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New Method for Well Kick Tolerance Calculation

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Abstract

Well kick is an important basic parameter in the well drilling operation, and it directly determines the Casing layers as well as casing depth. At the same time it also directly determines whether the well drilling will be performed continuously or whether the well-killing operation should be carried out in the well drilling process. Based on the current questions about the well kick tolerance values, the influence caused by several factors such as invasion amount of formation fluid, the distribution of formation fluid in the wellbore and the shut-in casing pressure should be taken into consideration. According to the annular multiphase flow theory, the well kick tolerance calculation model is brought out, besides the relationship between well kick tolerance and formation fluid permeability as well as formation pressure forecasting error is simulated and analyzed. Based on the above analysis it can be seen from the result that when the permeability increases, the well kick tolerance goes up by following the exponential function module. And when the formation pressure forecasting error increases, well kick tolerance goes up significantly. Therefore the simulation result could used to effectively direct the well structure design for complex deep wells.

Key words: Well kick tolerance; Casing depth; Permeability; Formation pressure; Well structure

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ILLUSTRATION OF SIGNS

ρ_g, ρ_o, ρ_m, ρ_c Density of gas, oil, drilling fluid and drillings, kg/m^3;

E_g, E_o, E_m, E_c Volume fraction of gas, oil, drilling fluid and drillings;

v_g, v_o, v_m, v_c Velocity of gas, oil, drilling fluid and drillings, m/s;

q_g, q_o Gas production speed and oil production speed in low-degree permeability formation, m^3/s;

R_s Producing gas-oil ratio;

B_o Volume coefficient of oil;

ρ_{os} Relative density of oil under Standard Condition;

ρ_{gs} Relative density of gas under Standard Condition;

A_P Cross sectional area inside drilling column, m^2;

A_a Cross sectional area inside annular space, m^2;

c_m Specific heat of drilling fluid, J/kg℃;

K_e Coefficient of thermal conductivity of formation, W/m℃;

m_p Mass flow inside drilling column, kg/s;

m_a Mass flow inside annular space, kg/s;

r_p Drilling column radius，m;

r_a Annular space radius, m;

T_p Temperature inside drilling column，℃;

T_a Temperature inside annular space, ℃;

T_e Temperature of formation or sea water, ℃;

T_{in} Temperature of entrance of drilling column, ℃;

U_p Overall heat transfer coefficient inside drilling column, W/m℃;

v_p Velocity of drilling fluid inside the drilling column, m/s;

U_a Overall heat transfer coefficient inside annular space, W/m℃;

v_a Velocity of drilling fluid inside the annular space, m/s;

v_{sg}, v_{so}, v_{sm}, v_{sc} Superfacial velocity of gas, oil, drilling fluid and drillings, m/s;

C_g, C_o, C_c Distribution coefficient of gas, oil and drillings;

v_{gr}, v_{or}, v_{cr} Superfacial velocity of gas, oil and drillings, m/s;

ρ_{cen} Comprehensive density of gas core fluid, kg/m^3;

f_{cen} Friction resistance coefficient of gas core fluid;

T_{pc} Critical temperature of natural gas, ℃;

P_{pc} Critical pressure of natural gas, MPa;

$\gamma_g = \frac{\rho_{gas}}{\rho_{air}}$; T Temperature, K;

p Pressure,MPa;

M_g Average molecular weight of natural gas, kg/kmol;

ρ_g Density of natural gas under mobility condition, kg/m^3;

T Temperature, ℃;

K Formation permeability, μm^2;

H Net pay thickness of gas layer, m;

μ Viscosity of gas, mPa·s;

B_g Volume coefficient of gas;

P_i Original formation pressure, MPa;

$P_{wf}(t)$ Flow pressure at well bottom, MPa.

INTRODUCTION

The well kick tolerance reflects the rick degree of well kick phenomenon. The value of this parameter is determined by the ability of controlling the well kick in the field. Currently, there are several kinds of definitions and calculation methods for well kick tolerance[1]. In some oversea reports the pit gain (PG), drilling fluid density increment and balanced formation pressure forecasting error are mainly used to represent this parameter. Domestically, well kick tolerance means the allowable value of well kick amount which is generated because of the error of formation pressure forecasting, which is described by equivalent density. And it's relevant to the formation pressure forecasting error. The value of well kick tolerance is mainly determined according to empirical operation. When the equipment technology is under good condition, the value could be set very low while if there is high risk in the well drilling operation, the value could be set very high relatively[2]. Along with the development towards vertical depth direction of the well drilling operation the drilling formation is complex, the drilling pressure layer system is rich and formation information is uncertain. Under these situation, when the regularly-recommended well kick value is used the higher error might be inevitable. In this essay, a series of factors such as permeability of formation, borehole, drill string size, drilling fluid, well depth, technology and operation are taken into comprehensive consideration. Furthermore, the gas invasion to formations with different permeability is given simulation and solution by applying the annular multiphase flow theory. In the simulation operation, the relationship between well kick tolerance and formation permeability, formation pressure forecasting error is analyzed, which provides enhanced direct to well structure design for complex deep wells.

