AN INVESTIGATION OF LIQUID LOADING PREDICTION IN GAS WELL

Mr. Sataporn Klaibanmai

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Petroleum Engineering
Department of Mining and Petroleum Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2010

การตรวจสอบวิธีการประเมินการสะสมตัวของของเหลวในหลุมก๊าซ

นายสถาพร คล้ายบ้านใหม่

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมปิโตรเลียม ภาควิชาวิศวกรรมเหมืองแร่และปิโตรเลียม
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2553

Thesis Title	AN INVESTIGATION OF LIQUID LOADING PREDICTION IN GAS WELL
By	Mr. Sataporn Klaibanmai
Field of Study	Petroleum Engineering
Thesis Advisor	Assistant Professor Jirawat Chewaroungroaj, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

.... Dean of the Faculty of Engineering

(Associate Professor Boonsom Lerdhirunwong, Dr.Ing.)

THESIS COMMITTEE

.... Chairman

(Associate Professor Sarithdej Pathanasethpong)

.... Thesis Advisor

(Assistant Professor Jirawat Chewaroungroaj, Ph.D.)

Witsarut T. .... External Examiner

(Witsarut Thungsuntonkhun, Ph.D.)

สถาพร คล้ายบ้านใหม่: การตรวจสอบวิธีการประเมินการสะสมตัวของของเหลวในหลุมก๊าซ. (AN INVESTIGATION OF LIQUID LOADING PREDICTION IN GAS WELL) อ. ที่ปรึกษาวิทยานิพนธ์หลัก: ผศ. ดร. จิรวัฒน์ ชีวรุ่งโรจน์, 174 หน้า.

การสะสมตัวของของเหลวเป็นหนึ่งในปัญหาของการผลิตก๊าซ การศึกษานี้มุ่งเน้นไปที่อิทธิพลของสัดส่วนระหว่างของเหลวและก๊าซต่ออัตราการไหลวิกฤตโดยเลือกความสัมพันธ์ของอัตราการไหลวิกฤต 3 ชุดเพื่อสำรวจการคาดคะเนการสะสมตัวของของเหลวจากข้อมูลการผลิตจริง เนื่องด้วยข้อมูลจริงนั้นมักจะมีความผันผวนของข้อมูลอยู่ การวิเคราะห์คุณสมบัติของของไหลได้จัดทำขึ้นเพื่อการตรวจสอบข้อมูลรวมถึงการวิเคราะห์อิทธิพลของคุณสมบัติของของไหลต่ออัตราการไหลวิกฤต ทั้งนี้ความถ่วงจำเพาะของก๊าซถือว่าเป็นคุณสมบัติที่สำคัญที่สุดต่อการสะสมตัวของของเหลวเพราะความถ่วงจำเพาะของก๊าซมีช่วงของค่าความเป็นไปได้ซึ่งกว้างที่สุด ความถ่วงจำเพาะของก๊าซยังเป็นตัวแปรที่มีอิทธิพลต่อค่าอัตรการไหลวิกฤตสูงที่สุด อิทธิพลของสัดส่วนของของเหลว ถือว่าเป็นตัวแปรที่มีความสำคัญเนื่องจากค่านี้ส่งผลกระทบต่อความสัมพันธ์ของอัตราการไหลวิกฤตที่เลือกมาศึกษาในรูปแบบที่ต่างกัน นอกจากนี้ อัตราการไหลของก๊าซยังถือว่าเป็นตัวแปรสำคัญในการทำนายสถานะของหลุม

ในส่วนท้ายของการศึกษา มีการเปรียบเทียบอัตราการไหลของก๊าซและอัตราการไหลวิกฤตที่ทำนายได้จากความสัมพันธ์เพื่อสำรวจสถานะของหลุม ผลการวิเคราะห์แสดงให้เห็นถึงสภาวะวิกฤตเพื่อใช้ทำนายสภาวะของหลุมผลิตจริง วิศวกรปิโตรเลียมสามารถนำผลการวิเคราะห์และข้อสรุปจากการศึกษานี้ไปใช้เป็นแนวทางในการแก้ปัญหาและการตัดสินใจอย่างเหมาะสมกับหลุมผลิตจริง

ภาควิชา วิศวกรรมเหมืองแร่และปิโตรเลียม ลายมือชื่อนิสิต...สถาพร คล้ายบ้านใหม่..........
สาขาวิชา วิศวกรรมปิโตรเลียม.................. ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก..........
ปีการศึกษา 2553..................................

5171617421: MAJOR PETROLEUM ENGINEERING

KEYWORDS : LIQUID LOADING / LIQUID HOLDUP / CRITICAL FLOWRATE CORRELATION / CRITICAL VELOCITY / FLUID PROPERTIES

SATAPORN KLAIBANMAI: AN INVESTIGATION OF LIQUID LOADING PREDICTION IN GAS WELL. ADVISOR: ASST. PROF. JIRAWAT CHEWAROUNGROAJ, Ph.D., 174 pp.

Liquid loading is one of common problems in gas production. This study focuses on the influences of liquid holdup to critical flowrate. Three critical flowrate correlations are selected in order to investigate liquid loading prediction of actual production data. Since there are several fluctuations in actual data, the analysis of fluid properties is made in order to investigate over the input data and evaluate the influences of fluid properties to critical flowrate. Gas specific gravity is proved as the most important property of liquid loading consideration because it has the widest range of possible value. Moreover, gas specific gravity has the most dominant influence on predicted critical flowrate. Influences of liquid holdup are found to be an important factor behind predicted values of each correlation because it has the effect on the selected correlations in different manners. Moreover, the gas production rate is clarified as a vital parameter of well status prediction.

At the end of this study, the comparison of gas production rate and predicted critical flowrate of each correlation is set in order to investigate the well status. Results of this analysis show the critical condition to predict the liquid loading in actual production wells. The results and conclusions can be utilized as guidelines for petroleum engineers about how to deal with this problem and make right decisions on actual production wells.

Department: Mining and Petroleum Engineering	Student's Signature Sataporn Klaibanmai
Field of Study: Petroleum Engineering	Advisor's Signature
Academic Year: 2010	

Acknowledgements

First of all, I would like to express my gratitude to Assistant Professor Dr. Jirawat Chewaroungraj, my thesis advisor, for the excellent guidance and advice throughout my graduated studies.

I would like to thank Dr. Witsarut Thungsuntonkhun and the DMF for courtesy of production data and useful advice to this study.

Finally, I would like to share my passion of success to my family and my friends for their unconditional love and encouragement, which help me pass through the hard time of this study.

Contents

Page

Chapter

Chapter Page

Chapter Page

List of Tables

Table Page

List of Figures

Figure Page

Figure Page

Figure Page

LIST OF ABBREVIATIONS

avg.	average
bbl	barrel
FTP	flowing tubing pressure, psia
GoT	Gulf of Thailand
M	thousand
MM	million
RB	reservoir barrel
scf	standard cubic feet
S.D.	standard deviation
STB	stock-tank barrel

NOMENCLATURE

a	gas core radius, ft
A	flow cross sectional area of a conduit, ft^2
°API	degree API
Bc	condensate formation volume factor, RB/STB
B_g	gas formation volume factor, ft^3/scf
Bw	water formation volume factor, RB/STB
C_d	drag coefficient
d_d	droplet diameter, inches
D_H	hydraulic diameter, ft
E_k	gas specific kinetic energy, lb_f ft/ft^3
E_{km}	minimum kinetic energy required to transport liquid droplets, lb_f ft/ft^3
E_{ksl}	kinetic energy required to hold/float liquid droplets stationary, lb_f ft/ft^3
f	moody's friction factor
g	local acceleration of gravity, ft/s^2
g_c	gravitational constant = 32.17 lb_m ft/lb_f s^2
h	film thickness, ft (Turner)
H_l	liquid holdup at wellhead
L	conduit length, ft
M	molecular weight
N_{Re}	Reynold's number
p	pressure, psia

P	pressure, lb_f/ft^2
P_{hf}	wellhead flowing pressure, lb_f/ft^2
P_{pc}	pseudocritical pressure, psia
P_{pr}	pseudoreduced pressure, psia
p_{sep}	separator pressure, psia
Q_{crit}	critical gas flowrate, MMscf/d
Q_g	gas production rate, scf/d
Q_{gm}	gas flow rate required to hold/float liquid droplets stationary, scf/d
Q_L	liquid volume flow rate
Q_o	oil production rate, bbl/d
Q_s	solid production rate, ft^3/d
Q_w	water production rate, bbl/d
q_t	gas critical rate, MMscf/d
R	tubing inside radius, ft
R_{eL}	liquid film Reynold’s number
Rs	solution gas-oil ratio, scf/STB
T	temperature, °R
$T_{^\circ F}$	temperature, °F
$T_{^\circ K}$	temperature, °K
T_c	critical temperature for water = 1164.7728 R
T_{pc}	pseudocritical temperature, R
T_{pr}	pseudoreduced temperature, R
T_{sep}	separator temperature, R

U_G^*	gas shear velocities
U_L^*	liquid shear velocities
W_E	entrainment mass rate
W_g	gas mass rate
w_s	salinity, fraction
v	velocity, ft/s
$v_{crit\text{-}N}$	critical velocity from Zhou’s correlation, ft/s
$v_{crit\text{-}T}$	critical velocity from Turner’s correlation, ft/s
v_g	gas superficial velocity, ft/s
v_{gm}	minimum gas velocity required to transport liquid droplets, ft/s
v_l	liquid superficial velocity, ft/s
v_{sl}	terminal settling velocity, ft/s
v_{sgwh}	gas superficial velocity at wellhead, ft/s
v_{slwh}	liquid superficial velocity at wellhead, ft/s
v_t	terminal velocity of free falling particle, ft/s
v_{tr}	transport velocity, ft/s
y	mole fraction
y_G^+	equivalent dimensionless number of gas
y_L^+	dimensionless liquid film thickness
z	gas compressibility factor

GREEK LETTER

β	the threshold value for Zhou *et al*. [12] correlation = 0.01
σ	interfacial tension, dynes/cm
σ_o	gas-condensate surface tension, dynes/cm
σ_w	gas-water surface tension, dynes/cm
α	the parameter for Zhou *et al*. [12] correlation = 0.06
γ_g	gas specific gravity
γ_o	oil specific gravity
γ_w	water specific gravity
ρ_g	gas density, lb/ft^3
$\rho_{h_{g/cc}}$	hydrocarbon density, g/cc
ρ_L	liquid density, lb/ft^3
ρ_w	water density, lb/ft^3
$\rho_{w_{g/cc}}$	water density, g/cc
δ	liquid film thickness, ft
λ_L	no-slip liquid holdup
τ	shear stress, lb_f/ft^2
τ_i	shear stress at the gas/liquid interface, lb_f/ft^2
τ_o	shear stress at the wall, lb_f/ft^2
υ_G	kinematic viscosity of gas
υ_L	kinematic viscosity of liquid

μ	viscosity, lb_m/ft s
μ_g	gas viscosity, lb_m/ft s
μ_L	liquid viscosity, lb_m/ft s

CHAPTER I

INTRODUCTION

Liquid loading is one of the regular problems of gas well with liquid production. There are two main sources of liquid which are a direct production of liquid from reservoir or condensation of liquid phase along production tubing. In general, when liquid cannot load out of the well, accumulation of liquid at the bottom of the well creates an additional back-pressure to the flow from reservoir resulting in a reduction in fluid production from reservoir. Moreover, presence of liquid phase in tubing causes a multiphase flow resulting in a complexity in technical analysis and potential to another production problem.

Several groups of researchers studied in this behavior and proposed their study on this topic. Turner *et al.* [1], who is considered as the pioneer of this study, proposed liquid droplet model since 1970. After that, modification of proposed theories and correlations were published continuously with a different in point of view because original model did not provide an acceptable accuracy in many fields. Since liquid loading only happens in multiphase flow, the parameter that can be referred to the status of multiphase flow may have an influence on liquid loading. The effect of other parameters that Turner *et al.* [1] did not mention in their study is one of the favorite modifications of Turner’s correlation. Therefore, together with critical flowrate, this study chooses liquid holdup as an important parameter in order to investigate the prediction of liquid loading because liquid holdup is usually mentioned in multiphase flow consideration

In term of critical flowrate determination, this study selects three correlations which is Turner’s correlation, Guo’s correlation and Zhou’s correlation in order to calculate the critical flowrate for the analysis of liquid loading. The selected correlations have a unique concept of themselves which can provide the various points of view to predicted critical flowrate. Together with them, production data from 24 wells located in Gulf of Thailand is chosen as the input parameters. Besides the complex of lithology, property of produced fluid is another signature for Gulf of Thailand. Thus, the analysis of fluid properties is made in order to clarify the influences of fluid properties to predicted critical flowrate of each correlation. Moreover, screening of input data is important because actual production data is selected for this study. In general, actual data usually contains several uncertainties which may lead to an excessive error to the results if uncertainties are not clarified or eliminated. Strength and weak points of each critical flowrate correlation are analyzed and concluded to determine the recommended correlation for each production condition.

After the analysis of selected parameters to predicted critical flowrate, an investigation of liquid loading prediction is performed in term of well status analysis. At the end of this study, the production condition that makes loaded condition is clarified. Results from this study should provide an additional tool to petroleum engineers to understand the behaviors of production well better in various situations and constraints and make a proper decision for each scenario. This study comprises of 6 chapters. Details of each chapter are

Chapter II, reviews on liquid loading theories and critical flowrate correlations from several groups of researchers.

Chapter III, reviews on selected correlations, production data and model construction.

Chapter IV, analyzes on fluid properties in term of statistical analysis and sensitivity analysis.

Chapter V, analyzes on liquid holdup and well status.

Chapter VI, makes conclusions and provides recommendations for future works.

CHAPTER II

LIQUID LOADING THEORIES AND LITERERATURES REVIEW

As discussed in previous chapter, several groups of researchers proposed their studies on liquid loading. In this chapter, those theories will be reviewed together with different point of views on this topic from them.

When gas is produced from gas well, there are many cases that liquid phase is also produced. Phases of the liquid can be condensate or water that might be produced directly from the reservoir or condensation process along the tubing. Normally, this liquid phase is usually lifted out of the well by energy of gaseous phase. When energy of gaseous phase is lower (in other words, lower gas flowrate), ability to lift liquid phase from the well is lower. Whenever the energy of gaseous phase is not enough to lift the liquid phase out of the well, accumulation of liquid in bottom of the well will happen and it is called “liquid loading”.

The accumulation of liquid will cause several problems to the well. For instance, it will apply an additional back pressure to the formation which can occur a variable degree of slugging or churning of the liquid. The slugging of liquid affects calculations used in routine well test especially the calculated bottom-hole pressure. Moreover, additional back pressure will add unnecessary pressure drop to the reservoir and cause a decreasing in production rate and, in many cases, kill the well [2].

There are several groups of researchers study on liquid loading as Turner *et al.* [1] are the pioneer of this topic. They proposed two mechanisms of liquid flowing in gas well as liquid film movement along the wall of the pipe and liquid droplet entrained in the high velocity gas core. They also mentioned that there probably is a continuous exchange of liquid between the gas core and the film, they will be treated separately for proposes of their study.

2.1 Liquid film model

Turner *et al.* [1] claimed that liquid phase accumulation on the walls of a conduit during two-phase gas/liquid flow is inevitable due to the impingement of entrained liquid drops and the condensation of vapors.

In an annular liquid film (thickness h) on the walls of a vertical tube, the transport in the upward direction is a result of the interfacial shear (τ_i) of the moving gas on the surface of the liquid. This motion is resisted by the action of gravity and wall friction. At any point y distance from the wall. There exists a velocity v and a shear stress τ. The resisting shear stress at the wall is τ_o. A steady-state force balance shows that at any point y,

$$\frac{\tau}{\tau_o} = 1+ \frac{y\rho_L g}{\tau_o g_c} \tag{2.1}$$

In dimensionless form, Eq. 2-1 becomes

$$\frac{\tau}{\tau_o} = 1+y^+ \frac{\sigma^3}{\eta} \tag{2.2}$$

Where

$$\sigma^3 = \frac{h^3 \rho_L^2 g}{\eta^2 \mu_L^2} \tag{2.3}$$

$$y^+ = \frac{v^* y \rho_L}{\mu_L} \quad \text{(dimensionless distance parameter)} \tag{2.4}$$

$$v^* = \sqrt{\frac{\tau_o g_c}{\rho_L}} \quad \text{(“friction” velocity)} \tag{2.5}$$

$$v^+ = \frac{v}{v^*} \quad \text{(dimensionless velocity parameter)} \tag{2.6}$$

$$\eta = \frac{h v^* \rho_L}{\mu_L} \quad \text{(dimension film thickness)} \tag{2.7}$$

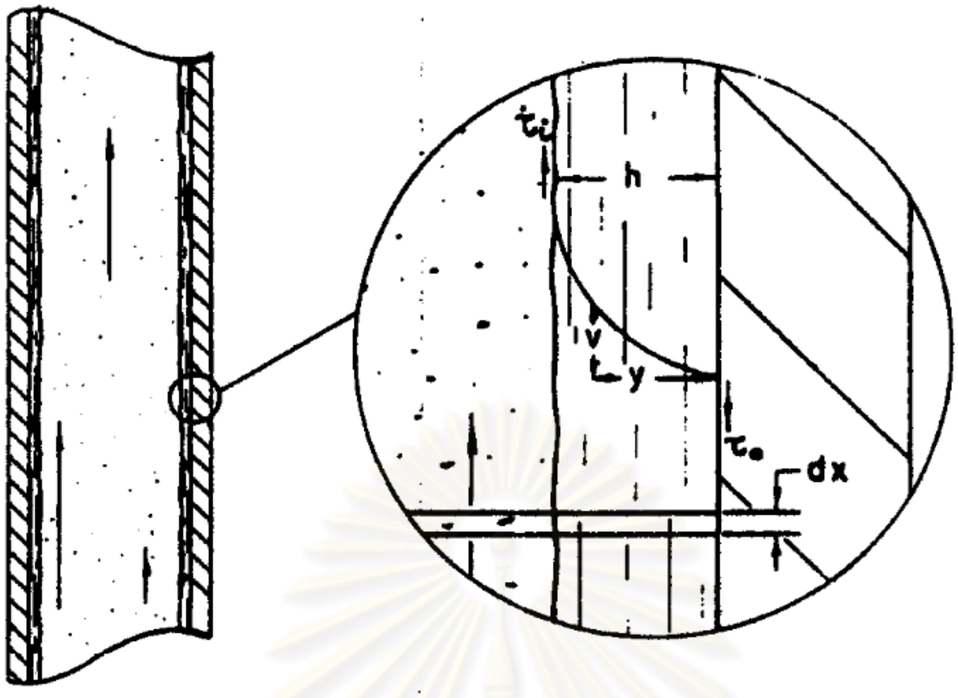


Figure 2.1: Liquid film model by Turner *et al.* [1]

Eq.2.2 is the shear stress distribution as a function of the distance from the wall of the tube. By using the Gill and Scher momentum transport hypothesis (eddy viscosity equation) and Eq. 2.2, the dimensionless velocity distribution in the flow stream is obtained

$$v^{+} = \int_0^{y^+} \frac{2(1+y\frac{\sigma^3}{\eta})}{1+\sqrt{1+4(0.36)^2 y^{+2}\left(1-e^{\frac{-\emptyset y0^+}{y_m^+}}\right)^2(1+y^+\frac{\sigma^3}{\eta})}}\, dy^{+} \qquad (2.8)$$

Where: $\emptyset = (y_m^+ - 60) / 22$

The velocity distribution in the liquid film can then be integrated to find the liquid-phase flow rate:

$$w_L = \pi d\mu_L \int_0^{\pi} v^+ dy^+ \qquad (2.9)$$

Eqs.2.8 and 2.9 may be used to evaluate the minimum gas flowrate required to move the film steadily upward. For this application, it is necessary to establish the relationship between the shear stresses and the gravitational force in the film at the minimum condition of upward flow.

Since the interfacial shear (τ_i) provides the motivating force for moving the film upward, and the gravitational shear stress, $(h\rho L\, g)/g_c$, and the shear stress at the wall (τ_o) are resisting movement will be when the interfacial shear (τ_i) approaches the value of the gravitational shear and shear stress at the wall (τ_o) approaches zero.

The ratio $\frac{h\rho_L g/g_c}{\tau_i}$ = X approaches 1.0 (i.e., the gravitational shear stress approaches the interfacial shear stress) at the limiting condition. For the purpose of analysis, X must be slightly less than 1 (i.e., the interfacial shear must be slightly larger than the gravitational shear stress, and τ_o must be greater than zero.

If it is assumed that X = 0.99 at the minimum gas flowrate condition, it is possible to evaluate the necessary parameters to integrate Eq.2.8 and 2.9. The relationship utilized is

$$\sigma^3 = \frac{X}{1-X}; \quad \frac{\beta}{\eta^{2/3}} = \frac{1}{X^{\frac{2}{3}}(1-X)^{2/3}} \qquad (2.10)$$

Where

$$\beta = \frac{Fd\rho_L^{2/3} g^{1/3}}{4\mu_L^{2/3}}; \quad F = \frac{\frac{\Delta p}{\Delta x} - \rho_g \frac{g}{g_c}}{\rho_L \frac{g}{g_c}}$$

$\Delta p / \Delta x - \rho_g(g/g_c)$ = the two-phase pressure drop = $(\Delta p / \Delta x)_{TP}$. A modification of Martinelli two-phase pressure drop correlation is employed to evaluate the $(\Delta p / \Delta x)_{TP}$.

The calculation procedure to test the development against field data required numerical integration and iteration by computer program. However, Turner *et al.* [1] concluded that the results from this model are not match with actual critical flowrate in many cases.

After Turner *et al.* [1] proposed their liquid film model, Ilobi and Ikoku [3] also proposed their study on liquid film model. They claimed that one limitation of Turner's work is the treatment of entrained liquid drops in the gas core independent of the continuous film region, even though it is knowledge that interaction between the two regions exist and are continuous in the entrainment process.

Ilobi and Ikoku [3] proposed that at any liquid rate, a decrease in gas rate caused more of liquid to be present in the film, the liquid film velocity to decrease and its thickness to increase. At a low enough gas rate, the liquid film velocity becomes zero and below this rate, a negative velocity of film near wall develops. The film thickness increase and penetrates the gas phase resulting in forth flow. For as increase of gas rate, turbulence occurs in the liquid film, the film thickness decrease, waves develop at the interface and droplets are torn off the film and entrained in the gas. The upper limit is the complete destruction of film layer as all liquid is transported as droplets. They clarified a force balance on the film and force balance on the gas core as shown Figure 2.2.

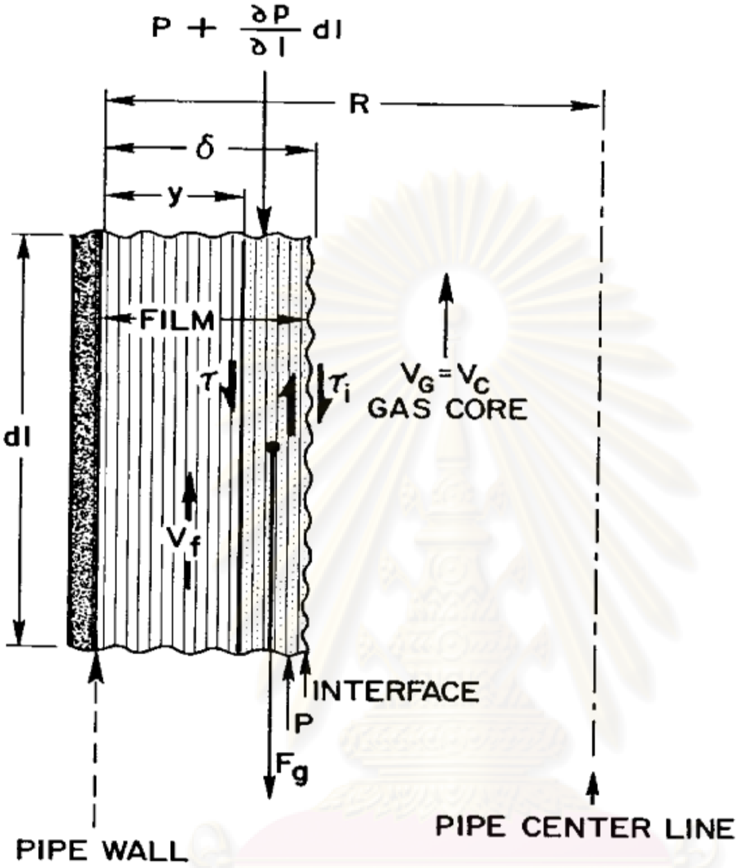


Figure 2.2: Force balance on liquid film related to Ilobi and Ikoku [3]

For force balance on the film, there are four forces acting on it as

1. A downward force acting at a radial distance (R-y) from the tubing center line as

   $\tau\ 2\pi\ (R-y)dl$

2. An upward force acting at a radial distance (R-δ) from the tubing center line as

   $\tau_i\ 2\pi\ (R-\delta)dl$

3. A downward force as a result of the gravitational force as

   $Fg = \frac{\pi}{4}[(D-2y)^2 - (D-2\delta)^2 d]\rho_L g$ where D=2R

4. An upward force as a result of the pressure gradient as

   $-\frac{\pi}{4}[(D-2y)^2-(D-2\delta)^2]dP$

A force balance on the film in this section results in the equation:

$$\tau = \tau_i\left(\frac{D-2\delta}{D-2y}\right) - \left(\frac{dP}{dl} + \rho_L g\right)(\delta - y) \qquad (2.11)$$

Where second order terms y^2, δy, δ^2 are negligible.

For force balance on gas core, there are three forces acting on it as

1. A downward force at the radial distance (R-δ) away from the center line as

   $\tau_i\, 2\pi\, (R-\delta)dl$

2. A resultant downward gravitational force as

   $\pi\, (R-\delta)^2\rho_g g dl$

3. An upward force as a result of the pressure gradient as

   $-\pi\, (R-\delta)^2 dP$

A force balance gives the following equation:

$$\tau_w = -\frac{dP}{dL}\frac{R}{2} - g\rho_L(R-a) - \frac{a^2}{2R}\rho_g g \qquad (2.12)$$

Eq. 2.12 can be rearranged as

$$\tau_w = [-\frac{dP}{dL} - g\rho_L(1-\frac{a^2}{R^2}) - \frac{a^2}{2R}\rho_g g]\ R/2 \qquad (2.13)$$

At high velocity, the liquid density term of Eq.2.13 is small in comparison to the pressure loss so that $\tau_w = \tau_i$. At low gas velocities representing the lower limit of the annular flow regimes, the wall shear stress is considerably smaller than the interfacial shear stress.

They also introduced dimensionless liquid film thickness, y_L^+, with liquid film Reynold's number, R_{eL} as

$$R_{eL} = 4\rho_L Q_L / \pi D\mu_L \qquad (2.14)$$

$$U_L^* = [(\tau_w + \tau_i) / 2\rho_L]^{1/2} \qquad (2.15)$$

$$U_G^* = [(\tau_w + \tau_i) / 2\rho_g]^{1/2} \qquad (2.16)$$

$$y_L^+ = yU_L^* / \upsilon_L \qquad (2.17)$$

$$y_G^+ = yU_G^* / \upsilon_G \qquad (2.18)$$

From their study, they found out that an empirical fit of the data for dimensionless liquid film thickness, y_L^+, and liquid film Reynold's number, R_{eL} resulted in following equation

$$2 < R_{eL} < 100,\ y_L^+ = 0.66\ (R_{eL})^{0.53} \tag{2.19}$$

$$100 < R_{eL} < 1000,\ y_L^+ = 0.347\ (R_{eL})^{0.667} \tag{2.20}$$

$$1000 < R_{eL},\ y_L^+ = 0.13\ (R_{eL})^{0.81} \tag{2.21}$$

They also proposed another relationship between the equivalent dimensionless number for gas, y_G^+ as

$$y_G^+ < 36,\ \alpha = 0 \tag{2.22}$$

$$36 < y_G^+ < 42,\ \alpha = -0.000442 + 0.000013\ y_G^+ \tag{2.23}$$

$$42 < y_G^+ < 60,\ \alpha = -0.000625 + 0.0000172\ y_G^+ \tag{2.24}$$

$$60 < y_G^+,\ \alpha = 5\text{x}10^{-8}\ y_G^{+\ 2.2} \tag{2.25}$$

$$\alpha = W_E\rho_g\ /\ W_g\rho_L \tag{2.26}$$

They selected Dun and Ros pressure gradient correlation for shear stress calculation since it provided a good match in mist and annular-mist flow pattern. The liquid film Reynold's number, R_{eL}, can be calculated for an assumed film thickness. The dimensionless liquid film thickness, y_L^+, is calculated from Eq. 2.19 to 2.21. Equation 2.17 gives a calculated value of δ, and by an iterative procedure, a true value of δ is obtained. It is necessary to know the densities and viscosities of the gas and liquid at prevailing in-situ conditions.

The equivalent dimensionless liquid film thickness for gas, y_G^+, is obtained from Eq. 2.18 and the volumetric flow ratio, α, is calculated from Eqs. 2.22 to 2.25. In Eq. 2.26, the volumetric flow ratio is written in term of the mass rate of liquid entrainment, W_E, and the mass flow rate of gas, W_g. The liquid entrainment possible with a specific gas flow rate can thus be determined. A systematic reduction in gas flow rate naturally results in reduced entrainment until the critical point is reached when entrainment is zero.

From Turner *et al.* [1] and Ilobi and Ikoku [3] their liquid film models are complex with requirement of solving multiple complex equations including numerical integration and iteration which is almost impossible to do it by hard. Moreover, Turner *et al.* [1] concluded that their liquid film model predicted critical flowrate a lot higher than actual critical flowrate in many cases and other model, which is liquid droplet model provided a better match to actual field data.

