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Capillary bundle model for gravitational flow of emulsion through granular media and experimental validation

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HIGHLIGHTS

- The model of the gravitational flow of emulsion through granular bed was developed.
- Dimensions of the bed, grain size distribution, properties of media were considered.
- Unsteady character of flow were taken into account.
- Emulsion concentration changes and retaining of droplets in the bed was predicted.
- The carried out experiments confirmed the applicability of the numerical model.

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ABSTRACT

Emulsion flow in porous systems is different from the flow of the individual phases, because there are different mechanisms that must be taken into account when modeling the movement of such liquids. In the literature, there are no mathematical models which take into account phenomena characterizing such flows. The development of such dependence would allow for substantial improvements on the assessment of contamination and facilitate the selection of appropriate methods of soil and groundwater remediation.

In this paper a numerical model, describing the process of gravitational flow of the emulsion through the porous structures, has been developed. Using this model, it was possible to predict the flow rate of fluid through the bed, and changes in the emulsion structure. This model was based on the concept of capillary bundles and assumed conversion of granular deposit into a network of capillaries. The calculation results obtained using the proposed model were compared with the results of own experimental works and high accordance was achieved.

1. Introduction

The progressive industrialization and development of the automotive and crude oil processing industry led to an increased demand for oil products as a source of an energy and a base for a production of chemical components. These substances may enter into the ground and water environment under gravitational forces, as a result of various leaks and disasters, which poses a serious threat from highly toxic and mutagenic character of these compounds. They have the ability to penetrate into all living organisms inhabiting the affected area, causing irreversible changes (Yang et al., 2010, 2013). Furthermore, the presence of oil products in the structure of the soil leads to its significant degradation, which contributes to reducing crop production. The oil contamination can cause far-reaching consequences and lead to the poisoning of a much larger ecosystem. Thus it is important to forecast properly the speed at which contaminants move through the granular layer of soil, under gravity, and when and at what concentration they reach the groundwater. Quick adoption of the appropriate steps and selecting suitable remediation methods will prevent the further spread of contamination, and will also significantly reduce any costs related to this (Rinaudo and Aulong, 2014). Therefore, the knowledge of the migration of oil derivatives inside the porous ground structures is of major importance, as it can contribute both to estimate the contamination, as well as being useful in operations related to the removal of such contaminants from the soil and groundwater (Parker et al., 2012; Zhang et al., 2014; Piscopo et al., 2015).

Oily components mix in the porous bed with underground or falling rainy waters to form emulsified systems. During flow of

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multiphase liquid through porous medium often occurs a situation in which the individual phases are mixed to form emulsion systems. Emulsion flow in porous media is different from the independent movement of the individual phases (Dullien, 1992), and must therefore be considered separately. In this case there are different mechanisms that need to be taken into account to describe the nature of such flows and it will allow to understand and to predict the manner in which emulsion systems behave during transport in a porous medium. This knowledge will be extremely useful to obtain a comprehensive picture of multiphase flow in such media. In the literature there are many works on numerical modeling of the flow of various fluids through porous media (Willson et al., 2006; Karapanagioti et al., 2003; Ataie-Ashtiani et al., 2003), but they do not refer to the flow of the emulsions.

Assumption of emulsion homogeneity is essential issue during description of the flow process of oil in water (O/W) emulsions in the porous medium. If the emulsion droplets are very small compared to the size of the flow channels it can be assumed that the fluid is continuous medium and existence of emulsion droplets has no effect on the flow (Vidrine et al., 2000). However, in most practical cases, the sizes of the emulsion droplets are not much smaller than the pore sizes, or even larger than them, which means that their presence in the bed cannot be ignored. In this case, there is a need to consider, how the various properties of the emulsion affect the flow through a porous medium (Heinemann, 2005).

During the gravitational flows of emulsion through the porous medium reduction of the relative permeability occurs. In order for the deposit pores to be effectively blocked by the internal phase drops, their size should be the same or smaller than the droplets size. The phenomenon of emulsion droplets blocking the flow channels is called the "straining" mechanism (Dullien, 1992). Researchers (Vidrine et al., 2000; Allan et al., 2006) have found that permeability reduction is mainly due to such a phenomenon. However, they observed that the droplets with diameters smaller than the pore size are also captured in the gaps or pockets in the bed (Soo and Radke, 1984; Cobos, et al., 2009). Authors concluded also that the reduction of permeability can be due to the effect of a different mechanism, called "interception" (Dullien, 1992; Török et al., 2006). This mechanism assumes that the emulsion droplets can be trapped in a porous medium due to the attachment to the pore walls under the action of van der Waals forces and hydrodynamic forces. It should be noted, however, that this mechanism has only a small impact on the overall reduction of permeability (Li and Gu, 2005).