1. CALCULATION MODEL OF WELL KICK TOLERANCE

According to the characteristics of fluid invasion in formations and by combining annular fluid mobility form and phase distribution under different situations, the key parameters such as the annulus pressure profile, volume fraction profile and shut-in casing pressure are determined correspondingly. Meanwhile the time factor which is related to formation fluid invasion is taken into consideration, therefore the calculation method of well kick tolerance of formation is generated.

1.1 Basic Assumption of Annular Multiphase Flow Model[3,4]

① Continuum theory, which means each phase of fluid is composed of consecutive mass points

② The fluid in the well is treated based on "Black oil model", in other words the phase conversion between oil and gas is taken into consideration, however there is no mass transfer between gas and drilling fluid (or water)

③ The compressibility of drilling fluid (or water) is not taken into consideration

④ The fluid mobility belongs to one-dimension mobility which is following the well borehole direction

⑤ It's assumed that there is stable radial heat-transfer between the formation and well borehole, then the fluid inside the well is situated as thermodynamic equilibrium state.

1.2 Mass Conversion Equation

Mass conversion equation of gas fraction:

$$\frac{\partial}{\partial t}(\rho_g E_g + \frac{R_s \rho_{gs} E_o}{B_o}) + \frac{\partial}{\partial s}(\frac{R_s \rho_{gs} E_o}{B_o} v_o + \rho_g E_g v_g) = q_g \quad (1)$$

Mass conversion equation of oil fraction:

$$\frac{\partial}{\partial t}(\frac{\rho_{os}}{B_o} E_o) + \frac{\partial}{\partial s}(\frac{\rho_{os}}{B_o} E_o v_o) = q_o \quad (2)$$

Mass conversion equation of drilling fluid:

$$\frac{\partial}{\partial t}(\rho_m E_m) + \frac{\partial}{\partial s}(\rho_m E_m v_m) = 0 \quad (3)$$

Mass conversion equation of drilling fluid drillings:

$$\frac{\partial}{\partial t}(\rho_c E_c) + \frac{\partial}{\partial s}(\rho_c E_c v_c) = 0 \quad (4)$$

1.3 Momentum Conservation Equation

$$\frac{\partial}{\partial t}(E_g\rho_g v_g + E_o\rho_o v_o + E_m\rho_m v_m + E_C\rho_C v_C) + \frac{\partial}{\partial s}(E_g\rho_g v_g^2 + AE_o\rho_o v_o^2 + E_m\rho_m v_m^2 + E_C\rho_C v_C^2) + g(E_g\rho_g + E_o\rho_o + E_m\rho_m + E_C\rho_C)\cos\alpha + \frac{\partial}{\partial s}(P) + (\frac{\partial P}{\partial s})_f = 0 \quad (5)$$

1.4 Energy Equation

Because the temperature distribution inside the wellbore could influence the physical parameters of each phase fluid, then it can influence the calculation of well kick tolerance. Therefore it's necessary to do research to the temperature field inside wellbore. There are three stages of recycling of drilling fluid which are shown as follows.

① Drilling fluid is pumped into the drilling pipe and moves downward inside the tube pipe; ② Drilling fluid flows out through the drilling bit and enters annular space; ③ Drilling fluid moves inside the annular space and returns back to ground surface.

