Send Orders for Reprints to reprints@benthamscience.net

Open Access

Study on Applicable Conditions and Mathematic Models of Bullheading

Xiaofeng Sun[1], Kelin Wang[1,*], Tie Yan[1], Yanze Wu[2], Shizhu Luan[1] and Shuai Shao[1]

[1]*College of Petroleum Engineering, Northeast Petroleum University, Daqing City, Heilongjiang Province, China;* [2]*Sinopec International Petroleum Service Corporation, Beijing City, China*

Abstract: In the recent years, some domestic overflow and blowout events have shown that we can not apply conventional methods to successful well killing under some certain conditions, therefore, bullheading as an unconventional well killing can be considered. Bullheading by pumping kill fluid into wellbore makes the wellbore gas compressed so that bottomhole pressure exceeds formation pressure and gas leaks off to the formation. In this study, applicable conditions of bullheading have been discussed. Based on gas compressibility law and gas-liquid flow behavoir, bullheading operation is divided into three stages, including gas compression stage, gas seepage stage and gas-liquid seepage stage. The mathematical model for each stage is formulated to predict and interpret well killing mechanism. The calculated results showed good agreement with field case data. This paper might serve as an operational guideline during bullheading.

Keywords: Bullheading, applicable conditions, mathematic model, well killing.

1. INTRODUCTION

Losing control on the blowout is one of the malignant accidents during the oil and gas exploration and development, and the blowout precursor is overflown and kicked due to the formation gas or liquid invasion. Moreover, the overflow induced by gas invasion is more difficult to controlled, for example, the "12.23" catastrophic blowout accident in Kaixian of Chongqing city, not only affected the company's economic benefits, but also threatened the lives and properties of drilling staff and people surrounding the well site. In the last decade, the number of drilling deep well, extended reach well, gas well with high sour, etc, has increases in China, which presents the new challenges for blowout control techniques. In addition, some domestic overflow and blowout events have shown that conventional methods to successful well killing under some certain conditions are not applicable, therefore, it is necessary to further study the unconventional killing techniques. Bullheading as an unconventional killing technique was successfully applied such as KC-1 well [1] and Sha-46 well [2], North Buzachi Oilfield [3].

Bullheading can be used in high pressure and high permeability gas wells when gas kick or blowout occurs. In general, when conventional well killing techniques are not possible or results in serious well control conditions, bullheading may be considered [4]. Bullheading technique is through pumping kill fluid directly into wellbore or annulus when gas kick occurs, until all the influx is displaced into the exposed open hole formation and wellbore is filled with sufficient density of kill fluid to contain the reservoir pressure. In practice, bullheading applied to gas well kick with known acid gas shows obvious advantages, but the misuse of bullheading also causes serious problems of well control. Based on previous researches [5-7], this paper has mainly discussed applicable conditions of bullheading, developed the mathematical model for each stage and analyzed the variations of casing pressure and bottom pressure.

*Address correspondence to this author at the Daqing high-tech industrial development zone No.199, Daqing, Heilongjiang province, China; Post code: 163318; Tel: 0459-6503521; Fax: 0459-6503482; E-mail: wwangkelin@163.com

2. APPLICABLE CONDITIONS OF BULLHEADING

The maximum bullheading pump pressure for well killing designs and operations should refer to wellhead casing pressure. Kill fluid can be original drilling fluid or prepared weighted drilling fluid. Furthermore, kill fluid volume should comprehensively consider the increment of pits gain, the length of gas invasion column, etc. Feasibility or success of bullheading depends on whether the casing pressure reduces to zero or it is equal to the standpipe pressure. Considering bullheading is not a routine well control method, it can be utilized only when normal well killing techniques are restricted or serious problems occurred. Before bullheading job is implemented, competent authorities should conduct a detailed discussion with specialists and field engineers about the affecting factors which may arise during bullheading. Following main aspects should be considered when using this method.

(1) The good properties of formation are the necessary conditions to utilize bullheading. Preferably in permeable formation, invasion fluid can be bullheaded with a superior speed, without fracturing formation.