2.2 Liquid droplet model

When liquid droplets flowing in gas stream, the minimum velocity required keeping liquid droplets in suspension is the result of a force balance between the drag exerted by the surrounding gas F_D and the droplet weight F_G as in Figure 2.3

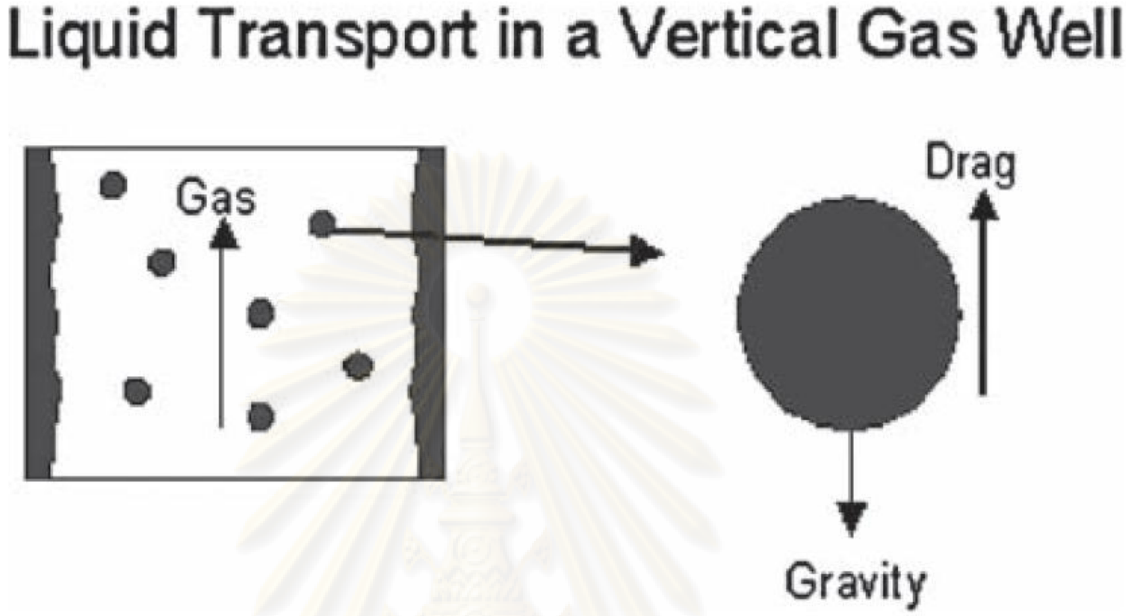


Fig 2.3: Liquid droplet in gas well [4]

The drag force acting on liquid droplet, F_D, and gravitational force acting on liquid droplet, F_G, are defined as

$$F_D = \frac{1}{2} C_d \left(\frac{d_d^2}{4}\right) \rho_g v_g^2 \tag{2.27}$$

$$F_G = \left(\frac{\pi d_d^3}{6}\right) g(\rho_L - \rho_g) \tag{2.28}$$

The critical gas velocity to remove the liquid droplet from the wellbore is defined as the velocity at which the droplet would be suspended in the gas stream. A lower gas velocity would allow the droplet to fall, resulting in liquid accumulation in the wellbore. A higher gas velocity would carry the droplet upward to the surface and remove the droplet from the wellbore [4]. Therefore, the critical gas velocity is attained when

$$F_D = F_G \text{ or } \frac{1}{2} C_d \left(\frac{d_d^2}{4}\right) \rho_g v_g^2 = \left(\frac{\pi d_d^3}{6}\right) g(\rho_L - \rho_g) \tag{2.29}$$

Solving for v_g gives

$$v_g = \sqrt{\frac{4g(\rho_L - \rho_g)d_d}{3\rho_g C_d}} \tag{2.30}$$

For the droplet diameter, d_d, Turner *et al.* [1] claimed that dimensionless Weber number, which is defined as the ratio between the velocity pressure, $v^2\rho_g/g_c$, and the surface tension pressure, σ/d, will be introduced to their study. They also claimed that critical Weber number for free falling drops was found to be on the order of 20 to 30. If Weber number exceeds critical value, a liquid drop would shatter. If larger drop size is used (Weber number = 30), the dimensionless Weber number will be

$$N_{WE} = \frac{v_g^2 \rho_g d_d}{\sigma g_c} = 30 \text{ or } d_d = 30\frac{\sigma g_c}{\rho_{g v_g^2}} \tag{2.31}$$

And substituting into Eq.2.29 gives

$$v_g = \left(\frac{40 g g_c}{C_d}\right)^{\frac{1}{4}} \left(\frac{\rho_L - \rho_g}{\rho_g^2}\sigma\right)^{1/4} \tag{2.32}$$

Turner *et al.* [1] made additional assumptions on shape of liquid droplet as a spherical shape and pointed out that typical Reynold's number for gas flowing in gas well range from 10,000 to 200,000 and Reynold's number for sphere which range from 1,000 to 200,000 is approximately constant. With those conditions, they claimed that drag coefficient is relatively constant at 0.44. After substitution value drag coefficient to Eq.2.32 gives

$$v_t = 17.6\frac{[\sigma(\rho_l - \rho_g)]^{1/4}}{\rho_g^{1/2}} \text{ ft/s} \tag{2.33}$$

And the equation for critical flowrate calculation is

$$q_t = \frac{v_t A}{B_g} = \frac{v_t A}{0.0283\frac{zT}{p}} \tag{2.34}$$

After mathematical manipulation, it gives

$$q_t = 35.34\,\frac{p v_t A}{zT} \text{ scf/s or } 3.06\,\frac{p v_t A}{zT} \text{ MMscf/d} \tag{2.35}$$

They also recommend 20% upward adjustment, which is from their analysis of data, due to three main reasons which are

1. Drag Coefficient used in this model is solid spheres rather than oscillating liquid.

2. The mathematical development predicts stagnation velocity, which must be exceeded by some finite quality to guarantee removal of the largest drops.

3. Critical Weber number, which is used to determine largest drop size, was established for drop falling in air experimentally and not for conditions that exist in gas wells.

They also recommended surface as an evaluation point because data at surface is easily available comparing to another point such as bottomhole where direct measurement of required data is not usually performed and calculation of required parameters based on surface data is usually deviated from actual data.

However, they concluded that liquid production rate is independent on their liquid droplet model since they performed an analysis on their field data and didn’t find any dependent on liquid production rate.

After Turner *et al.* [1] proposed their model, several groups of researchers also proposed their study on Turner’s liquid droplet model.

Coleman *et al.* [5] studied on Turner’s droplet model and pointed out that Turner’s field data has high wellhead pressure while they proposed that liquid loading usually happened in depleted reservoir where wellhead pressure is much lower than data that Turner’s used. Therefore, their field data were focused on low wellhead pressure (below 500 psi).

From their studied, they concluded that additional 20% upward adjustment for Turner’s correlation is not necessary since their results showed a consistency of actual critical rate and calculated critical rate without it. Secondly, their pointed out that source of liquid in gas well is likely to be a condensation of water vapor in tubing rather than liquid hydrocarbon and liquid production rate below 22.5 bbl/MMscf didn’t play any significant role on critical flowrate determination.

Moreover, they also noted that gas gravity, interfacial tension and temperature have little impact on the accuracy of the critical velocity determination. On the other hand, wellbore diameter and wellhead pressure playing a more significant role. It was observed that well with slug flow behavior didn’t obey the entrained droplet model [1].

Nosseir *et al.* [6] examined on Turner's droplet model and a conflict between Turner's and Coleman's conclusions about 20% upward adjustment by calculating Reynold's number for both Turner's and Coleman's field data and found out that Reynold's number for Turner's field data exceeded their assumed range (10,000 to 200,000) which they used for drag coefficient assumption.

In particular, field data of Turner's falls into 200,000 to 1,000,000 range which is correspond to drag coefficient equal to 0.2 and 20% upward adjustment is required while Reynold's number for Coleman's field data falls into original range which was made by Turner's (10,000 to 200,000). Therefore, no 20% upward adjustment is required.

Nosseir *et al.* [6] also proposed their modification on Turner's droplet model as they categorized two flow conditions based on Reynold's number as

1. Transition flow regimes. In this flow regime, they adopted Allen [7] concept which was developed for $1 < N_{Re} < 1000$ as

$$v_t = 0.2[\frac{g(\rho_L-\rho_g)}{\rho_g}]^{0.72} x \frac{d_d^{1.18}}{(\frac{\mu_g}{\rho_g})^{0.45}} \qquad (2.36)$$

And substitution the assumption of droplet size to Eq.2.36

$$v_t = 0.2[\frac{g(\rho_L-\rho_g)}{\rho_g}]^{0.72} x \frac{(\frac{30\sigma g_c}{\rho_g v_g^2})^{1.18}}{(\frac{\mu_g}{\rho_g})^{0.45}} \qquad (2.37)$$

$$v_t = C[\frac{g(\rho_L-\rho_g)}{\rho_g}]^{0.72} x \frac{(\frac{\sigma^{1.18}}{\rho_g^{1.18} v_g^{2.36}})}{(\frac{\mu_g}{\rho_g})^{0.45}} \qquad (2.38)$$

Where: $C = 0.2 \times 32.17^{0.72} \times 30^{1.18} \times 32.17^{1.18} = 8094.5$

Thus,

$$v_t = 14.6\, \sigma^{0.35} \frac{(\rho_L-\rho_g)^{0.21}}{\mu_g^{0.134} \rho_g^{0.134}} \qquad (2.39)$$

2. Highly turbulent flow regimes. In this flow regime, they modified Turner's droplet model as they used drag coefficient equal to 0.2 instead of 0.44 in original model. This model work in $N_{Re} > 1000$ range as recalled Eq.2.32

$$v_g = \left(\frac{40 g g_c}{C_d}\right)^{\frac{1}{4}} (\frac{\rho_L-\rho_g}{\rho_g^2} \sigma)^{1/4} \qquad (2.32)$$

Substituted drag coefficient = 0.2 into Eq.2.32 gives

$$\mathrm{v_t} = 21.3\frac{[\sigma(\rho_l-\rho_g)]^{1/4}}{\rho_g^{1/2}}\ \text{ft/s} \tag{2.40}$$

Poe, Jr. [8] stated that Nosseir's model for highly turbulent flow is only 5% different in coefficient when compares it to original Turner's model which make a better explanations of droplet model to liquid loading and Nosseir *et al.* [6] also confirmed that wellhead conditions are an appropriate conditions because it is the point at which gas slippage, and hence gas velocity, is at its maximum value. Using the maximum gas velocity will insure a maximum critical flowrate to unload the well.

Li *et al.* [9] studied in Turner's droplet model and they found out that Turner's correlation is over-estimated critical flowrate in many fields as they mentioned that field engineers in China reduced turner's critical rate as high as by two-third in many fields. They noticed that droplet shape using in Turner's correlation is a solid-spherical shape which shouldn't be corrected. They proposed that, when liquid droplet travelled in high velocity gas, shape of liquid droplet will be deformed to the convex bean (they called it flat shape) rather than spherical shape which is affected by differences of pressure shown as Figure 2.4

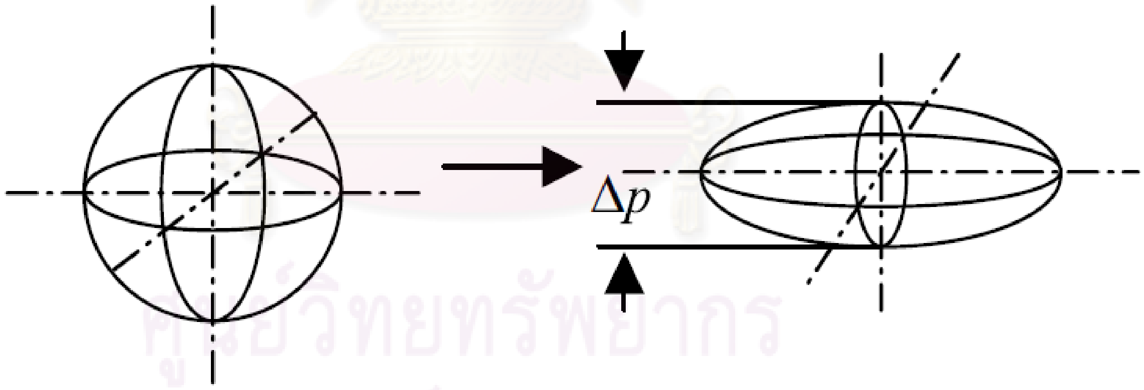


Figure 2.4: Shape of droplet proposed by Li *et al.* [9]

For the spherical droplet shape, there is smaller effective area (held by gas) and needs a higher critical velocity and critical rate in order to lift it out of the well than flat shape which has higher effective area. When the liquid drop remains motionless relative to the wellbore (i.e., the velocity of the liquid drop relative to the gas is v and equal to gas velocity v_g), it is clear that v_g is the terminal velocity v_t. With the condition that the gravity of the liquid drop equals the buoyancy plus the drag force as

$$\rho_L g V = \rho_g g V + \frac{1}{2}\rho_g v^2 s C_D \tag{2.41}$$

Where V = volume of liquid drop, m^3

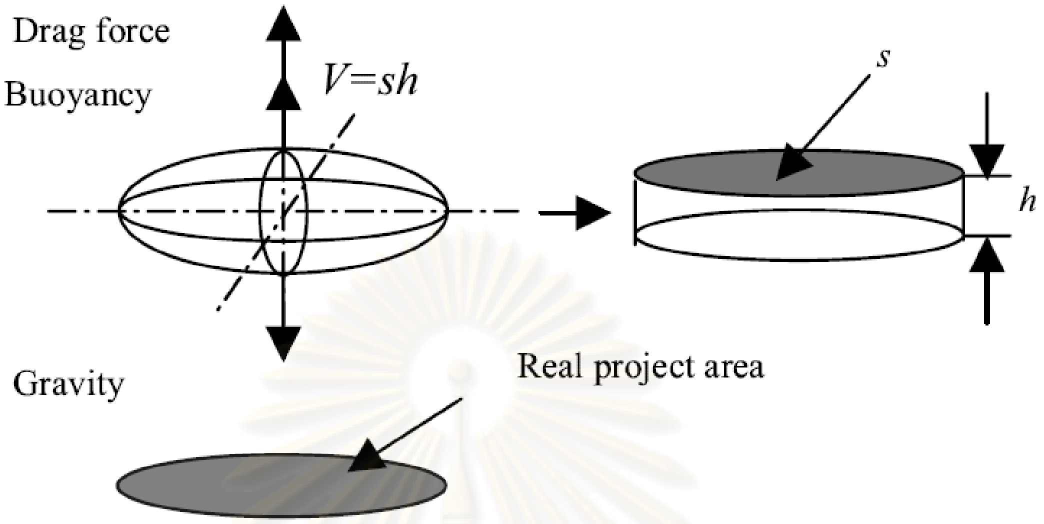


Figure 2.5: Assumption on flat shape liquid droplet

For the projected area of liquid drop, as the drop falls relatively to the gas stream at velocity v, a pressure difference appears between the fore and aft positions of the drop. According to the Bernoulli law is

$$\Delta p = \frac{10^{-3}\rho_g}{2} v^2 \tag{2.42}$$

The drop is deformed under the influence of the pressure difference and interfacial tension prevents the drop from further deformation. As a result of the competing effects of these forces, the drop acquires a certain steady shape related to the given velocity v. The condition for the balance of pressure and interfacial tension forces can be written in the following form.

$$\frac{\Delta p}{10^{-3}} s\Delta h + \sigma\Delta s = 0 \tag{2.43}$$

Where: h = drop’s dimension in direction of motion, m

The first term of Eq.2.43 indicated that pressure is expended in the deformation Δh. The second term represents the deformation effect of the interfacial tension forces. It is obvious that for a constant volume of the drop, the following condition must be satisfied

$$V = sh = \text{constant} \tag{2.44}$$

From Eq.2.43 obtains

$$\frac{\Delta ps}{10^{-3}\sigma} = \frac{\Delta s}{\Delta h} \tag{2.45}$$

And from Eq.2.44 gets

$$\frac{\Delta s}{\Delta h} = -\frac{V}{h^2} = -\frac{sh}{h^2} = -\frac{s}{h} \tag{2.46}$$

By combining Eq.2.45 and 2.46, thickness of the drop can be calculated as

$$h = \frac{10^{-3}\sigma}{\Delta p} \tag{2.47}$$

Substituting Δp from Eq.2.42 into Eq. 2.46 gives

$$h = \frac{2\sigma}{\rho_g v^2} \tag{2.48}$$

Substituting the Eq.2.48 into Eq.2.44 gives

$$V = \frac{2s\sigma}{\rho_g v^2} \tag{2.49}$$

Therefore, the projected area is estimated to be

$$s = \frac{\rho_g v^2 V}{2\sigma} \tag{2.50}$$

Substituting Eq.2.50 to Eq.2.41, with assumption of velocity is equal to terminal velocity in balance condition, gives

$$v_t = v = \sqrt[4]{\frac{4(\rho_L - \rho_g)g\sigma}{\rho_g^2 C_D}} \tag{2.51}$$

For the drag coefficient, Li *et al.* [9] proposed that for the particle's Reynold's number ranges from 10,000 to 100,000 with flat shape. The Reynold's number is 1.0. Therefore, critical velocity for Li *et al.* [9] correlation is

$$v_t = 2.5\sqrt[4]{\frac{(\rho_L - \rho_g)\sigma}{\rho_g^2}}\text{, m/s} \tag{2.52}$$

And critical flowrate is

$$q_t = 2.5\text{x}10^5\frac{Apv_t}{zT}\text{, m}^3\text{/d} \tag{2.53}$$

Since the unit of critical velocity of Li *et al.* [9] which is in m/s, is different from Turner *et al.* [1] which is in ft/s. Therefore, coefficient of Turner's correlation for critical velocity will be changed to 6.6 in the unit of m/s instead of 17.6 in the unit of ft/s.

Another modification of liquid droplet model was proposed by Guo *et al.* [10]. They introduced bread new concept of minimum kinetic energy in order to unload liquid out of the well. They began their own study with kinetic energy per unit volume of gas equation.

$$E_k = \frac{\rho_g v_g^2}{2g_c} \tag{2.54}$$

And they recalled Turner's critical velocity equation (in US unit) in order to substituting in Eq.2.54 as

$$v_{sl} = 1.3\frac{\sigma^{1/4}(\rho_L - \rho_g)^{1/4}}{C_D^{1/4}\rho_g^{1/2}} \tag{2.55}$$

Substituting Eq.2.55 into Eq.2.54 gives an expression for the minimum kinetic energy required to keep liquid droplet from falling as

$$E_{ksl} = 0.026\sqrt{\frac{\sigma(\rho_L - \rho_g)}{C_D}} \tag{2.56}$$

If the value of drag coefficient = 0.44 which is recommended by Turner *et al.* [1] is used, and the effect of gas density is neglected (a conservative assumption), Eq. 2.56 becomes

$$E_{ksl} = 0.04\sqrt{\sigma\rho_L} \tag{2.57}$$

They pointed out that the minimum gas velocity required for transport the liquid droplet upward is equal to the minimum gas velocity required for floating the liquid droplets plus the transport velocity of the droplet. They also mention that transport velocity might be calculated from liquid production rate, geometry of the conduit and liquid volume fraction which is difficult to quantify. Therefore, they adopted an idea of 20% upward adjustment for Turner's correlation as they proposed that transport velocity equal to 20% of minimum gas velocity required for floating the liquid droplets as

$$v_{gm} = v_{sl} + v_{tr} = 1.2\ v_{sl} \tag{2.58}$$

Substituting Eq.2.57 and 2.58 to Eq.2.54 gives an equation for minimum kinetic energy required for transporting the liquid droplets as

$$E_{km} = 0.0576\sqrt{\sigma\rho_L} \tag{2.59}$$

Eq.2.59 gives the minimum kinetic energy for any particular condition which is independent from gas flowrate. In order to find minimum kinetic energy at any given flowrate, two more equations will be introduced as

$$\rho_g = \frac{S_g P}{53.34T} \tag{2.60}$$

$$v_g = 4.71\text{x}10^{-5}\frac{TQ_g}{AP} \tag{2.61}$$

Substituting Eq.2.60 and 2.61 to Eq.2.55 gives

$$E_k = 6.46\text{x}10^{-13}\frac{S_g T Q_g^2}{A^2 P} \tag{2.62}$$

$$P = 6.46\text{x}10^{-13}\frac{S_g T Q_g^2}{A^2 E_k} \tag{2.63}$$

They also noticed that gas kinetic energy decreases with increased pressure, which means the controlling conditions are bottomhole conditions where gas has higher pressure and lower kinetic energy which is complied with the observations from air-drilling operations where solid particles accumulate at bottomhole rather than tophole. However, that analysis is conflict with Turner's conclusion as Turner *et al.* [1] indicated that wellhead conditions are the controlling conditions.

Nevertheless, bottomhole flowrate and pressure are the parameters that hardly measure in normal operation. Therefore, a gas-oil-water-solid four-phase mist-flow model was developed in order to solve those parameters as

$$b(P-P_{hf}) + \frac{1-2bm}{2}\ln\left|\frac{(P+m)^2+n}{(P_{hf}+m)^2+n}\right| - \frac{m+\frac{b}{c}n-bm^2}{\sqrt{n}}\left[\tan^{-1}\left(\frac{P+m}{\sqrt{n}}\right)-\tan^{-1}\left(\frac{P_{hf}+m}{\sqrt{n}}\right)\right]$$

$$= a(1+d^2e)L \tag{2.64}$$

Where: $a = \dfrac{15.33S_sQ_s + 86.07S_wQ_w + 86.07S_oQ_o + 0.01879S_gQ_g}{TQ_g}\cos(\theta)$ (2.65)

$$b = \frac{0.2456Q_s + 1.379Q_w + 1.379Q_o}{TQ_g} \tag{2.66}$$

$$c = \frac{4.712x10^{-5}TQ_g}{A} \tag{2.67}$$

$$d = \frac{Q_s + 5.615(Q_w + Q_o)}{86400A} \tag{2.68}$$

$$e = \frac{f}{2gD_H\cos(\theta)} \quad (2.69)$$

$$f = \text{Moody friction factor} = \left[\frac{1}{1.74 - 2\log\left(\frac{2\varepsilon}{D_H}\right)}\right]^2 \quad (2.70)$$

$$m = \frac{cde}{1+d^2e} \quad (2.71)$$

$$n = \frac{c^2e}{(1+d^2e)^2} \quad (2.72)$$

In summary, minimum kinetic energy at any given condition is determined by Eq.2.59 and kinetic energy at any given flowrate is determined by Eq.2.62 and Eq.2.64 is used to determine bottomhole flowrate using in Eq.2.63. Guo *et al.* [10] also validated their own model with Turner's field data and found a consistency with it.

However, liquid holdup is not introduced to critical velocity determination as Kumar [11] stated that there is no function of the amount of liquid flowing in Turner's droplet model. For larger flowrate of liquid, liquid droplets would begin to coalesce and the droplet model for most critical velocity expressions would no longer be applicable until Zhou *et al.* [12] presented a new model for calculating critical velocity.

They noticed that liquid loading still be a problem even its gas velocity high than calculated critical velocity which is presented by Turner *et al.* [1] (20% upward adjustment is added by Turner *et al.* [1] recommendation). They pointed out that liquid amount (liquid holdup) in a gas stream is also a major factor for liquid loading as an additional to gas velocity which is considered as independent parameter in previous model. They pointed out that the concentration of liquid droplets in gas stream should be another mechanism for liquid loading as in turbulent gas stream, which is a common flow regime in gas well, liquid droplets move not only upwards with the gas stream but also in all direction irregularly. The nearby liquid droplets may encounter each other and form a bigger droplet. This bigger droplet tends to fall down to bottom of the well since it required higher terminal velocity to suspend it. During falling, the bigger new-formed droplet may shatter into small droplets, and the small droplets may be picked up again by the drag forces from gas stream. However, if the bigger droplet or its shattered droplets encounter liquid droplets during their falling, they may form it up again and keep falling.

Concentration of liquid droplet also plays another role as the higher the concentration of liquid droplets in a turbulent gas stream, the higher the chance the droplets encounter. Turner’s entrained liquid droplet model is based on force balance on a single droplet and doesn’t include the encountering effect. For low liquid droplet concentration, the chance of encounterment is very low and Turner’s model works fine. However, when the liquid concentration reaches certain value, the encountering-coalescing-falling process of liquid droplets in a gas stream will dominate the entrained liquid droplet movement and cause Turner’s droplet model losses its function.

For liquid droplet concentration, Zhou *et al.* [12] adopted a concept of liquid holdup to their study as

$$H_l = \frac{v_l}{v_l+v_g} \tag{2.73}$$

For their model, Zhou *et al.* [12] proposed a threshold value of liquid droplet concentration, β. Below this value, the entrained liquid droplets couldn’t encounter or they encounter and coalesce but will be brought up by gas stream. Therefore, original Turner’s model can be used in this situation.

Above the concentration value, higher gas velocity is needed as higher gas velocity provides higher drag force and can bring bigger droplets up. Also, higher gas velocity has higher velocity pressure which prevents bigger liquid droplet formation and shatter bigger droplets faster. Therefore, the critical velocity for liquid loading is not a single value. It varies with the liquid droplet concentration in a gas stream once the concentration exceeds the threshold value, β.

Zhou *et al.* [12] proposed their model for critical velocity determination as

$$v_{crit\text{-}N} = v_{crit\text{-}T} = 17.6\frac{[\sigma(\rho_l-\rho_g)]^{1/4}}{\rho_g^{1/2}} \quad \text{for } H_l \le \beta \tag{2.74}$$

$$v_{crit\text{-}N} = v_{crit\text{-}T} + \ln\frac{H_l}{\beta} + \alpha \quad \text{for } H_l > \beta \tag{2.75}$$

At first, liquid holdup needs to be calculated by Eq.2.73. If liquid holdup not exceeded a threshold value (which is equal to 0.01), original Turner’s equation will be used for critical velocity determination. Otherwise, additional two more terms will be added to original Turner’s equation for critical velocity determination in order to calculate critical velocity for Zhou’s correlation. For critical flowrate determination, same equation as Turner’s correlation will be used in Zhou’s correlation.

For critical flowrate determination, same equation as be used in Turner’s correlation will be used in this correlation as

$$q_{crit-N} = \frac{3.06\, p v_{crit-N} A}{Tz} \tag{2.76}$$

Zhou *et al.* [12] also pointed out that upper limit for gas well that still in unloaded condition is value of threshold value, β, less than 0.24. If $\beta > 0.24$, flow patterns will be no longer a annular-mist flow and it will be considered as loaded condition automatically no matter of other parameters will be.

At the end of their paper, they also recommended wellhead condition as evaluating point as data at wellhead condition is easily available and it can be avoided a complex calculation. Moreover, more condensate and water may be condensed out from the gas stream near wellhead and the wellhead area has the highest liquid content along the wellbore.

Apart from proposing new model for critical velocity and flowrate, Sutton *et al.* [13] had presented a guideline for proper application of critical velocity calculations. They stated that Turner’s assumptions on fluid properties deviated from actual properties such as typical salinity of formation brine to be 28,000 ppm and stated a corresponding water specific gravity of 1.08. But examination of oil field waters note that water with a specific gravity of 1.08 has a salinity of 102,000 ppm. Conversely, water with a salinity of 28,000 ppm has a specific gravity of 1.025. In fact, condensed water does not contain any dissolved salts and has a specific gravity of 1.0.

Another fluid property which is stated by Sutton *et al.* [13] is surface tension. Turner *et al.* [1] assumed condensate and water surface tension to be constant which are 20 dynes/cm and 60 dynes/cm respectively are correct for particular conditions. For water surface tension, 60 dynes/cm is true for pressure between 2000-3000 psia and 120°F while 20 dynes/cm for condensate surface tension is only representative for condition less than 250 psia. At the end of their paper, Sutton *et al.* [13] concluded that pressure and temperature play an important role in fluid properties determination. They also recommended suitable correlations for determining these fluid properties in their study.

In next chapter, details of selected critical flowrate correlations of this study are clarified. Moreover, the input parameters of this study are analyzed because actual production data are applied to calculating model to investigate liquid loading problem. Using actual production data without data classification may cause an excessive error to the results because several uncertainties usually contain in actual production data. At the end of chapter III, details of calculating model of this study are clarified including the additional assumptions using to calculate critical flowrate of each selected correlation.

CHAPTER III

REVIEW ON SELECTED CORRELATIONS, PRODUCTION DATA AND MODEL CONSTRUCTION

In this chapter, selected critical flowrate correlations using in this study will be clarified for model construction in spreadsheet program. Classification of production data is discussed because this study selects actual production data as input parameters. Details of calculating model also classify including the additional assumptions on required parameters for model construction are summarized in this chapter.

3.1 Summary of selected critical flowrate correlations

Determination of critical flowrate is one of the most important procedures for dealing with liquid loading problems. One of the pioneers in this topic is Turner *et al.* [1] who proposed two mechanisms for liquid to load out of the well as liquid film and liquid droplet model. They found out that liquid film model did not provide a good match to actual critical flowrate in their study. On the other hand, liquid droplet model provided a good match between actual critical flowrate and their calculated flowrate and it became a popular model for critical flowrate determination.

After that, several groups of researchers proposed their own study on critical flowrate determination. However, three correlations which have the differences in their point of views are selected in this study, namely Turner’s correlation, Guo’s correlation and Zhou’s correlation. Turner’s correlation is chosen in this study as it is widely used in this industry and it is considered as a base for many correlations. Guo’s correlation is chosen as it introduces brand new concepts on critical flowrate determination and Zhou’s correlation is selected as it is the first correlation that includes liquid holdup as a direct parameter in critical velocity calculation. Details of these correlations will be reviewed in the following sections.

3.1.1 Turner's correlation

Turner's correlation is the very first liquid droplet model which has been reviewed and modified by several groups of researchers. Moreover, it is widely used in oil and gas industry. Therefore, Turner's correlation is selected for this study.