Basic assumption[5-6]:

① The formation heat transfer belongs to steady radial heat-transfer;② The density of rock, specific heat and thermal conductivity don't change when the temperature changes. Besides, specific heat and thermal conductivity are equal in horizontal and vertical directions;③ The heat source, axial forced convection heat transfer and radial forced convection heat transfer inside pipe string and annular space should be taken into consideration

Certain stage of drilling fluid inside the drilling pipe is chosen as the control body and the temperature model of drilling fluid inside the drilling pipe could be received:

Temperature field equation inside drilling pipe：

$$A_p\rho_m v_p c_m \cdot \frac{\partial T_p}{\partial s} + m_p c_m \frac{\partial T_p}{\partial t} - 2\pi r_p U_p (T_a - T_p) = 0 \quad (6)$$

Certain stage of drilling fluid inside the annular space is chosen as the control body and the temperature model of drilling fluid inside the annular space could be received:

Temperature field equation inside annular space:

$$A_a\rho_m v_a c_m \cdot \frac{\partial T_a}{\partial s} - m_a c_m \frac{\partial T_a}{\partial t} - 2\pi r_a U_a (T_e - T_a) + 2\pi r_p U_p (T_a - T_p) = 0 \quad (7)$$

Heat exchange equation on the interface of annular space and formation:

$$U_a(T_e - T_a) - K_e \left.\frac{\partial T_a}{\partial t}\right|_{r=r_a} = 0 \quad (8)$$

1.5 Phase Volume Fraction

Gas phase volume fraction:

$$E_g = \frac{v_{sg}}{C_g(v_{sg} + v_{so} + v_{sc} + v_{sm}) + v_{gr}} A \quad (9)$$

Drillings volume fraction:

$$E_c = \frac{(1-E_g)v_{sc}}{C_c(v_{sc} + v_{so} + v_{sm}) + (1-E_g)v_{cr}} \quad (10)$$

Oil phase volume fraction:

$$E_o = \frac{(1-E_g-E_c)v_{so}}{C_o(v_{so} + v_{sm}) + (1-E_g-E_c)v_{or}} \quad (11)$$

Drilling fluid volume fraction:

$$E_m = 1 - E_g - E_o - E_c \quad (12)$$

1.6 Multiphase Flow Friction Pressure Gradient

Bubble flow

$$\left(\frac{\partial P}{\partial s}\right)_f = \frac{f_m\rho_{mul}v_{mul}^2}{2D} \quad (13)$$

f_m can be calculated by using the implicit formula which is brought out by Colebrook, as follows:

$$\frac{1}{\sqrt{f_m}} - 4\lg\left[0.269\left(\frac{\varepsilon}{D}\right) + \frac{1.225}{R_{eM}\sqrt{f_m}}\right] \quad (14)$$

Slug flow

Usually, only the flow friction loss which is generated in the slug section of the fluid is taken into consideration, therefore the fraction pressure gradient calculation formulation could be received as follows:

$$\left(\frac{\partial P}{\partial s}\right)_f = \frac{f_l\rho_l v_l^2}{2D}(1-E_g) \quad (15)$$

The fraction with annular flow mode comes from the high-speed movement of gas core flow, therefore the corresponding gas core fraction pressure gradient calculation formulation could be described as follows:

$$\left(\frac{\partial P}{\partial s}\right)_f = \frac{2f_{cen}\rho_{cen}v_g^2}{D} \quad (16)$$

f_{cen} could be confirmed according to the corresponding Wallis formula.

$$f_{cen} = \frac{0.079[1+75(1-E_g)]}{R_{eg}^{0.25}} \quad (17)$$

1.7 Physical Property Parameters Calculation of Formation Fluid

① Gas compression factor

Gas compression factor represents the ratio of the real volume and ideal volume of gas with same quality under certain temperature and pressure condition. The relevant empirical formulas were brought out by Dranchuk and Abou-Kassem, as follows.

$$Z_g = 1 + c_1(T_{pr})\rho_{pr} + c_2(T_{pr})\rho_{pr}^2 + c_3(T_{pr})\rho_{pr}^5 + c_4(T_{pr}, \rho_{pr}) \quad (18)$$

$$\rho_{pr} = 0.27\frac{P_{pr}}{Z_g T_{pr}}, \quad T_{pr} = \frac{T}{T_{pc}}, P_{pr} = \frac{P}{P_{pc}} \quad (19)$$

② Density of natural gas

$$\rho_g = \frac{3484.4 p\gamma_g}{Z_{pg}T} \tag{20}$$

③ Volume fraction of natural gas

Volume fraction of natural gas means the ratio of the volume of natural gas with unit volume on formation condition and volume of natural gas with unit volume on ground surface condition, the relevant formula is shown as follows.

$$B = \frac{V_g}{V_{sc}} \tag{21}$$

④ Viscosity of natural gas

Viscosity of natural gas is the index that could evaluate the mobility of natural gas. It could impose important influence to the seepage process of natural gas underground and mobility process of natural gas in the pipelines. The viscosity of natural gas could be calculated according to the Lee formula as well as other formulas.