(2) The invasion fluid properties directly determine whether bullheading ycan be carried out. Therefore, it is not recommended to use the method for oil and water invasion. Obviously, gas can be easier to be displaced into formation during bullheading process, but oil, water and other high viscosity fluids have greater resistance in the process of seepage into formation, and may even form fracture.

(3) The position of casing shoe is an important factor considered for bullheading. We hope casing is run as deep as possible, that is, open hole interval is very short, which means that it can avoid fracture formation to a great extent.

(4) Bullheading operations are required to have a high internal pressure strength of casing, to avoid casing bursts during bullheading process. In general, maximum wellhead pressure is not allowed to exceed eighty percent of the internal pressure strength of casing according to the well control criterion.

3. IDEAL FLOW MODEL OF BULLHEADING

After gas kick or blowout occurs, kill fluid directly pumps into wellbore or annulus. Hence, kill fluid and gas move in opposite direction and collide with each other. As shown in Fig. (**1**), the ideal model assumes that there is a plastic plug between kill fluid and gas interface. The plastic plug hinders the combination of kill fluid and gas, which makes all the wellbore to divide into gas- and liquid-phase zone. As bullheading operations go on, gas is continuously compressed until the plastic plug reaches the bottom hole, and bullheading ends. The process is referred as ideal physical model of bullheading. The model has such advantage of simple calculation and easy to use that is why it is widely used. However, it doesn't consider the effect of gas slippage on well killing operations, which leads to a huge gap between calculated results and field tests.

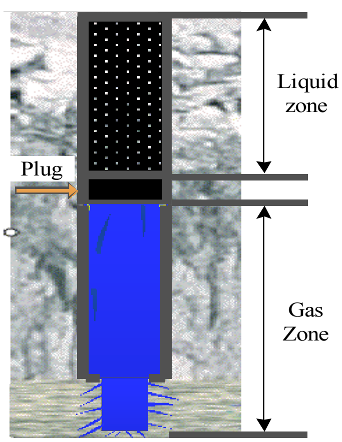

Fig. (1). The schematic of ideal wellbore model during bullheading process.

4. GAS-LIQUID TWO-PHASE FLOW MODEL OF BULLHEADING

In the actual process of bullheading, density differences lead to gas slippage along wellbore, and the gas-liquid mixture zone is formed in a certain interval of wellbore with the passage of time. The velocity in its upper interface is less than the liquid-phase zone, but in lower interface it is greater. Therefore, the mixture zone grows gradually during bullheading, as shown in Fig. (**2**), there eventually exists liquid-phase zone, mixture zone and gas-phase zone in the wellbore. Based on the gas-liquid flow behavior and gas compressibility characteristic, the well killing operations can be divided into three stages.

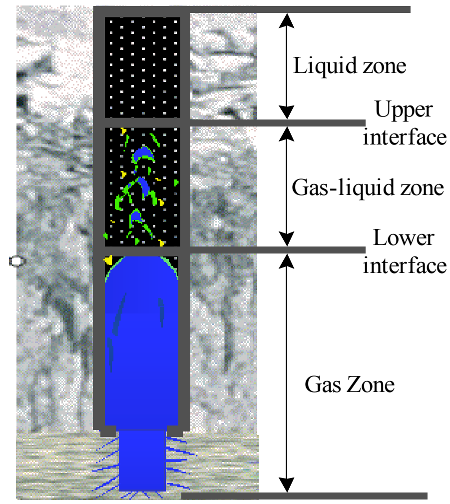

Fig. (2). The schematic of three zones partition during bullheading process.

Gas compression stage: The gas is only compressed, so the pressure rises constantly and the total volume decreases, but the gas mass remains constant. Gas begins to leak off into formation when the bottom pressure reaches the formation pressure.

Gas seepage stage: As gas leaks off to formation, kill fluid is continuously pumped into wellbore until bottom pressure becomes slightly greater than the formation pressure. When the mass of gas-phase zone continuously reduces to be fully bullheaded, the lower interface reaches the bottom.

