Open Journal of Yangtze Gas and Oil, 2019, 4, 100-112
http://www.scirp.org/journal/ojogas
ISSN Online: 2473-1900
ISSN Print: 2473-1889

Analysis of Gas and Liquid Two-Phase Slug Flow Production Logging Interpretation Model in near Horizontal Shale Gas Wells

Hongwei Song[1*], Haimin Guo[2], Sihui Xu[1]

[1]School of Geophysics and Oil Resources, Yangtze University, Wuhan, China
[2]Key Laboratory of Exploration Technologies for Oil and Gas Resources (Yangtze University), Ministry of Education Hubei, Wuhan, China
Email: *shw98wj@yangtzeu.edu.cn

How to cite this paper: Song, H.W., Guo, H.M. and Xu, S.H. (2019) Analysis of Gas and Liquid Two-Phase Slug Flow Production Logging Interpretation Model in near Horizontal Shale Gas Wells. *Open Journal of Yangtze Gas and Oil*, **4**, 100-112.
https://doi.org/10.4236/ojogas.2019.42008

Received: August 3, 2018
Accepted: April 16, 2019
Published: April 19, 2019

Abstract

The development of shale gas reservoir is mainly based on horizontal well production. Slug flow of gas-liquid two-phase is invariably encountered in inclined wells and horizontal wells of a producing environment. Due to gravitational differentiation, oil-water two-phase flow pattern, the local velocity and local phase holdup along the radial direction of pipe in near horizontal wells will perform complicatedly. This paper presented the results of an experimental study and a theoretical analysis of two-phase gas/water flow in horizontal and highly inclined systems. Extensive experiments were conducted using a test loop made of 124 mm diameter acrylic pipe with inclination angles from the horizontal of 0˚, 5˚, 15˚, 45˚, −2˚, −5˚ and −10˚, and with the total flow rate ranging from 50 to 800 m^3/day. Based on the research on the law of slug flow dynamics model for gas-water two-phase flow in near horizontal pipeline, the theoretical analysis and experimental researches were done to propose the expressions of stable and exact production logging interpretation model for two-phase flow in near horizontal pipeline. The performance of the proposed method for estimating water holdup and water superficial velocity is in good agreement with our measurements. As a result, the slug flow dynamics model of gas-water two-phase flow in near horizontal wellbore was developed. The application effect of production logging in near horizontal wells had been improved.

Keywords

Near Horizontal Well, Gas-Water Two-Phase Flow, Slug Flow, Production Logging

1. Introduction

As an unconventional energy source, the shale gas plays an important role in the global energy structure. The horizontal well mining method has obvious advantages in the development of shale gas reservoirs. Horizontal well production in shale gas reservoir is a mining technology developed after N2 fracturing, foam fracturing, gel fracturing, clear water fracturing and so on [1]. The drilling depth of these horizontal wells is about 1500 - 2500 m with high inclination. And the horizontal production section is 600 - 1600 m with 41/2 in (1 in = 25.4 mm) or 51/2 in casing and 23/8 in tubing usually [2]. **Figure 1** illustrates a multiphase production regime across a horizontal well.

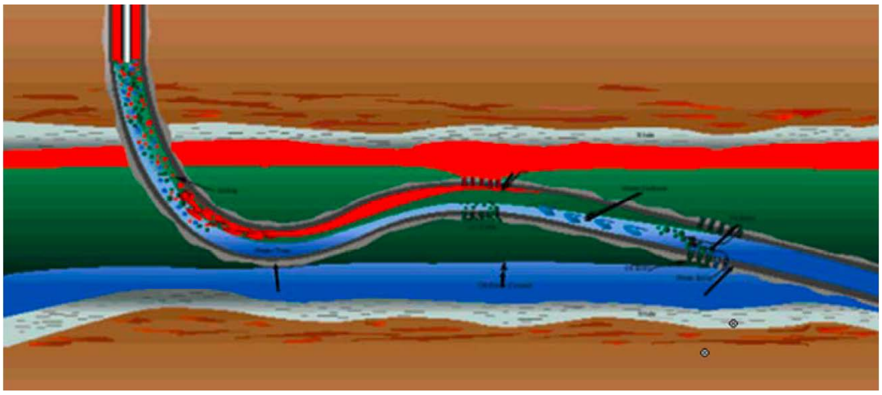


Figure 1. Horizontal well production illustration [2].

Accurate horizontal well production logging and interpretation evaluation technology undoubtedly provide a reliable basis for efficient development. The demand is also growing for well logging at horizontal and large inclined wells. Production profile logging is the main technical means for monitoring the production dynamics of production wells and is one of the important supporting technologies for the development of horizontal wells. The characteristics of gas-liquid two-phase flow in near horizontal wells are important for the establishment of the interpretation models of production profile logging data. And production wells are in the best state of production and the oil recovery is improved.

