Impact of Velocity and Interfacial Tension on the Performance of Horizontal Wells in Gas Condensate Reservoirs

Panteha Ghahri, Mahmoud Jamiolahmady* and Mehran Sohrabi
Heriot Watt University, Institute of Petroleum Engineering, Edinburgh, EH144AS
*Corresponding author: jami.ahmady@pet.hw.ac.uk

Abstract: Drilling horizontal wells (HWs) has recently received renewed attentions with the increasing trend in exploitation of tight gas reservoirs. An accurate estimation of productivity of such systems using a numerical simulator is a challenging task, because its 3D simulation requires a fine grid exercise to capture the abrupt variation of fluid and flow parameters around the wellbore. This is cumbersome and impractical for field applications.

In this work, Comsol mathematical package has been used to simulate 3D two-phase flow around a gas condensate HW under steady-state conditions. The model accounts for phase and composition changes and dependency of relative permeability to velocity and interfacial tension (IFT). The integrity of the model was verified by comparing some of its results with those obtained using fine grid option of a commercial compositional simulator under the same flow conditions. A sensitivity study of the impact of pertinent parameters on the HW performance was conducted with some important practical findings. The results demonstrated that for a given pressure drawdown, an increase in velocity or decrease in IFT improves HW performance at lower HW lengths, whilst the negative impact of high velocity inertial flow is more pronounced at higher total gas fractional flow rate (GTR), smaller wellbore radius and higher reservoir thickness values. Theses results also indicated that the rock properties could influence the productivity (the HW to vertical well flow rates) ratio significantly.

Keywords: gas condensate, horizontal wells, total gas fractional flow rate, interfacial tension, velocity, coupling, inertia.

1. Introduction

Due to the popularity of drilling HWs, many studies have been conducted to propose an accurate formulation for productivity of such wells at steady state (SS) or pseudo steady state (PSS) conditions. However, these are only applicable for single phase conditions, (Borosiv 1984, Joshi 1985, Giger 1985, Economides 1996, Babu-Odeh 1989 and Goode 1991). Theses equations have been obtained using semi-mathematical methods with some simplifying assumptions on the flow pattern around such flow geometries. In gas condensate reservoirs, the flow behaviour around HWs is more complex due to the combined effect of coupling (increase in kr by an increase in velocity or decrease in IFT) and inertia (a decrease in kr by an increase in velocity) Gas condensate fluid also involves complex thermodynamic behaviour, due to fluid compositions. A fully compositional modelling is required to predict accurately the well performance of HWs in gas condensate reservoirs. Therefore, a two phase compositional simulator using Comsol mathematical package has been developed, which incorporates a generalised correlation proposed by Jamiolahmady et al. (2009). This correlation accounts for the combined effect of inertia and coupling with universal parameters. The integrity of the simulator has been confirmed by comparing its results with the results of the ECLIPSE commercial reservoir simulator under the same flowing conditions. Next, a comprehensive sensitive study has also been conducted to evaluate the impact of pertinent parameters on the performance of HWs in gas condensate reservoirs.

1.1 Gas Condensate Flow

As noted earlier, the flow behaviour around HWs is complex, considering the 3-D flow geometry around the wellbore. That is, it is very difficult to obtain a 3-D analytical solution to forecast accurately the HW productivity. In gas condensate reservoirs, as the pressure falls below dew point, a bank of condensate forms around the wellbore, which affects the well productivity and flow behaviour around the wellbore. Fine grid compositional numerical simulation, similar to that of the in-house simulator presented here, is usually required to predict gas-condensate well productivity to account for high velocity phenomena, which result in variation of relative permeability due to the coupling and inertial effects.

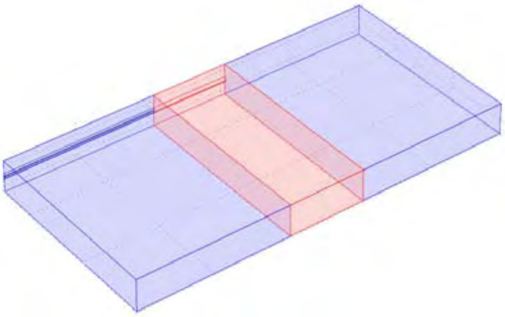


Figure 1: 3-D Geometry of the horizontal well in this study.

