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Determination of the most significant variables affecting the steady state pressure drop in selected foam flow experiments

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ABSTRACT

Foam generated with a surfactant solution and nitrogen is used for oil recovery, acid diversion and aquifer remediation. In laboratory experiments, the foam mobility is expressed in terms of the pressure drop across the porous medium and is related to many physical processes. There is lack of data that relate the pressure drop to a combination of three or more variables simultaneously. This paper investigates the steady state pressure drop for a combination of six variables, viz., permeability, surfactant concentration, pH, salinity, surfactant solution velocity and gas velocity. Fourteen pressure drop histories were measured for an Alpha Olefin Sulphonate solution before and after the injection of nitrogen gas across the unconsolidated sandpacks of two median grain sizes and across a Bentheimer consolidated core. Our data set was combined with data sets from the literature leading to 157 data points. Symbolic regression was applied to the entire data set to produce a number of analytical expressions describing the interactive effect of the variables without prior knowledge of an underlying physical process. A simple model with only one fitting parameter was selected to compare with the experimental data. The slope between the observed pressure drop and the predicted pressure drop turns out to be 0.85 ± 0.03. A sensitivity analysis of the chosen model shows that the variables affecting the predicted pressure drop, in order of importance, are permeability, salinity and surfactant solution velocity. The precision of the model parameter was determined by a bootstrap method. The pressure drop from our data set and one specific data set from the literature show significant deviation with respect to the pressure drop obtained from the regression equation. Possible reasons are that the specific data set from the literature uses mixtures of surfactants and that our data set is confined to conditions that lead to low pressure drops. The purpose of the data driven model applied to experimental data is only to improve the models based on physical processes, i.e., mechanistic models. In addition the data driven model can indicate the variable spaces for which more experiments are needed.

1. Introduction

Nitrogen foam (a mixture of nitrogen gas and surfactant with water) can reduce the mobility of a displacing mixture (dispersion) of water and gas, thereby increasing the oil recovery (Bond and Holbrook, 1958; Craig and Lummus, 1965; Holm, 1968; Farajzadeh et al., 2012). Other applications of nitrogen foam are acid diversion (Xu and Rossen, 2003) and aquifer remediation (Wang and Mulligan, 2004). The foam mobility reduction, essential for such applications of foam, is attributed to a reduction in the permeability of the porous medium to the gas (Bernard and Holm, 1964; Friedmann and Jensen, 1986) and/or to an increase of the gas viscosity (Svorstøl et al., 1996). In the laboratory, foam is generated by (1) co-injection of gas and surfactant solution in a porous medium pre-saturated with surfactant (Friedmann et al., 1991; Chou, 1991) or (2) by injection of alternate slugs of gas and surfactant solution through the core (Friedmann and Jensen, 1986; Rossen and Gauglitz, 1990). The surfactant lowers the surface tension of the solution and thereby, with the gas, creates and sustains lamellae in the porous medium. The gas trapped by the lamellae (Hirasaki and Lawson, 1985; Falls et al., 1989) and the immobile fraction of gas (Cohen et al., 1997; Tang and Kovscek, 2006; Nguyen et al., 2007; Balan et al., 2011) result into a pressure drop increase across the porous medium. Foam propagation occurs in two states: an initial unsteady state, characterized by an increase in pressure drop and later, a steady state, where the pressure drop becomes constant. The steady state pressure drop occurs when all transport processes affecting the pressure drop, viz., convection, diffusion, generation and destruction add up to zero (Ashoori et al., 2011). During the steady state, foam propagation through porous media can be described with the two-phase Darcy's law (Holm, 1968). In other words, gas is considered to travel

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through the porous medium as a separate phase and the flow rate is determined by the relative permeabilities (Buckley and Leverett, 1942). In such a steady state, the gas mobility can be expressed as a ratio of the effective permeability and the apparent viscosity, i.e., k_e/μ_a. Furthermore, the gas mobility is related to the flow rate of foam and the pressure drop observed across the core (Osterloh and Jante, 1992). The gas mobility is affected by a boundary condition where no water exits the core until $S_w = 1 - S_{gr}$ (S_{gr} is irreducible gas saturation and S_w water saturation) is the so-called capillary end effect condition (Barenblatt et al., 1989). Such condition leads to an enhanced saturation at the end of the core (Yortsos and Chang, 1990) and may cause a non-representative value of the pressure drop in the measurement during experimentation (Osoba et al., 1951). Eliminating errors due to the capillary end effect can be achieved by (1) measuring the saturation far enough away from the outflow face (Penn State Method) and (2) using high flow rates to make the error in the measured saturation negligible (Gas flow method) (Osoba et al., 1951).