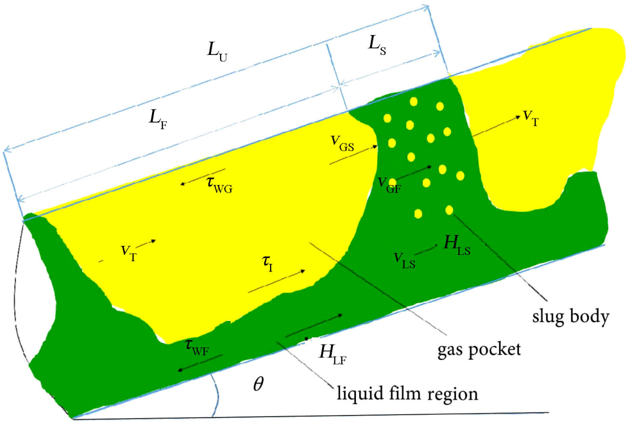
Slug flow is a common flow pattern in the horizontal or slightly inclined production oil-gas wells and oil-gas pipeline, which is the alternation of the liquid plug body and the long air bag in space and time, and that shows intermittent and unstable characteristics during the flow process [3]. Its flow mechanism is complex and its characteristic parameters are in large quantity. Since 1970s, researchers have used different methods to simulate the motion characteristics of slug flow, and put forward a variety of semi empirical slug flow models, such as drift flow model and slippage model. These models did not make a formal analysis of the slug flow, and the complex characteristics of the slug flow were not accurately described. Besides, the model is too simple. Therefore, the accuracy and application scope of the models are limited [3].

Slug flow and stratified flow often occur in the normal operation of oil and gas well production and oil and gas mixed transportation, and the slug flow is more frequent. Slug flow is almost always inevitable in long-distance pipeline. Actually, many researches on multi-phase flow of oil and gas mixed transportation are to study slug flow characteristics [4]. Therefore, it is necessary to study the flow characteristics of the slug flow in detail and reveal the characteristics of its fluctuation in the field, so as to effectively guide the dynamic monitoring logging evaluation and the design and operation of the pipeline system [3].

In this paper, a dynamic model of gas-liquid slug flow was established on the basis of the dynamic characteristics of gas-liquid two phase flow. By using a ground multiphase flow loop simulation experiment device, the internal relationship between the liquid holdup and the two-phase characteristic parameters of the slug flow in the horizontal and large inclined tubes was studied on the basis of the simulated well gas water two phase dynamic experiment to get a more perfect and more comprehensive law. The law can better guide the logging interpretation of horizontal and large inclined well production profile, and improve the production logging application technology.

2. The Theoretical Model of Gas-Liquid Slug Flow

For the convenience of analysis, it takes a section of the continuous flow tube with typical characteristics as a slug body unit. The typical model characteristics of a single slug unit are shown in **Figure 2**, which consists of three parts: liquid slug body, liquid film region and gas pocket [5] [6].



L_U is length of slug unit, L_F is length of liquid film, L_S is length of liquid slug, v_{LS} is in-situ liquid velocity in liquid film, v_{GS} is in-situ gas velocity in liquid slug, v_{LF} is in-situ liquid velocity in liquid slug, v_T is the translational velocity of the slug（It is front velocity of the slug body or gas pocket）, v_{GF} is in-situ gas velocity in Taylor bubble, H_{LF} is liquid holdup in liquid film, H_{LS} is liquid holdup in liquid slug, τ_{WG} is wall friction shear for the gas phase, τ_{WF} is wall friction shear for the film region, τ_I is interracial fric-tion shear, θ is inclination angle of the pipe

Figure 2. Physical model for slug flow.

2.1. The Mass Conservation Model of Slug Flow

For a slug body unit in which the slug body is stable, its translational velocity is equal to the slug head velocity and airbag velocity v_T. The average liquid mass flow rate over the time of the passage of a slug unit is [5] [7]

$$W_L = \frac{1}{T_U}\left(v_{LS} A H_{LS} \rho_L T_S + \int_0^{T_F} v_{LF} A H_{LF} \rho_L \mathrm{d}t\right) \tag{1}$$

where W_L is the input (or average) mass flow rate, kg/s; T_U, T_S, and T_F are the times for the passage of the slug unit, the liquid slug, and the liquid film/gas pocket, s; A is the pipe cross-sectional area, m^2; ρ_L is liquid phase density, kg/m^3.

$$T_U = \frac{L_U}{v_T}, \quad T_S = \frac{L_S}{v_T}, \quad T_F = \frac{L_F}{v_T} \tag{2}$$

If the liquid film height is stable, the superficial velocity of the liquid phase and gas phase of the slug body unit are respectively as follows.

$$v_{SL} = v_{LS} H_{LS} \frac{L_S}{L_U} + \frac{L_F}{L_U} v_{LF} H_{LF} \tag{3}$$

$$v_{SG} = v_{GS}\left(1 - H_{LS}\right)\frac{L_S}{L_U} + \frac{L_F}{L_U} v_{GF}\left(1 - H_{LF}\right) \tag{4}$$

where v_{SL} is the superficial velocity of the liquid phase; v_{SG} is the superficial velocity of the gas phase.

Because of that $T_U = T_S + T_F$, the length of the whole slug element can be expressed as follows.

