



Surface energy and wetting behavior of reservoir rocks



Naveed Arsalan^a, Jan J. Buiting^b, Quoc P. Nguyen^{a,*}

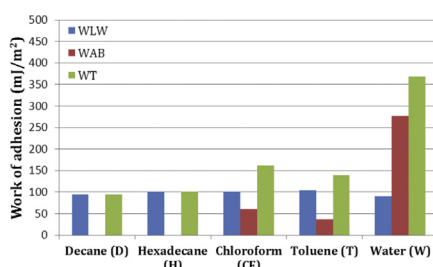
^a Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, 1 University Station, C0300, Austin, TX 78712-1061, USA

^b Saudi Aramco, PO Box 11391, Dhahran 31311, Saudi Arabia

HIGHLIGHTS

- Investigated the surface energy of a reservoir rock using IGC.
- Examined the effect of moisture and temperature on their surface energetics.
- The surface interaction forces at the rock–fluid interface were quantified.
- Proposed a new approach for measuring the wettability index of a rock–fluid system.
- Wettability index scales from –1 (strongly oil-wet) to +1 (strongly water-wet).

GRAPHICAL ABSTRACT



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ABSTRACT

An accurate description of the surface chemistry of the reservoir rock–fluid system is essential to understand the attractive forces between the various phases (crudes, brines and the rock surface). These physico-chemical interactions determine the fundamental nature of the reservoir wettability and the wetting behavior of fluids on the reservoir rock surface. Inverse gas chromatography (IGC) is used to characterize the surface chemistry of a Saudi Arabian reservoir rock (henceforth referred to as ‘reservoir rock’) at different moisture coverage and temperatures. This information combined with the surface tension of the interacting reservoir fluids is utilized to develop a new method for quantifying wettability in terms of a wettability index. This index is based on the relative magnitude of the work of adhesion between the rock surface and the competing oleic/aqueous phase.

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1. Introduction

Since the early days of the petroleum industry, attempts have been made to understand the spreading behavior of reservoir fluids on the rock surface and use this knowledge to improve the oil

recovery from the reservoir. This led to the concept of wettability, which describes the tendency of a fluid to spread on a rock surface in the presence of another immiscible fluid. Therefore the reservoirs were usually classified as oil-wet, water-wet or intermediate-wet based on the affinity of the rock surface toward oil or water phase. Wettability assumes significance since it determines fluid distribution in the reservoir and the capillary forces holding them and thus affecting reservoir production, waterflood recovery and the performance of enhanced oil recovery (EOR) processes [1–7]. However

* Corresponding author. Tel.: +1 0115124711204; fax: +1 0115124719605.
 E-mail address: quoc.p.nguyen@mail.utexas.edu (Q.P. Nguyen).

attempts to describe or generalize the concept of wettability have largely remained unsuccessful [8].

Currently wettability is estimated in the laboratory by restoring the in situ wettability of core samples by aging them at elevated temperatures for long periods of time. There are two standard analyses adopted by the industry for wettability estimation: Amott test and USBM method [2]. Both analyses are rather time consuming and expensive. Thus the ensuing paper is an attempt to develop a fast and reliable alternative technique for wettability estimation utilizing our knowledge of interfacial interactions between the various phases.

It has been commonly agreed, that the two major factors affecting wettability are surface morphology and the intermolecular surface forces between the 3 phases (rock–oil–brine) [1,8,9]. Regardless of the morphology, the wettability of the system is determined by the relative magnitude of the forces of interaction between the two liquid phases and the rock surface [8,9]. These fundamental interactions (or surface energies) are usually classified into two classes: Lifshitz–van der Waals interactions (non-polar) and acid–base interactions (polar) [10].

Surface free energy (also called surface energy) is an important thermodynamic characteristic of a solid and is defined as the energy required to form (or increase) the surface by a unit surface under reversible conditions. There are two indirect methods commonly used to assess the surface energy of solids: vapor adsorption measurements using probe vapors and wetting (contact angle) measurements using probe liquids. Contact angle measurement is generally limited in its application to low energy smooth surfaces where finite contact angles can be formed using appropriate probe liquids. In case of irregular particulate materials, wicking measurements are used to infer contact angles. Since many high energy surfaces of interest such as minerals are wet by most liquids, the ‘two-liquid’ approach is used to obtain finite contact angles for the solid–liquid interface. In contrast the vapor adsorption measurements using inverse gas chromatography (IGC) at infinite dilution involves studying the individual interaction of the probe molecules with the surface sites. This approach enables an accurate description of the surface at different temperatures and other physical conditions by taking into account surface heterogeneity and the interaction forces responsible for the adsorption. A brief review of the technique and application of IGC has been can be found in the literature [11,12].