2. 3-D Two-Phase HW Model

The 3-D system considered in this study consists of a HW with radius of r_w and length of L, in a single layer cubic reservoir, as shown in Figure 1. This homogenous porous medium has an absolute permeability k and formation thickness of h. The model length in the x and y directions is assumed to be 2.5 times the HW length. Due to the existing symmetry only a quarter of the reservoir has been considered in this study. This saves the computation time and reduces the complexity of having a high quality mesh.

3. Use of COMSOL Multiphysics

The equations describing the steady state two-phase flow of gas and condensate around a HW are those used by Jamiolahmady et al. (2005) in the study of flow behaviour around perforations:
The continuity equation for gas and condensate flow at steady state conditions

$$\nabla.\left((\rho v)_g + (\rho v)_c\right) = 0\,, \qquad (1)$$

where ρ is the density, v is the velocity and subscripts g and c represent the gas and condensate phases, respectively.
The flow equation for each phase:

$$v_i = \frac{kk_{ri}}{\mu_i}\nabla P\,.\ \text{i=g,c,} \qquad (2)$$

where, k is the absolute permeability, kr is the relative permeability and P is the pressure.
Combining continuity and flow equations, after some mathematical manipulation, gives:

$$\nabla.\left(\left\{\left[\frac{\rho k_r}{\mu}\right]_g + \left[\frac{\rho k_r}{\mu}\right]_c\right\} k\nabla P\right) = 0\,. \qquad (3)$$

The total fluid composition (zj) is constant as the fluid flows through the porous media. However, for each component, there is mass transfer between two phases as expressed by the following equation:

$$z_j = \frac{\rho_g y_j GTR + \rho_c x_j (1-GTR)}{\rho_g GTR + \rho_c (1-GTR)} = cons.\,, \qquad (4)$$

where GTR is the total gas fraction flow rate ratio defined by Equation 5.

$$GTR = \frac{Q_g}{Q_g + Q_c} = \frac{1}{1 + \frac{k_{rg}}{k_{rc}} \times \frac{\mu_c}{\mu_g}}\,. \qquad (5)$$

where Q is the volumetric flow rate.

In Equation 3, relative permeability which varies with interfacial tension (i.e. pressure for a given fluid composition) and velocity is estimated using the correlation proposed by Jamiolahmady et al. (2009). In this formulation, gas relative permeability is correlated to pressure, velocity. The condensate relative permeability is calculated using the definition of relative permeability ratio ($k_{rgtr}=k_{rg}/(k_{rg}+k_{rc})$ as the independent variable, which is closely related to gas fractional flow by Equation 5.
The composition and fluid properties of equilibrated phases of a fixed overall composition depend only on the pressure for a given temperature. A binary mixture of C1 (methane) and n-C4 (normal butane) was used as a model gas-condensate fluid. The values of composition, density (ρ), viscosity (μ) and interfacial tension (IFT) of C1-nC4 mixtures are those measured in the gas condensate group laboratory as well as literature data (Sage et al., 1940; SUPERTRAPP User's Guide, 1992; Weinaug and Katz, 1943) at 311 K over a wide pressure range, which were implemented in the model.

The above governing non-linear partial differential equation (PDE), Equation 3, is solved using general PDE mode of Comsol multi-physic software (Version 3.5, 2008). The main dependent variable in this equation is P (pressure). However, the equations are solved for both P and GTR.

The boundary conditions applied to this system are:

The pressure at outer boundary (external radius) is known.

The pressure at the inner boundary (wellbore radius) is known.

The pressure gradient in the wellbore has been ignored, i.e. infinite conductivity for the HW bore.

As noted earlier, the total composition is constant, so either the GTR or the total fluid composition is known at the wellbore.

