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Mixing of two immiscible phases measured by industrial electrical impedance tomography system

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Abstract. The mixing of two immiscible phases is a process commonly seen in many industrial applications. Whether it is desirable (e.g. mixing of ingredients in chemical or food industry) or undesirable (e.g. sediments or contaminants in water purification) process, it has to be taken into consideration and a detailed description would be beneficial to any end product. This paper deals with a method for observing the volume ratio of two immiscible phases from the state of total separation to the state of a homogenous mixture using industrial Electrical Impedance Tomography (EIT) system ITS p2+. This paper also shows a great advantage in combining the EIT measuring method with a theoretically derived formula. It is used to calculate the concentration of a non-conductive phase in the final mixture using the initial and final conductivity values. The authors were also able to show a possibility to successfully use the formula in situations, where the initial conditions for it are not fully met.

Keywords: Electrical impedance tomography / two phase mixing process / electrical conductivity / concentration

1 Introduction

In many areas of research and industrial applications there is a constant need for detailed description of mixing processes [1,2]. There are many ways how to analyse the process itself − optical methods, electrical methods, etc. [3]. In a previous article [4] the authors have used Electrical Impedance Tomography (EIT) for analysing and describing a two phase mixing process. To convert the conductivity values measured by EIT into concentration a simple formula given in [5] has been used. There it has been shown that the volume ratio of two mixed substances, where the first one has a known conductivity and the second one is non-conductive, can be calculated by the means of the following formula:

$$\varepsilon = \frac{2 - \dfrac{2\gamma}{\gamma_0}}{2 + \dfrac{\gamma}{\gamma_0}}, \tag{1}$$

where γ is the conductivity of the final homogenous mixture, γ_0 is the conductivity of the conductive substance

and ε is the volume ratio of both mixed substances and can be defined as follows:

$$\varepsilon = \frac{V_1}{V_0}, \tag{2}$$

where V_1 is the volume of non-conductive substance and V_0 is the volume of the conductive substance in the mixture.

In our previous article [4] we have measured two phase mixtures of silica sand–water and oil–water for one given concentration. The authors were able to show that the formula (1) is valid regardless of the second phase being solid or liquid. The aim of this article is to show the validity of the formula also for different concentration values. Because of the authors' research goals and future practical industrial application the focus here will be mainly on mixing two liquid phases − mineral oil and water.

2 Experiment methodology

In our experiments we used the EIT ITS p2+ system for measuring two different mixtures. In both cases the mixtures consisted of a conductive phase (water) and a non-conductive phase (mineral oil). Because of the need for

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a sufficient difference between conductive and non-conductive phases the conductivity of water was increased by adding a small amount of sodium chloride (NaCl). This way its conductivity was raised to 1 mS/cm.

The container used for the experiment was a cylindrical vessel with four sets of sixteen electrodes each (thus giving us four independent EIT measuring planes), though for the following experiments we used only three − because of the undesirable proximity of the top electrode set (P1) to the oil–water interface. The mixing process also took place in the vessel using a Rushton turbine [6] made of plastic on a long plastic-composite shaft (see Fig. 1). The vessel is equipped with a lid, which prevents aeration of the mixture during the mixing process.
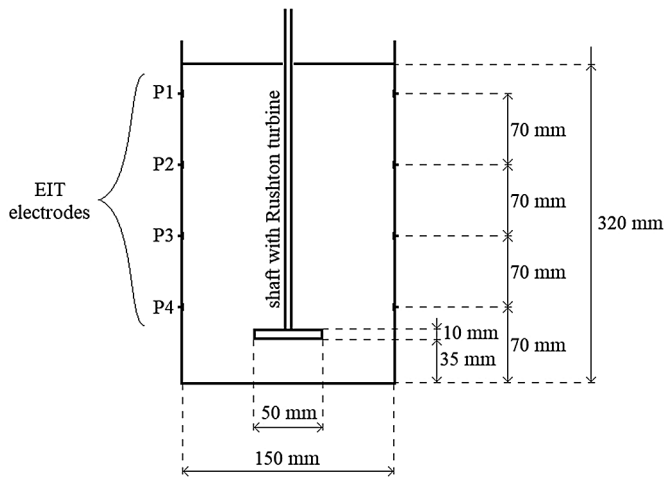

Fig. 1. Diagram of the measuring vessel with the Rushton turbine and EIT electrodes.