Then the total length of the slug unit can be derived from Equation (1):

$$L_U = L_S\left(\frac{v_{LS} H_{LS} - v_{LF} H_{LF}}{v_{SL} - v_{LF} H_{LF}}\right) = L_S\left[\frac{v_{GS}\left(1 - H_{LS}\right) - v_{GF}\left(1 - H_{LF}\right)}{v_{SG} - v_{GF}\left(1 - H_{LF}\right)}\right] \tag{5}$$

For the liquid slug body, the head of the slug moves forward at a velocity v_T. And it wraps the slow flow of fluid in the liquid film at a volume flow Q_{in} ($v_T > v_{LF}$). At the tail of the liquid slug, the liquid in the liquid film moves at a velocity of v_{LS}. Slug tail moves at airbag velocity v_T. As v_T is greater than v_{LS}, the amount of the remaining liquid slug tail is Q_{out}. With v_T as the reference coordinate, the followings are the liquid volume flow into the slug head and the amount of the remaining liquid of the slug tail respectively [5] [6].

$$Q_{in} = \left(v_T - v_{LF}\right) H_{LF} A \tag{6}$$

$$Q_{out} = \left(v_T - v_{LS}\right) H_{LS} A \tag{7}$$

When the liquid slug is stable, according to the law of conservation of mass, the mass flow rate of liquid into and out of the liquid slug is equal for the whole slug body unit.

$$\rho_L Q_{in} = \rho_L Q_{out} \tag{8}$$

$$\left(v_T - v_{LF}\right) H_{LF} = \left(v_T - v_{LS}\right) H_{LS} \tag{9}$$

That is, the liquid mass flow in liquid slug and liquid film is equal.

Similarly, the mass flow rate of gas phase in liquid slug and air bag is also equal.

$$\left(v_{\mathrm{T}}-v_{\mathrm{GF}}\right)\left(1-H_{\mathrm{LF}}\right)=\left(v_{\mathrm{T}}-v_{\mathrm{GS}}\right)\left(1-H_{\mathrm{LS}}\right) \tag{10}$$

For the whole slug unit, its average liquid holdup H_{LU} is defined by

$$H_{\mathrm{LU}}=\frac{H_{\mathrm{LS}}L_{\mathrm{S}}+H_{\mathrm{LF}}L_{\mathrm{F}}}{L_{\mathrm{U}}} \tag{11}$$

From Equations (3), (4), (9) and (11), the average liquid holdup of the whole slug unit can be expressed by

$$\begin{aligned} H_{\mathrm{LU}} &= \frac{H_{\mathrm{LS}}v_{\mathrm{T}}+\left(1-H_{\mathrm{LS}}\right)v_{\mathrm{GS}}-v_{\mathrm{SG}}}{v_{\mathrm{TB}}}=\frac{H_{\mathrm{LF}}v_{\mathrm{T}}+\left(1-H_{\mathrm{LF}}\right)v_{\mathrm{GF}}-v_{\mathrm{SG}}}{v_{\mathrm{TB}}} \\ &= \frac{H_{\mathrm{LF}}v_{\mathrm{T}}+v_{\mathrm{SL}}-H_{\mathrm{LF}}v_{\mathrm{LF}}-v_{\mathrm{SG}}}{v_{\mathrm{T}}} \end{aligned} \tag{12}$$

2.2. Momentum Conservation Model of Slug Flow

If the height of the liquid film is stable, the liquid film and the airbag are similar to the stratified flow in the slug body unit, and the momentum equation is

$$\tau_{\mathrm{WF}}\frac{S_{\mathrm{L}}}{A_{\mathrm{L}}}-\tau_{\mathrm{WG}}\frac{S_{\mathrm{G}}}{A_{\mathrm{G}}}-\tau_{\mathrm{I}}S_{\mathrm{I}}\left(\frac{1}{A_{\mathrm{L}}}+\frac{1}{A_{\mathrm{G}}}\right)+\left(\rho_{\mathrm{L}}-\rho_{\mathrm{G}}\right)g\sin\theta=0 \tag{13}$$

where A_{L} is cross-sectional area available to the liquid phase, m^2; A_{G} is cross-sectional area available to the gas phase, m^2; S_{L} is wetted periphery for the liquid phase, m; S_{G} is no-wetted periphery for the liquid phase, m; S_{I} is wetted periphery for the interface, m; g is gravitational acceleration, m/s^2; ρ_{G} is gas phase density, kg/m^3.

The momentum equation is an implicit equation of liquid holdup rate H_{LF} and gas/liquid superficial velocity v_{LF}, v_{GF}.

2.3. Calculation of Related Parameters

Evaluation of the correlations and models was based on the statistical parameters in the above equations. In the horizontal and vertical pipe flow, the length of the slug in the stable slug body unit is respectively as follows [5].

$$L_{\mathrm{S}}=30D \qquad (\theta=0) \tag{14}$$

$$L_{\mathrm{S}}=20D \qquad (\theta=90) \tag{15}$$

where D is the inner diameter of the pipe.