4. ECLIPSE 3-D Two Phase HW Model

The accuracy of the two-phase mathematical in-house simulator was confirmed by comparing some of its results with those of ECLIPSE300 at the same prevailing conditions.

The reservoir model in this exercise had the core properties of Texas Cream with porosity 0.21 and permeability 9.1 mD. The reservoir was 38 m in x and y directions and 4 m in z direction. The HW length was 15 m. Many different cases were simulated using the ECLIPSE300 and in-house simulators, over a wide range of velocities. The fractional flow at average reservoir pressure was the same in both simulators. The very fine grid was used to capture the abrupt changes in flow parameters near the wellbore. In ECLIPSE 300, seventy injection wells were placed at the boundary of the reservoir to maintain steady state conditions and keep the reservoir pressure at the drainage boundary constant.

Figure 2 shows the good agreement between the two results. The arithmetic average absolute percentage deviation (AAD%) of the predicted flow rate values by the ECLIPSE simulator compared to those estimated by the HW simulator was 2.9 %.

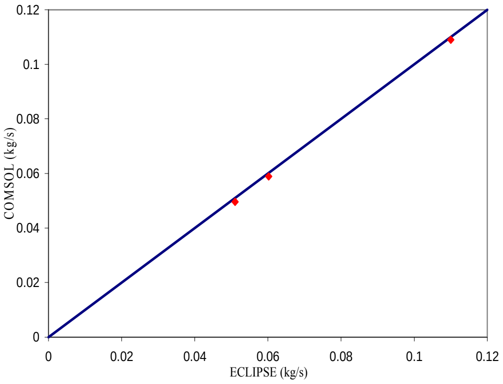
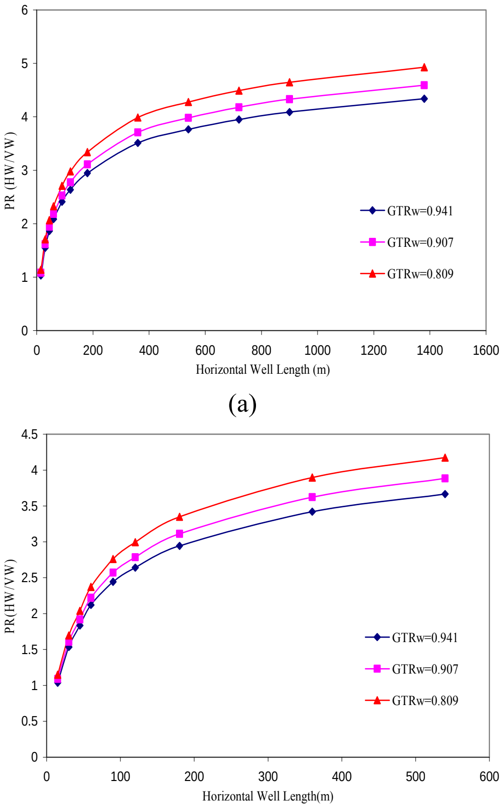


Figure 2: Comparison of the results of ECLIPSE two-phase model (gas and condensate) with those of the in-house simulator at three different pressure drops and fractional flow.

4. Results

The rock properties of Berea, were chosen to describe the reservoir rock characteristics. The reservoir and wellbore pressures were changed between 1800 and 700 psi and 1750 and 400 psi, respectively. The radius and length of the HW were varied from 0.07 to 0.21 and from 15 m to 1500 m, respectively. The reservoir thickness was 15 m. The total composition of the binary mixture was varied from 0.55 to 0.2. In addition, the gas fractional flow was changed from 0.809 to 0.941.