Turner *et al.* [1] proposed an equation for critical velocity determination as

$$v_t = 17.6 \frac{[\sigma(\rho_l - \rho_g)]^{1/4}}{\rho_g^{1/2}} \text{ ft/s} \tag{3.1}$$

For critical flowrate equation, critical velocity from Eq.3.1 will be used as

$$q_t = 3.06 \frac{p v_t A}{zT} \text{ MMscf/d} \tag{3.2}$$

Turner *et al.* [1] recommended wellhead as evaluation point because it is easily available compared to another point such as bottomhole where direct measurement of required data is not usually performed. Moreover, calculation of required parameters based on surface data is usually deviated from actual data.

3.1.2 Guo's correlation

This correlation uses a different approach in order to determine critical flowrate by adopting the concept of minimum kinetic energy for critical flowrate determination. They proposed their minimum kinetic energy equation for particular liquid properties as

$$E_{km} = 0.0576\sqrt{\sigma\rho_L} \tag{3.5}$$

This equation derived from kinetic energy per unit volume of gas together with critical velocity equation for droplet model from Turner's correlation. For kinetic energy for particular gas flowrate, they added two more equations from ideal gas law to kinetic energy per unit volume of gas and it results as

$$E_k = 6.46\text{x}10^{-13} \frac{S_g T Q_g^2}{A^2 P} \tag{3.6}$$

For evaluation point, they recommended that bottomhole condition should be used in their equations as they founded out that gas kinetic energy decreases with increased pressure. Therefore, bottomhole condition which gas has higher pressure and lower kinetic energy is chosen. It is complied with the observations from air-drilling operations where solid particles accumulate at bottomhole rather than tophole.

They proposed another set of equation for bottomhole flowrate determination as they developed a gas-oil-water-solid four-phase mist-flow model as

$$b(P-P_{hf}) + \frac{1-2bm}{2}\ln\left|\frac{(P+m)^2+n}{(P_{hf}+m)^2+n}\right| - \frac{m+\frac{b}{c}n-bm^2}{\sqrt{n}}\left[\tan^{-1}\left(\frac{P+m}{\sqrt{n}}\right)-\tan^{-1}\left(\frac{P_{hf}+m}{\sqrt{n}}\right)\right]$$

$$= a(1+d^2e)L \tag{3.7}$$

Where: $$a = \frac{15.33S_sQ_s + 86.07S_wQ_w + 86.07S_oQ_o + 0.01879S_gQ_g}{TQ_g}\cos(\theta) \tag{3.8}$$

$$b = \frac{0.2456Q_s + 1.379Q_w + 1.379Q_o}{TQ_g} \tag{3.9}$$

$$c = \frac{4.712x10^{-5}TQ_g}{A} \tag{3.10}$$

$$d = \frac{Q_s + 5.615(Q_w + Q_o)}{86400A} \tag{3.11}$$

$$e = \frac{f}{2gD_H\cos(\theta)} \tag{3.12}$$

$$f = \text{Moody friction factor} = \left[\frac{1}{1.74 - 2\log\left(\frac{2\varepsilon}{D_H}\right)}\right]^2 \tag{3.13}$$

$$m = \frac{cde}{1+d^2e} \tag{3.14}$$

$$n = \frac{c^2e}{(1+d^2e)^2} \tag{3.15}$$

After substituting Eq.3.6 into Eq.3.7, the equation for kinetic energy for any particular flowrate will be

$$b\left(6.46 \times 10^{-13}\frac{S_gTQ_{gm}^2}{A^2E_{km}} - P_{hf}\right) + \frac{1-2bm}{2}\ln\left|\frac{\left(6.46 \times 10^{-13}\frac{S_gTQ_{gm}^2}{A^2E_{km}}+m\right)^2+n}{(P_{hf}+m)^2+n}\right|$$

$$- \frac{m+\frac{b}{c}n-bm^2}{\sqrt{n}}\left[\tan^{-1}\left(\frac{6.46 \times 10^{-13}\frac{S_gTQ_{gm}^2}{A^2E_{km}}+m}{\sqrt{n}}\right)-\tan^{-1}\left(\frac{P_{hf}+m}{\sqrt{n}}\right)\right] = a(1+d^2e)L \tag{3.16}$$

This correlation uses different approaches and required parameters in order to determine critical flowrate. Additional assumptions on some required parameters are made in order to complete the calculation since Guo *et al.* [10] did not have any recommendations on each parameter except their assumptions on Turner's recommendation. The values of thermal gradient at 0.01°F/ft and tubing roughness at 0.000015 inch, which is the assumed values that Guo *et al.* [10] used to generate their charts at the end of their paper, are the assumed values for this study.

3.1.3 Zhou's correlation

This correlation is also developed from Turner's droplet model as they introduced liquid holdup into Turner's liquid droplet model for critical velocity determination as they proposed the threshold value, β. If liquid holdup is below threshold value, original Turner's equation for critical velocity determination will be used and two additional terms will be added to original Turner's equation in case of liquid holdup exceeding threshold value. Therefore, a set of equations for critical velocity determination proposed by Zhou *et al.* [12] is

$$v_{crit-N} = v_{crit-T} = 17.6\frac{[\sigma(\rho_l-\rho_g)]^{1/4}}{\rho_g^{1/2}} \quad \text{for } H_l \le 0.01 \qquad (3.17)$$

$$v_{crit-N} = v_{crit-T} + \ln\frac{H_l}{\beta} + \alpha \quad \text{for } H_l > 0.01 \qquad (3.18)$$

And critical flowrate determination – the same equation as in Turner's correlation will be used in this correlation as

$$q_{crit-N} = \frac{3.06\,p v_{crit-N} A}{Tz} \qquad (3.19)$$

In this correlation, wellhead condition is used as the evaluation point for the same reasons as Turner *et al.* [1] commented in their paper.

3.2) Data Classification

Together with the clarification of selected correlations. Classification of data is necessary as raw data of this study has a wide range and it contains some fluctuation in data collection. Moreover wrong assumptions and conclusions can be made by applying meaningless data to calculating model. Ranges of production data are shown in Table 3.1.

Table 3.1 Range of production data from actual production wells

Parameters	Minimum	Maximum
Pressure. psia	45	3,272
Gas production rate, MMscf/d	0	15.22
Oil production rate, bbl/d	0	1,728
Water production rate, bbl/d	0	2,309
Temperature, °F	54	250
Well depth (MD), ft	6,000	13,880
Inside Diameter of tubing, inches	2.441	2.992
Well life, days	86	4,592

Production history using in this study is actual data which has a wide range of data as shown in table 3.1. Moreover, data distribution for each parameter containing in each data set is also different and some of the data has to be eliminated such as no gas production data at the end of well life. Therefore, statistic classification of data is performed for four parameters which are gas production rate, flowing tubing pressure (FTP), liquid production rate and liquid holdup. Details of data classification of each parameter are clarified in next section.

3.2.1 Gas production rate

Gas production rate is one of the most important parameters in this study because the comparison of this parameter with predicted critical flowrate is used to determine liquid loading status. Moreover, it is used in other calculations such as liquid holdup calculation. A summary of this parameter is shown in Table 3.2 and Figure 3.1

Table 3.2: Summary of gas production rate data (in MMscf/d)

Parameter	Value (raw data)	Value (screened data)
Number of data	1300	1297
Mean	2.15	2.12
Median	1.5	1.5
Mode	0.01	0.01
Standard deviation	2.18	2.10
Minimum	0.01	0.01
Maximum	15.22	10.79
1st Quartile	0.5	0.5
3rd Quartile	2.87	2.85

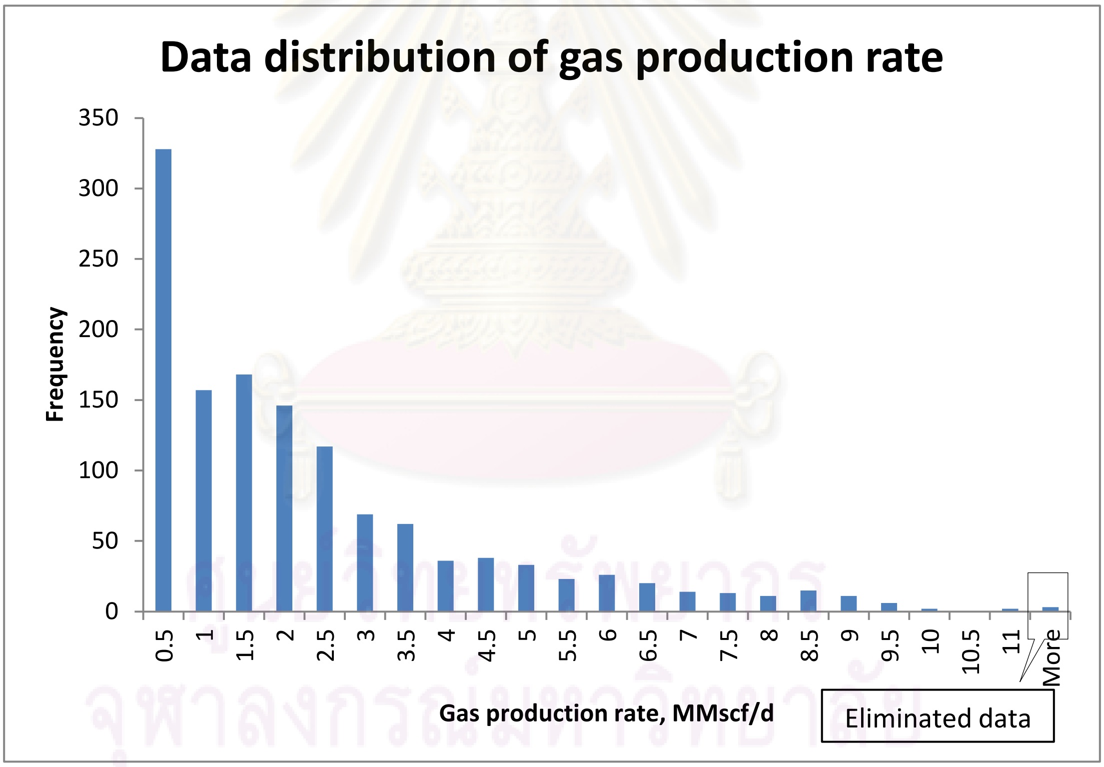


Figure 3.1: Histogram plot for gas production rate

No gas production rate data set is eliminated out of this study in primary screening because it is an indicator of no flow condition. After that, remaining data is sorted and summarized as shown in Table 3.2 and Figure 3.1. Even though range of this data is 0.01 to 15.22 MMscf/d, most of gas production rate data is in low value as median, first quartile, third quartile and mode of this data set are 1.5, 0.5, 2.87 and 0.1

MMscf/d respectively while arithmetic mean of this data is 2.15 MMscf/d. However, 3 data sets which are 12.18, 13.85 and 15.22 MMscf/d are significantly out of the group. Then, those three data are eliminated from this study and a new summary of data is shown in Table 3.2 for screened data column. After three data sets are eliminated, range of data, arithmetic mean and third quartile of data set change, namely 0.01 to 10.79 MMscf/d for range of data, 2.12 MMscf/d for arithmetic mean and 2.85 MMscf/d for third quartile.

3.2.2 Flowing Tubing Pressure (FTP)

Flowing Tubing Pressure (FTP) is a vital parameter for petroleum industry as it is used by production and reservoir engineers in many aspects and production period of any petroleum well is indicated by this parameter (together with production rate). A summary of this parameter is shown in Table 3.3 and Figure 3.2

Table 3.3: Summary of flowing tubing pressure data (in psia)

Parameter	Value (raw data)	Value (screened data)
Number of data	1403	1398
Mean	616	611
Median	501	501
Mode	275	275
Standard deviation	438	422
Minimum	45	168
Maximum	3272	2715
1st Quartile	315	315
3rd Quartile	685	685

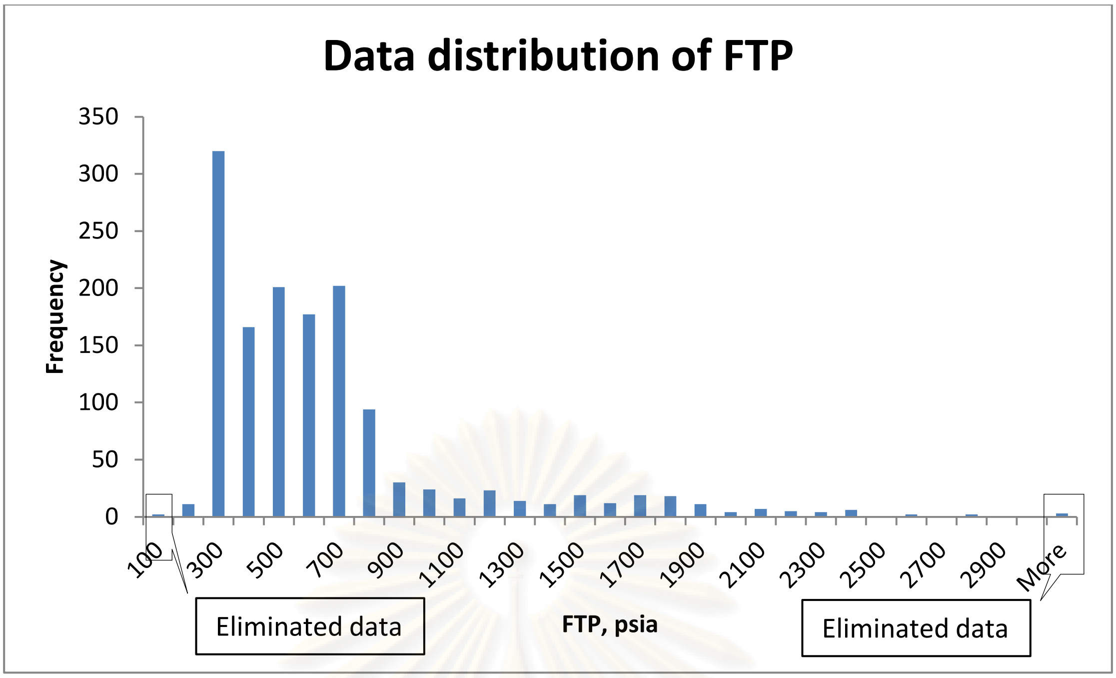


Figure 3.2: Histogram plot for flowing tubing pressure

Data set that has value of FTP equals to zero is eliminated in primary screening as it is an indicator of no flow condition. After that, remaining data is sorted and summarized as shown in Table 3.3 and Figure 3.2. The bin range that has the highest number of data is 200 to 300 psia. The next four bin ranges still have high number of data (between 150 to 200 data) but number of data in each bin range decreases constantly and stays below 30 data per bin range from 800-900 psia bin range to last bin range. Therefore, most of the data is in low value and data distribution is similar to gas production rate case as median, first quartile, third quartile and mode of this data set are 501, 315, 685 and 275 psia respectively while arithmetic mean of this data is 616 psia.

However, there are two bin range that isolate from the main group. The first bin range contains 45 psia and 70 psia data which rarely happens in normal operation. On the other hand, the last bin range (>3000 psia) stays out of the main group. Therefore, those two bin range are eliminated out of this study and a summary of data is shown in table 3.3 for screened data column. After three data are eliminated, range of data, arithmetic mean and third quartile of data set change to 168 psia to 2715 psia for range of data, 611 psia for arithmetic mean.

3.2.3 Liquid production rate

Since this study focuses on liquid loading in gas well, liquid production rate is considered as a vital parameter for this study. The definition of liquid production rate in this study is a summation of water and condensate production rate at standard condition which is calculated by equation 3.20. A summary of this parameter is shown in Table 3.4 and Figure 3.3

$$\text{Liquid production rate } (Q_l\text{, bbl/d}) = (q_w * B_w) + (q_o * B_o) \qquad (3.20)$$

Where: B_o = oil formation volume factor

B_w = water formation volume factor

q_o = measured oil production rate at wellhead, bbl/d

q_w = measured water production rate at wellhead, bbl/d

Table 3.4: Summary of liquid production rate data (in bbl/d)

Parameter	Value (raw data)	Value (screened data)
Number of data	1090	1090
Mean	295	295
Median	140	140
Mode	1	1
Standard deviation	396	396
Minimum	1	1
Maximum	2514	2514
1st Quartile	50	50
3rd Quartile	375	375

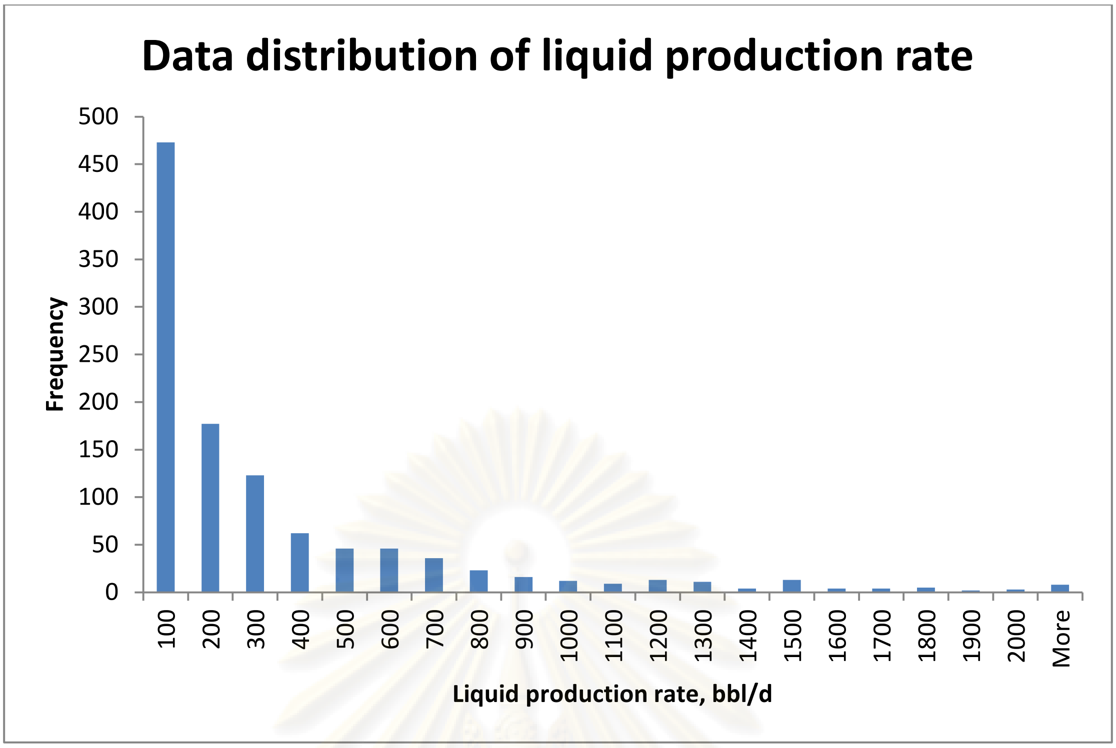


Figure 3.3: Histogram plot for liquid production rate

No liquid production rate data set is eliminated out of this study for primary screening as those sets of data did not make a liquid loading condition. After that, remaining data is sorted and summarized as shown in Table 3.4 and Figure 3.3. Data distribution for liquid production rate is almost the same as gas production rate because most of the data is in low value. In term of statistic value, median, first quartile, third quartile and mode of this data set are 140, 50 and 375 bbl/d respectively while arithmetic mean of this data is 295 bbl/d. However, it still has data distribution in high value as data is filled in every bin range which is different from gas production rate case where three data isolate out of main group. Therefore, no additional screen for liquid production rate data resulting in the similar values of each parameter which is shown in column 2 and 3 of Table 3.4.

3.2.4 Liquid Holdup

Liquid loading is a problem involving with liquid and gas, whereas liquid holdup is a direct relationship between liquid and gas. Therefore, it is chosen as an important parameter for this study in order to describe a relationship between liquid and gas. However, in multiphase flow, liquid holdup has several definitions which are varied by interpretation of each researcher. For this study, one of the most popular definitions which is chosen by this study is no-slip liquid holdup.

Beggs [14] provided the definition of no-slip liquid holdup as the ratio of the volume of the pipe element that would exist if the gas and liquid traveled at the same velocity (no slippage) divided by the volume of the pipe element. An equation form for that definition is written as

$$\lambda_L = \frac{q_L}{q_L + q_g} \tag{3.21}$$

Since the area of tubing string for each well in this study is constant for entire tubing string in each particular well, velocity terms can replace flowrate terms in Eq.3.21 as

$$\lambda_L = \frac{v_l}{v_l + v_g} \tag{3.22}$$

From Eq.3.22, liquid holdup can be determined at any locations in tubing string. Zhou *et al.* [12] recommended wellhead as an evaluation point because data is easily available and wellhead is the highest liquid content along the wellbore. Therefore, value of liquid holdup for this study will be calculated from Eq. 3.23. A summary of this parameter is shown in Table 3.5 and Figure 3.4.

$$\lambda_L = \frac{v_{slwh}}{v_{slwh} + v_{sgwh}} \tag{3.23}$$

Table 3.5: Summary of liquid holdup data

Parameter	Value (raw data)	Value (screened data)
Number of data	1086	1045
Mean	0.046	0.035
Median	0.018	0.017
Mode	0.003	0.003
Standard deviation	0.074	0.045
Minimum	$6.13\text{x}10^{-5}$	$6.13\text{x}10^{-5}$
Maximum	0.513	0.238
1st Quartile	0.006	0.006
3rd Quartile	0.051	0.046

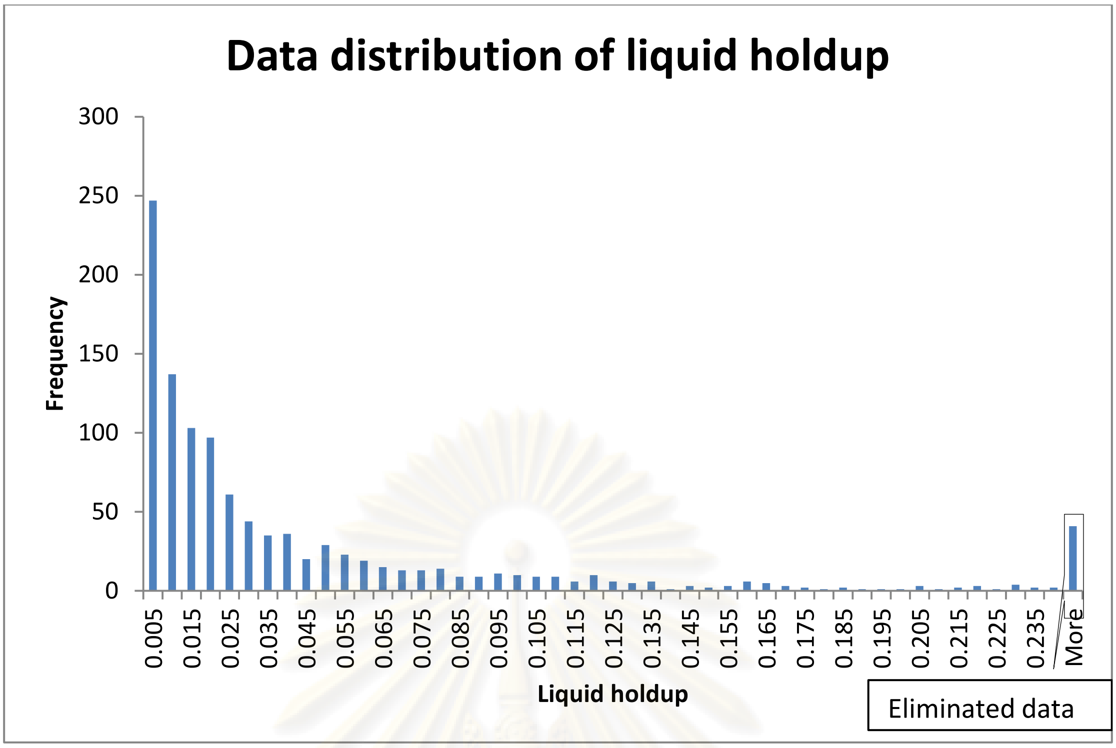


Figure 3.4: Histogram plot for liquid holdup

No gas production rate and no liquid production rate data are eliminated in primary screening because no gas production rate data gives infinity value for liquid holdup calculation and no liquid production rate will return zero back to the value of liquid holdup after calculated by equation 3.23. After that, remaining data is sorted and summarized as shown in Table 3.5 and Figure 3.4. In term of statistic value, median, first quartile, third quartile and mode of this data set are 0.018, 0.006, 0.051 and 0.003 respectively while arithmetic mean of this data is 0.046. Data distribution for liquid holdup is similar to liquid production rate as first bin range has the highest number of data and number of data in the next bin is declining constantly and there is no isolated data which is different from data distribution of gas production rate. However, Zhou *et al.* [12] mentioned in their research that flow pattern is no longer annular-mist flow if liquid holdup exceeds 0.24. As liquid droplet model relies on annular-mist flow pattern, liquid holdup data that exceeds 0.24 is eliminated out of this study. After that data is eliminated, range of data, arithmetic mean and third quartile of data set change to 6.13×10^{-5} to 0.238 for range of data, 0.035 for arithmetic mean and 0.046 for third quartile which is shown in screened data column in Table 3.5.

Since liquid holdup is considered as important parameter for this study, additional classification for liquid holdup is made. Liquid holdup is classified into separated groups with a certain range of value which has a significant technical or statistical meaning. A summary of liquid holdup classification is shown in Table 3.6.

Table 3.6: Classification of liquid holdup

Group	Value	Remark
Low	$H_l < 0.01$	H_l at 0.01 is threshold value for Zhou's correlation
Low-moderate	$0.01 < H_l < 0.03$	H_l at 0.03 locates at two-third of entire liquid holdup data (66th percentile)
Moderate-high	$0.03 < H_l < 0.1$	H_l at 0.1 locates at nine-tenth of entire liquid holdup data (90th percentile)
High	$0.1< H_l < 0.24$	$H_l > 0.24$ is out of liquid droplet's assumption [12]

3.3 Model construction

After three correlations are selected in this study, Microsoft Excel is chosen as a calculating program for this study as it has a strong point to manage spreadsheet and it is also commonly utilized. However, before Microsoft Excel model is generated, detail on input data for calculating model needs to be clarified.

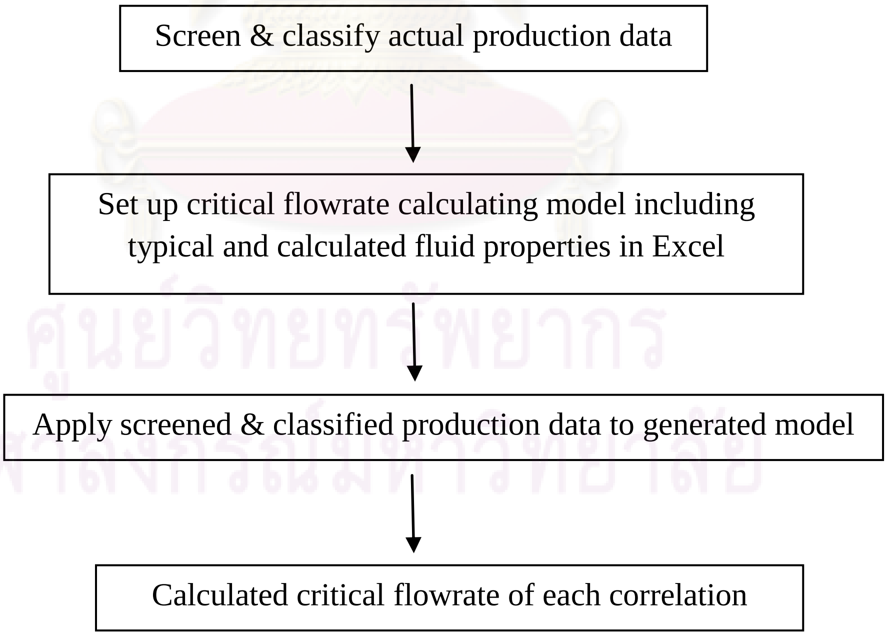
This study selects actual production data from Gulf of Thailand as raw data. The data is recorded during production period of each well. At each point of time, various kinds of data are collected. In order to avoid confusion, in this study the data recorded at a certain point of time is called a "data set". Details of each data set are shown in Table 3.7

Table 3.7: Detail of each data set

Detail of data in each data set	Unit
Flowing Tubing Pressure	psia
Gas production rate	MMscf/d
Oil production rate	bbl/d
Water production rate	bbl/d
Flowing tubing temperature	°F
Well depth	ft

One of the problems for critical flowrate determination is missing fluid properties data. For instance, some parameters such as surface tension, fluid density and gas z-factor are not regularly available for every well [1]. Thus, typical gas and condensate compositions are used to determine the values of fluid properties required for each critical flowrate correlation. Typical gas and condensate composition originate from the actual fluid compositions of produced fluid in Gulf of Thailand. However, only gas and condensate compositions cannot determine the values of every required parameter. Therefore, fluid properties correlations are used to calculate the values of fluid properties that cannot be determined by typical gas and condensate compositions. Nevertheless, water specific gravity is the one that cannot be evaluated by typical gas and condensate compositions and fluid properties correlations. Thus, the assumed value which is equal to 1.00 is used for this study. Considering this study, each fluid property has only single value applied to every production data of this study. Procedure of critical flowrate determination is summarized in term of flowchart shown in Figure 3.5

Figure 3.5: Flowchart of determining critical flowrate



In the next chapter, the influences of fluid properties to each selected critical flowrate correlation are analyzed. Furthermore, details of the values of fluid properties using in this study are examined in order to avoid applying the inappropriate values to calculating model resulting in the wrong critical flowrate.