In near-level large-diameter pipe flow ($\theta=\pm1^{\circ}$, $D>2\mathrm{in}$), the formula given by Scott *et al.* [5] [8] is as follows.

$$\ln\left(L_{\mathrm{S}}\right)=-25.4+28.5\left[\ln\left(D\right)\right]^{0.1} \tag{16}$$

In the inclined pipe section, the formula given by Zhang Hongquan *et al.* [5] [8] is

$$L_{\mathrm{S}}=30D\cos^2\theta+20D\sin^2\theta \tag{17}$$

The prediction formula of liquid holdup in liquid slug is given by Gomez *et al.*

[9] [10].

$$H_{\text{LS}} = 1.0\text{e}^{-\left(7.85\times10^{-3}\theta + 2.48\times10^{-6}R_{\text{eSL}}\right)},\quad \left(0 \le \theta \le 90^\circ\right) \tag{18}$$

where R_{eSL} is the apparent Reynolds number of the slug body.

The apparent Reynolds number of the slug body in the formula is as follows [4] [6].

$$R_{\text{eSL}} = \frac{Dv_{\text{M}}\rho_{\text{L}}}{\mu_{\text{L}}} \tag{19}$$

$$v_{\text{T}} = C_0 v_{\text{M}} + \left(0.542\sqrt{gD}\cos\theta + 0.351\sqrt{gD}\sin\theta\right) \tag{20}$$

where v_{M} is the average flow rate of the fluid [11].

The gas phase velocity in the liquid slug body is

$$v_{\text{GS}} = C_1 v_{\text{M}} + v_{0\infty}\sin\theta H_{\text{LS}}^{0.5} \tag{21}$$

where C_1 is the velocity distribution coefficient and Chokshi *et al.* [12] suggested that C_1 *is equal to* 1.15. $v_{0\infty}$ is the bubble rising velocity. Harmathy [13] suggest it was calculated using the following formula with correlation study.

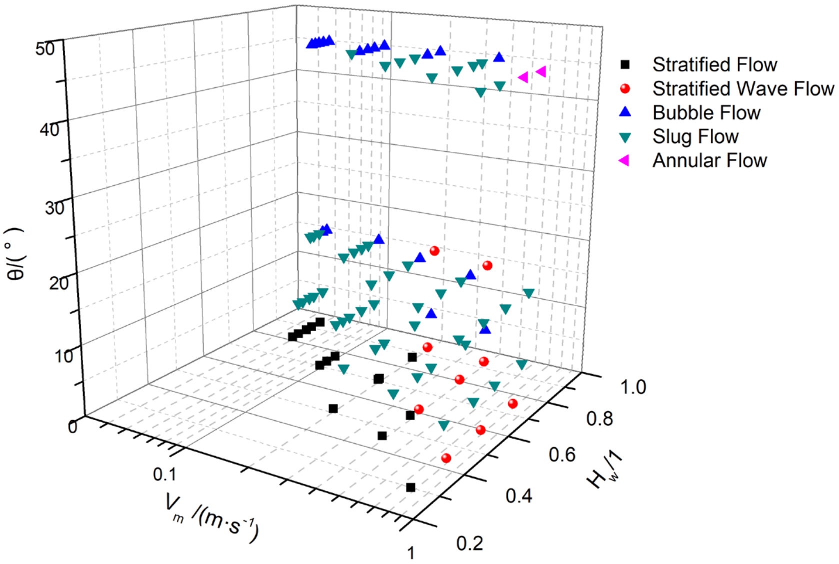
$$v_{0\infty} = 1.53\left(\frac{g\sigma\left(\rho_{\text{L}} - \rho_{\text{G}}\right)}{\rho_{\text{L}}^2}\right)^{0.25} \tag{22}$$

where σ is the viscosity of the liquid.

3. Experimental System and Experiment

The experiment was completed at the horizontal well and high inclination angle flow simulation test facility of Yangtze University. The two simulation wellbore holes of the test flow loop are 16 m organic transparent glasses with inner diameter of 159 mm and 124 mm respectively. The mobile loop can be set at any angle between the horizontal and the vertical. The experimental conditions are air and tap water. The experimental conditions are 16˚C and 1 atm, and the density of gas and water is 0.0012 g/cm^3 and 0.9992 g/cm^3 respectively. 5 flows were used from low to high in the whole experiment. v_M was 50, 100, 200, 400 and 800 m^3/d respectively, the inclination angle of corresponding horizontal direction was 0˚, 5˚, 15˚, 45˚, −2˚, −5˚, −10˚ respectively, and the moisture content was 0%, 10%, 30%, 50%, 70% and 90% respectively. The instantaneous shut well holdup was measured under each experiment. The fast cutting valve was installed in the two sections of the simulated wellbore. The closing time interval of the two valve was less than 0.5 s. After that, the vertical wellbore was simulated and the liquid height was measured. Thus the water holdup in the shut well was calculated, and the measured value was taken as the standard holdup.

