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Evaluation of representative elementary volume for a vuggy carbonate rock – Part II: Two-phase flow

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ABSTRACT

Large spatial variation of petrophysical properties and heterogeneous fluid displacement behavior are often associated with vuggy carbonate rocks. Because vugular rocks are characterized by large heterogeneity at the core-sample scale, the property measurements vary significantly between samples and the assessment of oil recovery is often unreliable.

This paper focuses on variability of two-phase flow properties in a vuggy carbonate material. Drainage and waterflood experiments were performed on 12 different sample sizes, ranging from cm to m scale. The results for oil recovery show that the largest sample is above REV and reflects the average for the smaller volumes. An arithmetic average is found to be an appropriate upscaling scheme for oil recovery, thus the studied vuggy material can be regarded as heterogeneously homogeneous. Based on 2D gamma-ray saturation maps semivariogram functions were calculated. Both initial and residual saturations were spatially correlated.

For two larger samples, the drainage and waterflood displacements were performed and monitored by x-ray providing high-resolution images. The results were used to measure the dispersion of the displacement front. The front behavior patterns and dispersion lengths were found to be similar for drainage and waterflood processes within the same sample.

The effect of heterogeneities on the drainage capillary pressure curve and on spontaneous imbibition has been investigated. Nuclear Magnetic Resonance (NMR) 1D-saturation monitoring performed on a sample after a centrifuge test was used to investigate the air–water drainage capillary pressure curve. The obtained curve indicated variations along the sample. Imaging of the displacement front for spontaneous imbibition was performed to investigate impact of heterogeneities on the process.

1. Introduction

Vuggy carbonates often exhibit multiscale heterogeneities that make the understanding of fluid flow and recovery a challenge. Reported studies show that classical theories of fluid flow are often not applicable for vugular carbonates (Archer and Wong, 1973; Dabbouk et al., 2002; deZabala and Kamath, 1995; Zhang et al., 2005). Connected vug channels or high vug density regions lead to preferential flow paths which cause heterogeneous fluid flow behavior.

The effect of sample support on drainage and waterflood in heterogeneous material is of great importance for the petroleum industry. To ensure correct multi-phase flow properties for application in reservoir simulators the laboratory measurements must be performed at a representative scale. An appropriate sample support for heterogeneous material is considered to be the volume for which a macroscopic property (e.g., permeability) is relatively insensitive to small changes in volume or location (Corbett et al., 1999). Bear (1988) introduced the concept of Representative Elementary Volume (REV), which denotes a volume of the property field that is large enough to capture a representative amount of the heterogeneity. When the sample volume is small compared to the correlation length of heterogeneity, a measured property will vary with small changes in the sample volume (Nordahl and Ringrose, 2008). At REV, the spatial property variations are minimized and a representative value can be averaged in the measurement. For a volume above the REV the porous medium can be treated as a continuum and classical concepts can be applied to describe the fluid flow. Further, the REV may differ for the various petrophysical properties and the proper sampling scale depends also on which property is measured.

The REV concept is essential to the effective medium approximation and provides the fundamental support volume for measurement, simulation and averaging. When the scale of measurement does not encompass the REV, the resulting measurements fluctuate with position. In geostatistical terminology, this indicates a problem

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of insufficient sample size (Corbett et al., 1999). Therefore, laboratory core experiments must be performed on representative samples in order to be able to extract meaningful two-phase properties from experimental data (Dauba et al., 1998). Obtaining information about the petrophysical properties through experimental analysis at various scales has therefore been a part of the two-phase displacement REV investigation for the vuggy carbonate material reported in this study.

The work presented here is the second part of a REV investigation of single- and two-phase properties for a vuggy carbonate material. First part of this study (Vik et al., in press) looked into single-phase properties. Porosity, effective permeability and dispersivity as functions of rock sample size were investigated. The measured properties showed decrease in variability with increasing sample size indicating a transition from a variable property regime into the REV. The average porosity and permeability values for small samples were in agreement with values for the larger rock samples. The material was characterized as heterogeneously homogeneous at the measured scales ($C_v < 0.5$) suggesting an arithmetic average as an appropriate upscaling scheme for porosity and permeability. The variability for porosity was the lowest for the properties investigated while the dispersivity showed largest variation. Both permeability and the value of Peclet number were stable for sample lengths > 30 cm.