CHAPTER IV

FLUID PROPERTIES ANALYSIS

In normal gas well operation, collection of data is considered as routine practice. However, not every data is collected for many reasons. For example, changing in normal production operation is required in order to collect a fluid sample or data which directly affect production rate. Moreover, some properties cannot directly be measured by field observation and they usually require a laboratory test in order to obtain those data. A favorite alternative for this problem is assumed values which may have a significant difference from actual values in several cases. Furthermore, literature reviews in chapter II show a strong relationship of fluid properties to selected critical flowrate correlations. Thus, the analysis of fluid properties is essential in order to study the effect of fluid properties on critical flowrate.

Fluid properties that are focused in this study are the properties that represent weight of fluid and ability to hold liquid droplet together because an importance of fluid properties on weight and ability to resist a demolition of liquid droplet are strong. Those fluid properties, which will be called “focused fluid properties”, are gas specific gravity, liquid density and surface tension of condensate and water. This chapter is divided into two sections which is the classification of fluid properties and sensitivity analysis on fluid properties. The main objective of sensitivity analysis is to evaluate the influences of each focused parameter to predicted values of each critical flowrate.

4.1) Classification of fluid properties data

The complexity of lithology is not the only signature of Gulf of Thailand (GoT) in terms of petroleum consideration. Properties of fluid are another significant notification of the production from GoT. For instance, heating value of produced gas is usually higher than 1,000 BTU/scf while heating value of dry gas is approximately at 600 BTU/scf. High heating value indicates that the composition of GoT’s gas is different from dry gas. Turner *et al.* [1] proposed a choice to solve a missing data problem in terms of "recommended values" which is originated by their field observation. However, those recommended values may not represent an actual value resulting in an erroneous calculation of critical flowrate and analysis of liquid loading problem. Another importance of data classification is the variation in production data because actual production data of 24 wells from 5 fields are selected for this study. Determination of fluid properties is done by typical gas and condensate compositions. Typical gas and condensate compositions are made by the average of 5 fluid compositions from Gulf of Thailand. The fluid properties which are determined by typical gas or condensate composition have only 1 value for every production data of this study. Fluid properties that determined by typical gas and condensate composition are gas and condensate specific gravity, condensate density and gas compressibility factor. However, there are some fluid properties that cannot be determined by typical gas and condensate compositions. Thus, fluid properties correlations are used to calculate those fluid properties. This group of fluid properties contains water density, condensate and water formation volume factor and surface tensions. Nevertheless, water specific gravity is the one that cannot be determine by typical gas and condensate compositions or fluid properties correlations. Therefore, the assumed value of water specific gravity at 1.00 is used in this study.

After the fluid properties are classified, a comparison of the values of focused fluid properties of this study to recommended values of Turner *et al.* [1] is set at the end of the section to investigate the differences between recommended values and actual values.

4.1.1) Gas specific gravity (γ_g)

Gas specific gravity is defined as the ratio of the density of the gas to the density of air, both of which are measured at standard conditions of pressure and temperature. In general, gas specific gravity from gas production well ranges from 0.554 (in case of producing gas is pure methane) to 0.8 or more (in case of producing gas is rich gas together with condensate production).

In this study, typical gas composition from GoT is used to represent the fluid composition for this study. Typical gas composition is determined by averaged values of actual 5 gas composition from GoT. The details of actual and typical gas compositions are shown in Table 4.1. Weighted-average of typical gas composition is the selected method to calculate gas specific gravity. Detail of gas specific gravity calculation is shown in Table 4.2.

Table 4.1: Details of actual and typical gas compositions

Well Composition	1	2	3	4	5	Typical Value
CO2	10.45	7.75	7.39	6.06	17.36	9.80
N2	0.04	0.10	0.08	0.08	0.10	0.08
C1	68.73	72.59	70.51	69.41	67.22	69.69
C2	13.49	13.00	14.07	14.60	10.84	13.20
C3	4.60	4.18	5.12	5.79	2.58	4.46
i-C4	0.80	0.69	0.77	0.93	0.63	0.76
n-C4	1.03	0.94	1.20	1.55	0.53	1.05
i-C5	0.32	0.27	0.32	0.43	0.25	0.32
n-C5	0.23	0.20	0.27	0.43	0.14	0.25
C6	0.17	0.16	0.17	0.48	0.22	0.24
C7+	0.14	0.12	0.10	0.24	0.13	0.15

Table 4.2: Detail of gas specific gravity calculation

Well Composition	Mole fraction, j_i	Molecular weight, M_i	Mass, lb, $M_i j_i$
CO2	0.0980	44.01	4.31
N2	0.0008	28.01	0.02
C1	0.6969	16.04	11.18
C2	0.1320	30.07	3.97
C3	0.0446	44.10	1.97
i-C4	0.0076	58.12	0.44
n-C4	0.0105	58.12	0.61
i-C5	0.0032	72.15	0.23
n-C5	0.0025	72.15	0.18
C6	0.0024	86.18	0.21
C7+	0.0015	98.08	0.15
Sum	1		23.27

$$\text{Gas specific gravity } (\gamma_g) = \frac{Mass}{Molecular\ weight\ of\ air} = \frac{23.27}{28.96} = 0.803 \qquad (4.1)$$

The value of gas specific gravity is applied to every production data of this study as a single constant value. Thus, there is no difference in gas specific gravity between each production data.

4.1.2) Condensate density (ρ_o)

The density of condensate is defined as a mass of condensate per unit volume. For petroleum fluid, condensate usually liberates gas out of it when thermodynamic conditions such as pressure and temperature are changed. In practice, pressure of condensate always changes along the tubing from reservoir to wellhead. Condensate density is one of the important parameters because it is used in several aspects. But, frequency of data collection is usually lower than FTP and gas production rate because it requires a special sample collection as the results of the gas liberation effect. Similar to gas specific gravity, typical condensate composition made by the average of actual condensate composition is used to calculate condensate density. Details of actual and typical condensate compositions are shown in Table 4.3

Table 4.3: Details of actual and typical condensate compositions

Well Composition	1	2	3	4	5	Typical Value
CO2	2.1	2.25	1.95	1.76	2.01	2.01
N2	0	0	0	0.01	0.01	0
C1	5.62	6.89	6.70	7.94	0.23	5.48
C2	6.99	7.78	7.61	7.78	2.92	6.62
C3	8.15	8.70	9.18	8.84	2.30	7.43
i-C4	3.52	3.57	3.30	2.99	1.40	2.96
n-C4	6.56	7.12	7.38	6.71	1.71	5.90
i-C5	5.00	5.01	4.63	4.43	2.89	4.39
n-C5	4.96	5.27	5.29	5.65	2.20	4.67
C6	9.47	9.77	9.59	10.24	10.67	9.95
C7+	47.63	43.64	44.37	43.65	73.66	50.59

After typical condensate composition is determined, density of condensate is calculated by ideal-solution principle. In summary, condensate density is calculated by mass of each composition divides by liquid volume at standard condition. The value of standard used in liquid volume calculations is not as important as for gas calculation. Liquid is not as compressible as gas, so the difference of few tenths of a psi in standard pressure has a negligible effect on liquid density [15]. Details of condensate density calculation are shown in Table 4.4. Similar to gas specific gravity, there is only single condensate density value for every production data sets of this study.

Table 4.4: Detail of condensate density calculation

Composition	Typical composition, Xj	Molecular weight, Mj	Mass, lb, XjMj	Liquid density @ S.C.,lb/ft^3, ρ_{oj}	Liquid volume @ S.C., ft^3, XjMj/ ρ_{oj}
CO2	0.0201	44.01	0.88	51.04	0.0173
N2	0	28.01	0	50.51	0
C1	0.0548	16.04	0.88	19.98	0.0440
C2	0.0662	30.07	1.99	29.34	0.0678
C3	0.0743	44.10	3.28	31.62	0.1036
i-C4	0.0296	58.12	1.72	35.11	0.0490
n-C4	0.0590	58.12	3.43	36.42	0.0942
i-C5	0.0439	72.15	3.17	38.96	0.0813
n-C5	0.0467	72.15	3.37	39.36	0.0856
C6	0.0995	86.18	8.27	41.40	0.2071
C7+	0.5059	134.2	67.89	48.61	1.3967
Sum	1		95.18		2.1466

$$\text{Condensate density } (\rho_o) = \frac{Mass}{Liquid\ volume} = \frac{95.18}{2.1466} = 44.34 \text{ lb/ft}^3 \qquad (4.2)$$

4.1.3) Gas compressibility factor (z-factor)

The gas compressibility factor or z-factor is the ratio of the volume actually occupied by a gas at given pressure and temperature to the volume the gas would occupy at the same pressure and temperature if it behaved like an ideal gas [15]. Considering this parameter, it is determined by the average value of actual data from

GoT. Average value of actual data is called typical value which is applied to every production data as a constant. Details of actual and typical gas compressibility factor are shown in Table 4.5.

Table 4.5: Details of actual and typical gas compressibility factor

Well	Gas compressibility factor
1	0.889
2	0.913
3	0.989
4	0.953
Typical value	0.936

4.1.4) Condensate formation volume factor (Bc)

Condensate formation volume factor is defined as the volume of reservoir condensate required to produce one barrel of condensate in the stock tank. There are 3 main factors that influence condensate formation volume factor. Firstly, and the most important one, is the evolution of gas from oil as pressure is decreased from reservoir pressure to surface pressure. The reduction in pressure also causes the remaining oil to expand slightly, but this is somewhat offset by the contraction of the oil due to the reduction of temperature [15].

Unlike the parameter in section 4.1.1 to 4.1.3, the actual data of this parameter is not available. Thus, the correlation that proposed by El-Banbi, and Fattah [16] is used to calculate condensate formation volume factor. El-Banbi, and Fattah [16] presented their model which is the modification of the model presented by Standing [17]. The modified Standing's correlation for condensate formation volume factor is shown in table 4.6. Similar to the fluid properties in section 4.1.1 to 4.1.3, the value of condensate formation volume factor of this study is a constant value for every production data. The value of condensate formation volume factor of this study is shown in Table 4.7.

$$Bc = A1+A2*[Rs\sqrt{(\gamma_{gsc}/\gamma_{osc})} + A3*(T-460)]^{A4} \qquad (4.3)$$

Where

A1, A2, A3, A4 = coefficient of El-Banbi and Fattah’s correlation (given in table 4.1)

Bc = condensate formation volume factor, bbl/STB

Rs = solution gas-oil ratio, scf/STB

T = temperature, °R

γ_{gsc} = gas specific gravity

γ_{osc} = condensate specific gravity

Table 4.6: Coefficients of modified Standing’s correlation for condensate formation volume factor

Coefficient	Value
A1	0.965109772
A2	0.000342547
A3	1.303305644
A4	1.053171234

4.1.5) Water formation volume factor (Bw)

The water formation volume factor is defined as the change in volume of the brine as it is transported from reservoir condition to surface conditions [15]. Similar to condensate formation volume factor, there are 3 factors that affect the value of water formation volume factor which are the evolution of dissolved gas from the brine, the expansion of the brine as pressure is reduced and the contraction of the brine as temperature is reduced. However, the effects of those 3 factors are smaller than condensate formation volume factor because water has the lower solubility of gas and compressibility. Thus, the value of water formation volume factor is usually less than condensate formation volume factor. Similar to condensate formation volume factor, actual value of water formation volume factor is not available. Therefore, fluid properties correlation proposed by Rowe and Chou [18] is used to calculate water formation volume factor. Details of water formation volume factor’s correlation proposed by Rowe and Chou [18] as

$$A_0 = 5.916365 - 0.0103\, T_{\circ K} + 0.9270048\text{x}10^{-5}\, T^2_{\circ K} - \frac{1127.522}{T_{\circ K}} + \frac{100674.1}{T_{\circ K}} \qquad (4.4)$$

$$A_1 = -2.5166 + 0.0111766\, T_{\circ K} - 0.170522\text{x}10^{-4}\, T^2_{\circ K} \qquad (4.5)$$

$$A_2 = 2.84851 - 0.0154305\ T_{\circ K} + 0.223982x10\text{-}4\ T^2_{\circ K} \tag{4.6}$$

The density of the water at standard pressure, the temperature of interest and without dissolved gas is defined as

$$\rho^0_w = (A_0 + A_1 w_s + A_2 w^2_s)^{-1} \tag{4.7}$$

The water density is also determined at standard pressure and temperature using equations 4.4 to 4.6. The water formation volume factor is determined from these results using equation 4.8. It should be noted that these equations use salinity in fraction.

$$B^0_{w(p_{sc},T)} = \frac{\rho_{w(p_{sc},T_{sc})}}{\rho^0_{w(p_{sc},T)}} \tag{4.8}$$

The water formation volume factor corrected for elevated pressure is given by equation 4.9 to 4.11

$$A_0 = 10^6(0.314 + 0.58w_s + 1.9x10^{-4}T_{\circ F} - 1.45x10^{-6}T^2_{\circ F}) \tag{4.9}$$

$$A_1 = 8 + 50w_s - 0.125w_s T_{\circ F} \tag{4.10}$$

$$Bw = B^0_{w(p_{sc},T)}\left(1 + \frac{A_1}{A_0}p\right)^{\left(\frac{-1}{A_1}\right)} \tag{4.11}$$

Where

Bw = water formation volume factor, bbl/STB

p = pressure, psia

p_{sc} = pressure at standard condition = 14.7 psia

$T_{\circ F}$ = temperature, °F

$T_{\circ K}$ = temperature, °K

T_{sc} = temperature at standard condition = 60°F

w_s = water salinity

Similar to condensate formation volume factor, the value of water formation volume factor is a constant value for every production data of this study. The values of pressure and temperature for water formation volume factor calculation are the average values of flowing tubing pressure and surface temperature of the production data of this study.

4.1.6) Water density (ρ_w)

The density of water is defined as a mass of water per unit volume. Unlike condensate, solubility of gas in water is less than condensate. As a result, the amount of gas can dissolve in water less than in condensate and less amount of gas that will liberate out of water when thermodynamic condition such as pressure and temperature are change than condensate. Therefore, an effect of gas to water is ignored in many water density determination cases. Even though water density has an influence on water properties in the same way as oil density does, determination of this parameter in an actual field is rarely done because water properties have much less importance than condensate properties in normal operation. Another reason is water density is rarely change between each well since gas liberation from water is much less than condensate and water density calculation usually ignores an effect of gas in the calculating equation. The equation for water density calculation for this study is shown in equation 4.12.

$$\text{Water density } (\rho_w) = \frac{62.4\gamma_w}{B_w} \qquad (4.12)$$

Where

62.4 = density of water at standard condition, lbm/ft^3

γ_w = water specific gravity

B_w = water formation volume factor

4.1.7) Gas-condensate surface tension (σ_o)

The surface tension is defined as the force required preventing destruction of the surface [15]. Surface tension usually involves with two fluid phases and it often neglects gaseous phase when it is called (in this case is condensate surface tension). Surface tension is rarely measured in normal operation because it has a limited usage of this parameter and it requires a laboratory test in order to measure it. Considering this study, gas-condensate surface tension is calculated by typical gas and condensate composition. The equation used to calculate gas-condensate surface tension is given as

$$\sigma = [\textstyle\sum_j P_j (x_j \frac{\rho_l}{M_l} - y_j \frac{\rho_g}{M_g})]^4 \qquad (4.13)$$

Where

M_g = apparent molecular weight of gas

M_l = apparent molecular weight of liquid

Pj = parachor value

x_j = mole fraction of liquid

y_j = mole fraction of gas

ρ_g = gas density, g/cc = 0.044 for this study

ρ_l = condensate density, g/cc = 0.710 for this study

σ = surface tension, dynes/cm

Similar to water density, there is only single value of gas-condensate surface tension for every production data of this study. Summary of the calculation of gas-condensate surface tension is shown in Table 4.7. The value of gas-condensate surface tension is shown in equation 4.13

Table 4.7: Calculation of gas-condensate surface tension

Component	x_j	y_j	Pj	Equation 4.13
CO2	0.0201	0.0980	78.0	-0.0025
N2	0	0.0008	41.0	-0.0001
C1	0.0548	0.6969	77.0	-0.0700
C2	0.0662	0.1320	108.0	0.0264
C3	0.0743	0.0446	150.3	0.0706
i-C4	0.0296	0.0076	181.5	0.0375
n-C4	0.0590	0.0105	189.9	0.0798
i-C5	0.0439	0.0032	225.0	0.0723
n-C5	0.0467	0.0025	231.5	0.0796
C6	0.0995	0.0024	271.0	0.1999
C7+	0.5059	0.0015	381.9	1.4401
Sum	1	1		1.9334

$$\sigma = (1.9334)^4 = 13.97 \text{ dynes/cm} \tag{4.14}$$

4.1.8) Gas-water surface tension (σ_w)

The gas-water surface tension is almost a similar definition to gas-condensate surface tension except that liquid phase switches from condensate to water and it is usually called water surface tension. This parameter is similar to condensate surface tension except that condensate is substituted by water. Normally, water has a stronger bond than condensate resulting in water droplet is harder to shatter than condensate droplet resulting in higher surface tension. In this study, gas-water surface tension correlation which is proposed by Sutton [19] is used. Details of Sutton [19] correlation are shown in equation 4.15.

$$\sigma_{gw} = \left[\left(1.53988 + \frac{2.08339}{\rho_{w_{g/cc}} - \rho_{h_{g/cc}}} \right) \left(\frac{T_{\circ R}}{T_c} \right)^{\left(0.821976 - 1.83785 x 10^{-3} T_{\circ R} + 1.34016 x 10^{-6} T_{\circ R}^{2}\right)} \left(\rho_{w_{g/cc}} - \rho_{h_{g/cc}} \right) \right]^{3.6667}$$

Where

σ_{gw} = gas-water surface tension, dynes/cm

$\rho_{h_{g/cc}}$ = hydrocarbon gas density, g/cc

$\rho_{w_{g/cc}}$ = water density, g/cc

T_c = critical temperature for water = 1164.7728 °R

$T_{\circ R}$ = temperature, °R

In summary, missing fluid properties data is one of the most important problems of this study. In order to solve this problem, several approaches are used to determine the values of missing data. Typical gas and condensate compositions, which originate from the average value of actual data from Gulf of Thailand, are selected to determine the values of missing data. However, there are some parameters that cannot be determined by typical gas or condensate compositions. Thus, fluid properties correlations are used to calculate the values of fluid properties that cannot be determined by typical gas or condensate compositions. Nevertheless, the value of water specific gravity cannot be evaluated by typical gas or condensate compositions or fluid properties correlations. Therefore, assumed value at 1.00 is used as the value of water specific gravity of this study. Summary of the values of fluid properties using in this study are shown in Table 4.8.

Table 4.8: Summary of Fluid properties values using in this study.

Parameter	Value	Method of determination
Gas specific gravity	0.803	Typical gas composition
Condensate density	44.34 lb/ft^3	Typical condensate composition
Gas compressibility factor	0.936	Typical gas composition
Condensate formation volume factor	1.14	El-Banbi and Fattah [16]
Water formation volume factor	1.013 bbl/STB	Rowe and Chou [18]
Water density	61.60 lb/ft^3	Water density equation
Gas –condensate surface tension	13.97 dynes/cm	Typical gas and condensate compositions
Gas-water surface tension	57.53 dynes/cm	Sutton correlation [19]
Water specific gravity	1.00	Assumed value

4.1.9) Comparison of Turner’s recommended values and the values of this study

Missing data is one of the most important obstacles in order to solve any problems including liquid loading problem. One of the favorite solutions for this problem is assumed values. Turner *et al.* [1] proposed the values of fluid properties which are made by their field observation. However, using Turner’s recommended values leads to a significant problem because actual values for any particular wells may have significant difference from recommended values as the result of the difference in fluid composition. Thus, a comparison of the values of fluid properties for this study and Turner’s recommended values are performed in order to investigate any significant differences between them. The differences between the values of this study and recommended values by Turner are calculated in percentage by equation 4.16. Details of them are shown in Table 4.9.

$$\% \text{ differences} = \frac{(Average\ value\ of\ this\ study - Recommended\ value\ by\ Turner)}{Recommended\ values\ by\ Turner} x100 \qquad (4.16)$$

Table 4.9: Summary of recommended values by Turner *et al.* [1] and the values of fluid properties using in this study

Parameter	Recommended values by Turner	The average values of this study	% differences
Gas specific gravity	0.6	0.803	33.83%
Condensate density	45 lb/ft^3	44.34 lb/ft^3	-1.47%
Water density	67 lb/ft^3	61.60 lb/ft^3	-8.06%
Condensate surface tension	20 dynes/cm	13.97 dynes/cm	-30.15%
Water surface tension	60 dynes/cm	57.53 dynes/cm	-4.12%

From Table 4.9, gas specific gravity has the highest variation when recommended values and the values of fluid properties using in this study are compared. The values of liquid density for this study are slightly lower than recommended values by Turner (1.47 % lower for condensate density and 8.06% lower for water density). Considering surface tensions, the values of condensate surface tension is lower than recommended value by 30.15% while water surface tension is lower than recommended value by 4.12%.

However, the variation in gas specific gravity is significantly higher than the others. The recommended value by Turner is 0.6 which is usually found in dry gas production while the value of this study is 0.803 which is usually found in rich gas production or impurities are found in gas stream. Gas specific gravity can be higher than the value of this study in case that the produced gas is associated gas or mole fraction of impurities in gas stream is high. For instance, produced gas has a high mole percentage of carbon dioxide which can be found in some reservoirs in Gulf of Thailand. In general, impurities usually have molecular weight higher than air. For example, the molecular weight of carbon dioxide is 44 and the molecular weight of hydrogen sulfide is 34. Thus, gas composition that has high impurities usually has high gas specific gravity. If recommended values by Turner are applied, it can introduce a major difference to the actual value in case gas composition is not dry gas. Thus, not only liquid loading consideration, estimation of gas specific gravity is a vital task because range of gas specific gravity is wide and it is used in several aspects. After the fluid properties data is classified, influences of them on predicted critical flowrate of each selected correlation are analyzed by sensitivity analysis in the next section.

4.2) Sensitivity analysis on fluid properties

After the influences of each fluid property are analyzed in the previous section, influences of fluid properties on critical flowrate are analyzed in this section. Sensitivity analysis is chosen as a tool to investigate the effects of fluid properties on each critical flowrate correlation. The calculating model for critical flowrate determination, whose model construction is detailed in Chapter III, is used as a base model for sensitivity analysis. Five focused fluid properties from section 4.1 are the main parameters for sensitivity analysis. Four sensitivity analysis cases which are 5%, 10%, 20% and 30% are chosen and applied to the values of each focused fluid property in addition and subtraction to cover the ranges of the values for focused fluid properties. However, applying high variation percentage to liquid density may cause the unrealistic values. Thus, variation in liquid density is limited at 20%. The values of fluid properties for base case and ranges of data are summarized in Table 4.10.

Table 4.10: Base value and range of data for sensitivity analysis

Parameter	Base value	Range of data for sensitivity analysis
Gas specific gravity	0.803	0.562 – 1.044
Condensate density	44.34 lb/ft^3	35.47 – 53.21 lb/ft^3
Water density	61.60 lb/ft^3	49.28 – 73.92 lb/ft^3
Condensate surface tension	13.97 dynes/cm	9.78 – 18.16 dynes/cm
Water surface tension	57.53 dynes/cm	40.27 – 74.79 dynes/cm

For Turner's and Zhou's correlation, all focused parameters are in critical velocity determination as shown in equation 4.17 for Turner's correlation and equation 4.18 and 4.19 for Zhou's correlation.

$$v_t = 17.6\frac{[\sigma(\rho_l - \rho_g)]^{1/4}}{\rho_g^{1/2}} \text{ ft/s} \qquad (4.17)$$

$$v_{crit\text{-}N} = v_{crit\text{-}T} = 17.6\frac{[\sigma(\rho_l - \rho_g)]^{1/4}}{\rho_g^{1/2}} \quad \text{for } H_l \le 0.01 \tag{4.18}$$

$$v_{crit\text{-}N} = v_{crit\text{-}T} + \ln\frac{H_l}{\beta} + \alpha \quad \text{for } H_l > 0.01 \tag{4.19}$$

Unlike liquid density and surface tension, gas specific gravity are not directly be used in equation 4.17 to 4.19. But, it is used in gas density calculation and it is the only variable parameter in gas density calculation as other parameters are fixed. For Guo's correlation, liquid density and surface tension play an important role on minimum kinetic energy and bottomhole pressure calculation which is shown in equation 4.20 and 4.21. Gas specific gravity is used in bottomhole pressure calculation and kinetic energy at any given flowrate determination which is shown in equation 4.21.

$$E_{km} = 0.0576\sqrt{\sigma\rho_L} \tag{4.20}$$

$$E_k = 6.46\text{x}10^{-13}\frac{S_g T Q_g^2}{A^2 P} \tag{4.21}$$

Nevertheless, only focused fluid properties cannot fulfill the requirements of each correlation to calculate critical flowrate. Thus, the additional constraints are made in order to be able to calculate critical flowrate. Focused fluid properties are not the only variable parameter for sensitivity analysis model. FTP and liquid production rate are another group of variable parameters for sensitivity analysis model. Variation in FTP and liquid production rate makes an extra coverage to actual production scenarios and they are easily available in normal field observation. These 2 parameters are varied in low and high value by first quartile and third quartile of entire screened data of this study. The values of FTP and liquid production rate used in sensitivity analysis are summarized in Table 4.11. However, some parameters have to be set as a constant to avoid the unnecessary complications resulting in the erroneous analysis. A summary of those constant parameters are shown in Table 4.12.

Table 4.11: The values of FTP and liquid production rate for sensitivity analysis model

Parameter	Case	Value
FTP	Low value (first quartile)	315 psia
	High value (third quartile)	685 psia
Liquid production rate	Low value (first quartile)	50 bbl/d
	High value (third quartile)	375 bbl/d

Table 4.12: Summary of constant parameters of sensitivity analysis

Parameter	Value
Gas production rate	1.5 MMscf/d (median of entire data)
Gas compressibility factor	0.936
Condensate specific gravity	0.779 (50.2°API)
Water specific gravity	1.00
Wellhead temperature	130°F (median of entire data)
Tubing inside diameter	2.441”
Well depth (TVD)	10,000’

After critical flowrate of each sensitivity analysis case is calculated, it is compared to original critical flowrate from a base case in terms of percentage which is calculated by equation 4.22. A comparison of the variations for each sensitivity analysis value is made in order to evaluate the influences of the differences on the value of fluid properties to predicted critical flowrate. Moreover, the influence of each fluid property on predicted critical flowrate is analyzed to investigate the effects of fluid properties on predicted critical flowrate.

$$\%\ \text{deviation} = \frac{(Q_{crit} form\ sensitivity\ analysis - Q_{crit} from\ base\ case)}{Q_{crit} from\ base\ case} x100 \qquad (4.22)$$

4.2.1) Gas specific gravity (γ_g)

Gas specific gravity is one of the most important parameters in gas production because it is used in several aspects. Sensitivity analysis of gas specific gravity is separated into two parts which are a condensate case and water case. For the condensate case, properties of condensate are used in sensitivity analysis model without the properties of water involved and vice versa for water case. A summary of base and sensitivity analysis values for gas specific gravity is shown in Table 4.13. In terms of production condition, there are four cases of production condition for each liquid phase. Details of each production condition case are shown in Table 4.14. Results from sensitivity analysis model for each production condition are shown in Figure 4.1 – 4.8.