Figure 3 presents productivity ratio versus HW length at rw of (a) 0.14 m and (b) 0.21 m. The reservoir pressure was 1800 psi; the pressure drop across the drainage area was maintained at 500 psi. Productivity Ratio (PR) is the ratio of total (gas plus condensate) produced mass flow rate of horizontal to vertical well for the same pressure drop. Since the wellbore pressure is the same this is also equal to volumetric flow rate ratio. The total gas fractional flow (GTR) was 0.941, 0.907 or 0.809. The corresponding velocity values of the HW changed from 4 to 970 m/day. These values were estimated by dividing the total flow rate (gas and condensate) by the HW area. For all cases considered here, as expected, an increase in the HW length (L) increases PR. Furthermore, as the total gas fractional flow decreases PR increases. It should be noted that at these low flow velocities and low GTR values, the positive coupling effect is more dominant in HW compared to that in VW, resulting in an increase in PR as GTR is reduced. At higher GTR, the impact of positive coupling is less pronounced in the HW, whilst inertia is still dominant in the VW system. Furthermore, for HWs with lower L, the absolute variation of PR as GTR is varied is less pronounced. This is mainly due to the fact that there is little difference between the velocity in VWs and HWs at such flow conditions.



(a)

Figure 3: Productivity ratio (horizontal to vertical well) versus horizontal well length at three different gas fractional flows, h= 15 m, P_{res}=1800 psi, P_w= 1300 psi, a) r_w=0.14 m b) r_w=0.21 m.

Figure 4 shows PR versus the HW length at three different wellbore radii and GTRw=0.809. The PR of the smallest wellbore radius (0.07 m) is slightly higher than the corresponding values for the wellbore radii of 0.14 m and 0.21 m. This is mainly due to the more pronounced negative impact of inertia (high velocity non-Darcy flow) on the flow of the corresponding VW for the low rw values.

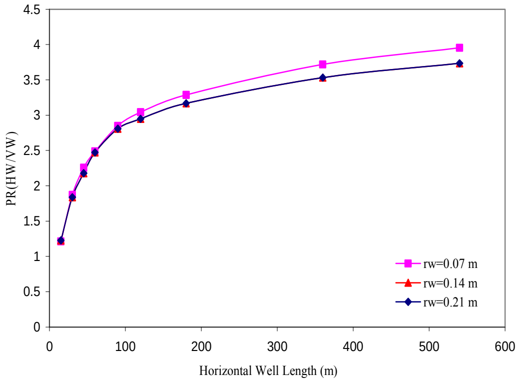


Figure 4: Productivity ratio versus horizontal well length at the wellbore radii of 0.07 m, 0.14 m and 0.21 m, GTR=0.809, h= 15 m, P_{res}=1800 psi, P_w= 1300 psi.

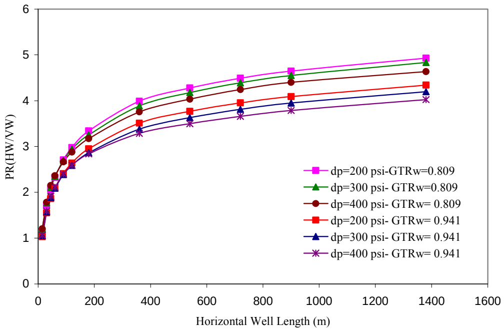


Figure 5: Productivity ratio versus horizontal well length, r_w=0.14 m, GTR_w=0.941 & 0.809, h= 15 m, P_w= 1300 psi, pressure drops of 200, 300 and 400 psi.

The effect of velocity on PR is shown in Figure 5. For this part of the study, three different pressure drops of 200 psi, 300 psi, and 400 psi and two GTR_w of 0.941 and 0.809 were studied. Furthermore, the wellbore pressure was 1300 psi. The actual velocity in these simulations at ΔP of 400, 300, 200 psi and GTR_w of 0.809 and 0.941, as HW length was varied, from 3, 2, 1, 8.4, 5.6, and 3.5 to 197, 125, 72, 496, 296, and 166 m/day, respectively. These values were obtained by dividing the flow rate by the flow area of the HW wellbore. At each GTR_w, as can be seen, decreasing the pressure drop, slightly improves PR because of the more pronounced effect of coupling in the HW system. Furthermore, the negative effect of inertia is more pronounced at a higher GTR_w of 0.941 for the VW: hence, the PR values are lower at this GTR_w. In other words, at the lower GTR_w value of 0.809, the positive coupling effect is more dominant for HWs. This results in an improved PR at lower GTR_w compared to that at higher GTR_w. At each GTR_w and lower HW lengths, the impact of velocity on the flow performance of HWs and VWs does not vary with the variation of ΔP, i.e. PR is independent of the applied ΔP. The similarity between the variation of velocity in HWs and VWs for these low L values also explains the small difference observed between the PR values corresponding to these two GTR_w values.