Gas-liquid seepage stage: Gas and liquid are simultaneously squeezed back into formation as kill fluid is continuously pumped. Bullheading operations end until the upper interface of the mixture zone reaches the bottom. The key for successful well killing is to accurately calculate the length of two-phase mixture zone, which determines the total volume of kill fluid and kill time.

In view of the complexity of real process, the following assumptions are made:

(1) The liquid is incompressible, and it has the same physical property in the system.

(2) The temperature gradient is constant or the function of temperature is known.

(3) The open hole formation is homogeneous and the flow is radial.

(4) In mixture zone, both liquid and gas are commingled uniformity.

(5) Killing well is completed when upper interface of mixture zone reaches the bottom.

4.1. Mathematic Models for Gas Compression and Seepage Stage

It has already been noted that when the formation fluid is gas, the compressibility must be considered. The gas compressibility equation is mathematically given by [8]:

$$C_{\mathrm{g}} = -\frac{dV}{V_{\mathrm{gi}}dp} \tag{1}$$

As kill fluid is pumped into wellbore, the gas will be subjected to compression. Equation (1) by integration combined with the correlation C_{g} [9] can be rewritten by:

$$p_{\mathrm{wf}} = p_{\mathrm{wfi}} + \frac{q(t)-q}{ZV_{\mathrm{gi}}}(Zp_{\mathrm{c}} + \rho_{\mathrm{pr}}p_{\mathrm{c}}(\frac{\partial Z}{\partial \rho_{\mathrm{pr}}})_{T_{\mathrm{pr}}})t \tag{2}$$

Where Z is a gas deviation factor, and the Dranchuk *et al.*'s equation [10] is used. ρ_{pr} is the pseudoreduced temperature, $\rho_{\mathrm{pr}} = 0.27p_{\mathrm{wf}}/(Zp_{\mathrm{c}}T_{\mathrm{pr}})$.

During the process of well killing, casing pressure can be obtained from:

$$p_{\mathrm{a}} = p_{\mathrm{wf}} - \rho_{\mathrm{m}}L_{\mathrm{m}}g - \rho_{\mathrm{l}}L_{\mathrm{l}}g - \rho_{\mathrm{g}}L_{\mathrm{g}}g + \Delta p \tag{3}$$

The friction loss of full gas flow is ignored in the study, and the liquid-phase and mixture-phase friction losses can be expressed by:

$$\Delta p = \frac{2f_{\mathrm{l}}L_{\mathrm{l}}\rho_{\mathrm{l}}v_{\mathrm{l}}^2}{d_{\mathrm{h}}} \text{ or } \Delta p = \frac{2f_{\mathrm{m}}L_{\mathrm{m}}\rho_{\mathrm{m}}v_{\mathrm{m}}^2}{d_{\mathrm{h}}} \tag{4}$$

In the equation (4), the friction factors are given by:

$$f_{\mathrm{l}} = \frac{32}{\mathrm{Re}_{\mathrm{l}}} \text{ or } f_{\mathrm{m}} = \frac{32}{\mathrm{Re}_{\mathrm{m}}} \text{ for laminar conditions} \tag{5}$$

$$f_{\mathrm{l}} = 0.0295\left(\frac{\mu_{\mathrm{l}}}{\rho_{\mathrm{l}}d_{\mathrm{h}}v_{\mathrm{l}}}\right)^{0.2} \text{ or } \frac{1}{\sqrt{f_{\mathrm{m}}}} = -2.01\lg\left(\frac{\varepsilon}{3.7065d_{\mathrm{h}}} + \frac{2.5226}{\mathrm{Re}_{\mathrm{m}}\sqrt{f_{\mathrm{m}}}}\right)$$

for turbulent conditions (6)

Due to gas leak-off rate as function of time, the unsteady flow equation will be given by [11]:

$$p_{\mathrm{r}} - p_{\mathrm{wf}} = \frac{Z_{\mathrm{i}}T\mu_{\mathrm{gi}}q}{18160khp_{\mathrm{r}}B_{\mathrm{g}}}\left[\ln\left(\frac{kt}{250\gamma\varphi\mu_{\mathrm{g}}C_{\mathrm{t}}r_{\mathrm{w}}^2}\right) + 2S_{\mathrm{a}}\right] \tag{7}$$