The materials of the shaft and turbine were chosen intentionally non-conductive, so the EIT analysis software would be able to mask their presence, thus ensuring that the measurement results would show only the two mixing phases.

3 Experiments

The following set of experiments was chosen to verify the theoretical formula (1). They also serve to prove the viability of ITS p2+ tomography system for measuring and analysing of mixing processes.

For the first experiment we prepared a 20% oil–water mixture. The EIT measurement was then started synchronously with the turbine. This provided the data from the whole mixing process from the very beginning until the measured conductivity values became constant. This does not necessarily mean a homogeneous state, but it indicates the final state of the mixture for given RPM. To ascertain the homogeneous character of the mixture we have to use the scalar conductivity maps for each measuring plane.

In Figure 2 we can see the time development of conductivity averaged over the whole measuring plane P2, P3 and P4. It is clear that the change from the initial conductivity value changes first in the topmost measuring plane P2 as a reaction to the start of the mixing process. The lowering of conductivity serves as an indication of the oil reaching the given measuring plane. As the oil vortex reaches deeper into the measuring vessel the lower measuring planes also start to notice its presence as a change in conductivity distribution.

The overshoot in each data set (curve) is caused by the complex dynamics of the measured mixing process. It can also be seen that after 40–50 s the conductivity values
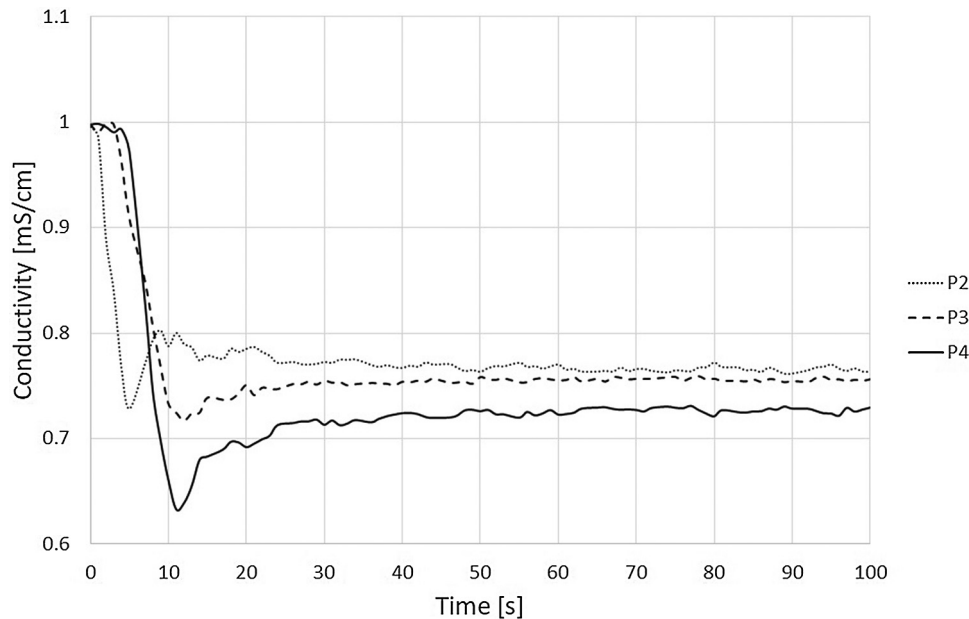

Fig. 2. Graph of time development of average conductivity in measuring planes P2, P3 and P4 during the mixing of 20% oil–water mixture at turbine speed 740 RPM.

became constant. This indicates that the state of the mixture for these mixing conditions (turbine RPMs, vessel dimensions, etc.) is final. To assure the true homogeneity of the mixture we have to either use an optical method or analyse other important information we have from the EIT measurement − scalar conductivity map. This provides the conductivity distribution in each measuring plane, see Figure 3.

Since we can see the conductivity distribution is almost constant over each measuring plane with the value approximately 0.76 mS/cm, we can state that the mixture is truly homogeneous. This however does not answer the question of final concentration. Using formula (1) this concentration can be calculated and results can be seen in Figure 4. It shows the time development of concentration in measuring planes P2, P3 and P4.

