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A novel protocol for estimation of minimum miscibility pressure from slimtube experiments

K. Mogensen

Eni S.p.A., Via Emilia 1, 20097 San Donato Milanese, Italy

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ABSTRACT

A slimtube experiment is an industry-accepted method for estimating minimum miscible pressure (MMP) of a reservoir fluid with respect to a particular injection gas. The displacement efficiency of the gas is evaluated at immiscible as well as at multi-contact miscible pressure conditions. Although experimental protocols and operational aspects vary among investigators, the MMP is often inferred from the bend of the oil recovery curve versus pressure. From an equation of state (EOS) calibration point of view, the experiments conducted below and near the MMP are more valuable than the miscible runs. Since the number of slimtube runs is often limited to 4–6, this means that the mass transfer in the near-miscible may not be adequately captured and the uncertainty in the MMP estimation can be significant.

In this work, a modification to the standard slimtube experimental protocol is presented to overcome the inconsistency in the interpretation of the MMP and to provide more information about the mass transfer in the near-miscible region close to the MMP. The new protocol takes advantage of the fact that chromatographic separation occurs during two-phase flow at pressures below the MMP and it is shown that the C1/C3 ratio in the produced gas is a very useful parameter to track as a function of pressure. If all slimtube runs are conducted at pressures below MMP, an efficient iterative procedure can be implemented to select a limited number of pressure steps leading towards the MMP.

The proposed method requires compositional analysis of the produced gas, which adds to the cost of a study but may require fewer slimtube runs while yielding a more accurate estimation of the MMP.

1. Introduction

Gas injection is a well-established enhanced oil recovery (EOR) method where mass exchange occurs between the injection gas and the reservoir fluid, which at a certain threshold pressure leads to development of miscibility between gas and oil. This threshold pressure is an important operational parameter and is denoted the minimum miscibility pressure (MMP). It is generally agreed that the recovery factor of a gas flood is improved if the injection pressure exceeds MMP. In most cases, miscibility is achieved after multiple contacts, which leaves a small, but non-zero microscopic residual oil saturation.

The slimtube experiment presumably dates back to the early 1950s, but the originator of the method is not known to the author of this paper. Randall and Bennion (1987) provide a good description of the experimental details and considerations. The slimtube itself is a 40–60 ft long column pre-packed with glass beads or sand grains of known particle size, with a Darcy-range permeability and hence low pressure drop across the column. It is contained within a 0.25-in. diameter coiled tubing of stainless steel to limit complicating flow-related phenomena like viscous fingering, gravity override, and transverse dispersion. The slimtube is cleaned and saturated with live oil before injecting gas at specified pressure and temperature. A windowed PVT cell and camera can be added to the setup to visually observe the time at which gas breakthrough occurs. A high pressure densitometer can also be added to measure the density of the effluent fluid. The exact point of gas breakthrough will be clearly observed by a significant increase in GOR, a decrease in residual liquid density, and a change in gas composition/gas gravity.

For each pressure run the oil recovery, among other variables, is recorded versus pore volumes injected. Typically, 4–6 runs are conducted and the oil recovery after 1.2 PV is plotted versus pressure, as shown in Fig. 1. The 1.2 PV is a bit arbitrary but is a value agreed on by most investigators. The recovery curve will often exhibit a clear bend which separates the immiscible runs from the miscible ones. The intersection of the two lines passing through the immiscible and the miscible points, respectively, yields a pressure which can then be interpreted as the MMP.

Although many elements of the experimental procedure have been standardized, there is still variation in both design and interpretation of the MMP between various investigators;

E-mail addresses: kristian.mogensen@eni.com, kristianogtrine@gmail.com

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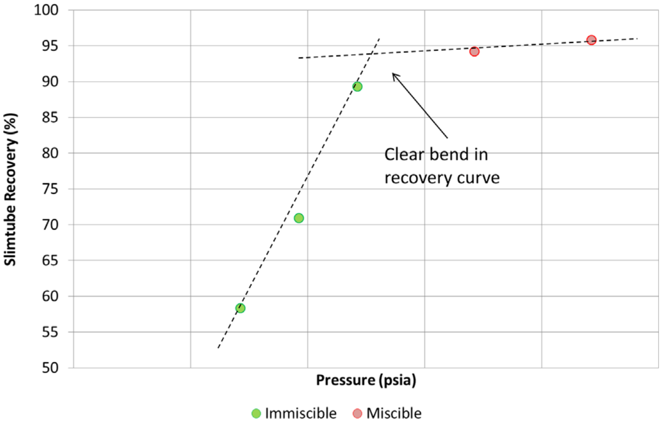

Fig. 1. Example of slimtube recovery measured versus pressure with clear bend.

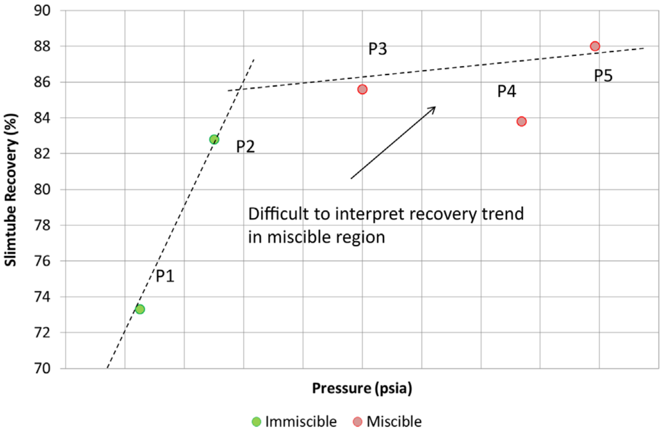

Fig. 2. Example of slimtube recovery measured versus pressure with less clear bend.