Where S_{a} related to flow rate is the apparent skin factor, and gas viscosity μ_{g} is calculated by using Carr *et al's* correlation [12]. Owing to the fact that the gas flows from wellbore into the reservoir during bullheading, the above equation can be rearranged as:

$$q = \frac{18160khp_{\mathrm{r}}B_{\mathrm{g}}}{Z_{\mathrm{i}}T\mu_{\mathrm{gi}}\left[\ln\left(\frac{kt}{250\gamma\varphi\mu_{\mathrm{g}}C_{\mathrm{t}}r_{\mathrm{w}}^2}\right) + 2S_{\mathrm{a}}\right]}(p_{\mathrm{wf}} - p_{\mathrm{r}}) \tag{8}$$

Where

$$\gamma = M/28.97$$

$$B_{\mathrm{g}} = 3.4582\times10^{-4}ZT/p_{\mathrm{wf}}$$

The velocity in the mixture zone should be considered to calculate the length of mixture zone. The drift flux model for gas-liquid two-phase flow in downward vertical pipe is utilized to determine the interface velocity in this study [13-16].

$$v_{\mathrm{g}} = C_0v_{\mathrm{m}} - v_{\infty} \tag{9}$$

$$\alpha_{\mathrm{g}}(t) = \frac{v_{\mathrm{sg}}}{C_0v_{\mathrm{m}} - v_{\infty}} \tag{10}$$

Where v_{∞} is the rising velocity of gas in static liquid and can be calculated by the Ha Marseille formulation.

$$v_{\infty} = 1.53\left[g\sigma\left(\rho_{\mathrm{l}} - \rho_{\mathrm{g}}\right)/\rho_{\mathrm{l}}^2\right]^{1/4} \tag{11}$$

Through the analysis of the experimental data [17-19]. Hasan [20] recommends C_0=1.2, v_{∞}=0.24. Therefore, the velocity in upper interface is written as:

$$v_{\mathrm{ml}} = C_0v_{\mathrm{l}} - v_{\infty} \tag{12}$$

Where v_{l} is the flow rate of kill fluid in the casing or annulus, $v_{\mathrm{l}} = q(t)/A$.

According to the upper interface velocity, the lower interface velocity can be given by:

$$v_{\mathrm{mg}} = \frac{dL_{\mathrm{g}}}{dt} = v_{\mathrm{ml}} + \frac{v_{\mathrm{l}} - v_{\mathrm{ml}}}{1-\alpha_{\mathrm{g}}(t)} \tag{13}$$

By integrating equation (13), the liquid zone length can be obtained by:

$$L_{\mathrm{g}} = H - (v_{\mathrm{ml}} + \frac{v_{\mathrm{l}} - v_{\mathrm{ml}}}{1-\alpha_{\mathrm{g}}(t)})t \tag{14}$$

In the above correlations, the densities of mixture phase and gas phase are given by:

$$\rho_{\mathrm{m}} = (1-\alpha_{\mathrm{g}}(t))\rho_{\mathrm{l}} + \alpha_{\mathrm{g}}(t)\rho_{\mathrm{g}} \tag{15}$$

$$\rho_{\mathrm{g}} = \frac{Mp_{\mathrm{wf}}}{ZRT} \tag{16}$$

4.2. Mathematical Model for Gas-Liquid Seepage Stage

In this stage, both gas and liquid are simultaneously displaced into formation. In order to avoid the high bottom pressure during bullheading process which fractures the formation, the gas-liquid two-phase flow is kept steady, and can be expressed by:

$$p_{\mathrm{wf}} = p_{\mathrm{a}} + \rho_{\mathrm{l}}gL_{\mathrm{l}} + \rho_{\mathrm{m}}gL_{\mathrm{m}} - \Delta p \tag{17}$$