The graph in Figure 4 shows the same characteristics described in detail on graph in Figure 2. However, the additional information contained in the graph of concentration time development is the actual final value of concentration of the homogeneous mixture. In all three measuring planes the oil concentration reaches approximately the same value of 20%, which was the known starting value.

The same measurements were repeated for mixtures of initial oil concentrations of 15% and 10% and the results can be seen on graphs in Figures 5 and 6.

It is redundant at this point to show conductivity graphs again, because we have already shown that the graphs of conductivities and concentrations provide the same information. The conductivity data was simply put into formula (1) resulting in oil concentration graphs. Scalar conductivity maps were used just as a verification tool to ascertain the homogeneity in each of the measuring planes.

To show the importance of initial conditions when using the EIT in combination with formula (1), the experiment with the same oil concentration (10%) was repeated with much lower turbine speed (275 RPM) − see Figure 7.

From the results it is clear that the only plane, which registered any change, is the topmost measuring plane P2. Also, the calculated oil concentration value is approximately 3% in contrast with the real oil concentration of 10%. This is caused by the low mixing speed, which ends up creating only the oil vortex inside water (reaching to the measuring plane P2) and is not enough to break up the oil
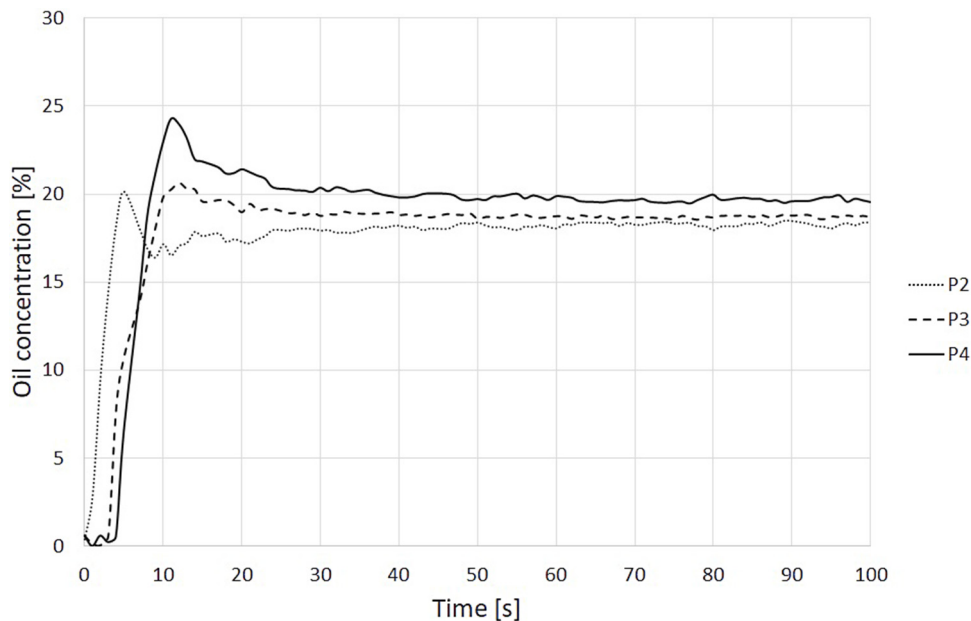

Fig. 3. Scalar conductivity map for measuring planes P2, P3 and P4 after 90 s of mixing of 20% oil–water mixture at turbine speed 740 RPM.