The observed steady state pressure drop can be further used to calculate the foam resistance factor (Pang, 2010) or mobility reduction factor (Simjoo et al., 2013). The steady state pressure drop is affected by several variables, i.e., permeability of the porous medium, surfactant formulation/concentration, injection rates, presence of oil, gas fraction, temperature, etc. (Friedmann and Jensen, 1986; Friedmann et al., 1991; Isaacs et al., 1988; Huh and Handy, 1989; Hanssen, 1993; Bertin et al., 1999; Simjoo, 2012; Solbakken et al., 2014; Kapetas et al., 2015). Therefore, the steady state pressure drop during foam flow through porous media depends on a complex system of multiple variables. To simplify the complex system of multiple variables, most research studies focus on a base case after which they modify one or two variable(s) at a time, to study their effect on the steady state pressure drop, for example, flow rate and concentration (Fergui et al., 1998) or gas velocity and surfactant solution velocity (Martinez, 1998; Martinez et al., 2001). In addition, such studies use a physical base to construct a model for explaining the steady state, i.e., a mechanistic approach (Kovscek et al., 1997; Rossen et al., 1999). In this respect, Khatib et al. (1988) explained his experiments with a model based on the capillary pressure (pressure difference between gas and surfactant solution phase), which itself depends on the surfactant formulation, the permeability and the gas velocity. However, some other researchers (de Vries and Wit, 1990; Persoff et al., 1991) observed that the steady state pressure drop is a function of the permeability and surfactant velocity, dominated by bubble trapping and mobilization. To explain both contrasting results, Osterloh and Jante (1992) and further Rossen et al. (1995) and Rossen and Wang (1999) proposed two regions in the pressure drop contour plot vs. gas and surfactant solution velocity for a given surfactant formulation and permeability. The region in the pressure drop contour plot, where the pressure drop is nearly independent of the gas velocity, is called the high quality region; the term "quality" is defined as the ratio of gas volume and total, i.e., gas plus surfactant solution volume. The region in the pressure drop contour plot, where the pressure drop is nearly independent of surfactant solution velocity, is called the low quality region. Martinez (1998) and Martinez et al. (2001) introduced the concept of critical foam quality to distinguish between the two regions. In addition, there are other models based on the concepts of local equilibrium (foam texture is an algebraic function of local conditions (Rossen et al., 1999; Ma et al., 2014; Rossen and Boeije, 2015; Boeije and Rossen, 2015) and foam bubble population (Kovscek et al., 1997; Falls et al., 1988; Bertin et al., 1998; Ettinger and Radke, 1992; Kam and Rossen, 2003; Zitha et al., 2006). The difference between local steady state and bubble population models is well described in Ma et al. (2015). In combination with the mechanistic approaches discussed above, Zhao et al. (2012) studied the effect of salinity and surfactant formulation on the steady state pressure drop by orthogonal experiments (Montegomery, 2007) to increase the oil displacement efficiency. Similarly, Wang et al. (2012) studied the quantitative effect of surfactant concentration, foam quality, temperature and oil saturation on the steady state pressure drop by design and analysis of experiment (DAOE) methodology (Montegomery, 2007). The ensuing polynomial expression consists of the product of the individual effects of interacting variables, e.g., foam quality and surfactant concentration, along with a fitting parameter for each combination of the variables to accommodate the interactive effect. Among the variables, the effect of pH on the liquid film for the applications in porous media has been well considered (Nguyen et al., 2002; Farajzadeh et al., 2011), however, not in combination with other variables.

The modeling approaches mentioned above pose practical difficulties for reasons of the required large number of experiments and the large number of fitting parameters. For example, the high and low quality regions for constant permeability and constant surfactant concentration are found by doing experiments for a range of combination of gas and surfactant solution velocities (Ma et al., 2013; Boeije and Rossen, 2013). Such models require physical understanding and are difficult to derive for such a complex system as foam flow. In addition, there is a lack of experimental data that combine orthogonal or even box design (Mason et al., 2003) for variables such as permeability, surfactant concentration, foam quality and salinity affecting the pressure drop. It is difficult to generalize conclusions from the literature as those studies are (deliberately) designed to be unique and are intended for restricted variable spaces. One might ask: (i) can limited experimental data with DAOE methodology represent the whole population of foam experiments from the literature?, (ii) is there a way to use the previous experimental results to generalize the effect of various variables on the steady state pressure drop? and finally, (iii) can we rank the effect of variables on the pressure drop? The path towards resolving these questions could be elucidated with data driven models constructed by applying regression to experimental results. However, conventional regression involves a presumed interrelationship between the variables, which might miss the importance of one variable over another affecting the pressure drop. Therefore, we are motivated to find the hierarchy between the variables with a maximally feasible set of experiments using a non-conventional regression analysis called symbolic regression (Schmidt and Lipson, 2009; Vladislavleva et al., 2010). Symbolic regression, with its ability to search for the model that best describes the data behavior without imposing a priori assumptions, would offer the advantage over conventional multiple regression. Based on a literature survey, we attempt the random variation of six experimental variables, viz., permeability (1860 Darcy, 130 Darcy and 3 Darcy), the concentration of surfactant (0.0375 w/w%, 0.075 w/w% and 0.15 w/w%), gas and surfactant solution velocity (0.27–3.97 m/day), salinity (zero, 0.5 M NaCl) and the pH (6.5, 3.0) as representative conditions in a reservoir. Complimentary to studies conducted in the literature (Simjoo et al., 2013), experiments were conducted with Bentheimer with a low AOS concentration (0.0375 w/w%) and at a low gas fraction ($\approx$24%) for two injection rates. Such random variation would circumvent the practical difficulty of conducting an infeasible number of experiments (orthogonal or box design) to rank the variables with respect to their relative importance to affect the pressure drop. Our experiments were designed to add data points that are at conditions less studied in the literature. To overcome the difficulty of statistical inference with only 14 (our) data points, we add 112 data points from Martinez (1998) and Martinez et al. (2001), 21 data points from Osterloh and Jante (1992) and 12 data points from Persoff et al. (1991). The selected data points were similar in some experimental conditions (surfactant-nitrogen co-injection)