Journal of Natural Gas Science and Engineering 9 (2012) 160–165

Contents lists available at SciVerse ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Effect of disjoining pressure on the onset of condensate blockage in gas condensate reservoirs

Mohammad Mohammadi-Khanaposhtani [a], Alireza Bahramian [b,*], Peyman Pourafshary [b], Babak Aminshahidy [b], Babak Fazelabdolabadi [b]

[a] Faculty of Chemical Engineering, University of Tehran, Tehran, Iran
[b] Institute of Petroleum Engineering, University of Tehran, Tehran, Iran

ARTICLE INFO

Article history:
Received 24 May 2011
Received in revised form
5 June 2012
Accepted 11 June 2012
Available online 22 July 2012

Keywords:
Condensate blockage
Disjoining pressure
Interfacial tension
Film instability
Scheludko number

ABSTRACT

An in-depth analysis was performed to investigate the formation of a condensate lens, as the primary stage of a phenomenon known as condensate blockage in gas condensate reservoirs. The lens formation is considered to be caused by the instability of the condensate film on the pore walls. Owing to the small sizes of the pores and low values of interfacial tension in gas condensate reservoirs, the stabilizing effect of the disjoining pressure may become more significant than the corresponding destabilizing effect of interfacial tension. To model this phenomenon, we employed the augmented Young–Laplace equation to determine the film pressure and subsequently, the film stability. Consequently, this analysis would incorporate the effects of interfacial tension, curvature, and the disjoining pressure on lens formation. The Scheludko dimensionless number, ξ, originally introduced by Gumerman and Gomsy [Chem. Eng. Commun. 2 (1975), 27–36], was used in order to compare the effects of the disjoining pressure and interfacial tension on the stability of the condensate film. The calculation results are provided for the Scheludko dimensionless number in the range $10^{-6} < \xi < 10^{-2}$. The selected range covers interfacial tensions between 0.01 and 0.25 (mNm^{-1}) and the pore diameters between 0.2 and 10 (μm). We found that the critical film thickness required for lens formation, strongly depends on the dimensionless quantity when $\xi > 10^{-5}$. For a typical value of $\xi \approx 10^{-2}$, the value of onset saturation for lens formation is found to be about 60%, whilst for much lower ranges, where the disjoining pressure has a negligible effect, the calculation results in a unique onset saturation of 13.5%.

1. Introduction

Gas condensate reservoirs compromise for a great number of worldwide gas. These reservoirs are initially in a gaseous state but when production starts, some retrograde condensate is formed due to the pressure drop. The accumulation of condensate in the region near the wellbore and its competition with the gas phase for flow can dramatically decrease the well deliverability. This problem is recognized as condensate blockage. It may reduce the gas production down to 5% of the initial rate (Al-Anazi et al., 2005). Therefore, due to its importance, the flow behavior of gas and condensate near the wellbore region, and the associated problem of condensate blockage has been the subject of intensive research (Al-Anazi et al., 2005; Henderson et al., 1995, 1996; Jamiolahmady et al., 2000). The main result of these studies is that flow behavior in gas condensate reservoirs is essentially different from the two-phase gas/oil flow within under-saturated oil reservoirs (Henderson et al., 1995, 1996). In oil reservoirs, because of high values of interfacial tension, the capillary effect plays an important role in the distribution of the gas and liquid phases. As a result, oil and gas flow in separate paths within the reservoir (Jamiolahmady et al., 2000). However, in gas condensate reservoirs, the newly-formed condensate deposits on the pore wall. As interfacial tension between the gas and the condensate is small, capillary force cannot distribute the two phases in separate pores. As a result, a pore-scale two-phase flow is established within the majority of pores in the reservoir (Henderson et al., 1995, 1996; Jamiolahmady et al., 2000). Pore-scale coupled flow of gas and condensate is responsible for increasing gas relative permeability as a result of the increase in gas production rate. This phenomenon was first observed by Henderson and is known as the positive coupling effect in gas condensate reservoirs (Henderson et al., 1995). Knowledge of the pore-scale two phase flow is necessary to model both gas condensate flow and condensate blockage. Condensate blockage was formerly thought to be caused by the complete filling of smaller pores by condensate but this view is in

* Corresponding author. Tel.: 98 21 61114715: fax: +98 2188632976.
E-mail address: abahram@ut.ac.ir (A. Bahramian).

1875-5100/$ – see front matter
http://dx.doi.org/10.1016/j.jngse.2012.06.002

contrast to the occurrence of two-phase flow in the majority of pores. The micromodel experiments of Jamiolahmady et al. (Jamiolahmady et al., 2000) revealed that oscillatory formation and removal of condensate lenses on the gas pathway is responsible for condensate blockage. A similar observation on cyclic blockage was made by Persoff and Pruess (Persoff and Pruess, 1995). According to their observations, the formation of a liquid lens as a result of liquid film instability is the primary stage of the condensate blockage.