$$\mu_g = C\times 10^{-7}\exp\left[x\left(\left(\frac{\rho_g}{1000}\right)^y\right)\right] \tag{22}$$

$$C = \frac{\left(9.4+0.02M_g\right)(1.8T)^{1.5}}{209+19M_g+1.8T} \tag{23}$$

⑤ Solution gas oil ratio in formation oil

The natural gas could be dissolved in formation oil. There are huge difference about the amount of natural gas which is dissolved in formation oil due to different types of oil reservoir. And solution gas oil ratio is one physical parameter which could evaluate the ability of formation oil to dissolve natural gas. And it means the gas amount which is dissolved in the formation oil under the temperature and pressure of the reservoir (Standard condition).

$$R_s = C_1 r_g p^{c_1}\exp[c_3\left(\frac{1.076}{r_o}-1\right)/(3.658\times 10^{-3}T+1)] \tag{24}$$

⑥ Saturated pressure of formation oil

The saturated pressure of formation oil means the pressure under which the dissolved natural gas in the oil starts to separate from the oil under certain formation condition. The value of saturated pressure is mainly determined by the components of oil and gas, as well as the temperature of oil reservoir. And it should be determined by PVT sampling analysis method. However if such analysis material is not existing, it could be determined by the Standing formula[7~8] as follows.

$$P_b = 24.47[\left(\frac{R_s}{r_g}\right)^{0.83}\exp\left(3.7723\times 10^{-3}T-\frac{4.073}{r_o}\right)] \tag{25}$$

⑦ Volume coefficient of formation oil

When the oil is exploited and transferred onto the ground surface, the dissolved gas in the oil starts to separate from the oil and the volume of previous oil declines because the decrease of temperature and pressure. The volume coefficient of formation oil means the ratio of volume of oil underground and volume of oil after the dissolved natural gas separate from the oil on the ground surface. It could be determined by the Vazgues and Beggs empirical formulas[9], as follows.

When pressure is equal or lower than saturated pressure,

$$B_{ob} = 1 + C_1 R_s + \frac{(C_2 + C_3 R_s)(0.064286T-1)(\frac{1.076}{r_o}-1)}{r_g} \tag{26}$$

When pressure is higher than saturated pressure,

$$B_o = B_{ob}\exp[c_0(P_b - P)] \tag{27}$$

Seepage formulation of two-phase mobility which is influenced by different gas influx

$$q_{sc} = \frac{kh}{\mu B_g 2.121*10^{-3}\lg(\frac{8.0853\eta t}{r_w^2})}\times[p_i - p_{wf}(t)] \tag{28}$$

In the process of gas invasion, when the time goes by the gas rises and expands in the wellbore which engenders more drilling fluid to flow out. Therefore the pressure at the well bottom will be lower and lower, then pressure drop will increase accordingly. Hence the more gas enters the well borehole and overflow becomes more and more severe. And it is very accurate to demonstrate this process by using this formula.

It can be discovered by research that under the certain well structure, the well kick tolerance is mainly influenced by formation pressure forecasting error, formation permeability and formation fluid invasion. To be more specific, the increment of drilling fluid pond represents the gas invasion amount into the wellbore, which is relevant to formation permeability and overflow time. Therefore, the main factors what influence the well kick tolerance are formation pressure forecasting error and formation permeability.

2. THE CALCULATION EXAMPLE OF WELL KICK TOLERANCE

According to the geological and drilling materials about Northeast-Sichuan region and by using the well kick tolerance calculation method which is mentioned in this essay, the change principle of well kick tolerance along with the change of permeability and formation pressure forecasting error is simulated and analyzed.

2.1 The Change Principle of Well Kick Tolerance Along with the Change of Time and Permeability

The change principle of well kick tolerance which is influenced by different gas phase permeability is observed (The overflow time is 10 min, 30 min, 60 min and 90 min separately) and the corresponding result is shown in Figure 1, as follows. Besides the basic data for the well kick tolerance analysis and calculation are shown in Table 1.

