CSCanada
Advances in Petroleum Exploration and Development
Vol. 9, No. 2, 2015, pp. 53-57
DOI:10.3968/6659

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

Mechanistic Modeling of Upward Gas-Liquid Flow in Deviated Wells

SUN Shihui[a],*; YAN Tie[a]; BI Xueliang[a]; YU Guoqing[b]

[a] Petroleum Engineering College, Northeast Petroleum University, Daqing, China.
[b] Daqing Oil Filed Co., Ltd. of PetroChina, Daqing, China.
* Corresponding author.

Supported by National Natural Science Foundation of China (51374077).

Received 18 March 2015; accepted 14 April 2015
Published online 30 June 2015

Abstract
Underbalanced drilling (UBD) has increased in recent years because of the many advantages associated with it. The precise wellbore pressure prediction is the key for safe and efficient underbalanced drilling. With the quantity of deviated and horizontal wells using UBD increases, pressure prediction of these wells is important. In this paper, a new mechanistic model has been developed to predict flow pattern and calculate flow behavior for each pattern in deviated annular during UBD operation. And the proposed model has been validated with field data. In addition, a comparison of the model results against two empirical models indicating the presented models perform better in predicting two phase flow parameters in UBD operation.

Key words: Underbalanced drilling (UBD); Deviated wells; Mechanistic modeling

Sun, S. H., Yan, T., Bi, X. L., & Yu, G. Q. (2015). Mechanistic modeling of upward gas-liquid flow in deviated wells. *Advances in Petroleum Exploration and Development*, *9*(2), 53-57. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/6659
DOI: http://dx.doi.org/10.3968/6659

INTRODUCTION

Underbalanced drilling (UBD) offers a major advantage in increasing the rate of penetration and reducing lost circulation. It is generally accepted that the success of UBD is dependent on the maintaining the wellbore pressure in a safe operational window. Therefore, the accuracy of wellbore pressure is critically important for UBD design. With the quantity of deviated and horizontal wells increases, pressure prediction of these wells is important. Empirical correlations and mechanistic models are often used to model the characteristic of annulus flow. Although empirical models such as Beggs & Brill model[1] lead to acceptable results in certain wells, none of them could give acceptable outcome in all data ranges. The main objective of this research is to study and model the effect of well deviation on pressure and flow profile under UBD conditions through the use of mechanistic two phase flow models.

1. FLOW PATTERN PREDICTION MODELS

1.1 Bubble to Slug Transition

During bubble flow, discrete bubbles rise with the occasional appearance of a Taylor bubble. The discrete bubble rise velocity for upward flow in vertical and inclined channels as follows[2]:

$$v_\infty = 1.53\left[\frac{(\rho_L-\rho_G)g\sigma}{\rho_L^2}\right]^{0.25}. \quad (1)$$

Hasan and Kabir[3] stated that the presence of an inner tube tends to make the nose of the Taylor bubble sharper, causing an increase in the Taylor bubble rise velocity. As a result, Hasan and Kabir developed Equation (2) where the diameter of the outer tube should be used with the diameter ratio K (D_{OT} / D_{IC}) to get the following expression for the Taylor bubble rise velocity in inclined annulus.

$$v_{\mathrm{TB}}=\left[0.345+0.1\frac{D_{\mathrm{OT}}}{D_{\mathrm{IC}}}\right]\sqrt{\sin\theta}\left(1+\cos\theta\right)^{1.2}\sqrt{gD_{\mathrm{IC}}\frac{\rho_L-\rho_G}{\rho_L}}. \quad (2)$$

Where D_{OT} is the outside pipe diameter and D_{IC} is the inner casing diameter. ρ_L, ρ_G is the liquid density and gas density, respectively. g is the gravitational acceleration. σ is liquid surface tension. θ is the inclination angle from horizontal.