Elsharkawy et al. (1992) made a comprehensive review of the variations in design and operational procedures. Identification of the bend is just one of several ways to infer the MMP. Some authors choose to define the MMP as the pressure at which the recovery attains some cut-off value such as 90% or 95%. Either value can be justified but is nevertheless somewhat arbitrary. Zick (1986) tracked the change of oil density versus time, a procedure which is now offered by many commercial laboratories. Complicating factors may arise if the recovery curve does not attain the required cut-off value or if the transition between immiscible and miscible displacement is gradual rather than sharp; this may happen if physical dispersion is significant or if the crude oil splits into two liquid phases and a gas phase (VLLE phase behavior) in which case the injection gas may develop miscibility with one of the liquid phases, leading to LLE (Lindeloff et al., 2013). Fig. 2 shows an example of a system where it is not obvious from the recovery curve alone where the MMP lies even though the curve slope is clearly changing.

These complicating factors are well-recognized in the literature and prompted Amao et al. (2012) to suggest the use of the instantaneous recovery rate as a metric for defining whether miscibility has been reached. Despite many efforts, a universal method to accurately estimate the MMP from any slimtube test dos not seem to be available.

In addition to the slimtube experiment, a number of other methods have been proposed to estimate the conditions at which miscibility occurs, such as flooding of scaled laboratory models (Pozzi and Blackwell, 1963), gas injection into long cores (Rathmell and Stalkup, 1971), vanishing interfacial tension (VIT) by Rao (1997) and the rising-bubble apparatus (RBA) by Christiansen et al. (1987). Limitations to the VIT and RBA methods have been pointed out previously by Zhou and Orr (1998), Orr and Jessen (2007) and by Jessen and Orr (2008) who expressed concern that the two methods did not capture the combined condensing/vaporizing mass transfer mechanism. Even though the slimtube experiment requires a long time to perform and is far more costly than the RBA and the VIT methods, it has gained industry-wide acceptance as a reliable method for estimating the MMP because it mimics the actual displacement process, which means that the analytical solutions for 1D displacement developed over the past two decades (Johns et al., 1993) can be used to interpret the results. Jaubert et al. (2002) questioned the necessity of slimtube measurements for injection gases containing a mixture of hydrocarbon components and concluded that swelling tests and multi-contact tests were sufficient to constrain the Equation of State (EOS).

The purpose of this paper is not to rank one method over the other, but to suggest improvements to the slimtube experimental protocol to improve both the MMP estimation and provide more mass transfer information for EOS calibration in the near-critical region while keeping the required slimtube runs to a minimum. Such mass transfer data may subsequently be matched with a mixing-cell model (Ahmadi and Johns, 2011) or with a tie-line based approach (Khorsandi and Johns, 2015).

2. The proposed technique

As mentioned earlier, one of the issues with the current technique for estimating MMP is the choice of metrics, whether it is a change of the recovery curve slope, a particular cut-off recovery or something similar. In this paper, a new metric is introduced in an attempt to overcome this issue. The proposed technique takes advantage of the well-known effect of chromatographic separation, which is prominent during immiscible flow. Due to mass transfer between the injection gas and the reservoir fluid, a methane bank forms ahead of the connected gas front, regardless of the choice of injection gas. Methane banking has been verified experimentally (Sibbald et al., 1990), theoretically (Orr et al., 1993), and at the field-scale (Panda et al., 2011).

2.1. *Experimental evidence*

During production of the methane bank, the GOR may stabilize, and can even drop before increasing sharply as the main gas front breaks through. Fig. 3 shows an example where the GOR is recorded versus PV injected for five different pressure runs. At pressure P2, the GOR curve levels off, which is an indication that

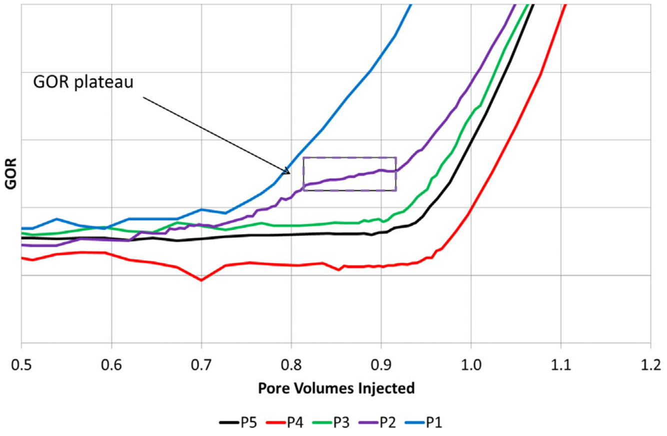

Fig. 3. GOR versus pore volumes injected. A GOR plateau is observed for P2.

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