In order to simulate the mixed flow of gas and water in the near horizontal well, the smooth stratified flow (SF), the wave stratified flow (SWF), the bubble flow (BF), the slug flow (SLF) and the annular flow (AF) appeared in the 124 mm transparent wellbore under the above experimental conditions. The flow pattern of three different parameters of well deviation angle, different water holdup and total flow rate were obtained by analyzing the experimental data, as shown in **Figure 3** and **Figure 4** [14].



v_m is the average flow rate of the water and gas; H_w is water holdup

Figure 3. Flow pattern cross-plot of gas-water two-phase flow with horizontal and inclined upward angle.

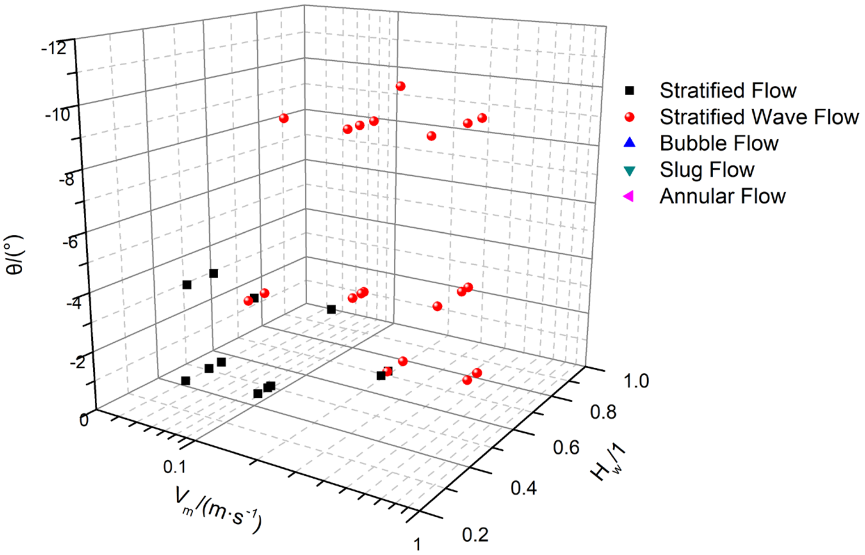
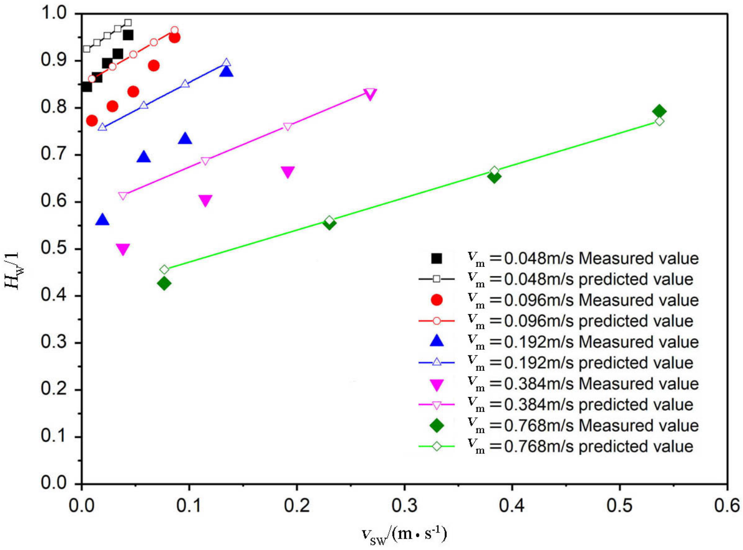


Figure 4. Flow pattern cross-plot of gas-water two-phase flow with inclined downward angle.

According to the flow pattern analysis observed by the experiment, the inclined angles of the slug flow were +5°, +15° and +45° under the above experimental conditions. The slug flow was not observed under the condition of horizontal and inclined downward angle.

4. Prediction of Water Holdup of Gas-Water Two-Phase Slug Flow

The experimental gas and water apparent velocity of the slug flow was taken as the true theoretical gas and water velocity. And the water holdup was substituted by the theoretical model of liquid holdup (Equation (12)) as a prediction variable. It is calculated that the relationship between the calculated value of water holdup and the actual value of the slug flow angle of +5˚, +15˚ and +45˚ under various experimental conditions. As shown in **Figures 5-7**, the theoretical water holdup is in good agreement with the experimental results.



v_{sw} is the apparent speed of the water

Figure 5. Experimental water holdup compared with model predictions for 5˚ upward flows.

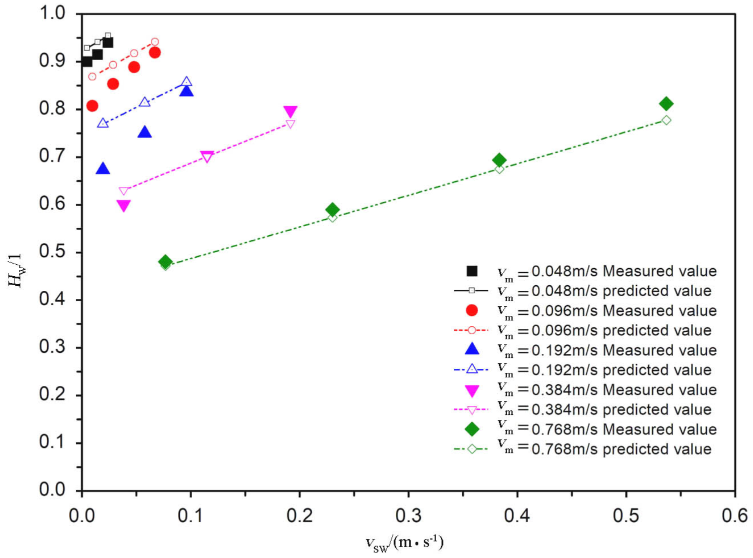


Figure 6. Experimental water holdup compared with model predictions for 15˚ upward flows.