Table 4.13: Base and sensitivity analysis values of gas specific gravity

Sensitivity analysis case	Value
+30%	1.044
+20%	0.964
+10%	0.884
+5%	0.844
Base case	0.803
-5%	0.763
-10%	0.723
-20%	0.643
-30%	0.562

Table 4.14: Details of each production condition case for gas specific gravity

Case No.	Case Definition	FTP (psia)	Phase of Liquid	Liquid production rate (bbl/d)
1	Low FTP, low Ql, condy case	315	Condensate	50
2	Low FTP, high Ql, condy case	315		375
3	High FTP, low Ql, condy case	685		50
4	High FTP, high Ql, condy case	685		375
5	Low FTP, low Ql, water case	315	Water	50
6	Low FTP, high Ql, water case	315		375
7	High FTP, low Ql, water case	685		50
8	High FTP, high Ql, water case	685		375

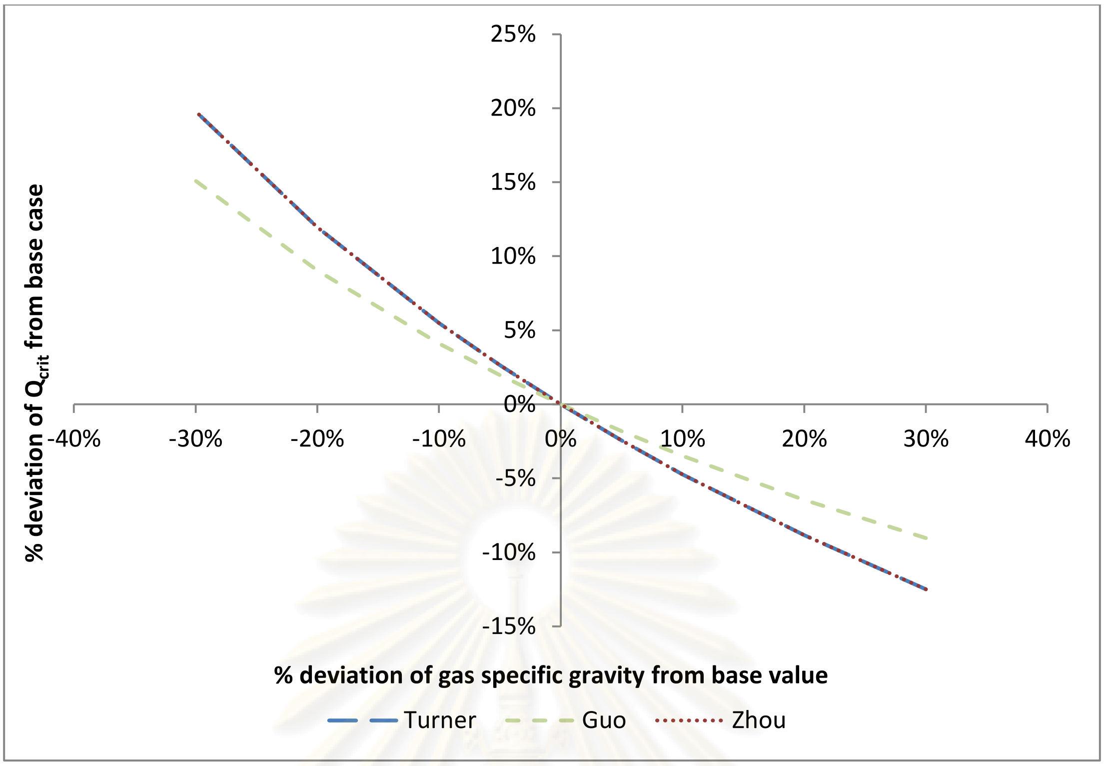


Figure 4.1: Sensitivity analysis on gas specific gravity (low FTP, low Ql, condy case)

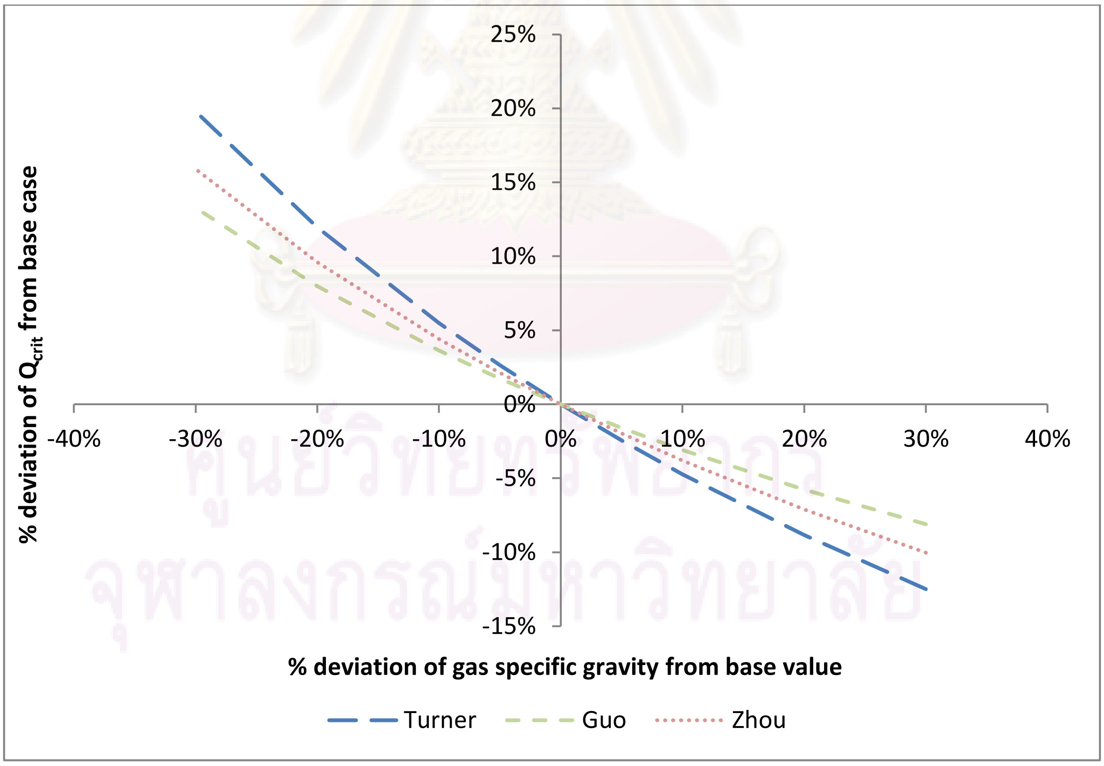


Figure 4.2: Sensitivity analysis on gas specific gravity (low FTP, high Ql, condy case)

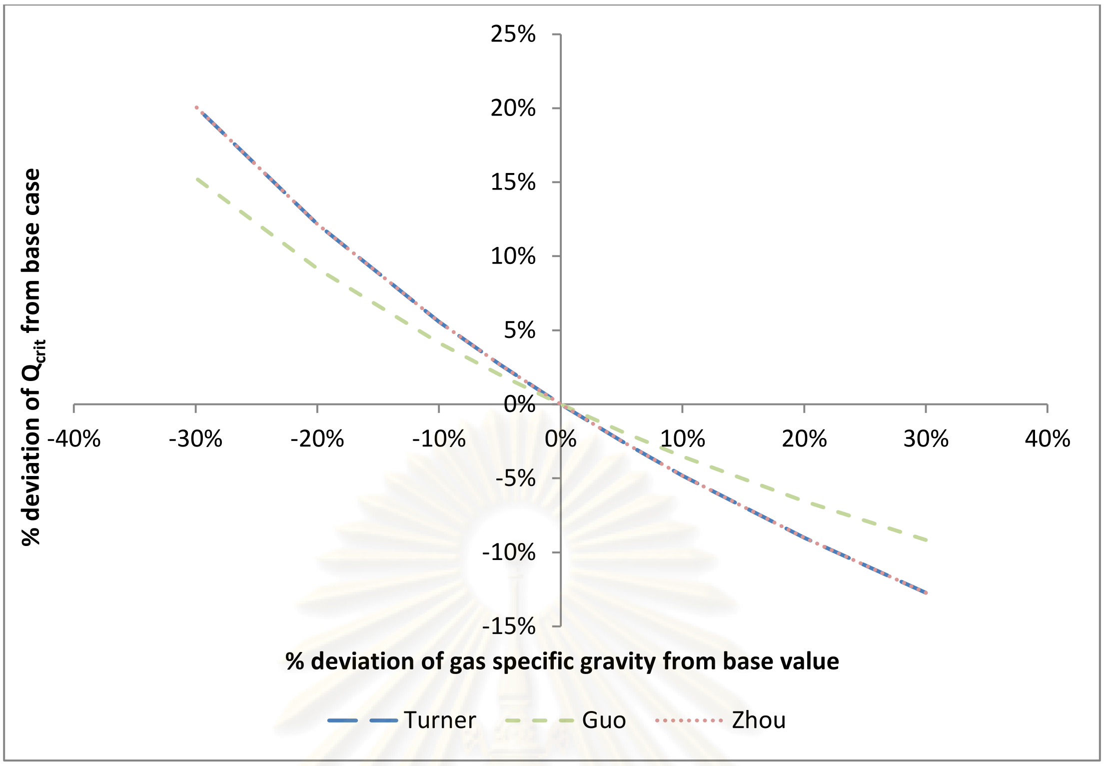


Figure 4.3: Sensitivity analysis on gas specific gravity (high FTP, low Ql, condy case)

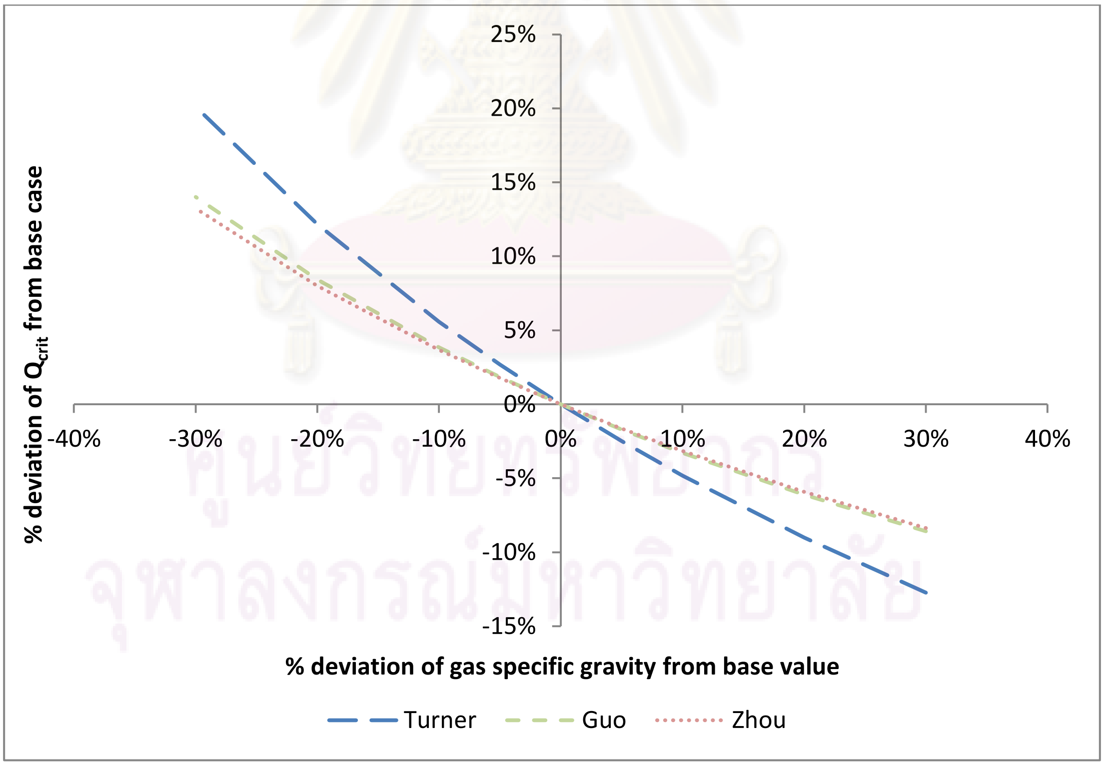


Figure 4.4: Sensitivity analysis on gas specific gravity (high FTP, high Ql, condy case)

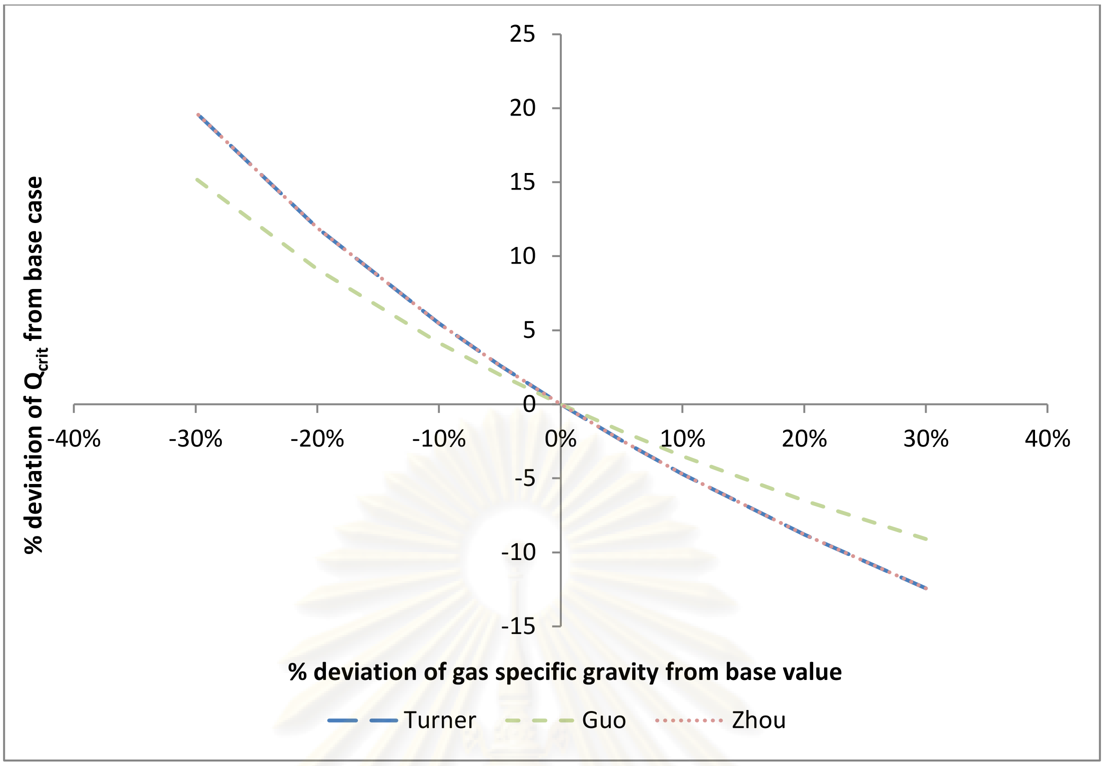


Figure 4.5: Sensitivity analysis on gas specific gravity (low FTP, low Ql, water case)

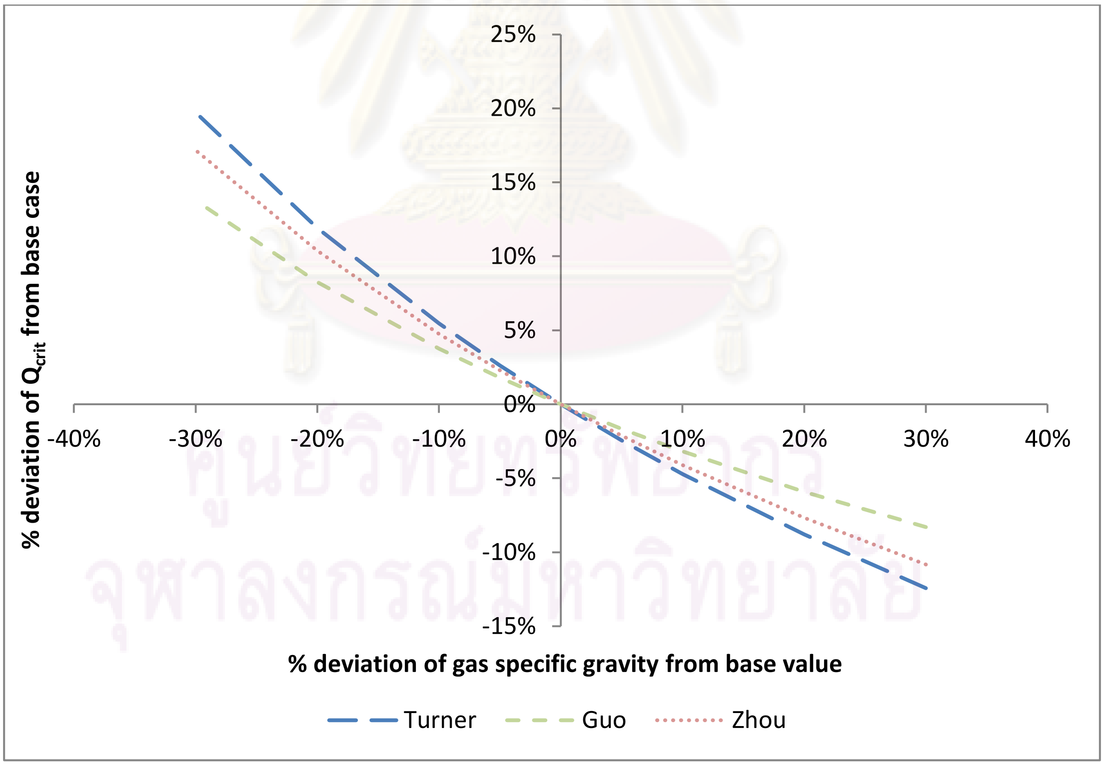


Figure 4.6: Sensitivity analysis on gas specific gravity (low FTP, high Ql, water case)

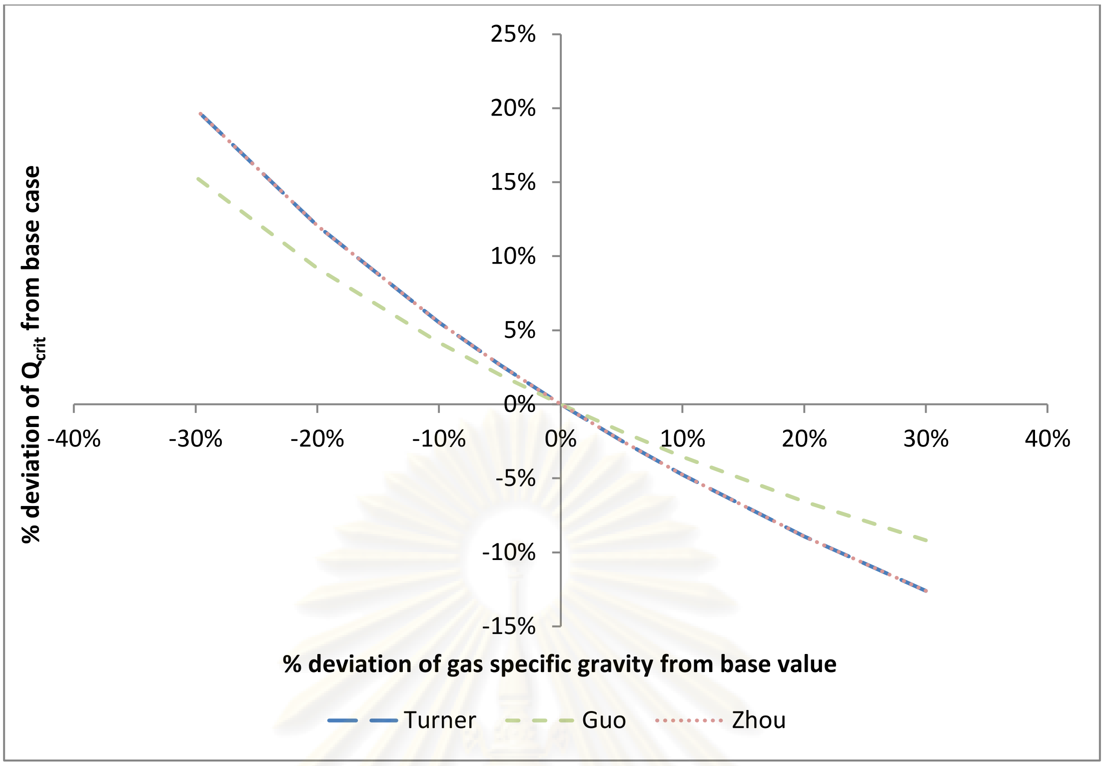


Figure 4.7: Sensitivity analysis on gas specific gravity (high FTP, low Ql, water case)

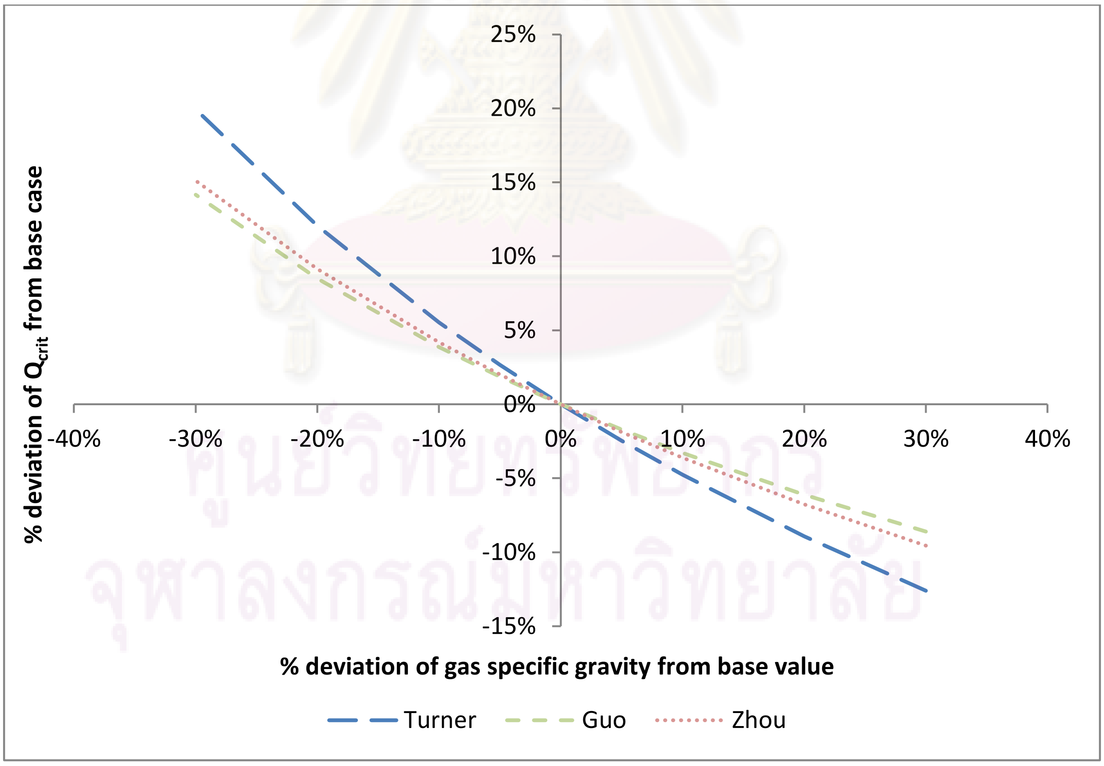


Figure 4.8: Sensitivity analysis on gas specific gravity (high FTP, high Ql, water case)

In terms of the differences from base cases, Guo's correlation has the differences from the base case less than other correlations for the majority of sensitivity analysis case. On the other hand, Turner's correlation usually has the deviation from the base case greater than other correlations. It can be described in terms of complexity of each correlation. Turner's correlation is the least complex correlation and only fluid properties are required parameters. Thus, variation in fluid properties creates a major impact on predicted critical flowrate of Turner's correlation. Adversely, Guo's correlation is the most complex correlation which contains several input parameters. Therefore, only the variation in fluid properties will not generate a major difference of predicted critical flowrate of Guo's correlation.

The change in gas specific gravity has an inverse relationship to critical flowrate. If gas specific gravity increases, then, an ability to carry liquid droplet is increased in terms of an increase in drag force acting on liquid droplet for the same gas velocity. In other words, for the same driven energy from the reservoir, gas that has higher gas specific gravity flows at lower velocity than the gas that has less gas specific gravity. Therefore, higher gas specific gravity makes lower critical velocity and critical flowrate. Turner's correlation is the one that has the least effect on a change in production conditions because it is the only change in FTP that affects this correlation for each set of analyzed fluid. The main reason is liquid production rate does not have any effect on input parameters of Turner's correlation. However, the change in liquid production rate plays a role in other critical flowrate correlations in a different manner. Liquid production rate is a direct input parameter of Guo's correlation. Although liquid production rate is not a direct parameter of Zhou's correlation, liquid production rate is used to calculate liquid holdup which is a direct input parameter of Zhou's correlation.

However, Turner's and Zhou's correlations predict the same critical flowrate in the case that liquid holdup stays below 0.01. As liquid holdup is lower than 0.01, variable parameters of Turner's correlation and Zhou's correlation are the same because no liquid holdup involved in critical flowrate determination. Production condition that has liquid holdup less than 0.01 is case No. 1, 3, 5 and 7. The effect of changing FTP can be described that if FTP increases, gas formation volume factor (B_g) will decrease since the same amount of gas is denser because of increasing pressure. Decreasing B_g will cause a reduction in gas velocity and higher liquid holdup. Higher FTP also makes an increase in gas density and less critical flowrate.

4.2.2) Condensate density (ρ_o)

When the weight of liquid is considered, density is a favorite tool to evaluate the weight of liquid. In order to compile the phase of focused fluid, input parameters of the sensitivity analysis of this case is condensate. A summary of base and sensitivity analysis values for condensate density is shown in Table 4.15. In terms of production condition, there are four cases of production condition for each liquid phase. Details of each production condition case are shown in Table 4.16. Results from sensitivity analysis model for each production condition are shown in Figure 4.9 – 4.12.

Table 4.15: Base and sensitivity analysis values of condensate density

Sensitivity analysis case	Value (lb/ft^3)
+20%	53.21
+10%	48.77
+5%	46.56
Base case	44.34
-5%	42.12
-10%	39.91
-20%	35.47

Table 4.16: Details of each production condition case for condensate density

Case number	Case Definition	FTP (psia)	Liquid production rate (bbl/d)
1	Low FTP, low Ql case	315	50
2	Low FTP, high Ql case	315	375
3	High FTP, low Ql case	685	50
4	High FTP, high Ql case	685	375

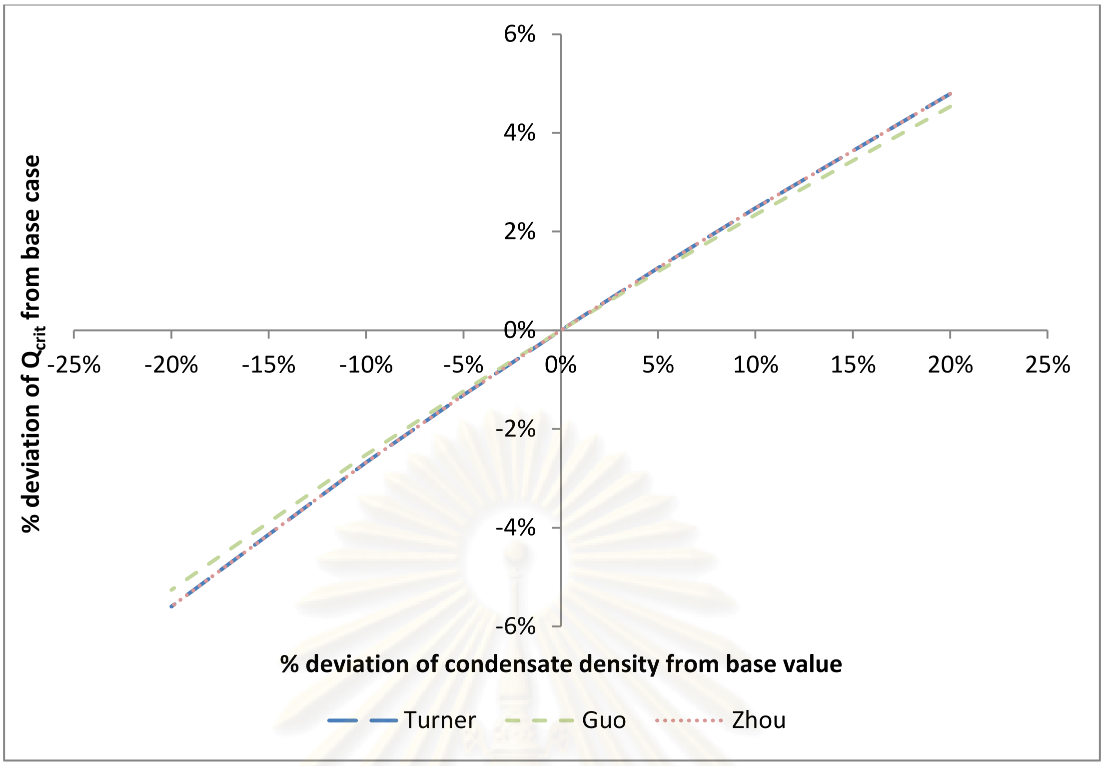


Figure 4.9: Sensitivity analysis on condensate density (low FTP, low Ql case)

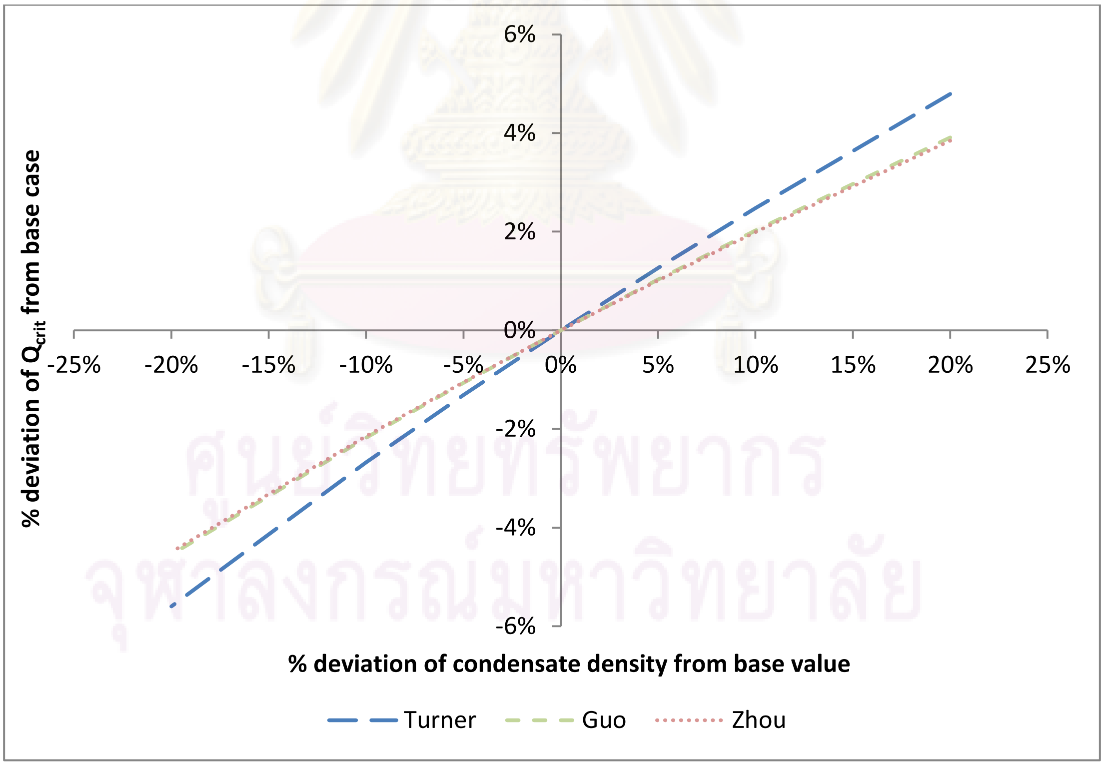


Figure 4.10: Sensitivity analysis on condensate density (low FTP, high Ql case)