5. FIELD CASE SIMULATION

When a well is drilled down to about 4587 m, gas kick occurs. The total overflow reached 30 m^3, and casing pressure is 17 MPa after shut in. Based on bottom hole assembly and wellbore size, the overflow is converted into the length of gas column up to 1207 m. Through the analysis of overflow characteristics and required operational conditions, kill fluid flow rate is controlled between 16 and 20 L/s, and kill job lasts about 50 min. Finally, the entire gas is squeezed back into formation, and the job finishes waiting to be circulated by the weight drilling fluid. The detailed parameters of the well are shown in Table **1**. The above models are applied to predict the casing pressure and bottom pressure, and the results are shown in Figs. (**3**) and (**4**).

Table 1. The Measured Well Parameters

Mud density (g/cm^3)	Drill pipe diameter (mm)	Wellbore diameter (mm)	Temperature gradient (°C/100m)	Formation porosity (%)	Empty bubble rate (%)	Casing pressure (MPa)
1.25	127	215.9	3	10	20	17

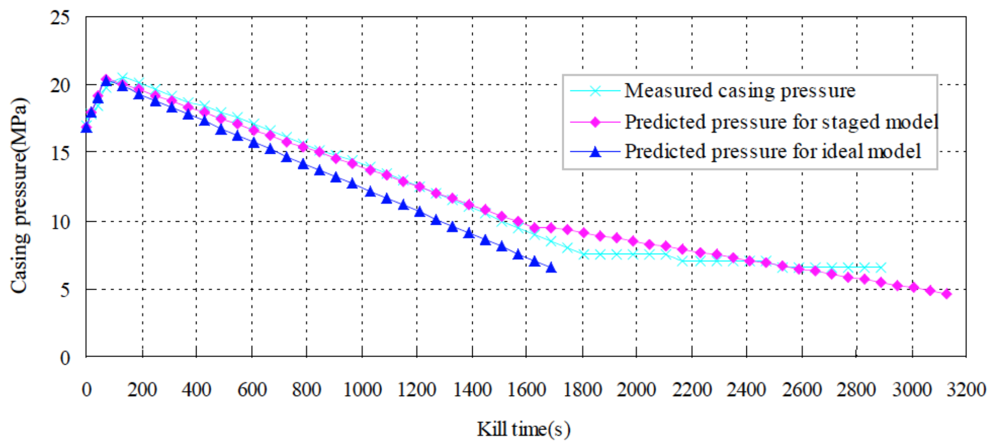

Fig. (3). The comparison of predicted casing pressure and measured pressure.

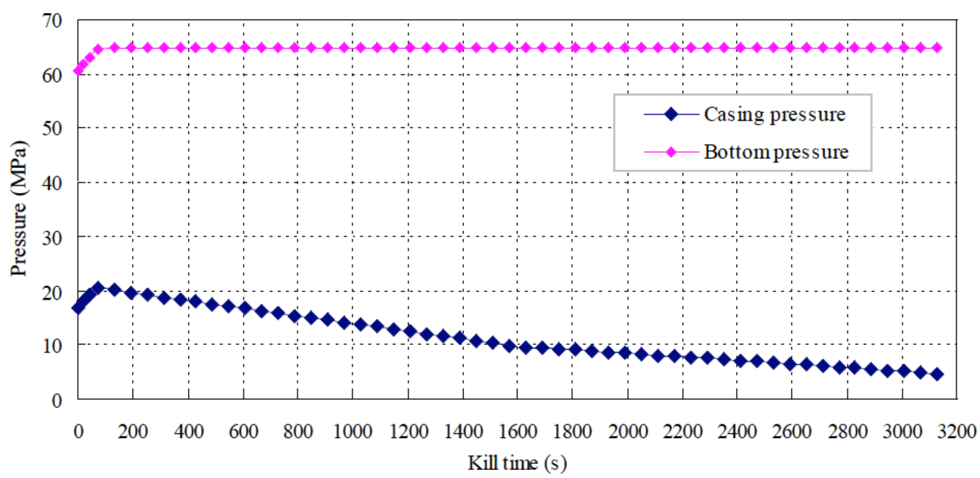

Fig. (4). The calculated results in terms of observed well casing and bottom pressure.