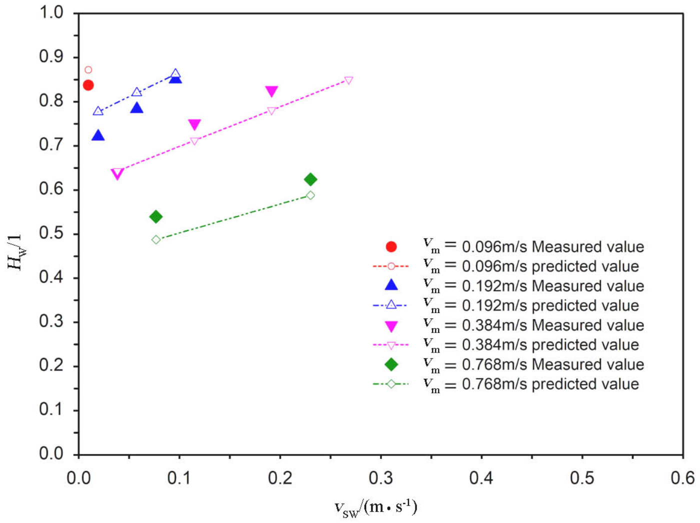
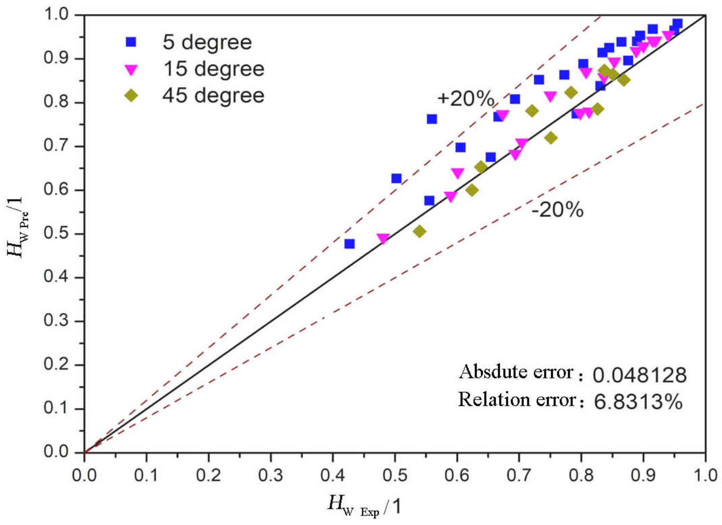


Figure 7. Experimental water holdup compared with model predictions for 45° upward flows.

By using Equation (12) and the apparent velocity of gas and water, the comparison between the predicted and actual values of the slug flow theoretical model and the error analysis can be gotten as shown in **Figure 8**.



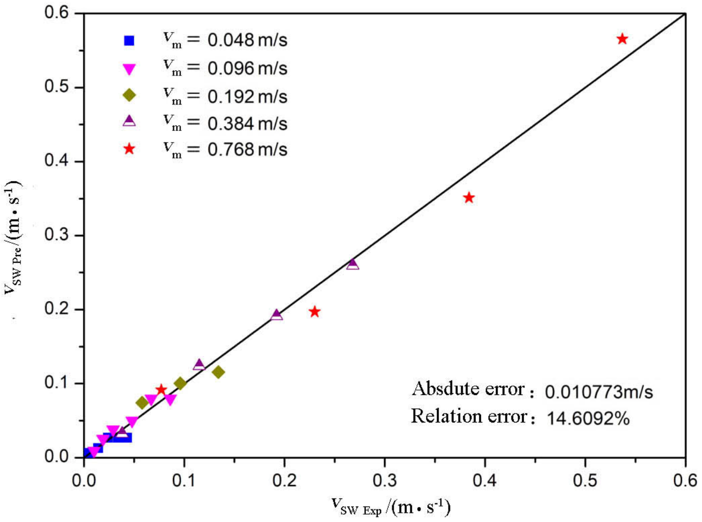
$H_{w\ Pre}$ is the calculated water holdup; $H_{w\ Exp}$ is the experimental water holdup

Figure 8. Over comparison of experimental water holdup with model predictions.

According to the analysis of the experimental and theoretical calculation results above, it can be seen that the water holdup predicted by the theoretical model of gas and water two-phase flow model corresponding to the flow pattern structure is in good agreement with the experimental results. The higher the total flow rate is, the higher the coincidence rate is. The average absolute error of predicted water holding capacity and actual water holding capacity is 0.048128, and the average relative error is 6.8313%. The theoretical model corresponding to the slug flow can better reflect the flow characteristics of the multiphase flow, and the prediction error of water holdup and experimental water holdup is within the allowable error range of production log interpretation.