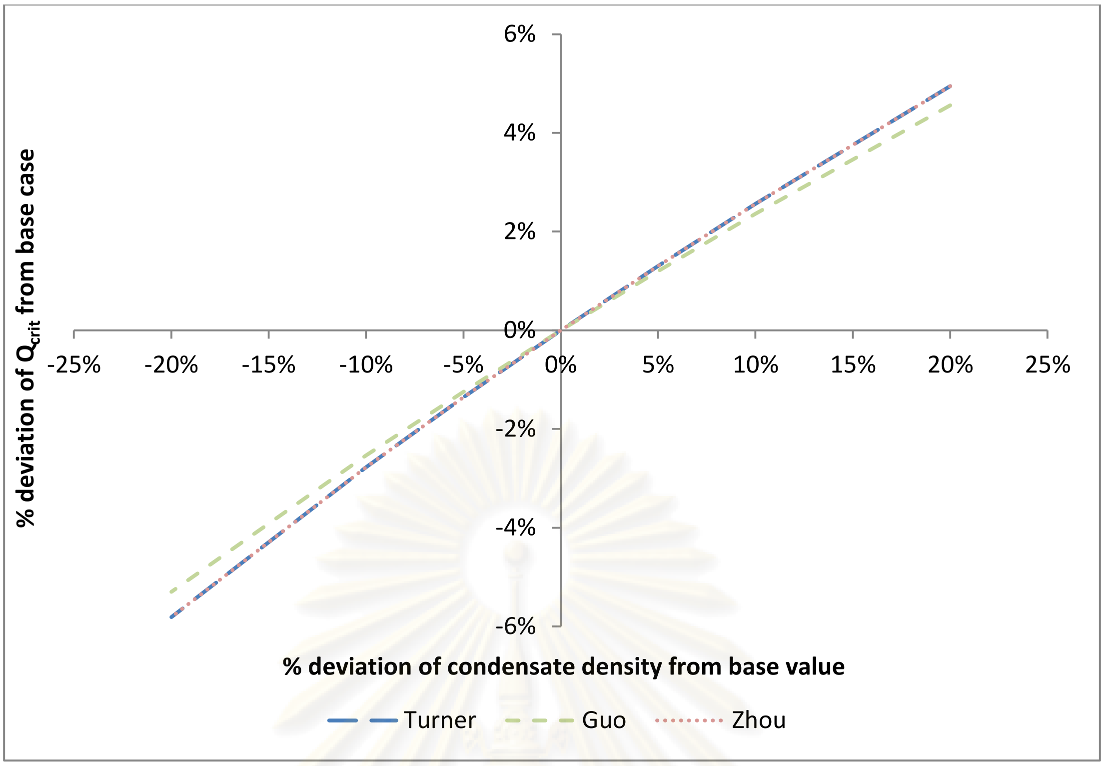


Figure 4.11: Sensitivity analysis on condensate density (high FTP, low Ql case)

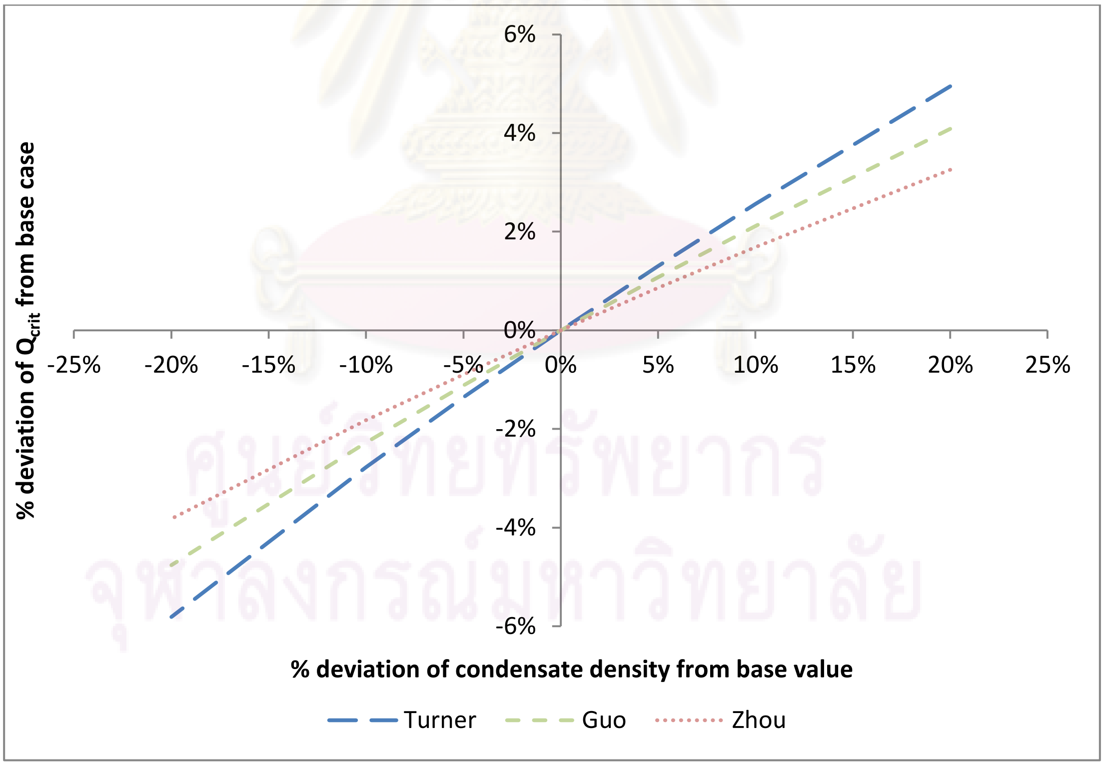


Figure 4.12: Sensitivity analysis on condensate density (high FTP, high Ql case)

Considering the comparison of the values from sensitivity analysis case and base case, Turner’s correlation is still the one that usually has the highest deviation from base case. For the production condition that liquid holdup is less than 0.01, the deviations predicted by Zhou’s and Turner’s correlations are equal. Moreover, those deviations are higher than the deviations that predicted by Guo’s correlation. On the other hand, Zhou’s correlation is the one that predicted the least deviations for the production condition that liquid holdup is greater than 0.01. It can be described by the difference in an influence of condensate density to Guo’s and Zhou’s correlation. Considering Guo’s correlation, condensate density is a strong function of minimum kinetic energy determination. Minimum kinetic energy plays an important role in predicted critical flowrate of Guo’s correlation and any variations on it will generate a significant difference in predicted critical flowrate. For Zhou’s correlation, liquid holdup is introduced to critical flowrate determination when liquid holdup is greater than 0.01. When liquid holdup is used to determine critical flowrate of Zhou’s correlation, the value of liquid holdup is constant for each sensitivity analysis case. An additional of constant value creates a larger portion of critical flowrate calculation that is fixed for sensitivity analysis resulting in lower deviation from base case. With those reasons, the deviation of Guo’s correlation is higher than Zhou’s correlation for the production condition that liquid holdup is greater than 0.01. However, simplicity of Turner’s correlation still has the greatest influence on sensitivity analysis resulting in the highest deviation in each production condition case. Nevertheless, overall differences in condensate density cases are less than the differences in gas specific gravity cases which means gas specific gravity has a higher effect on critical flowrate prediction than condensate density.

The change in liquid density has a direct relationship to critical flowrate. Heavier liquid will require more gas energy (or gas velocity) in order to suspend or lift this liquid droplet in gas stream and cause higher critical flowrate to unload this liquid out of the well. For liquid density, variations in production conditions play the same role as gas specific gravity case. FTP is still the only parameter that affects Turner’s correlation. Influences of a variation in liquid production rate still play the same role in Guo’s and Zhou’s correlations.

4.2.3) Water density (ρ_w)

Water density is the third fluid properties of sensitivity analysis. In order to compile the phase of focused fluid, input parameters of the sensitivity analysis of this case are water. A summary of base and sensitivity analysis values for condensate density is shown in Table 4.17. In terms of production condition, there are four cases of production condition for each liquid phase. Details of each production condition case are shown in Table 4.18. Results from sensitivity analysis model for each production condition are shown in Figure 4.13 – 4.16.

Table 4.17: Base and sensitivity analysis values of water density

Sensitivity analysis case	Value (lb/ft^3)
+20%	73.92
+10%	67.76
+5%	64.68
Base case	61.60
-5%	58.52
-10%	55.44
-20%	49.28

Table 4.18: Details of each production condition case for water density

Case number	Case Definition	FTP (psia)	Liquid production rate (bbl/d)
1	Low FTP, low Ql case	315	50
2	Low FTP, high Ql case	315	375
3	High FTP, low Ql case	685	50
4	High FTP, high Ql case	685	375

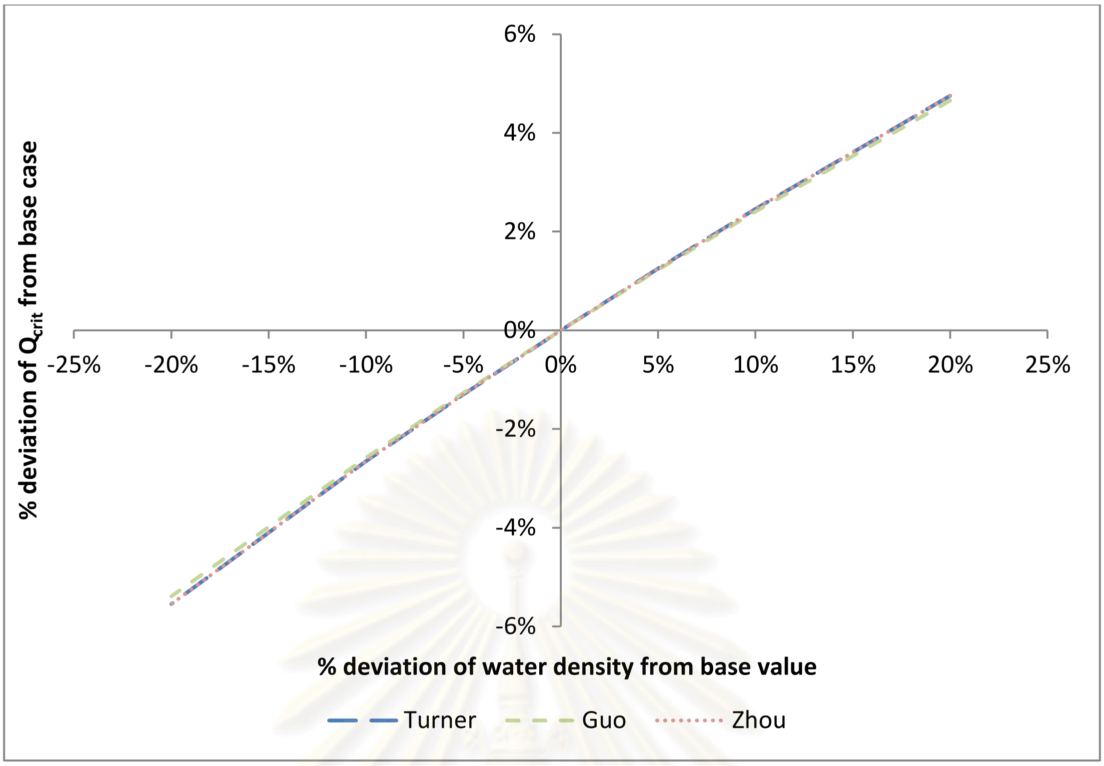


Figure 4.13: Sensitivity analysis on water density (low FTP, low Ql case)

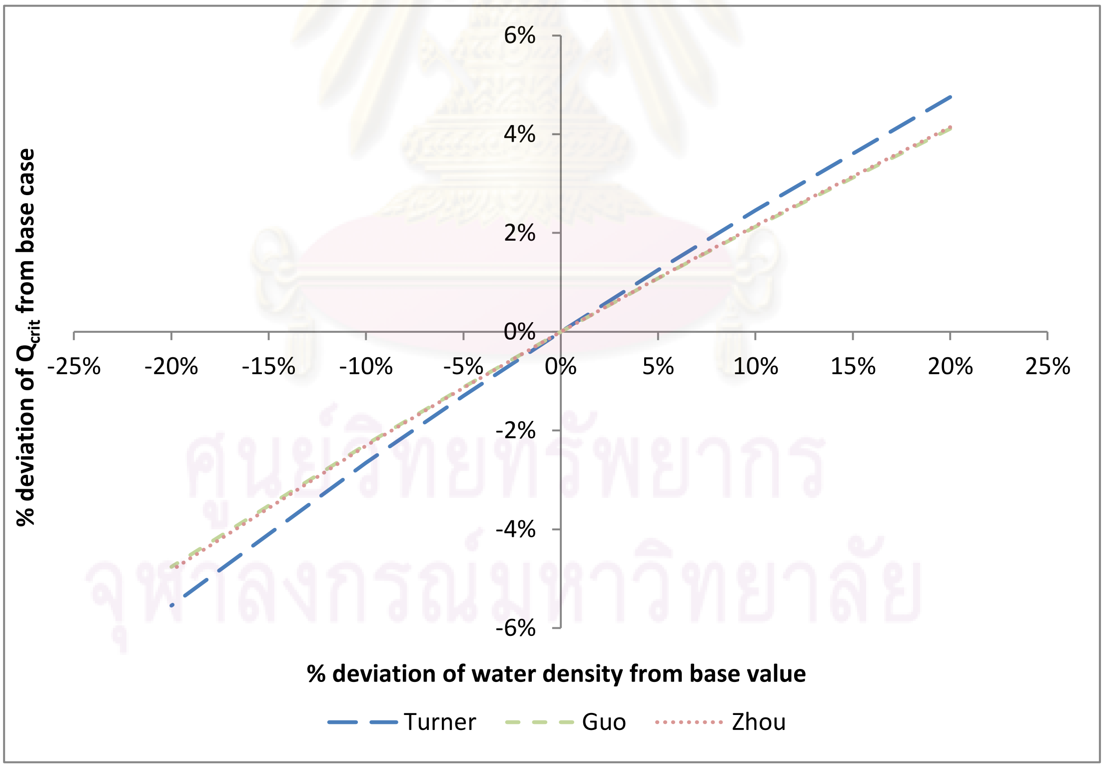


Figure 4.14: Sensitivity analysis on water density (low FTP, high Ql case)

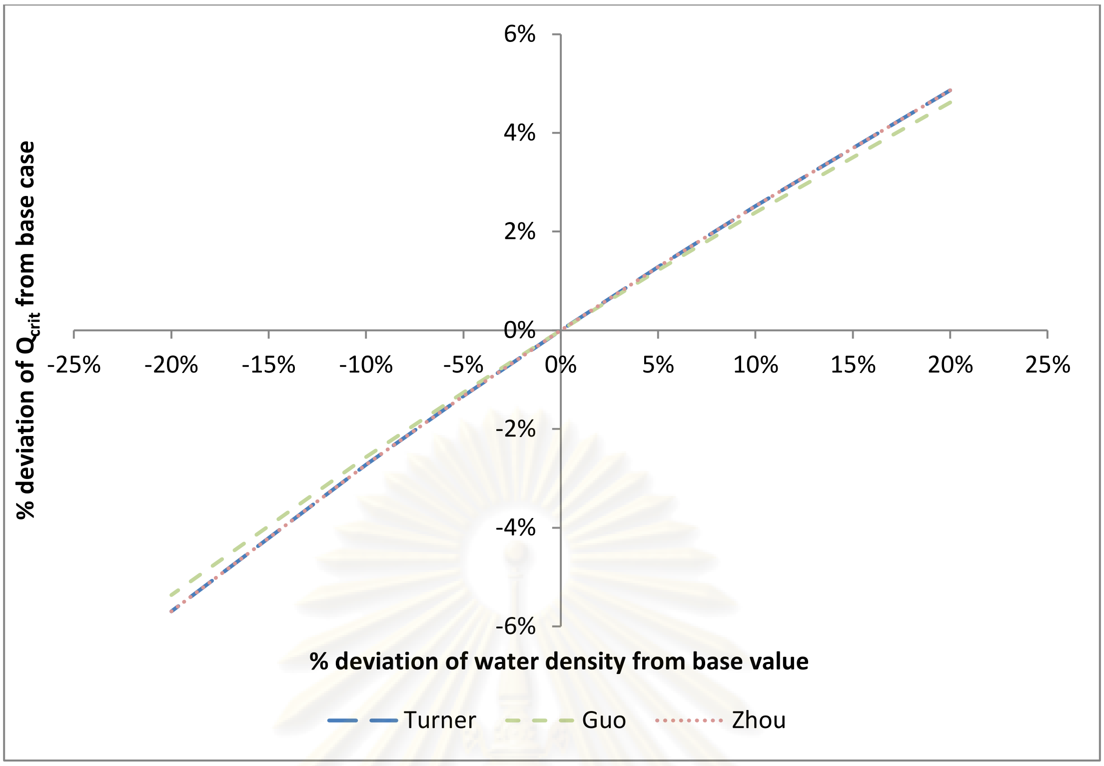


Figure 4.15: Sensitivity analysis on water density (high FTP, low Ql case)

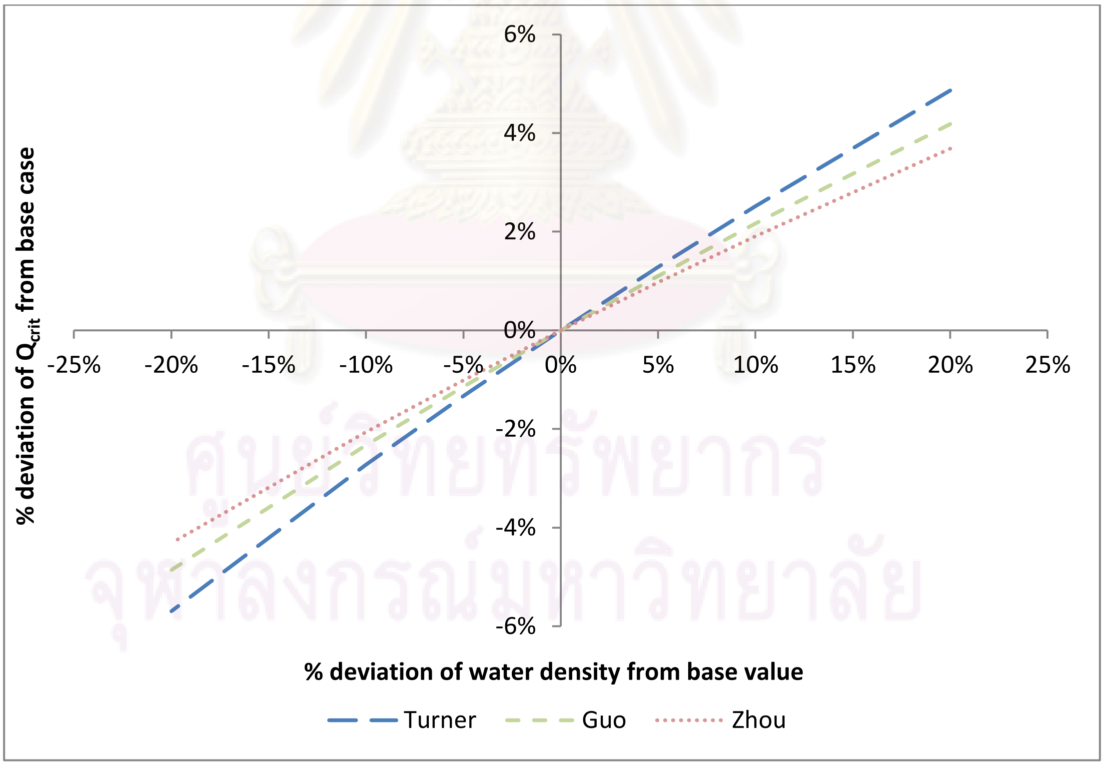


Figure 4.16: Sensitivity analysis on water density (high FTP, high Ql case)

Considering water density, the deviation of sensitivity analysis is similar to condensate density. Turner’s correlation is still the one that predicts the highest deviation and the deviation of production condition that liquid holdup less than 0.01 is equal to Zhou’s correlation. For the production condition that liquid holdup is less than 0.01 (case No. 1 & 3), Guo’s correlation predicts the lowest deviation while the lowest deviation for the production condition that is greater than 0.01 belongs to Zhou’s correlation. In terms of the value, the variation of sensitivity analysis is slightly less than condensate density. The similarity of water density and condensate density in sensitivity analysis can be described by the effects of water density on each critical flowrate correlation that are similar to condensate density. Thus, the phase of liquid does not have a significant role in predicted critical flowrate. Nevertheless, every correlation recommends that water is a preferred liquid phase when both of liquid phases are detected.

4.2.4) Gas-condensate surface tension (σ_o)

Gas-condensate surface tension is the fluid properties that are rarely measured in normal routine because of the requirement of laboratory test to determine it and limited usage. Similar to condensate density, the phase of liquid for input parameters is condensate. A summary of base and sensitivity analysis values for condensate density is shown in Table 4.19. In terms of production condition, there are four cases of production condition for each liquid phase. Details of each production condition case are shown in Table 4.20. Results from sensitivity analysis model for each production condition are shown in Figure 4.17 – 4.20.

Table 4.19: Base and sensitivity analysis values of gas-condensate surface tension

Sensitivity analysis case	Value (dynes/cm)
+30%	18.16
+20%	16.76
+10%	15.37
+5%	14.67
Base case	13.97
-5%	13.27
-10%	12.57
-20%	11.18
-30%	9.78

Table 4.20: Details of each production condition case for gas-condensate surface tension

Case number	Case Definition	FTP (psia)	Liquid production rate (bbl/d)
1	Low FTP, low Ql case	315	50
2	Low FTP, high Ql case	315	375
3	High FTP, low Ql case	685	50
4	High FTP, high Ql case	685	375

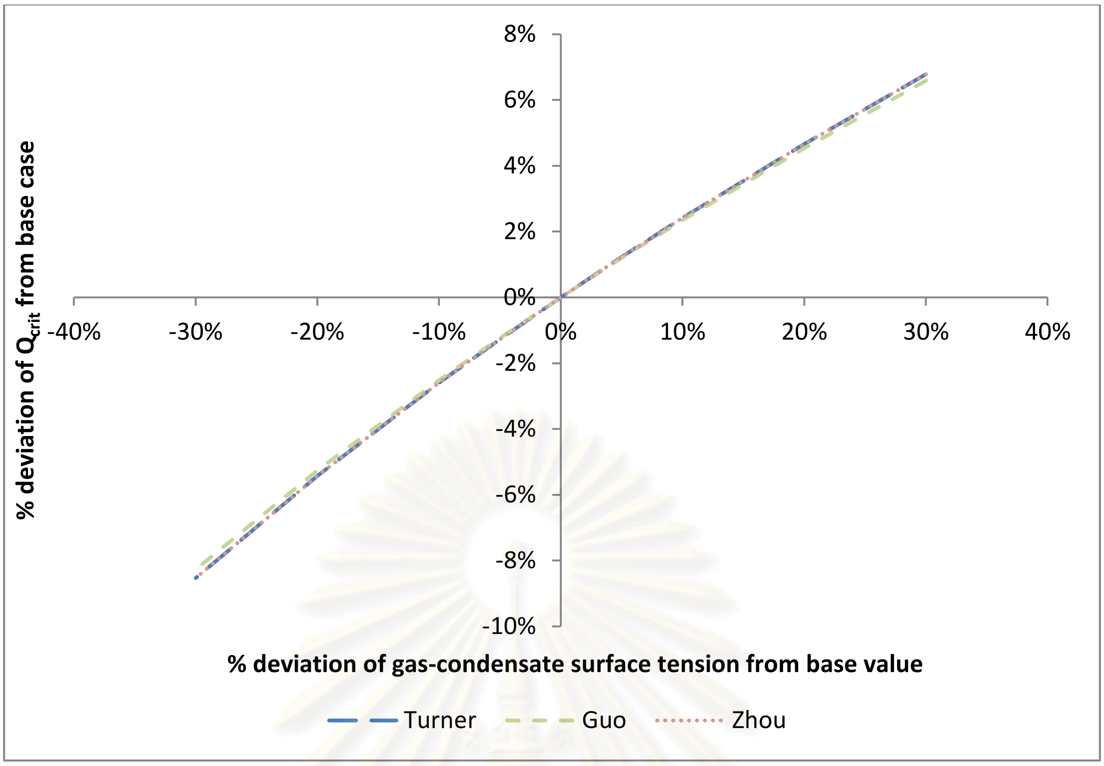


Figure 4.17: Sensitivity analysis on gas-condensate surface tension (low FTP, low Ql case)

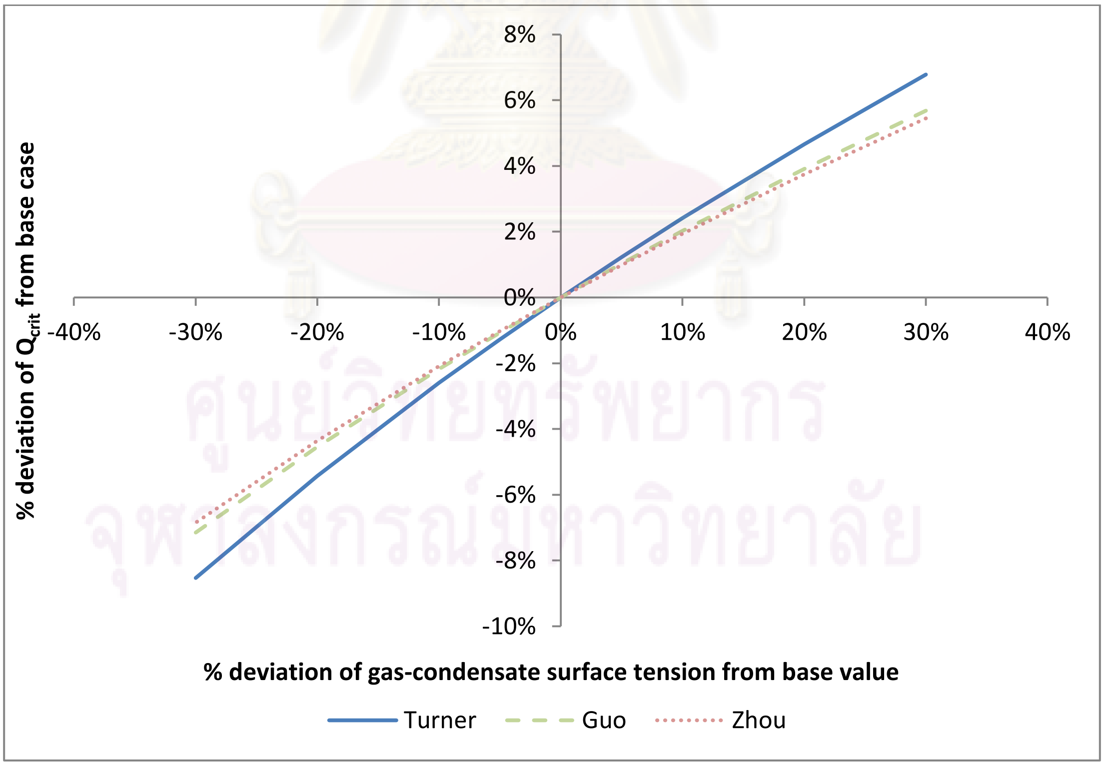


Figure 4.18: Sensitivity analysis on gas-condensate surface tension (low FTP, high Ql case)

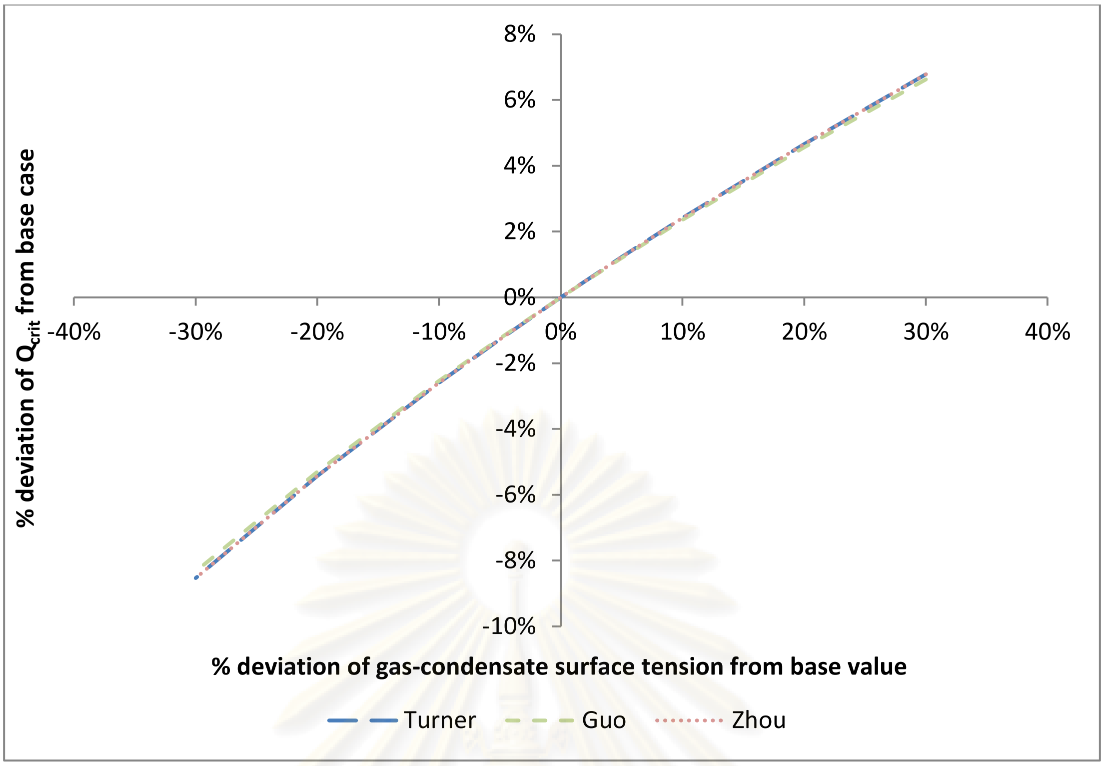


Figure 4.19: Sensitivity analysis on gas-condensate surface tension (high FTP, low Ql case)

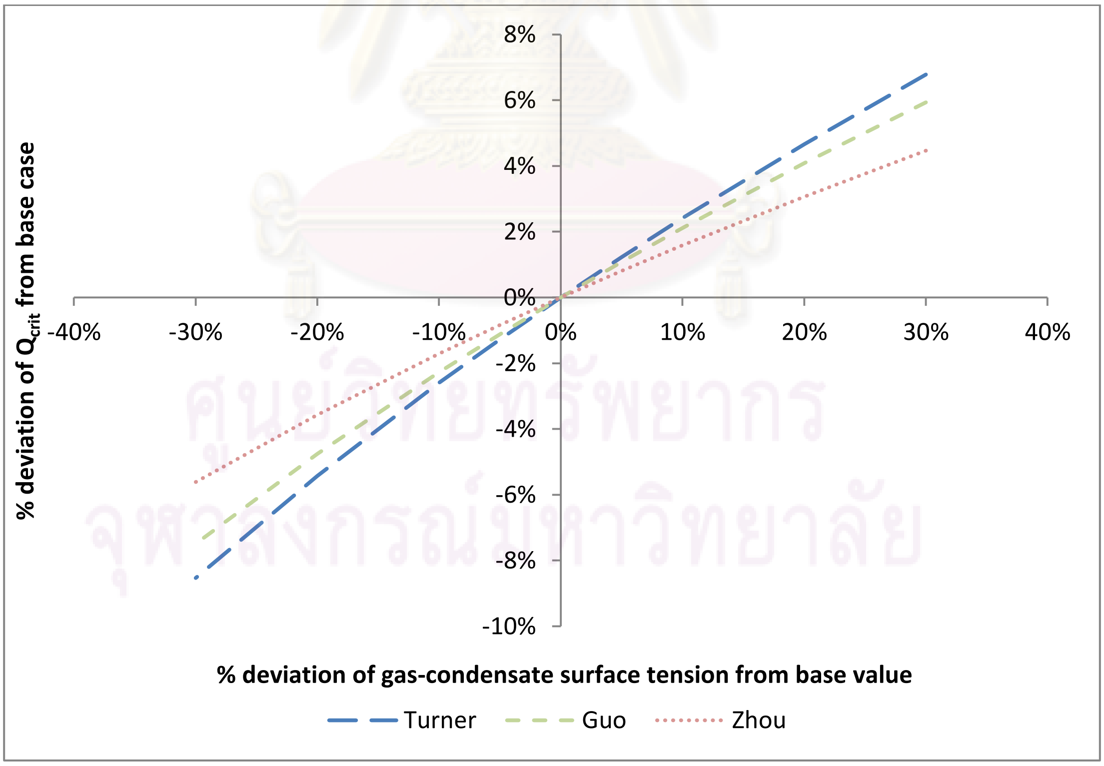


Figure 4.20: Sensitivity analysis on gas-condensate surface tension (high FTP, high Ql case)

In terms of the deviation calculated by sensitivity analysis model, the results of gas-condensate surface tension are similar to condensate density. However, Turner's correlation predicts the same deviation for every production condition which is different from previous analysis that FTP causes a variation in Turner's predicted value. This behavior of Turner's correlation can be described as FTP does not have any influence on surface tension while liquid density and gas specific gravity are affected by FTP. Thus, the predicted value by Turner's correlation is constant for every production condition. However, the predicted values of Guo's and Zhou's correlations are in the same direction as condensate density. Considering the predicted values, the deviation of each correlation for each production condition is slightly lower than condensate density resulting in gas specific gravity is still the fluid property that has the highest influence on predicted critical flowrate.