As shown in Fig. (**3**), field test demonstrates that there are three stages in a bullheading process. The ideal model doesn't consider the gas slippage, and there only exists the gas compression stage and gas seepage stage during bullheading process, which make a big difference with field test. But the proposed model considers that gas slippage has a good agreement with measured casing pressure, and also, the entire bullheading process is completely depicted.

As shown in Fig. (**4**), in the beginning stage, both casing pressure and bottom pressure rapidly increase which kill fluid is pumped. When gas begins to leak off to formation, casing pressure gradually decreases, but bottom pressure slightly increases. When both gas and liquid are simultaneously squeezed into formation, casing pressure continues to decrease and bottom pressure remains consant. It is obvious that the maximum bottom pressure and minimum casing pressure are presented in the gas-liquid seepage stage, as a result, the two magnitudes can be referred for designing well killing parameters.

CONCLUSIONS

(1) According to the characteristics of bullheading operations, in order to achieve efficient well controlled without any fracture formation, these necessary conditions should be considered, including higher formation permeability, setting depth of casing close to bottom, wellhead and casing string strength bearing the maximum pressure during operations.

(2) Bullheading process can be divided into three continuous stages on the basis of gas compressibility law and gas-liquid flow behavior. Combining the drift flux model with unsteady gas flow equation can be applied to depict well killing models, and predicted results when compared with field case data showed a higher accuracy. Following

three stages of bullheading, bullheading process would be controlled better, when each parameter is dominated.

(3) During bullheading process, in the gas compression stage, casing pressure and bottom pressure rapidly increase. When well killing enters into gas seepage stage, the casing pressure begins to decrease, and bottom pressure slightly increases. As both gas and liquid simultaneously seep into formation, casing pressure continues to decrease, and bottom pressure remain constant.

CONFLICT OF INTEREST

The author(s) confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENT

The support of National Science and Technology Major Project of China (No. 2011ZX05009-005) and the National Natural Science Foundation of China (No. 51174043, No. 51204056) are gratefully acknowledged.

NOMENCLATURE

A = Wellbore or annulus area, m^2
B_g = Volume factor
C_g = Gas compressibility factor, MPa^{-1}
C_t = Total compressibility factor, MPa^{-1}
C_0 = Flow coefficient
d_h = Hydraulic diameter, m
f_m = Mixture flow factor
f_l = Liquid-phase flow factor
H = Well depth, m
h = Effective formation height, m
L_l = Liquid-phase zone length, m
L_{lg} = Mixture zone length, m
L_g = Gas-phase zone length, m
M = Average molecular weight of gas, g/mol
p_{wf} = Bottom pressure, MPa
p_{wfi} = Initial bottom pressure, MPa
p_c = Critical pressure of the gas, MPa
p_a = Casing pressure, MPa
p_r = Formation pressure, MPa
q = Gas leak-off rate, m^3/s
$q(t)$ = Kill fluid rate, m^3/s
Re_m = Reynolds number for mixture zone
r_w = Wellbore radius, m
S_a = Apparent skin factor
T = Formation temperature, k
t = Kill time, s
T_{pr} = Pseudoreduced temperature of the gas
v_m = Mixture flow rate, m/s
v_l = Liquid flow rate, m/s
v_g = Gas velocity, m/s
V_{gi} = Initial gas volume, m^3
Z = Deviation factor
Z_i = Initial deviation factor
ρ_l = Kill fluid density, g/cm^3
ρ_{lg} = Mixture zone density, g/cm^3
ρ_g = Gas density, g/cm^3
μ_l = Liquid-phase viscosity, Pa·s
μ_g = Gas viscosity, mPa·s
μ_{gi} = Initial gas viscosity, mPa·s
ε = Wellbore roughness, m
γ = The specific gravity
k = Formation permeability, D
ϕ = Formation porosity, %
$\alpha_g(t)$ = Empty bubble rate, %
σ = Interfacial tension, Pa