Hasan and Kabir stated that the presence of an inner tube does not appear to influence the bubble concentration profile (C_0) and thus, the bubble-slug transition is defined by:

$$v_{\mathrm{SL}}=\frac{\left(4-C_0\right)v_{\mathrm{SG}}}{\sin\theta}-v_{\mathrm{TB}}. \quad (3)$$

1.2 Bubble or Slug to Dispersed Bubble Transition

Caetano model[4, 5] is recommended for the bubble or slug to dispersed bubble flow transition, which is given by:

$$v_M^{1.2}\left(\frac{2f^{0.4}}{D_h}\right)^{0.4}\left[\frac{1.6\sigma}{\left(\rho_L-\rho_G\right)g}\right]^{0.5}\left(\frac{\rho_L}{\sigma}\right)^{0.6}=0.725+4.15\left(\frac{v_{\mathrm{SG}}}{v_M}\right)^{0.5}. \quad (4)$$

The hydraulic diameter of the casing-tubing annulus is given by:

$$D_h=D_{\mathrm{IC}}-D_{\mathrm{OT}}. \quad (5)$$

1.3 Dispersed Bubble to Slug Flow Transition

Taitel et al.[6] determined that the maximum allowable gas void fraction under bubble flow condition is 0.52. Higher values will convert the flow to slug, hence the transition boundary could be equated as follows.

$$v_{\mathrm{SL}}=0.923v_{\mathrm{SG}}. \quad (6)$$

1.4 Slug to Churn Transition

Tengesdal et al.[7] stated that the slug structure will be completely destroyed and churn flow will occur if the gas void fraction equals 0.78. Thus churn flow will occur. The transition from slug flow to churn flow can thus be represented by:

$$v_{\mathrm{SL}}=0.0684v_{\mathrm{SG}}-0.292\sqrt{gD_{\mathrm{ep}}}. \quad (7)$$

Where D_{ep} is the equi-periphery diameter defined as follows.

$$D_{\mathrm{ep}}=D_{\mathrm{IC}}+D_{\mathrm{OT}}. \quad (8)$$

1.5 Churn to Annular Transition

Based on the minimum gas velocity required to prevent the entrained liquid droplets from falling back into the gas stream that would originate churn flow, Taitel et al.[6] proposed the following Equation to predict the transition to annular flow.

$$v_{\mathrm{SG}}=3.1\left[\frac{\left(\rho_L-\rho_G\right)g\sigma}{\rho_G^2}\right]^{0.25}. \quad (9)$$

2. FLOW BRHAVIOR PREDICTION MODELS

For steady state flow, the total pressure gradient is composed of gravity, friction, and convective acceleration losses and is calculated as follows.

$$\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{T}}=\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Hy}}+\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Fric}}+\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Acc}}. \quad (10)$$

Where $\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{T}}$ is the total pressure gradient; $\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Hy}}$ is the gravity pressure gradient; $\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Fric}}$ is the friction pressure gradient; and $\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Acc}}$ is the acceleration pressure gradient.

The gravity component is given by:

$$\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Hy}}=\rho_M g\sin\theta. \quad (11)$$

Where

$$\rho_M=\rho_L H_L+\rho_G(1-H_L). \quad (12)$$

The frictional pressure loss is given by:

$$\left(\frac{\mathrm{d}p}{\mathrm{d}Z}\right)_{\mathrm{Fric}}=\frac{f_M\rho_M v_M^2}{2D_{\mathrm{IT}}}. \quad (13)$$

As suggested by Caetano, the Fanning friction factor f_M is calculated with the Gunn and Darling[8] approach for turbulent flow.

$$\left[f_M\left(\frac{F_P}{F_{\mathrm{CA}}}\right)^{0.45\exp\left[-\left(N_{\mathrm{RE}}-3000\right)/10^6\right]}\right]^{-0.5}$$

$$=4\log\left[N_{\mathrm{RE}}\left(f_M\left(\frac{F_P}{F_{\mathrm{CA}}}\right)^{0.45\exp\left[-\left(N_{\mathrm{RE}}-3000\right)/10^6\right]}\right)\right]-0.4, \quad (14)$$

which is a function of the diameter ratio K (D_{OT} / D_{IC}) and mixture Reynolds number defined by:

$$N_{\mathrm{RE},M}=\frac{\rho_M v_M D_h}{\mu_M}. \quad (15)$$

Where F_p and F_{CA} are geometry parameters defined by Equations (16) and (17).

$$F_P=16/N_{\mathrm{RE},M}, \quad (16)$$

$$F_{\mathrm{CA}}=\frac{16\left(1-K\right)^2}{\left[\frac{1-K^4}{1-K^2}-\frac{1-K^2}{\ln\left(1/K\right)}\right]}. \quad (17)$$