The behavior of the emulsified systems during flow in the porous bed is dependent upon various properties of emulsion and porous medium. Emulsion properties meaningful for the flow are: concentration of the inner phase, average size of emulsion oil droplets and their size distribution, viscosities of internal and external phases and tendency to undergo coalescence, which is emulsion stability (Cortis and Ghezzehei, 2007). The contents of the internal phase of the emulsion influence the rheological properties. Emulsions O/W type having a volumetric concentration of less than 0.4 (or 40%) show Newtonian behavior during the flow through porous medium, and those with higher concentrations exhibit non-Newtonian shear-thinning (Cobos et al., 2009).

Emulsion flow in porous media is a complex process and its characterization, using mathematical models, is a great challenge. Presently, three theories describe the flow of emulsions in porous media: bulk viscosity or homogenous models, the droplet retardation model and the filtration model (Dullien, 1992). 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. Within this theory the emulsion flow in a porous medium is modeled by using well – documented concepts of Newtonian and non-Newtonian fluid flow in porous media (Heinemann, 2005).

As mentioned earlier, the rheology of emulsions depends on a number of factors, primary among which is the concentration of the inner phase. For Newtonian emulsions, the viscosity is independent of the shear rate, and the simple Darcy's law is used for description of these emulsions flow in porous media. The viscosity of emulsion, however, depends on several factors, such as concentrations of emulsion, viscosities of dispersed and continuous phases, properties of interfacial film, oil – water surface properties, droplet size, and droplet size distributions. A number of correlations can be used to determine the viscosity of Newtonian emulsions for use in Darcy's equation. The major drawback of this approach is that no permeability reduction is predicted (Dullien, 1992).

Model based on a concept of droplet retardation during passage through pore constructions in a porous medium should also be mentioned. When the emulsion droplet enters into pore construction smaller than its own diameter, it deforms and squeezes through. During this process, as a result a capillary resistance force, droplets move with lower velocity than the continuous phase and thereby cause a reduction in permeability. The mathematical formulation of this model was made by Devereux based on the classical Buckley–Leverett theory for two-phase flow in porous media and equations developed by Scheidegger (Abou-Kassem and Ali, 1995). Such an approach allows to calculate the permeability reduction but it does not account the changes of emulsion concentration.

A model based on the deep-bed filtration principles was proposed by Soo and Radke (1984), who suggested that the emulsion droplets are not only retarded, but they are also captured in pores network. There are two types of capture mechanisms: straining and interception. Capture of emulsion droplets reduces effectively pore diameter, diverts flow to large pores, and therefore effectively reduces permeability.

On the basis of this physical mechanisms, Soo and Radke (1984) proposed a model to describe the flow of dilute and stable emulsion in the porous medium. The flow redistribution phenomenon and permeability reduction are included in the model. Both low and high interfacial tensions were considered. Attention should be paid to high complexity of this model. The flow is dependent on three different parameters that are interdependent of each other and their determination requires experimental studies. Therefore, despite the inclusion of interactions in this model, its complexity makes it difficult to use it to predict the flow of emulsions in porous media. The emulsion transport model described above underwent multiple modifications and was used in a variety of numerical simulations but it does not take into account changing flow conditions, such as variable driving force (Cobos et al., 2009; Abou-Kassem and Ali, 1995; Wang and Dong, 2011; Cai et al., 2012).

There is another modeling approach to the flow in porous media, which is based on the concept of capillary bundles, according to which the granular bed can be represented as a bundle of tortuous tubes in which the movement takes place. For single-phase flow this concept was described by Kozeny–Carman dependence (Wyllie and Gardner, 1958). Two-phase flow in two connected parallel capillaries was considered by Dullien (1992). Nutt (1982) has developed a model of elution of oil from bundle of capillaries with different diameters, like other authors (Dahle et al., 2005; Yang et al., 2009; Idorenyin and Shirif, 2012). The modeling works, based on the concept of capillary bundles,