extend the durability of the testing.

3.2 Evaluation of electroosmosis performance under stable conditions

Figure 5 shows the measured flow rate during the testing. It lasts 2000 seconds. It can be seen that when Stage 2 started, the flow rate due to gravity was around 68 μL/min and after 1800 minutes EO process, the flow rate due to gravity only reduced to around 60 μL/min. Assuming that the reducing rate of flow rate due to gravity only is linear, the total flow rate (Gravity and EO), gravity driven flow rate and EO driven flow rate against time have been shown in different colours. The EO driven line is calculated by subtracting predicted gravity driven flow rate from total flow rate in realtime. From the selected range of testing, it can be seen that the ratio of electroosmosis effect is around 15% to 20% of the total amount of the flow rate. At different stage of testing, this value varies depended on the inside desiccant condition.

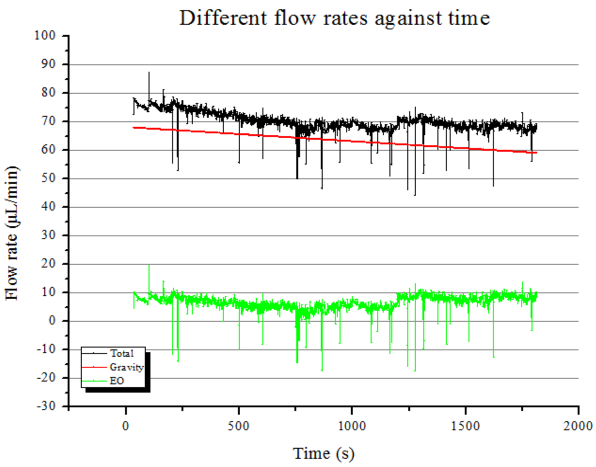


Fig. 5: Ratio of Electroosmosis effect in total flow rate

3.3 Evaluation of Electroosmosis pumping effect with current

The average EO regeneration rate shown in Figure 6 is 10μL/min. As the section diameter of the channel (same as the area of electrodes) is 16mm and the water density is 1000 kg/m^3, the regeneration rate can be calculated as:

$$\dot{m}_{eo} = \rho_{water} v_{eo} = \psi \rho_{water} \mu_{eo} \frac{\Delta\varphi}{L} = 0.746 g m^{-2} s^{-1}$$

As depicted in Figure 6, the initial current is as high as 1.7mA and it gradually decreases which is mainly caused by reduced contact surface due to the voids inside the pump and the corrosion of electrodes due to the chemical compounds formed at the interface. Interestingly, the actual electroosmosis pumping force maintains at certain rate (10μL/min) although the current decreased dramatically. Based on the electroosmotic theory, the flow is generated by the voltage difference in the channel. It is explained that the actual voltage from bench power is kept constant which exerts same effect on the particles and during this stage the resistance inside the channel deceased with more water entering into the electroosmosis pumping section.

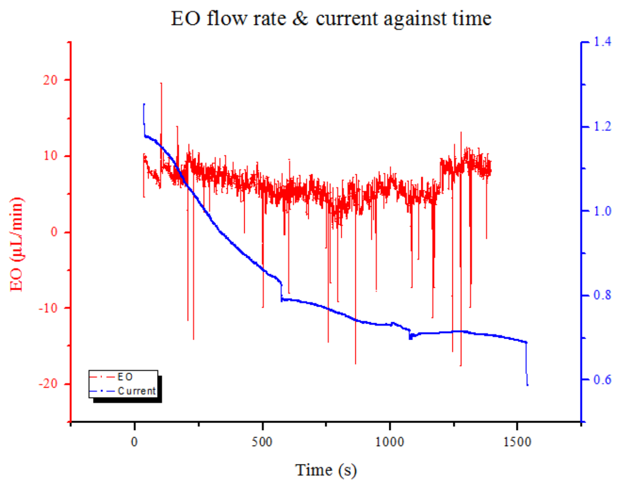


Fig. 6: Electroosmosis pumping effect with the recorded current

In addition, electrolytic reactions in electrodes happen throughout the EO process. These reactions corroded the anode and made the insoluble substance depositing into the material. Both of them contribute to the increase of resistance and the decrease of current. The main reactions were summarised as:

Anode

$$2H_2O - 4e^- \rightarrow 4H^+ + O_2 \uparrow$$

$$Fe + 3H^+ \rightarrow Fe^{3+}$$

$$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3 \downarrow$$

Cathode

$$4H_2O + 4e^- \rightarrow 4OH^- + 2H_2 \uparrow$$

3.4 Evaluation of electroosmosis pumping at different total flow rate

According to Figure 6, the EO driven flow rate in the first 9000s before the sudden reduction is relatively stable, around 10μL/min. However, the flow rate of EO driven flow was suddenly reduced to negative. This is because that the occurrence of bubbles as oxygen and hydrogen had been produced at anode and cathode. These gases could significantly affect the pressure within the channel and the sudden change of pressure could lead to the error of flow sensor. Therefore, the flow rate after 9000s was not reasonable to present the actual EO driven flow rate.

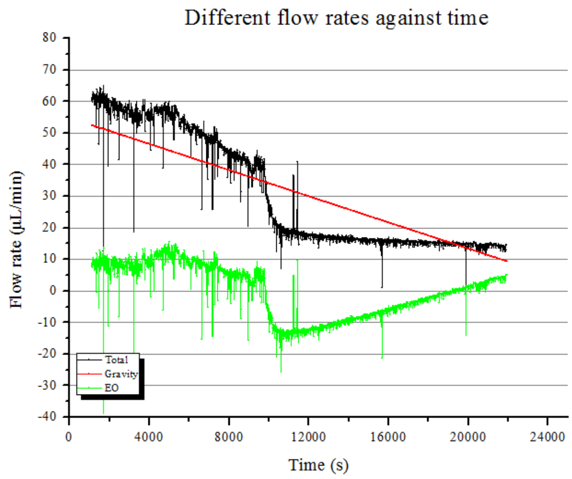


Fig. 7 Different flow rates against time in two Tests

4 Conclusions

In this paper, the electroosmotic flow in the microporous desiccant powders is investigated regarding to the flow rate caused by the electroosmosis and the gravity. In particular, the coupling effect of electroosmosis and dehumidification in the flow is studied. It is noticeable that the actual electroosmosis pumping force maintains at certain rate (10μL/min) although the current decreased dramatically during the testing. It is interpreted that the actual voltage from bench power is kept constant which exerts same effect of electric field on the desiccant particles. And during this stage the resistance inside the channel deceased with more water entering into the electroosmosis pumping section which is affected by the capacity of dehumidification of the desiccant particles. Moreover, the mass flow rate by electroosmosis pumping effect is achieved by 0.746 $gm^{-2}m^{-1}$ under 5V DC supply. These experimental results in this study provide useful instructions of electroosmosis performance when designing the microporous channel in such as filtering the compounds of drug delivery, particle purification and liquid separation applications etc.

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