Fig. 4. Graph of time development of oil concentration value calculated using formula (1) in measuring planes P2, P3 and P4 during the mixing of 20% oil–water mixture at turbine speed 740 RPM.
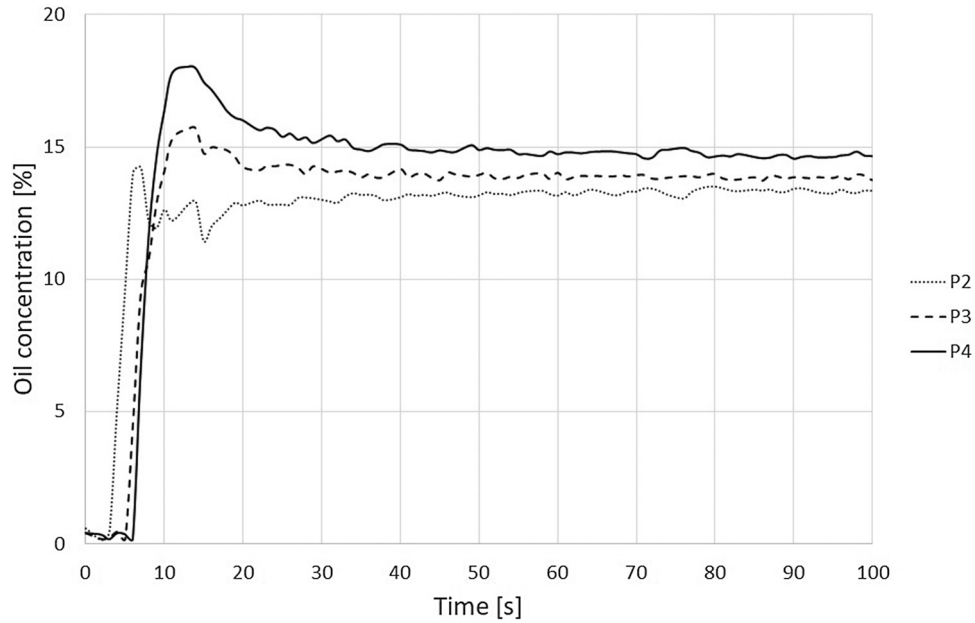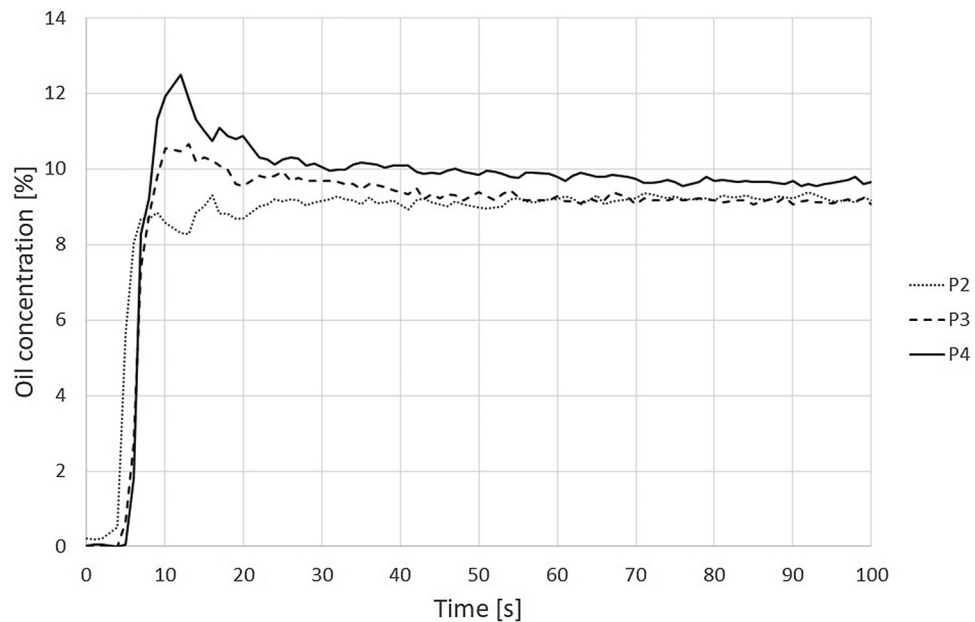
Fig. 5. Graph of time development of oil concentration value calculated using formula (1) in measuring planes P2, P3 and P4 during the mixing of 15% oil–water mixture at turbine speed 740 RPM.

Fig. 6. Graph of time development of oil concentration value calculated using formula (1) in measuring planes P2, P3 and P4 during the mixing of 10% oil–water mixture at turbine speed 740 RPM.

mass into microscopic droplets and mixing them with water, as happened in the three previous experiments. This state can be seen in scalar conductivity map, see Figure 8.