The acceleration component is calculated using Beggs and Brill[1] approach.

$$\left(\frac{\mathrm{d}p}{\mathrm{d}L}\right)_{\mathrm{Acc}}=\frac{\rho_M v_M v_{\mathrm{SG}}}{p}\frac{\mathrm{d}p}{\mathrm{d}L}. \quad (18)$$

2.1 Dispersed Bubble Flow Model

Since nearly a uniform bubble distribution in the liquid, the flow can be treated as a homogenous flow. Thus, the liquid holdup is very close to the no-slip holdup H_L. The pressure gradient components are calculated as those in bubble flow.

2.2 Slug Flow Model

For slug flow, the gravitation component is given by[9]:

$$\left(\frac{dp}{dL}\right)_{Hy} = \left[(1-\beta)\rho_{M_{LS}} + \beta\rho_{M_{TB}}\right]g . \tag{19}$$

The friction component by:

$$\left(\frac{dp}{dL}\right)_{Fric} = \frac{2 f_{F_{Ls}} \rho_{M_{LS}} v_M^2}{D_{IT}}(1-\beta) . \tag{20}$$

The pressure drop due to acceleration across the mixing zone at the front of the liquid slug by:

$$\left(\frac{dp}{dZ}\right)_{Acc} = \frac{H_{L_{LS}}\rho_L}{L_{SU}}\left(v_{L_{LS}} + \left|v_{L_{TB}}\right|\right)\left(v_T - v_{L_{LS}}\right) . \tag{21}$$

Where $\rho_{M_{LS}}$ is the mixture density in the liquid slug zone defined by:

$$\rho_{M_{LS}} = \rho_L H_{L_{LS}} + \rho_G (1-H_{L_{LS}}), \tag{22}$$

and the friction factor is calculated as described above with a Reynolds number defined by:

$$N_{RE,M} = \frac{\rho_{M_{LS}} v_M D_{IT}}{\mu_L H_{L_{LS}} + \mu_G\left(1-H_{L_{LS}}\right)} . \tag{23}$$

β is the relative bubble length parameter, $\rho_{M_{TB}}$ is the mixture density in the Taylor bubble zone, and $v_{L_{TB}}$ is the in-situ liquid velocity in the Taylor bubble zone, which are function of the slug flow conditions.

For fully developed Taylor bubble slug flow,

$$\beta = \frac{L_{TB}}{L_{SU}} \text{ and } \rho_{m_{TB}} = \rho_G , \tag{24}$$

and for developing Taylor bubble slug flow,

$$\beta = \frac{L_{dTB}}{L_{dSU}},\ \rho_{m_{TB}} = \rho_L H_{L_{dTB}} + \rho_G\left(1-H_{L_{dTB}}\right), \text{ and } v_{L_{TB}} = v_{L_{dTB}} . \tag{25}$$

2.3 Annular Flow Model

As explained above, in common UBD operations, the window of occurrence of annular flow is quite limited and when it occurs, it takes place in the annulus at a few meters close to the surface. The simplified annular flow model proposed by Taitel and Barnea[10] was implemented only to avoid convergence problems during the computations.

$$\left(\frac{dp}{dL}\right)_T = \frac{4\tau_i}{D_e - 2\delta} + \left[\rho_L H_L + \rho_G\left(1-H_L\right)\right]g\sin\theta . \tag{26}$$

The annular film thickness δ can be defined as follow:

$$\delta = 0.115\left(\frac{\mu_L^2}{g\left(\rho_L-\rho_G\right)\rho_L}\right)^{1/3}\left(\frac{\rho_L v_{SL} D_e}{\mu_L}\right)^{0.6} . \tag{27}$$

D_e is the equivalent pipe diameter and is calculated by:

$$D_e = \sqrt{D_{IC}^2 - D_{IT}^2} . \tag{28}$$

The interfacial shear stress (τ_i) is defined by:

$$\tau_i = \frac{0.5 f_i \rho_G v_{SG}^2}{\left[1-2\left(\delta / D_e\right)\right]^4} . \tag{29}$$