In this paper, we investigate the variability of two-phase flow in vuggy carbonate material. The experimental part of this work is divided into three parts. In the first, the variation of drainage and waterflood production data is presented. The variation of oil recovery with sample size and analysis of correlation for residual saturations is also included. In the second, the effect of heterogeneities on the displacement fronts is studied. In the third, variation of the capillary pressure curves is analyzed in terms of the traditional Hassler–Brunner interpretation and the 1D NMR saturation profile centrifuge method. In addition, the influence of heterogeneity for the spontaneous imbibition process is investigated.

2. Previous work REV

Representative Elementary Volume laboratory studies reported in the literature take up mainly the variation of single-phase properties such as porosity and permeability. There is still lack of fundamental studies on the two-phase flow across different scales. Although, core analysis studies on carbonate material have revealed large variations in oil recovery, the effect of sample size on multiphase flow in carbonate rock has not been reported in the literature. Most likely, the highly variable oil recovery can partly be attributed to sampling below a representative scale of heterogeneities present in the tested carbonate samples.

There are few references in the literature to multiphase flow studies in vuggy carbonates. This is likely due to difficulty in obtaining representative samples and the experimental uncertainties (deZabala and Kamath, 1995). When the vugs are well connected, permeability contrasts violate the classical theories of fluid flow. Early water breakthrough and anomalously shaped relative permeability curves have been reported in several studies (Archer and Wong, 1973; Corey and Rathjens, 1956; Ehrlich, 1971).

deZabala and Kamath (1995) characterized the porosity, permeability and waterflood displacement behavior in core material from two different vugular carbonate settings. The porosity semivariogram along the flow direction for both samples had a correlation length of 10 mm. CT scanning after drainage showed that most of the vugs were oil filled while the matrix porosity remained water saturated. During unsteady waterflood an early breakthrough occurred and a diffusive front was observed. They concluded that the heterogeneities were above the sample scale and the conventional core analysis methods failed to explain the experiment data. The concept of laboratory relative permeability and its use in large-scale simulators was questioned.

Dabbouk et al. (2002) conducted waterflood through a vuggy carbonate whole core sample at full reservoir conditions. X-ray computed tomography (CT) was applied to obtain porosity map and to monitor saturation profiles. For both miscible displacement and waterflood, fingering ahead of the front occurred in the high permeable vuggy and matrix regions. However, the front was stabilized again when it moved into less heterogeneous region. The authors concluded that the fingering of the displacement fronts was caused by the connectivity of the vugs that increased the permeability.

Moctezuma-Berthier et al. (2002) determined water–oil relative permeabilities in two vuggy carbonate rocks analyzing them in terms of vug connectivity. Early breakthrough was associated with water flow through a main high permeability system existing of connected/percolating vugs. Piston like displacement with most of the oil produced at water breakthrough was associated with the second sample where the vugs were not well connected and only accessible through the matrix. The relative permeability curves for the connected-vugs sample had discontinuities reflecting the heterogeneous nature of the displacement.

Moctezuma-Berthier et al. (2004) studied connectivity, capillary pressure and relative permeability in vugular media using the artificial generated dual porosity models. The capillary pressure calculations were found to be strongly influenced by the presence of percolating vugs. For the non-wetting phase, some threshold pressure was necessary to enter the percolating vugs. Above this pressure most of the vugular porosity was accessible. The capillary curve had a secondary threshold pressure that was associated with the matrix porosity. The capillary pressure curve for a non-percolating vugular system was influenced by the matrix properties as they control the access to the isolated vugs.

Siddiqui et al. (2000) performed CT monitoring of saturations at static conditions and during fluid displacements. The measurements provided information about the variability along a composite core plug taken from a carbonate reservoir. The coefficient of variation, C_v, calculated for saturations at 100% water, residual water and residual oil along the sample, indicated highest variation for the residual water saturation. The lowest variation was found for the porosity. All values of the C_v were in the 0.1–0.2 range. It was concluded that the C_v for the residual saturations appears to be a result of local heterogeneities and the types of fluids present in the sample.

Numerous studies of property variation with sample support in porous media have been conducted using both real rocks (Henriette et al., 1989; Tidwell and Wilson, 1997; Corbett et al., 1999; Tidwell and Wilson, 1999, 2000; McKinley et al., 2004) and numerical rock models (Jackson et al., 2003, 2005; Nordahl and Ringrose, 2008). Field and laboratory studies involve measurement of a property at different scales and sample volumes. The reported studies vary in terms of investigated property and rock type, the measurement techniques, and the sample sizes investigated. However, investigation of the oil recovery variation with sample size is lacking in the literature.

For the interested reader a more extensive review of previous work on REV is given in the first part of this study (Vik et al., in press).

3. Experimental work and results

3.1. Sampling strategy

The work presented here is the second part of the investigation of single- and two phase property variation for the vuggy