7. Conclusions

The two phase flow of gas and condensate around horizontal wells under steady state conditions was simulated using Comsol mathematical package. The integrity of the model has been confirmed by comparing its results with those of the same model constructed using ECLIPSE300. A sensitivity study has been conducted to evaluate the impact of a number of pertinent parameters on the horizontal well productivity. The results demonstrated that:

At the same pressure gradient, the effect of inertia on productivity ratio (PR of HW to VW) is more pronounced at higher values of total gas fractional flow at the wellbore (GTR_w) where the impact of positive coupling is less pronounced in the HW, whilst inertia is still dominant in the VW system. As GTR_w decreases PR increases because the positive coupling effect is more dominant in HW compared to that in VW.

At the same GTR_w, increasing velocity decreases PR due to the more pronounced effect of inertia in HWs compared to that in VWs.

The effect of the wellbore radius on PR is negligible.

8. References

1. Babu D.K. and Odeh A.S., 1989: Productivity of a Horizontal well, SPE Reservoir Engineering, 4(4), 417-421.
2. Borisov Ju. P., 1984: Oil Production Using Horizontal and Multiple Deviation Wells, Nedra, Moscowfl 964. Translated by J.Strauss, S. D. Joshi (ed.) Phillips Petroleum Co., the R&D library translation, Bartlesville.
3. Economides Michael J., Deimbacher Franz X., Brand Clement W. and Heinmann E. Zoltan, 1991: Comprehensive Simulation of Horizontal Well Performance, SPE 20717.
4. Economides M.J., Brand C.W. and Frick T.P., 1996: Well Configurations in Anisotropic Reservoirs, SPEFE, 257-262. (Also Paper SPE 27980, 1994.).
5. Giger, F., 1985: Reduction du nombre de puits pm I'tilisation de forages horizontals, Reveue de L'institute Gancais du Petrole, 38.
6. Giger, FM., Reiss, L.H. and Jourdan A.P., 1984: The Reservoir Engineering Aspects of Horizontal Drilling, SPE 13024, presented at the 1984 meeting SPE Annual Technical Conference and Exhibition, Houston.
7. Goode P.A. and Kuchuk F.J., 1991: Inflow Performance of Horizontal Wells, SPE Reservoir Engineering, p 319-323.
8. Joshi S.D., 1991: Horizontal Well Technology, PennWell, Tulsa, Oklahoma.
9. Jamiolahmady M., Danesh A., Sohrabi M. and Ataei R., 2007: Gas condensate flow in perforated region, SPE Journal, 12 (1), pp. 89-99, also in Proceedings of the SPE Europec Conference, SPE 94072.
10. Jamiolahmady M., Sohrabi M., Ireland S., and Ghahri P., 2009: A Generalized Correlation for Predicting Gas-Condensate Relative Permeability at near the Wellbore Conditions, Journal of Petroleum Science and Engineering.
11. Sage B.H, Hick B.L. and Lacey W.N. , 1940: Phase Equilibria in hydrocarbon system-the methane-n-butane systems in the two-phase region, Ind. Eng. Chem. 32, 1058-1092.
12. SUPERTRAPP (NIST Thermophysical Properties of Hydrocarbon Mixture Database) User‘s Guide by National Institute of Standards and Technology (NIST), NIST Standard Reference Database 4, July 1992, Version 1.0.

9. Acknowledgements

The above study was conducted as a part of the Gas-condensate Recovery Project at Heriot-Watt University. This research project is sponsored by: The BP Exploration Company (Colombia) Ltd, ENI petroleum Co., Inpex Corporation, Kuwait Oil Company, Petrobras and Total Exploration UK plc, which are gratefully acknowledged.