Table 1
Basic Calculation Data

Well Depth (m)	3000	Gas Relative Density	0.75
Density of Drilling (g/cm^3)	2.6	Ground Surface Temperature(℃)	20
Ground Temperature Gradient (℃/100m)	2.3	Density of Drilling Fluid (g/cm^3)	1.1
Drilling Fluid Volume (L/s)	30	Plastic Viscosity (mPa·s)	30
Yield Value (Pa)	3	Formation pressure Forecasting Error(MPa)	3
Yield Layer Thickness(m)	20	Depth of Casing Shoe Position(m)	2500
Drill String Size (mm)	127	Open Hole Diameter (mm)	215.9
Drill String Length (m)	2500	Casing Diameter (mm)	220.5
Length of Drill Collar (m)	500	Drill Collar Size (mm)	137.3

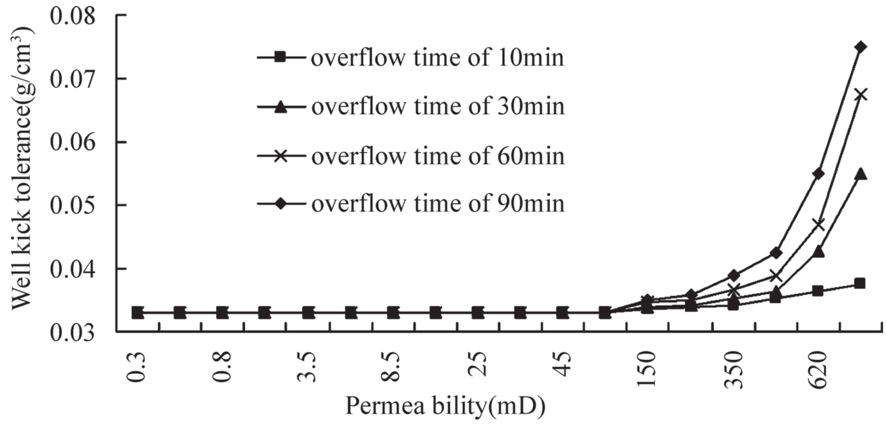

Figure 1
Well Kick Tolerance Change with Permeability Under Different Overflow Time

It can be seen from the Figure 1 that based on the classification standard of formation permeability-namely it belongs to super-low permeability formation when the average permeability is lower than 1.0×10^{-3} μm^2, while it belongs to very-low permeability formation when the average permeability is between 1.0×10^{-3}-10.0×10^{-3} μm^2 and it belongs to low permeability formation when the average permeability is lower than 50.0×10^{-3} μm^2, within the low permeability range when the overflow time increases the well kick tolerance almost has no change along with the increase of permeability. In other words, the average well kick tolerance almost remains around 0.0335 g/cm^3. Furthermore with this range the well kick tolerance is almost not influenced by time. When the permeability is higher than 50×10^{-3} μm^2, the well kick tolerance begins to show significant change. And when the permeability increases, the well kick tolerance goes up based on the index function trend. To be more specific, when the overflow time is about 90 min and the permeability is around 500×10^{-3} μm^2, the well kick tolerance increases up to 0.0745 g/cm^3 approximately.

2.2 Change Principle of Well Kick Tolerance Along with the Change of Formation Pressure Forecasting Error

The principle of influence to well kick tolerance which is caused by different formation pressure forecasting error is researched (The relevant formation permeability is 1×10^{-3}, 10×10^{-3}, 30×10^{-3}, 100×10^{-3}, 500×10^{-3} μm^2 and 1000×10^{-3} μm^2 separately) and the result is shown in Figure 2, as follows. It can be seen from the Figure 2 that the formation pressure forecasting error could influence the well kick tolerance apparently. When the formation pressure forecasting error is about 2.5 MPa, the well kick tolerance is only below 0.02 g/cm^3. However when the formation pressure forecasting error increases up to 5MPa the well kick tolerance is higher than 0.115 g/cm^3. At the same time it can be received from the Figure 2 that the well kick tolerance curves which show the low-degree permeability situation almost overlap together. It means formation pressure forecasting accuracy is the main factor which influences the well kick tolerance. However when the permeability is relatively higher, the well kick tolerance increases very fast along with the increment of formation pressure forecasting error. Hence it means formation pressure forecasting accuracy and permeability are two major factors which affect the well kick tolerance.