The interfacial shear friction factor is calculated as suggested by Alves et al.[11] as follows :

$$f_i = f_{SC} I . \tag{30}$$

Where f_{sc} is the superficial core friction factor (gas phase) and is calculated based on the core superficial velocity, density and viscosity. The interfacial correction parameter I is used to take into account the roughness of the interface. The parameter I is an average between the horizontal angle and the vertical angle and is calculated based on an inclination θ,

$$I_\theta = I_H\cos^2\theta + I_V\sin^2\theta . \tag{31}$$

The horizontal correction parameter is given by Henstock and Hanratty[12]:

$$I_H = 1+800F_A . \tag{32}$$

Where

$$F_A = \frac{\left[\left(0.707 N_{RE,SL}^2\right)^{2.5} + \left(0.0379 N_{RE,SL}^{0.9}\right)^{2.5}\right]^{0.4}}{N_{RE,SL}^{0.9}}\left(\frac{v_L}{v_G}\right)\left(\frac{\rho_L}{\rho_G}\right)^{0.5} . \tag{33}$$

Where $N_{RE,SL}$ and $N_{RE,SG}$ are the superficial liquid and gas Reynolds number respectively. Both are calculated below,

$$N_{RE,SL} = \frac{\rho_L v_{SL} D_{IT}}{\mu_L} , \tag{34}$$

$$N_{RE,SG} = \frac{\rho_G v_{SG} D_{IT}}{\mu_G} . \tag{35}$$

The vertical correction parameter is given by Wallis[13] as follow:

$$I_V = 1+300(\delta/D_e) . \tag{36}$$

Considering that the liquid film thickness δ is constant, the liquid holdup can be estimated by:

$$H_L = 4\left[\frac{\delta}{D_e} - \left(\frac{\delta}{D_e}\right)^2\right] . \tag{37}$$

3. FIELD DATA VALIDATION

The presented model has been validated with a field case. Table 1 shows drill-string and casing data in simulated well. And physical parameters of fluid are shown in Table 2. Inclination angles are shown in Table 3.

Table 1
Data of Drill-String and Casing

Casing		Drill-string		
Depth/m	**ID/mm**	**Depth/m**	**OD/mm**	**ID/mm**
0-2,010	244.5	0-1,380	88.9	68.3
2,010-2,058	177.8	1,380-1,548	88.9	55.6
2,058-2,300	152.4	1,548-2,280	88.9	61.9
Total Depth	2,328	2,280-2,300	88.9	57.2

Table 2
Physical Parameters of Fluids

Gas flow rate (m^3/min)	Gas density (kg/m^3)	Liquid flow rate (m^3/min)	Liquid density (kg/m^3)	Mud viscosity (mpa·s)
18	1.25	1.2	950	3

Table 3
Measured Inclination Angle

Depth (m)	Inc. angle (°)	Depth (m)	Inc. angle (°)	Depth (m)	Inc. angle (°)	Depth (m)	Inc. angle (°)
2,054.86	0	2,096.27	30.57	2,137.2	60.78	2,178.37	89.23
2,057.81	2.18	2,099.11	32.67	2,140.11	62.93	2,181.42	89.33
2,060.77	4.36	2,102.11	34.88	2,143.01	65.08	2,184.32	89.62
2,063.62	6.47	2,105.02	37.03	2,145.96	67.25	2,187.4	89.73
2,066.57	8.65	2,107.95	39.19	2,148.88	69.41	2,190.52	89.74
2,069.63	10.9	2,110.79	41.29	2,151.83	71.59	2,193.61	89.81
2,072.53	13.04	2,113.69	43.43	2,154.85	73.82	2,196.56	89.9
2,075.39	15.16	2,116.56	45.55	2,157.69	75.91	2,227.03	89.94
2,078.34	17.33	2,119.56	47.76	2,160.62	78.07	2,230.04	89.97
2,081.49	19.66	2,122.47	49.91	2,163.59	80.27	2,233.18	89.99
2,084.28	21.72	2,125.35	52.04	2,166.56	82.46	2,263.66	90
2,087.26	23.92	2,128.31	54.22	2,169.46	84.61	2,266.74	90
2,090.25	26.13	2,131.4	56.02	2,172.55	86.88	2,297.22	90
2,093.16	28.27	2,134.32	58.66	2,175.55	89.09	2,328	90