5. Flow Rate Prediction of Gas-Water Two-Phase Slug Flow

In the same way, the total gas-water flow rate of the slug flow was used as the true theoretical air-water total flow rate, and the actual water hold-up rate was measured as the true theoretical water holdup. Air-water superficial velocity was used as a predictor to substitute for the momentum conservation model of Equation (13). The theoretical calculations of gas and water apparent velocities under the experimental conditions of 5˚, 15˚, and 4˚ gas-water slug flow were calculated and compared with the experimental values, as shown in **Figures 9-12**.



($v_{\text{sw Pre}}$ is the calculated water superficial velocities, $v_{\text{sw Exp}}$ is the experimental water superficial velocities).

Figure 9. Experimental water superficial velocities compared with model predictions for 5˚ upward flows.

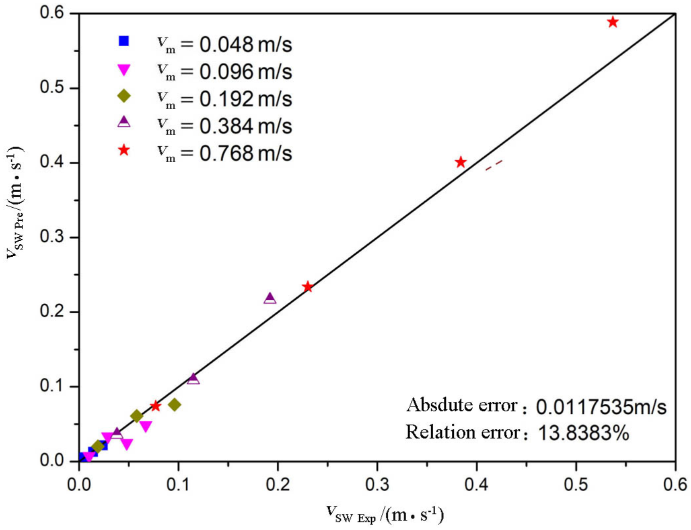


Figure 10. Experimental water superficial velocities compared with model predictions for 15˚ upward flows.

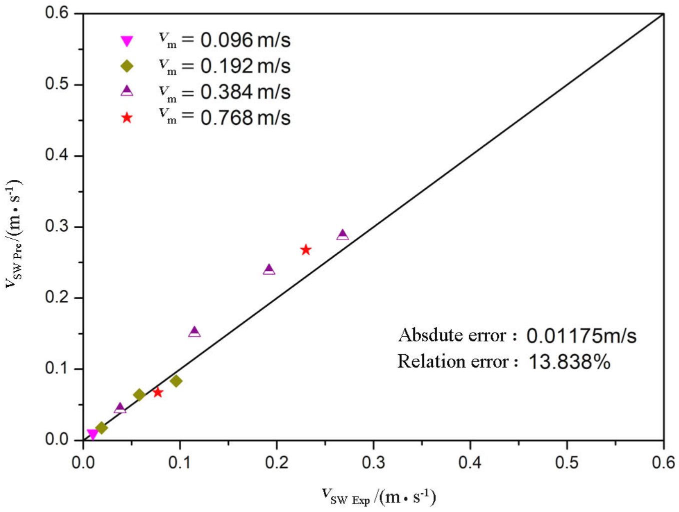


Figure 11. Experimental water superficial velocities compared with model predictions for 45˚ upward flows.

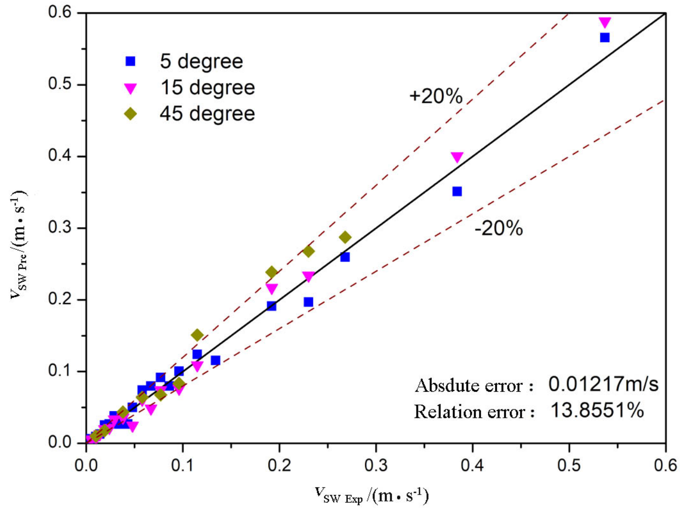


Figure 12. Overall comparison of experimental water superficial velocities with model predictions.

According to the results of the comparison, it can be seen that the apparent velocity of the water phase predicted by the theoretical model (Equation (13)) of the gas-water two-phase model based on the slug flow pattern structure is close to the experimental value. The average absolute error is 0.01217 m/s, and the average relative error is 13.8551%. The theoretical and experimental results are in good agreement.