4 Conclusion

In this paper it has been shown that formula (1) in combination with EIT is a viable tool for measuring mixing processes. This has been proven on a series of experiments

measuring mixing process of oil–water mixture of various oil concentrations. It was shown that it is also viable as a tool for ascertaining the homogeneity of the final mixture. This has to be done by combining the results from time development of conductivity, which give us the moment, when the mixture is in its final state (for given conditions) and the information contained in the scalar conductivity maps, which assures homogeneous distribution of conductivity over the whole measured plane. By comparing the values measured in each of the measuring planes we can say
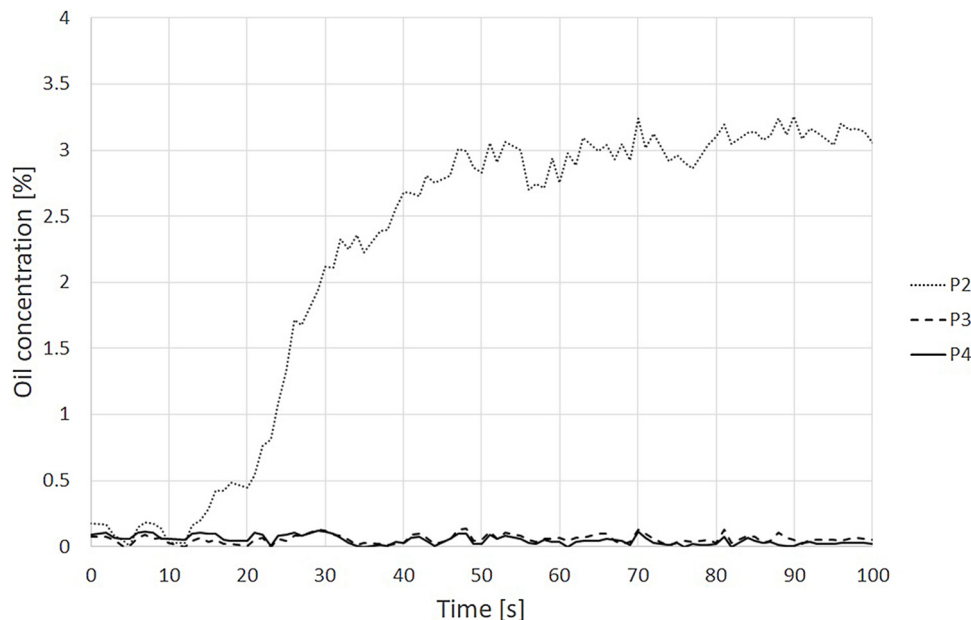
Fig. 7. Graph of time development of oil concentration value calculated using formula (1) in measuring planes P2, P3 and P4 during the mixing of 10% oil–water mixture at turbine speed 275 RPM.
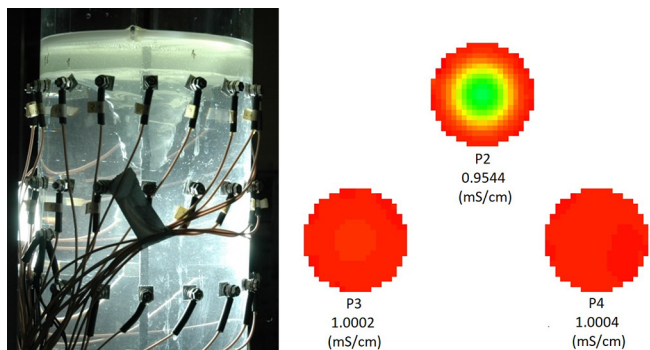

Fig. 8. Photo of oil vortex and a scalar conductivity map for measuring planes P2, P3 and P4 after 90 s of mixing of 10% oil–water mixture at turbine speed 275 RPM.

if the mixture is homogeneous in the whole volume.

The authors have also shown the possibility of applying the formula (1) in situations, where it should not have been used, since the conditions do not agree with those, for which it was derived (homogeneous mixture). The information this experiment provided are not invalidated, but a greater emphasis has to be put on combining all the information provided by the EIT (conductivity time development and scalar conductivity map).

Research of observing the mixing processes using EIT still continues on the Technical university of Liberec in Czech Republic.

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