Thus the focus of our study is to quantify and understand the nature of these interactions by using inverse gas chromatography and use this knowledge to determine the wettability of the rock surface. The authors have successfully demonstrated the technique to quantify these fundamental interactions by characterizing the surface energetics of some sandstone and carbonate rocks using inverse gas chromatography [13,14]. Here we extend this technique to a carbonate rock obtained from a Saudi Arabian reservoir. This information is used it to demonstrate a new approach to quantify the wettability of a reservoir rock by relating it to a wettability index. The method for calculating the wettability index of the reservoir rock is based on measuring the difference between the work of adhesion between the two liquid phases and the rock surface using the van Oss–Chaudhury–Good approach. The ensuing paper will illustrate the mechanics of this process right from performing the surface energetic analysis of the reservoir rocks to calculating their respective wettability indices.

2. Theory

The principle and technique behind IGC measurements has been extensively discussed in the literature [13,14]. In this section, we will describe the process for determining the wettability index for

a reservoir rock, in contact with a brine phase and an oil phase. This step utilizes the knowledge of the surface energies of the three interacting phases (rock, oil and brine) in terms of their Lifshitz–van der Waals components and polar components.

The work of adhesion (W^A) is a thermodynamic property and is defined as the work required for separating two different surfaces (denoted by 1 and 2) from each other. In other words, the work of adhesion between any two surfaces determines how strongly the surfaces are attracted to one another.

$$W^A = \gamma_1 + \gamma_2 - \gamma_{12} \quad (1)$$

where γ_{12} is the interfacial tension between the two surfaces 1 and 2, γ_1 is the surface tension of the surface 1 and γ_2 is the surface tension of the surface 2.

Building on the work of Good and Girifalco [15] and Fowkes [10], the van–Oss–Chaudhury–Good model [16,17] expresses the work of adhesion (W_{12}^A) between two surfaces (1 and 2) as follows:

$$W_{12}^A = 2\sqrt{\gamma_1^{LW}\gamma_2^{LW}} + 2\sqrt{\gamma_1^-\gamma_2^+} + 2\sqrt{\gamma_1^+\gamma_2^-} \quad (2)$$

where γ_1^{LW} is the Lifshitz–van der Waals component of surface energy of surface 1, γ_1^- is the basic component of surface energy of surface 1 and γ_1^+ is the acidic component of surface energy of surface 1. Similarly γ_2^{LW} , γ_2^- and γ_2^+ represent the Lifshitz–van der Waals component, basic component and acidic component of surface energy of surface 2 respectively.

Knowing the surface energy and its components for all the three phases: rock (S), brine (W) and oil (O), we can calculate the work of adhesion (W_{WS}^A) between brine and the rock surface using Eq. (2) as follows:

$$W_{WS}^A = 2\sqrt{\gamma_W^{LW}\gamma_S^{LW}} + 2\sqrt{\gamma_W^-\gamma_S^+} + 2\sqrt{\gamma_W^+\gamma_S^-} \quad (3)$$

where γ_S^{LW} is the Lifshitz–van der Waals component of surface energy of reservoir rock surface, γ_S^- is the basic component of surface energy of reservoir rock surface and γ_S^+ is the acidic component of surface energy of reservoir rock surface. Similarly γ_W^{LW} , γ_W^- and γ_W^+ represent the Lifshitz–van der Waals component, basic component and acidic component of surface tension of brine respectively.

Similarly the work of adhesion (W_{OS}^A) between the oil and the rock surface can be calculated as follows:

$$W_{OS}^A = 2\sqrt{\gamma_O^{LW}\gamma_S^{LW}} + 2\sqrt{\gamma_O^-\gamma_S^+} + 2\sqrt{\gamma_O^+\gamma_S^-} \quad (4)$$

where γ_O^{LW} , γ_O^- and γ_O^+ represent the Lifshitz–van der Waals component, basic component and acidic component of surface tension of oil respectively.

Based on our hypothesis stated at the beginning, the wettability of the system is determined by the relative magnitude of the forces of interaction between the two liquid phases and the rock surface. The relative wetting property (Δ_W) is defined as follows:

$$\Delta_W = W_{WS}^A - W_{OS}^A \quad (5)$$

If Δ_W is positive, this implies water preferentially wets the rock surface, whereas if Δ_W is negative, this implies oil preferentially wets the rock surface. A value of zero for Δ_W indicates that there is no preferential interaction between the rock surface to either the oil phase or the brine phase. Thus the rock surface behaves like an intermediate wet surface if $\Delta_W = 0$.

Based on this approach, we propose a wettability index (WI) by normalizing the relative wetting property (Δ_W) as follows:

$$WI = \frac{W_{WS}^A - W_{OS}^A}{W_{WS}^A + W_{OS}^A} \quad (6)$$

Thus for a water-wet rock, the value of WI scales from 0 (intermediate wet) to 1 (strongly water-wet), whereas for an oil-wet

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