6. Conclusions

Through the production logging interpretation theoretical model based on slug flow structure, the following conclusions were obtained by comparing the predicted results of water holding capacity and water surface velocity with the experimental values in the inclined well.

1) In this paper, the theoretical distribution models for production logging interpretation of slug flow were substituted into the theoretical values of experimental gas, the water apparent velocity and the water holdup as known values for positive and negative inversion calculations. The calculated results are in good agreement with the experimental results, demonstrating that the model is stable.

2) For the gas-water two-phase flow, the theoretical model for production log interpretation based on the flow pattern structure can better reflect the flow characteristics of the gas-water two-phase flow in oil wells, and theoretically predict the water holding capacity and water phase. The apparent velocity is close to the experimental result, and the error value is within the allowable range of the production log interpretation output industry. The theoretical model can be used to explain the production gas and water two-phase output profile.

3) The total flow rate and the phase flow rate calculated by participating in the theoretical model are experimental rations, and the water holdup is the instantaneous water retention rate measured by the shut-in well. There is a certain error between the experimental ration value and the well logging instrument response value. When it is applied to multiphase flow interpretation of horizontal wells and inclined well production logging, it is also necessary to make certain corrections to the logging instrument response values, and the calculation accuracy needs to be further verified.

Acknowledgements

The research is supported by Educational Commission of Hubei Province of China (D20141302), Open Fund of Key Laboratory of Exploration Technologies for Oil and Gas Resources (Yangtze University), Ministry of Education (No. K2018-02) and National Natural Science Foundation of China (41474115).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Zhao, X., He, S.L. and Liu, D.T. (2010) Production Logging Technology of Horizontal Wells in Shale Gas Reservoirs in the US. *Foreign Oilfield Engineering*, **12**, 55.

[2] Heddleston, D. (2009) Horizontal Well Production Logging Deployment and Measurement Techniques for US Land Shale Hydrocarbon Plays. 2009 *SPE Production and Operations Symposium*, Oklahoma City, 4-8 April 2009, 1-9.

[3] Jiang, J.Z. and Zhang, W.M. (2012) Accurate Model for Calculating Gas-Liquid Two-Phase Slug Flow Parameters in Horizontal Pipeline. *Journal of Chemical Industry and Engineering* (*China*), **12**, 3826.

[4] Xiao, R.G., Wei, B.Q., Sha, H.T., *et al.* (2012) Characteristics of PSD and PDF of Gas-Liquid Slug Flow. *Journal of Xi'an Petroleum University*, **5**, 58.

[5] Zhang, H.-Q. and Sarica, C. (2005) Unified Modeling of Gas/Oil/Water Pipe Flow-Basic Approaches and Preliminary Validation. 2005 *SPE Annual Technical*

Conference and Exhibition, Dallsa, 9-12 October 2005, 1-9.

[6] Kong, L. (2003) Two Phase Fluid Mechanics. Higher Education Press, 20.

[7] Meng, W.H., Chen, X.Z.T., Brill, J.P., *et al.* (1999) Experimental Study of Low Liquid Loading Gas-Liquid Flow in Near-Horizontal Pipes. 1999 *SPE Annual Technical Conference and Exhibition*, Houston, 3-6 October 1999, 1-12.

[8] Scott, S.L. and Kouba, G.E. (1990) Advances in Slug Flow Characterization for Horizontal and Slightly Inclined Pipelines. 65*th Annual Technical Conference and Exhibition of the Society of Petroleum Engineer*, New Orleans, 23-26 September 1990, 125-140. https://doi.org/10.2118/20628-MS

[9] Beggs, H.D. and Brill, J.P. (1973) A Study of Two-Phase Flow in Inclined Pipes. *JPT*, *Trans.*, *AIME*, 255.

[10] Gomez, L.E., Shoham, O., Schmidt, Z., *et al.* (1999) Unified Mechanistic Model for Steady-State Two Phase Flow: Horizontal to Vertical Upward Flow. 1999 *SPE Annual Technical Conference and Exhibition*, *Houston, 5*-8 October 1999, 339-350.

[11] Bendiksen, K.H., Maines, D., Moe, R., *et al.* (1991) The Dynamic Two-Fluid Model OLGA: Theory and Application. 1991 *SPE Annual Technical Conference and Exhibition*, 171-180.

[12] Kaya, A.S., Sarica, C. and Brill, J.P. (1999) Mechanistic Modeling of Two-Phase Flow in Inclined Wells. 1999 *SPE Annual Technical Conference and Exhibition*, Houston, 3-6 October 1999, 156-165.

[13] Chokshi, R.N. (1994) Prediction of Pressure Drop and Liquid Holdup in Vertical Two-Phase Flow through Large Diameter Tubing. The University of Tulsa.

[14] Song, H.W., Guo, H.M. and Dai, J.C. (2012) Experimental Analysis of Gas-Water Flow Pattern during Production Well Logging in Horizontal Wells. *Journal of Oil and Gas Technology*, **12**, 96.