To our knowledge, the only mechanistic model for the description of gas and condensate coupled flow based on condensate film instability, has been presented by Jamiolahmady et al. (Jamiolahmady et al., 2000). They modified the Gauglitz and Radke model (Gauglitz and Radke, 1990) for instability of thin films in constricted capillaries. Using their model, they observed the positive rate effect on gas production. However, the model they used for film instability (Gauglitz and Radke, 1990) suffers from some shortcomings. These include the small slope assumption used to simplify the curvature expression in the Young–Laplace equation and the approximate flow rate expression for annular film flow. More important than these simplifying assumptions, they neglected the size effect of the pores in their modeling. Unfortunately, the latter parameter is almost always neglected in flow modeling of petroleum reservoirs. A reservoir is composed of tiny pores ranging from less than one micron to several tens of microns. Hence, the liquid film on the pore wall may be much thinner than one micron. At this film size, the effect of van der Waals forces on the stability of wetting films cannot be neglected (Israelachvili, 1992). For thin wetting films, these forces are repulsive (Israelachvili, 1992) and they are termed as the disjoining pressure (Deryagin and Kussakov, 1939). Disjoining pressure could be defined as the difference in the normal and tangential components of the pressure tensor within a thin film of liquid (Deryagin and Kussakov, 1939). It should be noted that for a bulk liquid phase, the components of pressure tensor are identical in normal and tangential directions.

Disjoining pressure resists further thinning of a wetting film. In this way it cancels the destabilizing effect of interfacial tension on thin liquid films and postpones the formation of liquid lenses. This is more pronounced for lower values of interfacial tension as encountered in gas condensate reservoirs.

This study focuses on the formation of a liquid lens as the primary stage of condensate blockage, under the effect of disjoining pressure and interfacial tension. By including the disjoining pressure in the condensate blockage modeling, one can determine the lens formation saturation as a function of pore size and interfacial tension. This saturation could be thought as the saturation for the onset of condensate blockage.

In the following section, the disjoining pressure and augmented Young–Laplace equation (AYLE) will be briefly reviewed. This is followed by a derivation of the film evolution equation under cylindrical geometry. We shall present and discuss our results for the effects of interfacial tension, disjoining pressure, and pore size on the onset of condensate blockage based on the derived model. The final section is devoted to our concluding remarks.

2. Disjoining pressure and augmented Young–Laplace equation

The Young–Laplace equation describes the normal stress balance for a curved gas–liquid interface:

$$p_g - p_l^N = \sigma C \tag{1}$$

where: p_l^N is the normal component of the pressure tensor; σ is the interfacial tension, and C is the sum of principle curvatures at the interface. For cylindrical geometry, curvature is given by:

$$C = \frac{1}{R_i\left(1+R_{i,z}^2\right)^{1/2}} - \frac{R_{i,zz}}{\left(1+R_{i,z}^2\right)^{3/2}} \tag{2}$$

where: R_i is the interface radius; $R_{i,z}$ and $R_{i,zz}$ are the first and second derivatives with respect to the longitudinal direction, z. For a bulk liquid phase, the normal and tangential components of the pressure tensor are identical, whilst for a thin liquid film according to Deryagin (Deryagin and Kussakov, 1939):

$$p_l^N - p_l^T = \Pi \tag{3}$$

p_l^T is the tangential component of the pressure tensor, and Π denotes the disjoining pressure. Substitution of (2) into (1) results in the augmented Young–Laplace equation:

$$p_g - p_l^T = \sigma C + \Pi \tag{4}$$

As the film flow is a result of the gradient ofp_l^T, it is usually called film pressure and is denoted by p_f.

According to Lifshitz theory (Lifshitz, 1956) for phases 1 and 2 interacting through phase 3 of thickness h with infinite planar interfaces 1–3 and 2–3, the disjoining pressure is given by:

$$\Pi = -\frac{A_{132}}{6\pi h^3} \tag{5}$$

A_{132} is the Hamaker constant for interaction of phases 1 and 2 through phase 3. Based on the Lifshitz theory (Lifshitz, 1956), the Hamaker constant is related to the dielectric constant of the media. Furthermore, the value of the Hamaker constant is positive for attractive forces and negative for repulsive forces. For the wetting films, the intermolecular forces are repulsive, and hence the value of the Hamaker constant will be negative. This corresponds to a positive value of disjoining pressure. The positive disjoining pressure resists film thinning and this results in film stability.

It should be noted that Equation (5) has been derived for planar interfaces. However, it has been extensively used to model non-planar interfaces, such as non-uniform films involved in film stability analysis (Gauglitz, 1986; Sharma and Ruckenstein, 1986; Sharma and Ruckenstein, 1987). Using this equation will effectively neglect the effect of film configuration on the disjoining pressure and the results of such an analysis are questionable (Yi and Wong, 2007; Dai and Leal, 2008). Dai et al. (Dai and Leal, 2008) derived an equation for the disjoining pressure of non-uniform films by minimizing the free Helmholtz energy:

$$\Pi = -\frac{A_{132}\left(4 - 3h_z^2 + 3hh_{zz}\right)}{24\pi h^3} \tag{6}$$

h_z and h_{zz} are the first and second derivatives of film thickness, respectively. This expression reduces to Equation (5) for a planar interface. In this study, Equation (6) will be used for calculation of the disjoining pressure and its effect on film stability. Using this equation, the effect of film slope and its curvature on the disjoining pressure at any position is included.

3. Film flow modeling

3.1. Film evolution equation

Annular flow of condensate film in a horizontal cylindrical capillary is modeled based on the following assumptions:

i) Flow is axisymmetric due to negligible gravity effect. The direction along the film is z and the radial direction is r.
ii) Condensate is incompressible and Newtonian and it wets the pore wall, i.e., very small contact angle.