The change in surface tension has a direct relationship with critical flowrate because surface tension plays an important part in terms of the strength of liquid droplet. When surface tension is higher, a condensate droplet tends to hold in the same shape with stronger bond. It requires more force to break this droplet out into a smaller droplet and makes it behave like mist in gas stream. In terms of critical velocity, it requires more critical velocity to lift larger droplet size since an increase in larger droplet size will make flow pattern of the well fade away from annular-mist flow pattern which is an assumption of liquid droplet model for critical velocity determination.

4.2.5) Gas-water surface tension (σ_w)

The final fluid property for sensitivity analysis is gas-water surface tension. Similar to water density, the phase of liquid for input parameters is water. A summary of base and sensitivity analysis values for condensate density is shown in Table 4.21. In terms of production condition, there are four cases of production condition for each liquid phase. Details of each production condition case are shown in Table 4.22. Results from sensitivity analysis model for each production condition are shown in Figure 4.21 – 4.24.

Table 4.21: Base and sensitivity analysis values of gas-water surface tension

Sensitivity analysis case	Value (dynes/cm)
+30%	74.79
+20%	69.04
+10%	63.28
+5%	60.41
Base case	57.53
-5%	54.65
-10%	51.78
-20%	46.02
-30%	40.27

Table 4.22: Details of each production condition case for gas-water surface tension

Case number	Case Definition	FTP (psia)	Liquid production rate (bbl/d)
1	Low FTP, low Ql case	315	50
2	Low FTP, high Ql case	315	375
3	High FTP, low Ql case	685	50
4	High FTP, high Ql case	685	375

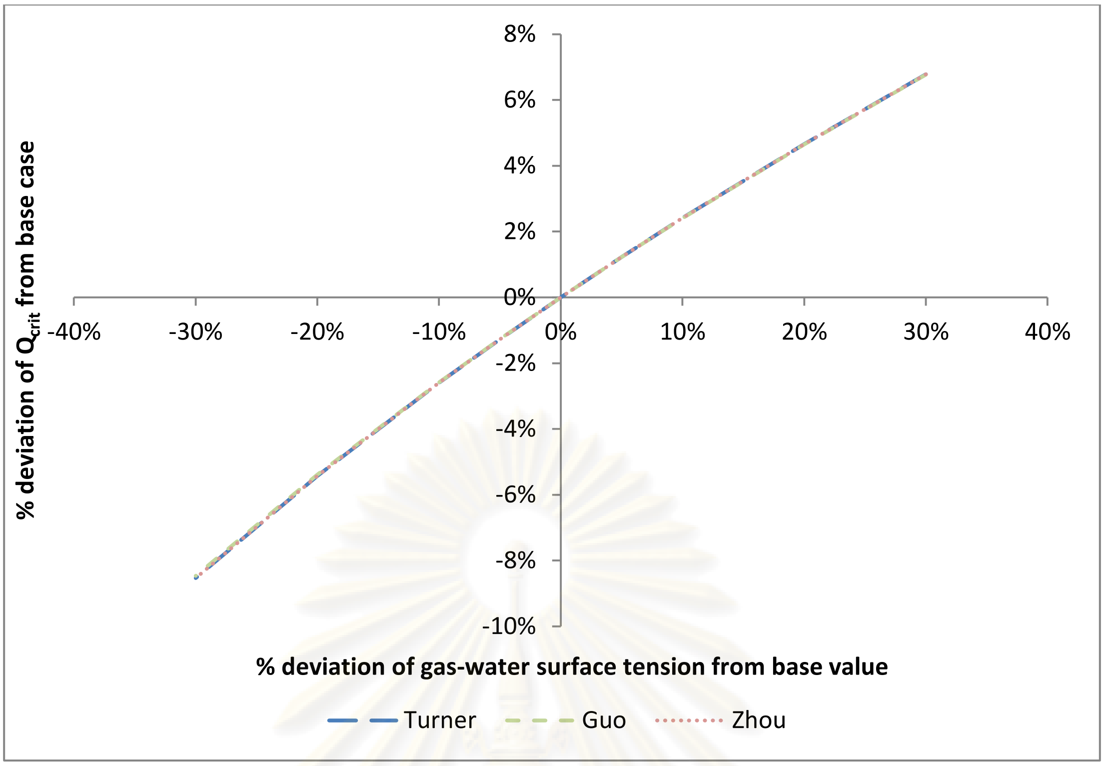


Figure 4.21: Sensitivity analysis on gas-water surface tension (low FTP, low Ql case)

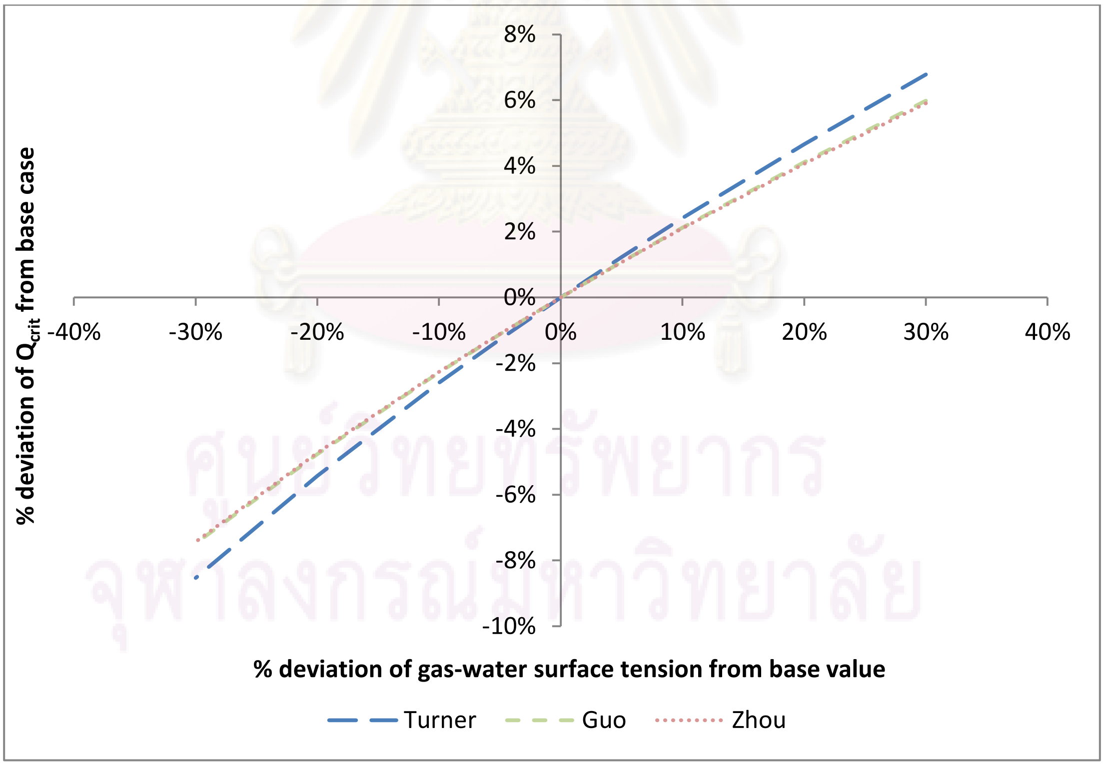


Figure 4.22: Sensitivity analysis on gas-water surface tension (low FTP, high Ql case)

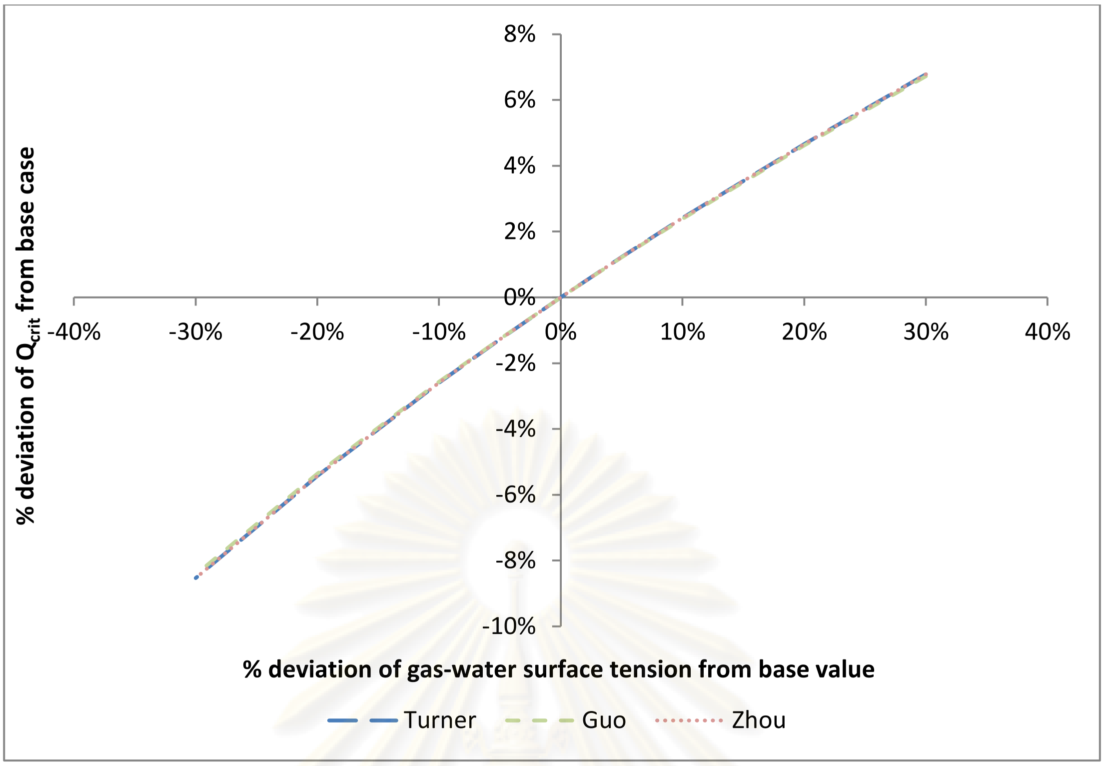


Figure 4.23: Sensitivity analysis on gas-water surface tension (high FTP, low Ql case)

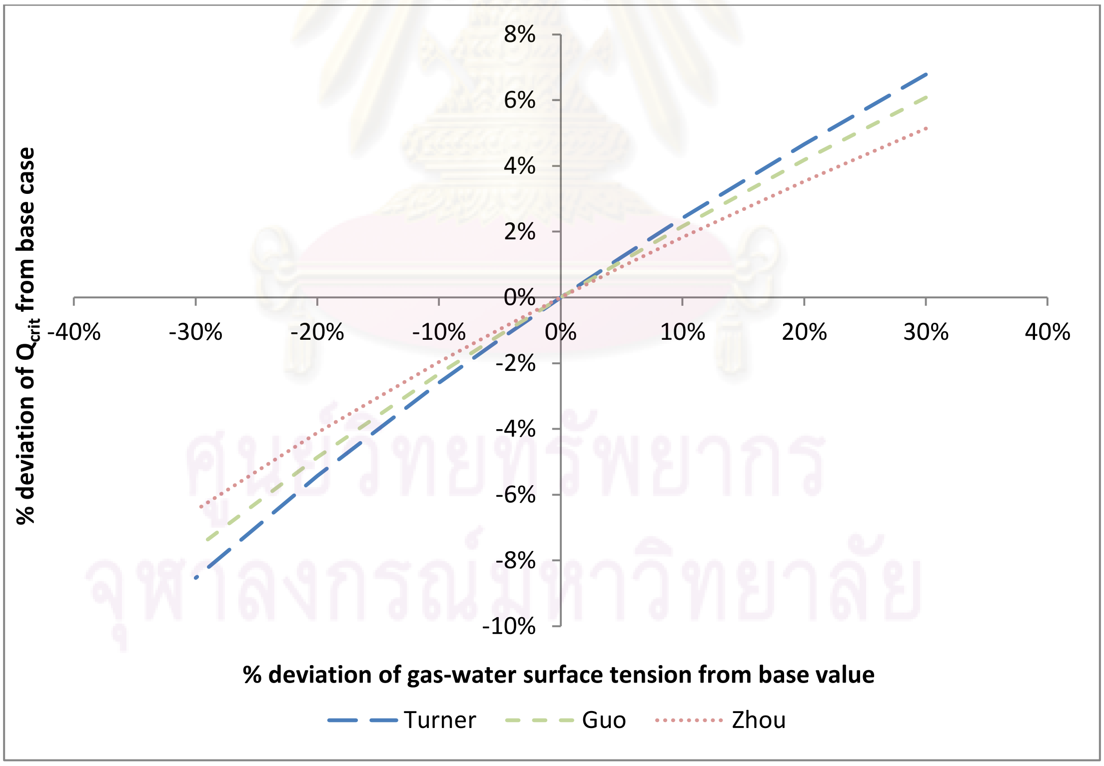


Figure 4.24: Sensitivity analysis on gas-water surface tension (high FTP, high Ql case)

Complementary to the similarity between condensate density and water density, gas-condensate surface tension and gas-water surface tension have several similarities. Begin with the highest and constant deviation predicted by Turner's correlation. Moreover, the deviation of gas-water surface tension is the exact value as gas-condensate surface tension. The tendency of predicted values by Guo's and Zhou's correlations is still the same as gas-condensate surface tension. The predicted deviation of gas-water surface tension is slightly less than gas-condensate surface tension which is similar to liquid density cases. Therefore, gas specific gravity is the one that has the highest influence on predicted critical flowrate of each selected correlation.

Property of the fluid is one of the most important considerations in petroleum activities. Fluid properties play a critical role in gas and liquid behavior of liquid droplet model. Five properties which are gas specific gravity, condensate density, liquid density, gas-condensate surface tension and gas-water surface tension are selected to study the influences of them on liquid loading consideration. Classifications of fluid properties data together with the influences of them on selected critical flowrate correlation are analyzed in this chapter. In section 4.1, the origin of the values of each selected property is clarified. At the end of the section, comparisons of the values of this study and recommended values made by Turner are presented. Sensitivity analysis is the chosen tool to evaluate the influences of each fluid property on predicted critical flowrate. The conclusions of fluid properties analysis can be summarized as

1.) Fluid property that has the most variation is gas specific gravity. This conclusion is made by the fact that gas specific gravity has the widest range of possible value. It can be varied in the range of 0.554 to 1.1. Moreover, the value of gas specific gravity of this study has the highest deviation in comparison with recommended values made by Turner. Considering other focused parameters (liquid density and surface tension, the differences between the values of this study and Turner's recommended values are lower than gas specific gravity. Thus, recommended values by Turner can be applied in case of missing data with certain accuracy. However, the evaluation of fluid properties and apply the reasonable values of fluid properties are the proper procedure in order to reduce the errors made by wrong values of fluid properties.

2.) Gas specific gravity is the one that has the highest deviation when sensitivity analysis is applied to selected fluid properties. Moreover, the variation in production condition plays a role in the values of predicted critical flowrate in a different manner. The differences in the phase of liquid do not play any significant role in predicted critical flowrate because it has a very small difference when the same production conditions are compared. Together with the conclusion from section 4.1, it can be concluded that gas specific gravity is the most important fluid properties for liquid loading determination.

In the next chapter, intensive analysis of production condition is conducted because the variation in production condition proves that it has an influence on predicted critical flowrate. This study selects liquid holdup to represent the variation in production condition. After the factors that affect the evaluation of critical flowrate are analyzed, predictions of well status by each selected correlation are investigated in order to analyze liquid loading in actual production data.

CHAPTER V

LIQUID HOLDUP AND WELL STATUS ANALYSIS

Liquid loading can be determined by several methods. For instance, the presence of liquid slug at surface or significantly dropped of production rate versus time plot of decline curve analysis. Another popular method, which is selected by this study, is the analysis of critical flowrate. In this study, critical flowrate is calculated by three correlations via user-generated calculating model. Details of selected correlations and calculating model are clarified in chapter III. In last chapter, the influences of fluid properties on critical flowrate are analyzed. However, the conclusions about how the amount of liquid plays a role on critical flowrate are still not unanimous because there are some conflicts between the conclusions from different groups of researchers. Therefore, liquid holdup, which is used to represent liquid production rate for this study, is analyzed in order to investigate the influences of liquid holdup to critical flowrate. After the analysis of the factors that affect the prediction of critical flowrate is finalized, the analysis of well status is made in order to investigate the well status of actual production well.

5.1) Liquid holdup analysis

When liquid is produced from gas well, liquid loading is one of the problems that usually concerns petroleum engineer. This study selects five scenarios of fluid production which tend to cause liquid loading. Those conditions are 1.) low to low-moderate H_l range with low gas production rate, 2.) low to low-moderate H_l range with low liquid production rate, 3.) low to low-moderate H_l range with high liquid production rate, 4.) moderate-high to high H_l range with low gas production rate and 5.) moderate-high to high H_l range with high gas production rate. In this study, these five scenarios of fluid production are called “focused production condition”. Other conditions such as no liquid production or low to low-moderate H_l range with high gas production rate are eliminated from this analysis because liquid loading condition will not happen in those conditions. Classification of liquid holdup analysis conditions is presented in table 5.1.

Table 5.1: Classification of liquid holdup analysis conditions

Conditions	Liquid holdup value	Gas production rate	Liquid production rate
low to low-moderate H_l range with low gas production rate	0.0001 – 0.03	< 1.5 MMscf/d (median of entire data)	Not specified
low to low-moderate H_l range with low liquid production rate	0.0001 – 0.03	Not specified	< 140 bbl/d (median of entire data)
low to low-moderate H_l range with high liquid production rate	0.0001 – 0.03	Not specified	> 140 bbl/d (median of entire data)
moderate-high to high H_l range with low gas production rate	0.03 – 0.24	< 1.5 MMscf/d (median of entire data)	Not specified
moderate-high to high H_l range with high gas production rate	0.03 – 0.24	> 1.5 MMscf/d (median of entire data)	Not specified

The values that are used to define production scenario (1.5 MMscf/d for gas production rate, 140 bbl/d for liquid production rate and range of liquid holdup value) originate from data classification in chapter III. Considering each scenario, the results of each scenario are separated into 2 sets by the parameters involving in each scenario. For instance, gas production rate and liquid holdup for scenario 5.1.1. Each set of the results is classified into 4 groups by median and quartile of each parameter. Analysis of production scenarios is presented in following section.

5.1.1 Low to low-moderate liquid holdup range with low gas production rate

In this condition, gas well is produced at low production rate and liquid production is also in a low rate resulting in low to low-moderate liquid holdup range. This condition usually happens in declining period of gas well and this condition often ends up with no gas production. Results in this section are separated into 2 sets by the parameters that used to define the production scenario which is presented in next section.

5.1.1.1Classified by gas production rate.

Considering the data sets that have the value of liquid holdup in low to low-moderate range and gas production rate less than 1.5 MMscf/d, they are separated into 4 groups in order to monitor any changes in the results. Median and quartiles are used to break the data sets into 4 groups. For gas production rate in 0.05 to 0.48 MMscf/d range, it is classified to the first group. Gas production rate at 0.49 to 0.75 MMscf/d, 0.76 to 1.16 MMscf/d and 1.17 to 1.50 MMscf/d are categorized into second, third and fourth groups respectively. Results from this section are displayed in term of the percentage of the data sets in each gas production rate group which is shown in Figure 5.1.

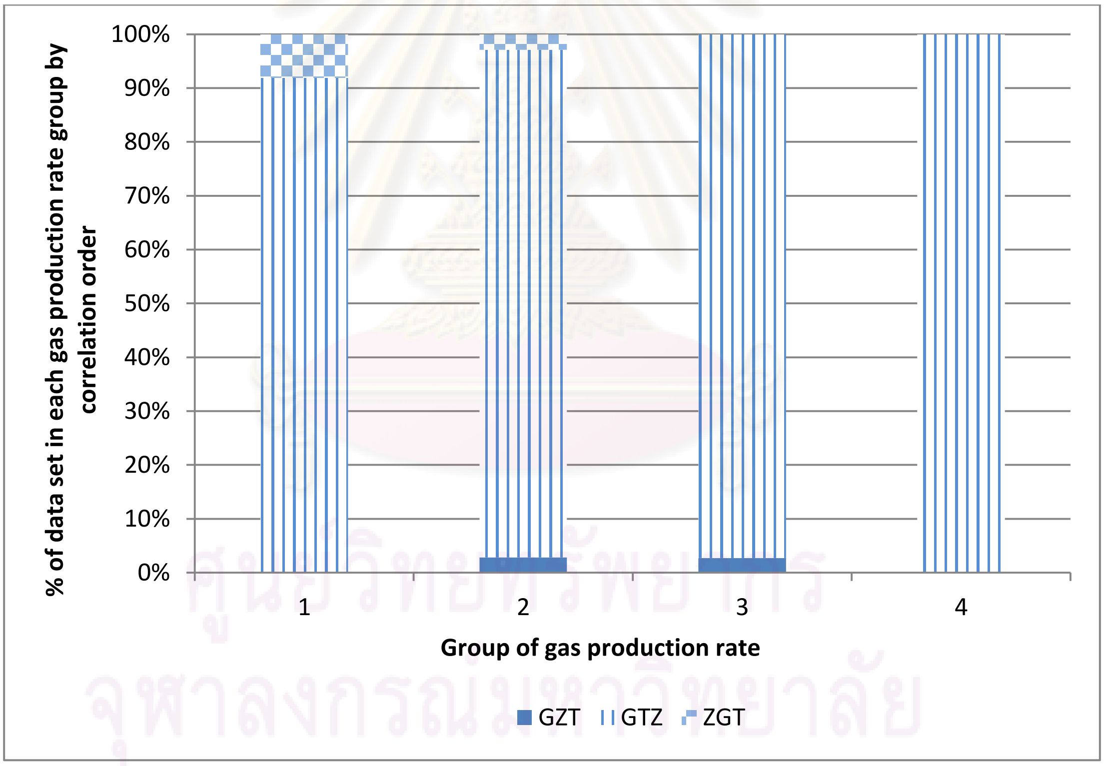


Figure 5.1: Details of critical flowrate data for low to low-moderate H_l range with low gas production rate (classified by gas production rate)

For Figure 5.1 and 5.2, 4 columns in each chart represent the percentage of the data sets in each gas production rate group. There are 3 possible orders of predicted critical flowrate presented in the different color of the sub-column. For instance, 92%

of the first column in Figure 5.1 belongs to “GTZ” category. The “GTZ” means Guo’s correlation predicts the highest critical flowrate, followed by Turner’s correlation and Zhou’s correlation. This pattern of Figure is presented in Figure 5.2 to 5.10.

Considering Figure 5.1, Guo’s correlation predicts the highest critical flowrate for the majority of data sets. In details, for the data sets that have gas production rate in 0.01 to 0.48 MMscf/d group, Guo’s correlation predicts the highest critical flowrate for 91.89% of the entire data in this group and 97.14% for 0.49 to 0.74 MMscf/d gas production rate group. For the data sets that have gas production rate in the range of 0.74 to 1.16 and 1.17 to 1.50, Guo’s correlation predicts the highest critical flowrate for every data set. There are only 8.11% of the data sets of data in 0.01 to 0.48 MMscf/d and 2.86% of data sets of 0.49 to 0.74 MMscf/d that Zhou’s correlation predicts the highest critical flowrate. Even though Turner’s correlation is the one that cannot predict the highest critical flowrate in any data sets, it predicts the second highest critical flowrate for the most of the data sets that Guo’s correlation predicts the highest critical flowrate. The prediction of each correlation can be described by the signature of each correlation and the definition of this production condition. Guo’s and Zhou’s correlation are the correlations that use production condition as their input parameters while the input parameter of Turner’s correlation is only fluid properties. Thus, there is no significant difference in predicted values of each correlation for a low value of production condition. However, Guo’s correlation is the one that usually predicts a significantly higher critical flowrate than others resulting in the highest number of data sets that Guo’s correlation predicts the highest critical flowrate. Although Zhou’s correlation takes production condition into its input parameter, it uses liquid holdup as its representative of production condition which all of the data in this production condition have a low value of liquid holdup. Thus, predicted critical flowrate of Zhou’s correlation does not have a significant effect by a variation in production condition resulting in low number of the data sets that Zhou’s correlation predicts the highest critical flowrate.

5.1.1.2Classified by liquid holdup

In this section, the data sets that have the value of liquid holdup in low to low-moderate range and gas production rate less than 1.5 MMscf/d are categorized by liquid holdup. Four groups of liquid holdup classified by median and quartiles are set. Range of liquid holdup for the first group is 0.0002 to 0.0027. The ranges of liquid holdup at 0.0028 to 0.0076, 0.0077 to 0.0161 and 0.0162 to 0.0294 are set as second, third and fourth range respectively. Results of this section are shown in Figure 5.2.