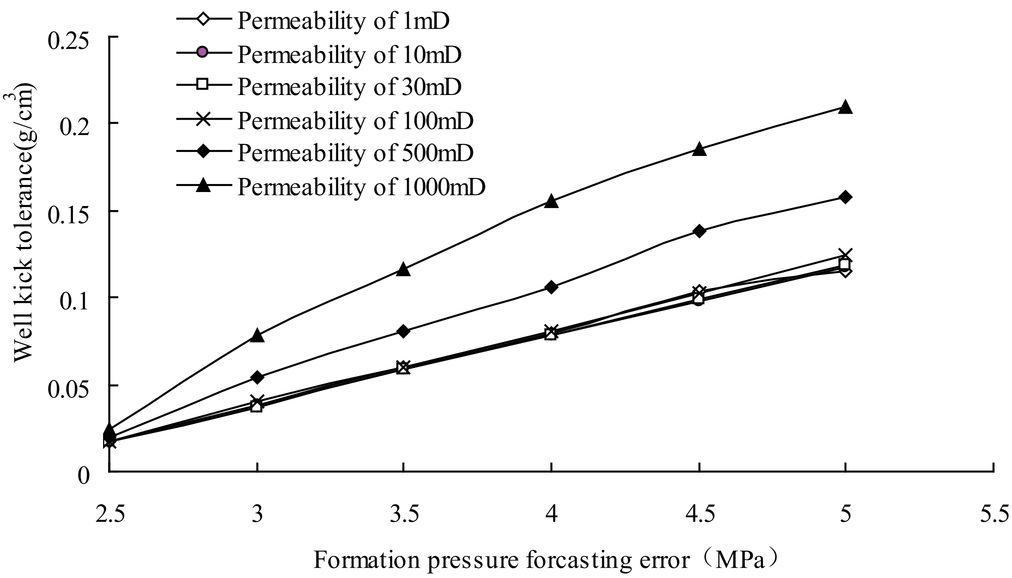

Figure 2
Well Kick Tolerance Change with Formation Pressure Forecasting Error Under Different Permeability

CONCLUSION

(1) Well kick tolerance is an important parameter in drilling engineering design, the reasonability of well kick tolerance calculation directly related with the reasonability of well structure and safety of drilling operation for HTHP deep well and super-deep well.

(2) Well kick tolerance is mainly determined by formation pressure forecasting error, formation permeability and formation fluid invasion amount. And increment of drilling fluid pond represents the gas invasion amount into the wellbore, which is relevant to formation permeability and overflow time. Hence, well kick tolerance is mainly influenced by formation pressure forecasting error and formation permeability.

(3) It can be seen from the simulation result that when the overflow time goes up, the well kick tolerance almost has no change along with change of permeability. However when the permeability is higher than certain value, well kick tolerance increases based on index function trend along with the increment of permeability. When the formation pressure forecasting error increases, the well kick tolerance goes up dramatically.

REFERENCES

[1] Li, K. X. (1990). *A Maual Drilling* (pp. 294-298). Beijing: Petroleum Industry Press.

[2] Zhuo, L. B., Ge, Y. H., & Wang, H. G. (2009). Early Kick Detection Methods for Deep Water Drilling and Its Future Development. *Oil Drilling & Production Technology*, *31*(1), 22-26.

[3] Nicken, H. V. (1985). A Dynamic Computer Model of a Kicking Well: Part II-Model Predictions and Conclusions. *SPE Annual Technical Conference and Exhibition*, 22-26 September 1985, Las Vegas, Nevada.

[4] Bilicki, Z. (1987). Traosition Criteria for Two-Phase Flow Patterns in Vertical Upward Flow. *Int. J. of Multiphase FIow*, *3*(3), 283-294

[5] Kytomaa, H. K., & Brennen, C. E. (1991). Small Amplitude Kinematic Wave Propagation in Two-Component Media. *Int. J. of Multiphase Flow*, *17*(1),13-26.

[6] Lammers, J. H., & Biesheuvel, A. (1996). Concentration Waves and the Instability of Bubbly Flows. *Journal of Fluid Mechanics*, *328*, 67-93.

[7] Wang, Z. Y., & Sun, B. J. (2009). Multiphase Flow Behavior in Annulus with Solid Gas Hydrate Considering Nature Gas Hydrate Phase Transition. *Petroleum Science*, *6*(1), 57-63.

[8] Cheng, H., Hills, J. H., & Azzopardi, B. J. (1998). A Study of the Bubble-to-Slug Transition in Vertical Gas-Liquid Flow in Columns of Different Diameter. *Int. J. of Multiphase Flow*, *24*(3), 431-452.

[9] Ohnuki, A., & Akimoto, H. (2000). Experimental Study on Transition of Flow Pattern and Phase Distribution in Upward Air–Water Two-Phase Flow Along a Large Vertical Pipe. *Int. J. of Multiphase Flow*, *26*(3), 367-386.