During drilling, a pressure recording tool was installed above the bit to measure the bottomhole pressure (BHP). At depth 2,308 m MD, the bottomhole pressure tool recorded a value of 11.7 MPa. When reached the total depth 2,328 m, the observed BHP was 16.8 Mpa. Beggs & Brill and Hasan & Kabir[14] models were also calculated in compare to the new model. The error of the developed model's predictions, the empirical models' results with filed measurements are shown in Table 4. The average absolute error E_a is given by:

$$E_a = \left| \frac{P_{\text{calc}} - P_{\text{meas}}}{P_{\text{meas}}} \right| \times 100\% . \tag{38}$$

Table 4
Comparison of Absolute Average Error

Comparison	2,308 m		2,328 m	
	Calc. BHP /MPa	E_a	**Calc. BHP /MPa**	E_a
Developed Model	17.8	3.8	17.2	2.6
Beggs & Brill	16.3	5.0	15.7	6.2
Hasan & Kabir	18.6	8.2	18.1	8.0

As shown in Table 4, the developed model has increased the accuracy in predicting bottomhole pressure with an error of less than 4%. Since Beggs & Brill, Hasan & Kabir models are based on empirical correlations, the results shown in Table 4 indicate that the empirical models predict the bottomhole pressure reasonably, however the mechanistic model performs better.

CONCLUSION

(a) The effect of wellbore deviation on pressure and flow profile in deviated wells under UBD conditions is studied in this paper.

(b) A new mechanistic model has been developed to predict flow pattern and calculate flow behavior for each pattern in deviated annular during UBD operation.

(c) The model calculation have a good match with field data, which indicates an average absolute error of less than 4%.

REFERENCES

[1] Beggs, H. D., & Brill, J. P. (1973). A study of two-phase flow in inclined pipes. *Journal of Petroleum Technology*, *25*(5), 607-617.

[2] Harmathy, T. Z. (1960). Velocity of large drops and bubbles in media of infinite or restricted extent. *AIChE J.*, *6*, 281-288.

[3] Hasan, A. R., & Kabir, C. S. (1992). Tow-phase flow in vertical and inclined annuli. *International Journal of Multiphase Flow*, *18*(2), 279-293.

[4] Caetano, E. F., Shoham, O., & Brill, J. P. (1992). Upward vertical two phase flow through annulus. Part I: Single-phase friction factor, taylor bubble rise velocity, and flow pattern prediction. *Journal of Energy Resources Technology*, *114*(1), 1-13.

[5] Caetano, E. F., Shoham, O., & Brill, J. P. (1992). Upward vertical two phase flow through an annulus part II: Modeling bubble, slug and annular flow. *Journal of Energy Resources Technology*, *114*(1), 14-30.

[6] Taitel, Y., Barnea, D., & Duckler, A. E. (1980). Modeling flow pattern transitions for steady upward gas-liquid flow in vertical tubes. *AIChE J., 26*, 345-354.

[7] Tengesdal, J. O., Kaya, A. S., & Sarica, C. (1999). Flow pattern transition and hydrodynamic modeling of churn flow. *SPE J.*, *4*(4), 342-348.

[8] Gunn, D. J., & Darling, C. W. W. (1963). Fluid flow and energy losses in non circular conduits. Trans. *AIChE J.*, *41*, 163.

[9] Perez-Tellez, C. (2002). *Improved bottomhole pressure control for underbalanced drilling operations* (Doctoral dissertation). Louisiana State University, Philadelphia.

[10] Taitel, Y., & Barnea, D. (1983). Counter current gas-liquid vertical flow, model for flow pattern and pressure drop. *Int. J. Multiphase Flow*, *9*, 637-647.

[11] Alves, I. N., Caetano, E. F., Minami, K., & Shoham, O. (1991). Modeling annular flow behavior for gas wells. *SPE Production Engineering*, *6*(4), 435-440.

[12] Henstock, W. H., & Hanratty, T. J. (1976). The interfacial drag and the height of the wall layer in annular flow. *AIChE J.*, *22*(6), 990-1000.

[13] Wallis, G. B. (1969). *One dimensional two phase flow*. USA: McGraw-Hill.

[14] Hasan, A. R., & Kabir, C. S. (1988). A study of multiphase flow behavior in vertical wells. *SPE Production Engineering*, *3*(2), 263-272.