REFERENCES

[1] H.J. Liang, X.D. Deng, L.C. Jia, and Z.X. Xu, "Down hole trouble shooting techniques in KC-1 well", *Oil Drilling & Production Technology*, vo1. 19, pp. 35-39, 1997.
[2] B.W. Li, " Kick treatment measures for tabei Sha-46 well and understanding", *Petroleum Drilling Techniques*, vol. 26, pp. 14-15, 1998.
[3] H. Chen, Z.H. Li, and J.G. Huang, "Applications of bullheading in the north buzachi oilfield", *West-china Exploration Engineering*, vol. 10, pp. 96-98, 2008.
[4] D.G. Robert, *Blowout and well control manual*. Beijing: Petroleum Industry Press, 2006.
[5] P. Oudeman, D.T. Avest, E.O. Grodal, H.A. Asheim, and R.J.H Meissner, *Bull Heading To Kill Live Gas Wells*, presented at European Petroleum Conference, 1994, pp. 303-310.
[6] P. Oudeman, *Kill Procedures to Avoid Formation Damage in the High Rate Gas Wells of an Underground Storage Project*, presented at European Formation Damage Conference, 1999, pp. 1-6.
[7] V.G. Vallejo-Arrieta, "*Analytical Model to Control off Bottom Blowouts Utilizing the Concept of Simultaneous Dynamic Seal and Bullheading*", University of Louisiana, Louisiana, U.S.A., 2002.
[8] R.A. Wattenbarger, and H.J. Ramey, "Gas well testing with turbulence, damage and wellbore storage", *Journal of Petroleum Technology*, vol. 20, pp. 877-887, 1999.
[9] Y.F. Tan, and D.B. Yang, "Calculation of gas isothermal compressibility factor", *Journal of Harbin University of C.E. & Architecture,* vol. 32, pp. 65-67, 1999.
[10] B.C. Craft, and M.F. Hawkins, *Applied Petroleum Reservoir Engineering*, 2nd ed. New Jersey: Prentice-Hall, Inc, 1991.
[11] C.L. Li, *Fundamentals of Reservoir Engineering*. Beijing: Petroleum Industry Press, 2005.
[12] Syllabus. *PETE 7201-Flow in Porous Media*. The Craft and Hawkins Department of Petroleum Engineering, Louisiana State University, Baton Rouge, 1999.
[13] N. Zuber, and J. Findlay, "Average volumetric concentration in two-phase flow systems", *ASME Journal of Heat Transfer*, pp. 87-453, 1965.
[14] G.W. Govier, and K. Aziz. *The Flow of Complex Mixtures in Pipes*. New York: Van Nostrand Reinhold Co., 1972.
[15] A.R. Hasan, and C.S. Kabir, "Predicting multiphase flow behavior in a deviated well", *SPE Production Engineering*, vol. 3, pp. 474-482, 1988.

[16] A.R. Hasan, *Inclined Two-Phase Flow: Flow Pattern, Void Fraction and Pressure Drop in Bubbly, Slug and Chum Flow, Particulate Phenomena and Multiphase Transport*. New York: Hemisphere Publishing Corp, 1988.

[17] H.D. Beggs, "*An Experimental Study of Two-Phase Flow in Inclined Pipes*", University of Tulsa, Tulsa, U.S.A, 1972.

[18] H. Mukherjee, "*An Experimental Study of Inclined Two-Phase Flow*", University of Tulsa, Tulsa, U.S.A, 1979.

[19] S. Kokal, "*Study of Two-Phase Flow in Inclined Pipes*", University of Calgary, Calgary, Canada, 1987.

[20] A.R. Hasan, "Void fraction in bubbly and slug flow in downward vertical and inclined systems", *SPE Production & Facillities*, vol. 10, pp.172-176, 1995.

Received: May 15, 2013 Revised: December 06, 2013 Accepted: December 18, 2013

© Sun *et al.*; Licensee *Bentham Open.*

This is an open access article licensed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/-licenses/by-nc/3.0/) which permits unrestricted, non-commercial use, distribution and reproduction in any medium, provided the work is properly cited.