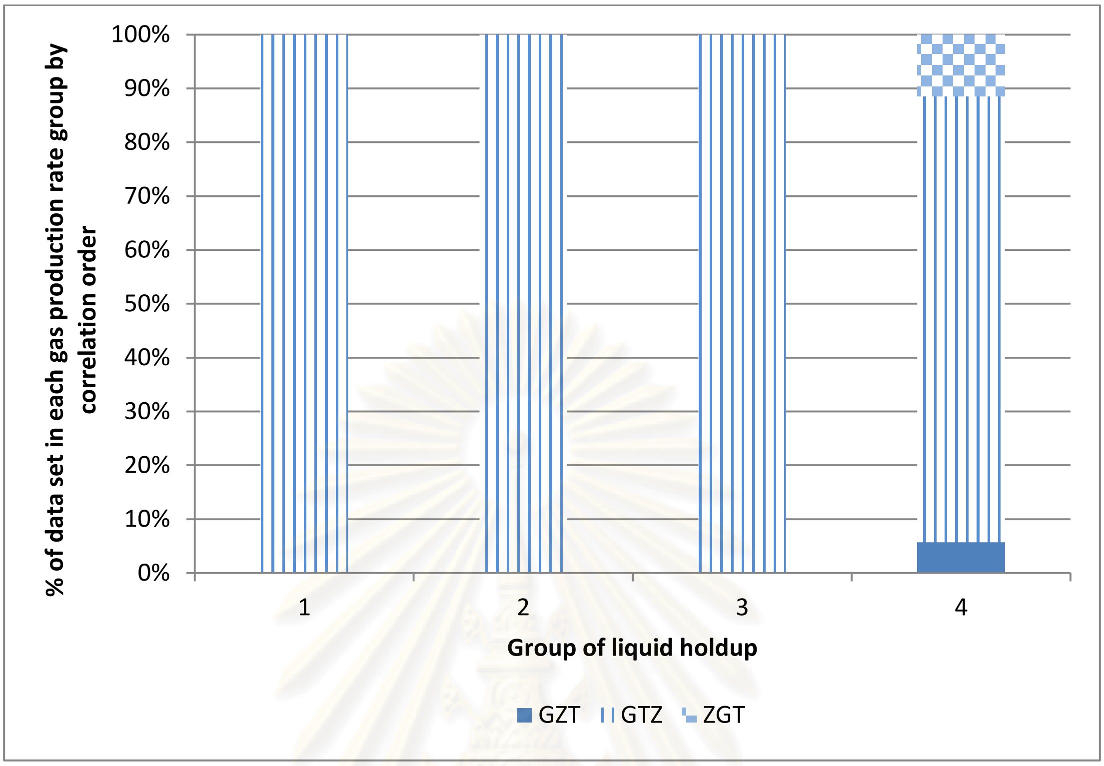


Figure 5.2: Details of critical flowrate data for low to low-moderate H_l range with low gas production rate (classified by liquid holdup)

Considering Figure 5.2, Guo's correlation predicts the highest critical flowrate in every liquid holdup range. In details, Guo's correlation predicts the highest critical flowrate for all of the data sets that have liquid holdup value from 0.0002 to 0.0161. Predicted value of Zhou's correlation is the highest critical flowrate for 11.43% for the data sets in the highest liquid holdup group. Effects of production condition also play the roles on this prediction. However, liquid holdup value in this case is low because it is limited by the definition of the case. Thus, the influence of liquid holdup in predicted value of Zhou's correlation is low resulting in lower critical flowrate than others. Although liquid production rate is not directly considered in this case, liquid holdup can be calculated back to liquid production rate. Higher liquid holdup indirectly indicates that liquid production rate is higher. Thus, the increase in liquid production rate makes an increase in predicted critical flowrate from Guo's correlation.

5.1.2 Low to low-moderate liquid holdup range with low liquid production rate

This condition can be found in the declining period of gas production well or in the case that dew point pressure is higher than reservoir pressure resulting in condensate drop out. Moreover, the source of liquid can be condensation of a gaseous phase along the tubing. Similar to section 5.1.1, the results in this section are separated into 2 sets which are classified by liquid production rate and liquid holdup.

5.1.2.1 Classified by liquid production rate

In this section, similar concept of the classification of input parameter, which is median and quartiles, is used to categorize the results into 4 groups. Considering the first group, the data sets that have liquid production rate in 1 to 36 bbl/d belong to this group. For other groups, liquid production rate at 37 to 62 bbl/d, 63 to 89 bbl/d and 90 to 140 bbl/d are set as second, third and fourth group respectively, Results in this section are presented in Figure 5.3

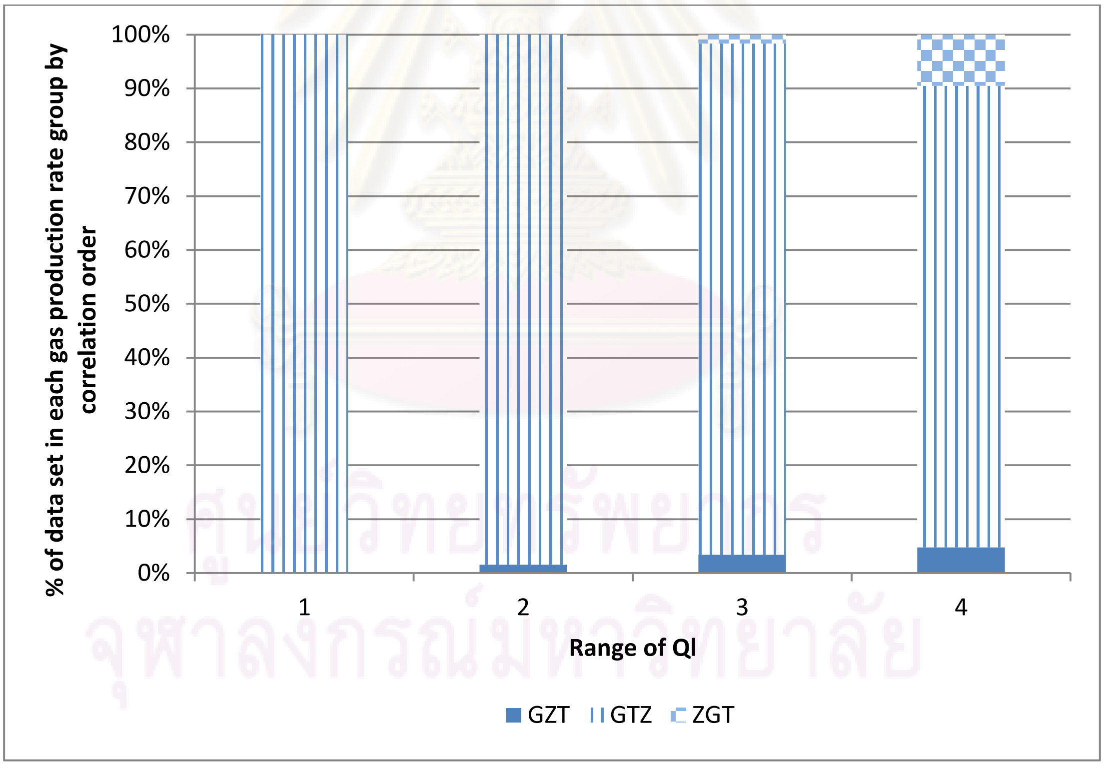


Figure 5.3: Details of critical flowrate data for low to low-moderate H_l range with low liquid production rate (classified by liquid production rate)

Considering Figure 5.3, in terms of number of data sets that each correlation predicts the highest critical flowrate, this condition is similar to low to low-moderate H_l range with low gas production rate. Guo's correlation predicts the highest critical flowrate for the majority of data. Only 1.69% of the data set in 63 to 89 bbl/d group and 9.52% of the data sets in 89 to 140 bbl/d group that Zhou's correlation predicts the highest critical flowrate. Turner's correlation stills cannot predict the highest critical flowrate in any data sets. However, similar to low to low-moderate liquid holdup range and low gas production rate case, Turner's correlation predicts the second highest critical flowrate for the most of data sets. The values of production condition are the main reason of the results from each correlation. As discussed in previous section, each critical flowrate is affected by production condition in a different manner. Liquid production rate is a direct input parameter of Guo's correlation. Higher liquid production rate generates an additional value to predicted critical flowrate of Guo's correlation. Even though Zhou's correlation does not take liquid production rate as its direct input parameter, liquid production rate is the important parameter of liquid loading determination. An increase in liquid production rate usually increases the liquid holdup value resulting in a higher predicted value of Zhou's correlation. However, the low value of liquid holdup makes the low predicted value of Zhou's correlation resulting in the high number of data sets that Turner's correlation predicts higher critical flowrate than Zhou's correlation.

5.1.2.2 Classified by liquid holdup

In this section, the data sets that have the value of liquid holdup in low to low-moderate range and liquid production rate less than 140 bbl/d are categorized by liquid holdup. Four groups of liquid holdup classified by median and quartiles are set. Range of liquid holdup for the first group is 0.0002 to 0.0024. The ranges of liquid holdup at 0.0025 to 0.0040, 0.0041 to 0.0076 and 0.0077 to 0.0295 are set as second, third and fourth range respectively. Results of this section are shown in Figure 5.4.

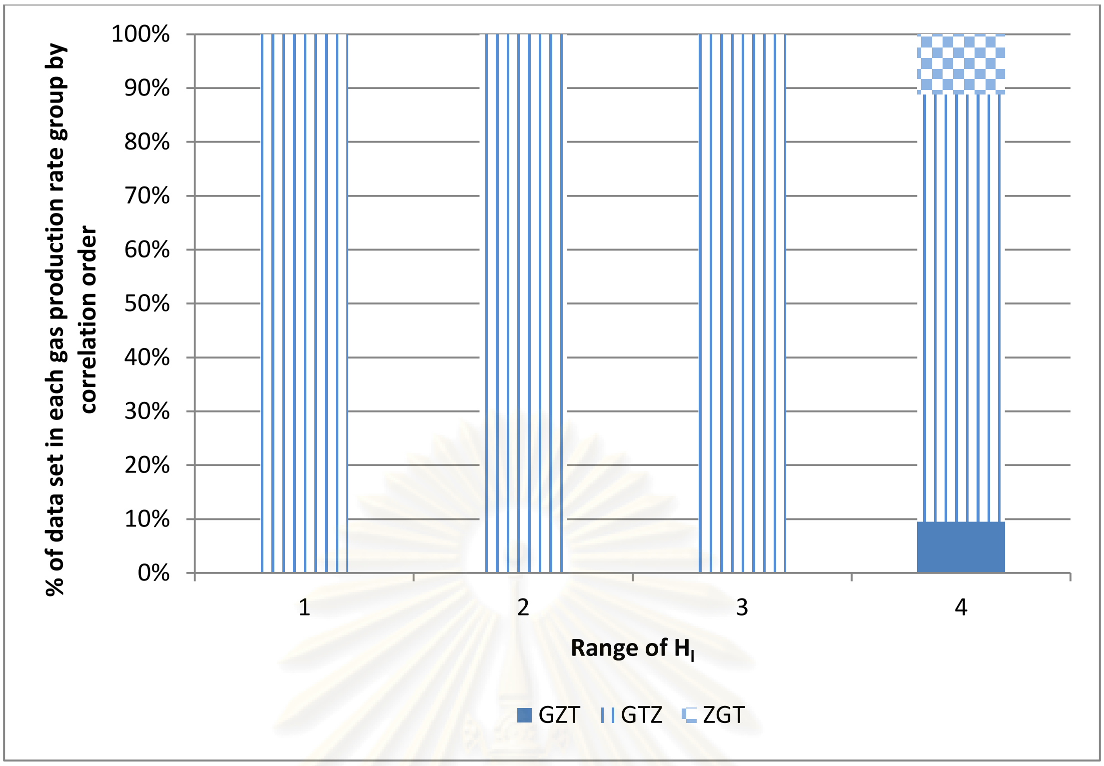


Figure 5.4: Details of critical flowrate data for low to low-moderate H_l range with low liquid production rate (classified by liquid holdup)

Considering Figure 5.4, a majority of the highest critical flowrate is predicted by Guo's correlation. Nevertheless, the influence of liquid holdup plays a significant role on the number of data sets that Zhou's correlation predicts the highest critical flowrate because there are 11.11% of the data sets in the highest liquid holdup range that Zhou's correlation predicts the highest critical flowrate. As discussed in previous section, higher liquid holdup value acts as an addition to predicted value by Zhou's correlation resulting in 11.11% of the data sets that Zhou's correlation predicts the highest critical flowrate. However, the value of liquid holdup is low because it is limited by the constraint of this condition. The results of section 5.1.1 and 5.1.2 lead to a conclusion that Guo's correlation is the recommended correlation for conservative prediction of critical flowrate in low liquid holdup condition.

5.1.3 Low to low-moderate liquid holdup range with high liquid production rate

In this condition, gas well has a significant liquid production rate and gas production rate is high resulting in low to low-moderate liquid holdup range. Liquid loading problem can be identified by high liquid production rate in many cases. This condition might happen after new perforation is done or water breakthrough problem is detected. Similar concept which is applied in section 5.1.1 and 5.1.2, the results in this section are separated into 2 sets which are classified by gas production rate and liquid holdup.

5.1.3.1 Classified by liquid production rate

In this section, four ranges of liquid production rate are set in order to analyze the variation in the results between each group. Considering the first group, the data sets that have liquid production rate in 146 to 201 bbl/d are classified into this group. For other groups, the data sets that have liquid production rate in 202 to 242 bbl/d, 243 to 303 bbl/d and 304 to 884 bbl/d are categorized into second, third and fourth group respectively. Results of this section are presented in Figure 5.5.

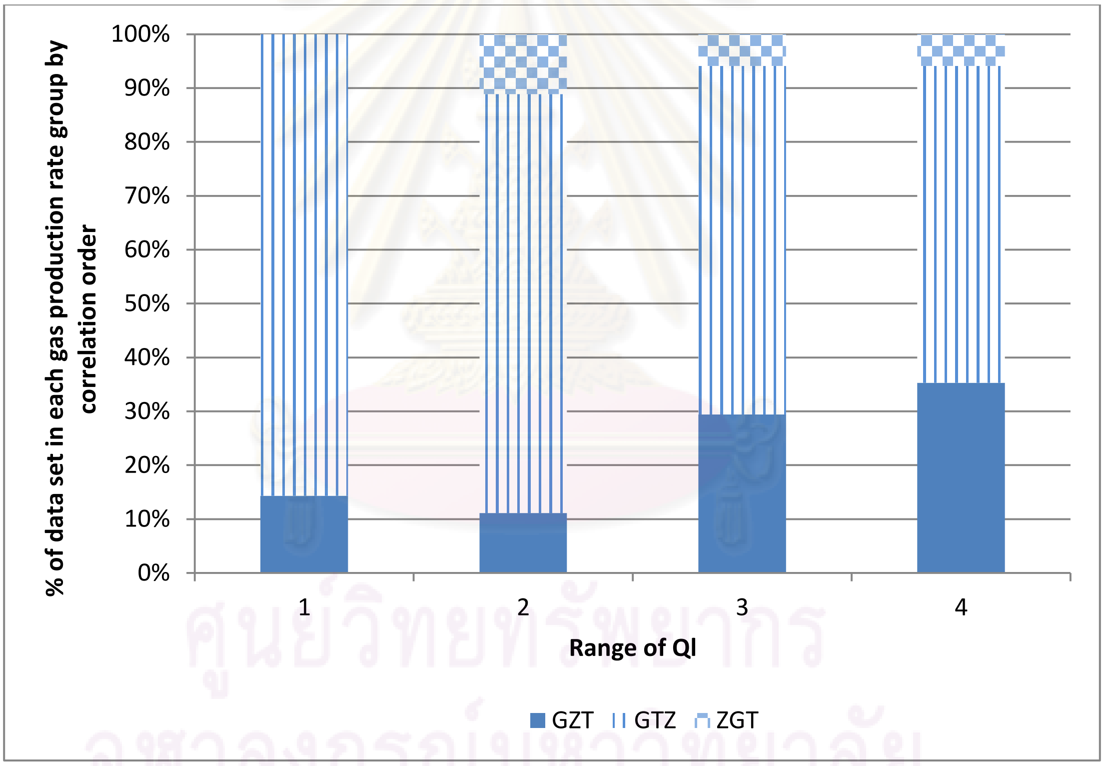


Figure 5.5: Details of critical flowrate data for low to low-moderate H_l range with high liquid production rate (classified by liquid production rate)

Considering Figure 5.5, number of data set that Guo's correlation predicts the highest critical flowrate is the highest number in every liquid production rate group resulting in highest number of total data sets (94.24% of the entire data in this production scenario). The number of data set that Zhou's correlation predicts the highest critical flowrate is much less than Guo's correlation (5.76% of the entire data in this production scenario). Influence of production condition plays an important role on predicted values of Guo’s correlation because Guo’s correlation takes liquid production rate in their consideration. High liquid production rate acts as an addition to predicted critical flowrate from Guo’s correlation resulting in the highest critical flowrate in the majority of data set. Even though there is no data set that Turner’s correlation predicts the highest critical flowrate, Turner’s correlation usually predicts higher critical flowrate than Zhou’s correlation in case Guo’s correlation predicts the highest critical flowrate. The major difference between Turner’s and Zhou’s correlation is Zhou’s correlation uses liquid holdup calculation instead of 20% upward adjustment in Turner’s correlation. In low liquid holdup value, additional terms of Zhou’s correlation usually calculate additional value less than 20% upward adjustment. Therefore, Turner’s correlation usually predicts higher critical flowrate than Zhou’s correlation in low liquid holdup value.

5.1.2.2 Classified by liquid holdup

In this section, the data sets that have the value of liquid holdup in low to low-moderate range and liquid production rate greater than 140 bbl/d are categorized by liquid holdup. Four groups of liquid holdup classified by median and quartiles are set. Range of liquid holdup for the first group is 0.0051 to 0.0118. The ranges of liquid holdup at 0.0119 to 0.0182, 0.0183 to 0.0234 and 0.0235 to 0.0299 are set as second, third and fourth range respectively. Results of this section are shown in Figure 5.6.

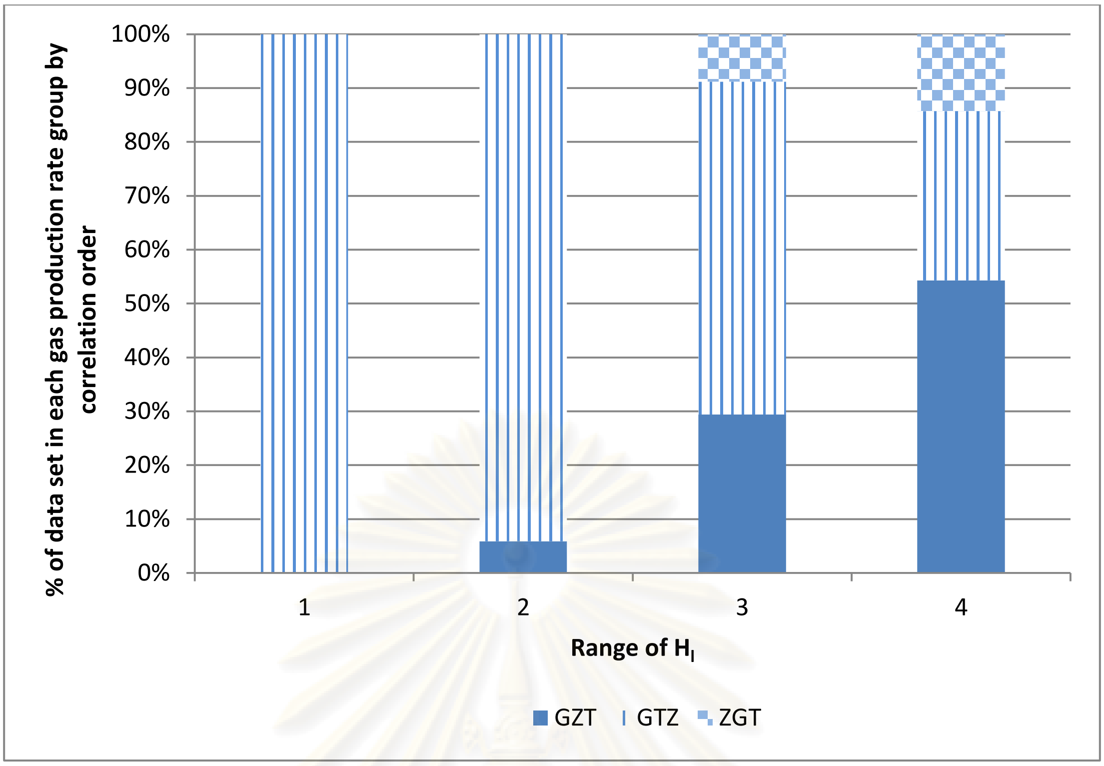


Figure 5.6: Details of critical flowrate data for low to low-moderate H_l range with high liquid production rate (classified by liquid holdup)

There is a significant notification on predicted value by Zhou's correlation. From Figure 5.6, there are 8.82% of the data sets in the third production rate group and 14.29% of the data sets in fourth liquid holdup group that the highest critical flowrate is predicted by Zhou's correlation. Moreover, considering the data sets that Guo's correlation predicts the highest critical flowrate, there are 31% of the data sets that Zhou's correlation predicts higher critical flowrate than Turner's correlation. Although the number of data sets that Zhou's correlation predicts higher critical flowrate than Turner's correlation is small, the proportion of Zhou's correlation predicts higher critical flowrate than Turner's correlation is higher than the number in section 5.1.1 and 5.1.2 (1.45% for the data in section 5.1.1 and 2.48% for the data in section 5.1.2). It can be explained by the definition of this condition as liquid production rate of this condition is high. Together with low to low-moderate liquid holdup range, the mean value of liquid holdup for this case is higher than the section 5.1.1 and 5.1.2 as the results of higher liquid production rate. Nonetheless, similar to section 5.1.1 and 5.1.2, the influence of liquid holdup on predicted value of Zhou's correlation is not fully applied because it is limit by the constraint of this case.

5.1.4 Moderate-high to high liquid holdup range with low gas production rate

In this condition, gas production rate is in low rate but liquid is produced at a significant rate leading to moderate-high to high liquid holdup range. This condition might happen in condensate well or gas well that has a significant liquid production rate. After the end of well life, liquid loading is usually mentioned as a reason for no gas flow. Two sets of the results, which are defined by gas production rate and liquid holdup, are presented in next section.

5.1.4.1 Classified by gas production rate

In this section, four ranges of gas production rate are set in order to analyze the variation in the results between each group. Considering the first group, the data sets that have gas production rate in 0.10 to 0.35 MMscf/d are classified into this group. For other groups, the data sets that have gas production rate in 0.36 to 0.54 MMscf/d, 0.55 to 1.01 MMscf/d and 1.02 to 1.50 MMscf/d are categorized into second, third and fourth group respectively. Results of this section are presented in Figure 5.7.

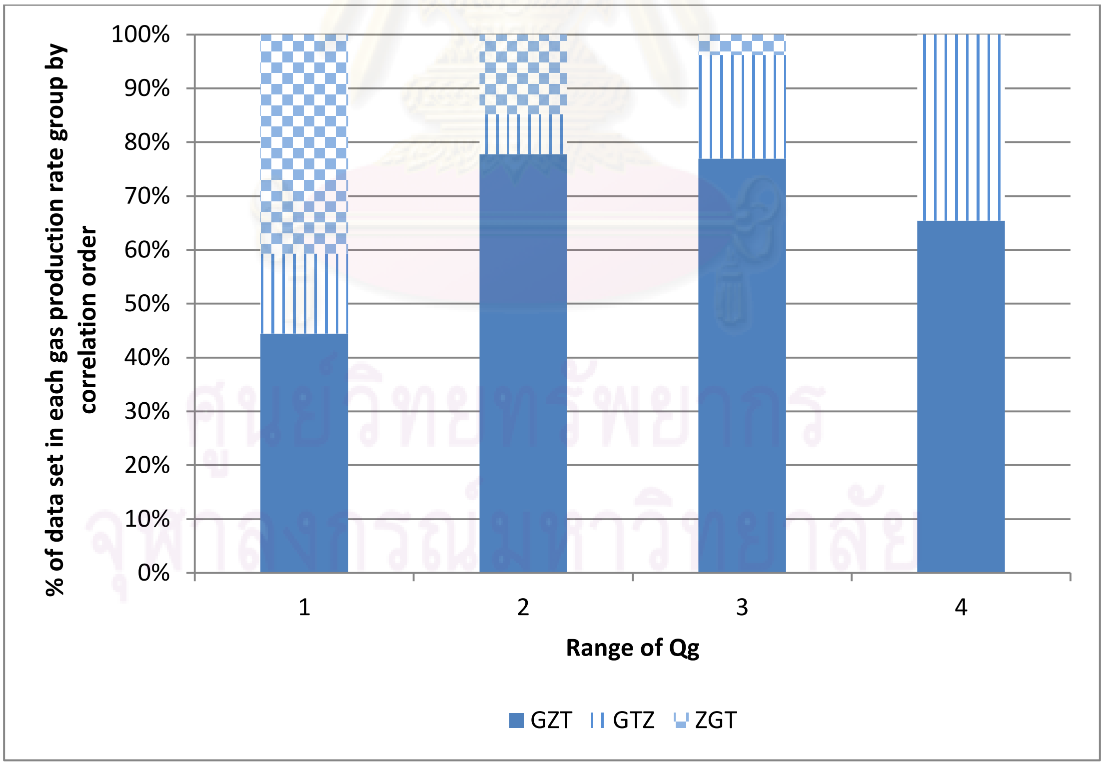


Figure 5.7: Details of critical flowrate data for moderate-high to high H_l range with low gas production rate (classified by gas production rate)

Although liquid production rate is not directly mentioned, it can be calculated by liquid holdup and gas production rate. Liquid production rate in this case is usually high because of moderate-high to high liquid holdup and low gas production rate. An effect of high liquid production rate generates the high number of data set that Guo’s correlation predicts the highest critical flowrate. Since liquid production rate is high, low gas production rate data sets usually have high liquid holdup resulting significant number of data set that Zhou’s correlation predicts the highest critical flowrate (15.09% of the entire data sets in this production scenario). However, with the higher gas production rate, the amount of liquid production rate does not rapidly increase because range of liquid production rate is narrow. Therefore, number of data set that Zhou’s correlation predicts the highest critical flowrate is decreasing with an increase in gas production rate. High liquid production rate and liquid holdup are not the conditions that favor Turner’s correlation to predict high critical flowrate as no data set in every range that Turner’s correlation predicts the highest critical flowrate.

5.1.4.2 Classified by liquid holdup

In this section, the data sets that have the value of liquid holdup in moderate-high to high range and gas production rate less than 1.5 MMscf/d are categorized by liquid holdup. Four groups of liquid holdup classified by median and quartiles are set. Range of liquid holdup for the first group is 0.0321 to 0.0482. The ranges of liquid holdup at 0.0483 to 0.0736, 0.0737 to 0.1402 and 0.1403 to 0.2360 are set as second, third and fourth range respectively. Results of this section are shown in Figure 5.8.

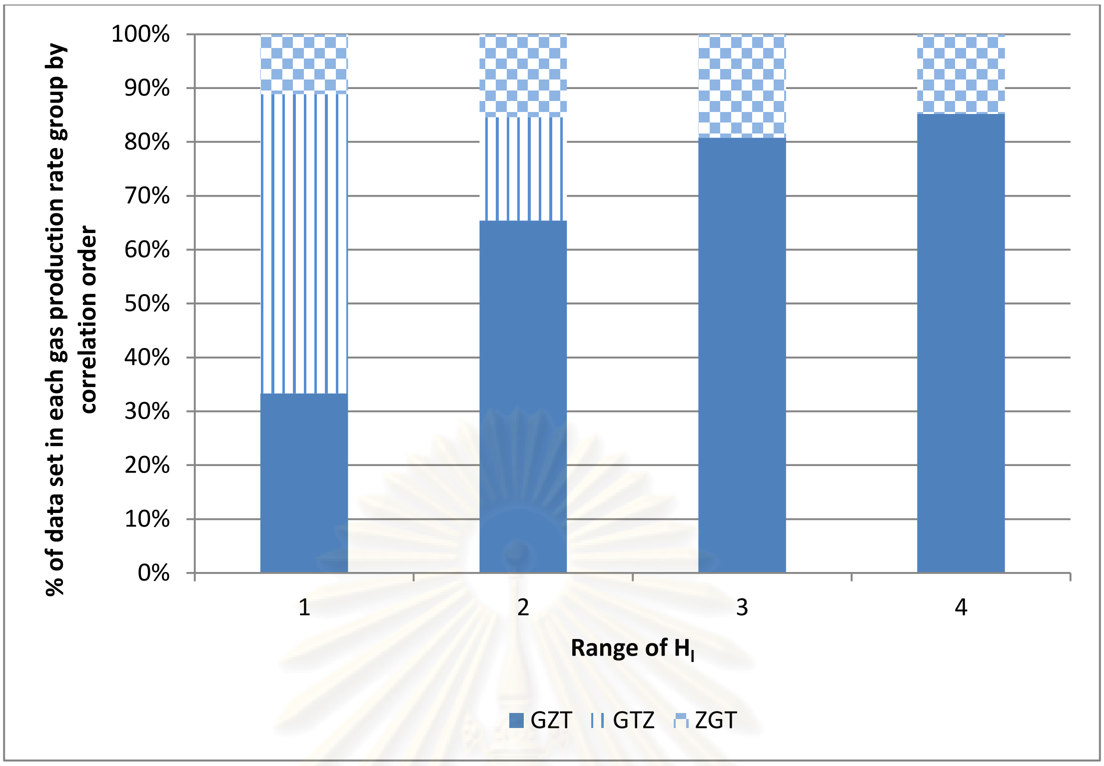


Figure 5.8: Details of critical flowrate data for moderate-high to high H_l range with low gas production rate (classified by liquid holdup)

Influences of high liquid holdup value plays another role in this production scenario because the number of the data sets that Zhou's correlation predicts higher critical flowrate than Turner's correlation is significantly increased in comparison with section 5.1.1, 5.1.2 and 5.1.3. In detail, the percentage of the data sets that Zhou's correlation predicts higher critical flowrate than Turner's correlation in section 5.1.1, 5.1.2, 5.1.3 and this section are 4.17%, 5.10%, 28.06 and 81.13% respectively. The results show in Figure 5.8 can provide a good explanation of the influence of liquid holdup because Turner's correlation predicts higher critical flowrate than Zhou's correlation only in the lowest liquid holdup range. For the rest of liquid holdup range, the predicted values of Zhou's correlation are often higher than Turner's correlation.

5.1.5 Moderate-high to high liquid holdup range with high gas production rate

In this condition, gas and liquid production rate is high resulting in moderate-high to high liquid holdup range. This condition usually happens in condensate well with high production rate or water can breakthrough to perforated zone. A well that produces under this condition usually has a report of massive liquid production and it is usually followed by a report of liquid loading problem by field observation. Similar to section 5.1.1 to 5.1.4, two sets of the results, which are defined by gas production rate and liquid holdup, are presented in next section.

5.1.5.1 Classified by gas production rate

In this section, four ranges of gas production rate are set in order to analyze the variation in the results between each group. Considering the first group, the data sets that have gas production rate in 1.50 to 2.44 MMscf/d are classified into this group. For other groups, the data sets that have gas production rate in 2.45 to 4.08 MMscf/d, 4.09 to 5.45 MMscf/d and 5.46 to 10.79 MMscf/d are categorized into second, third and fourth group respectively. Results of this section are presented in Figure 5.9.

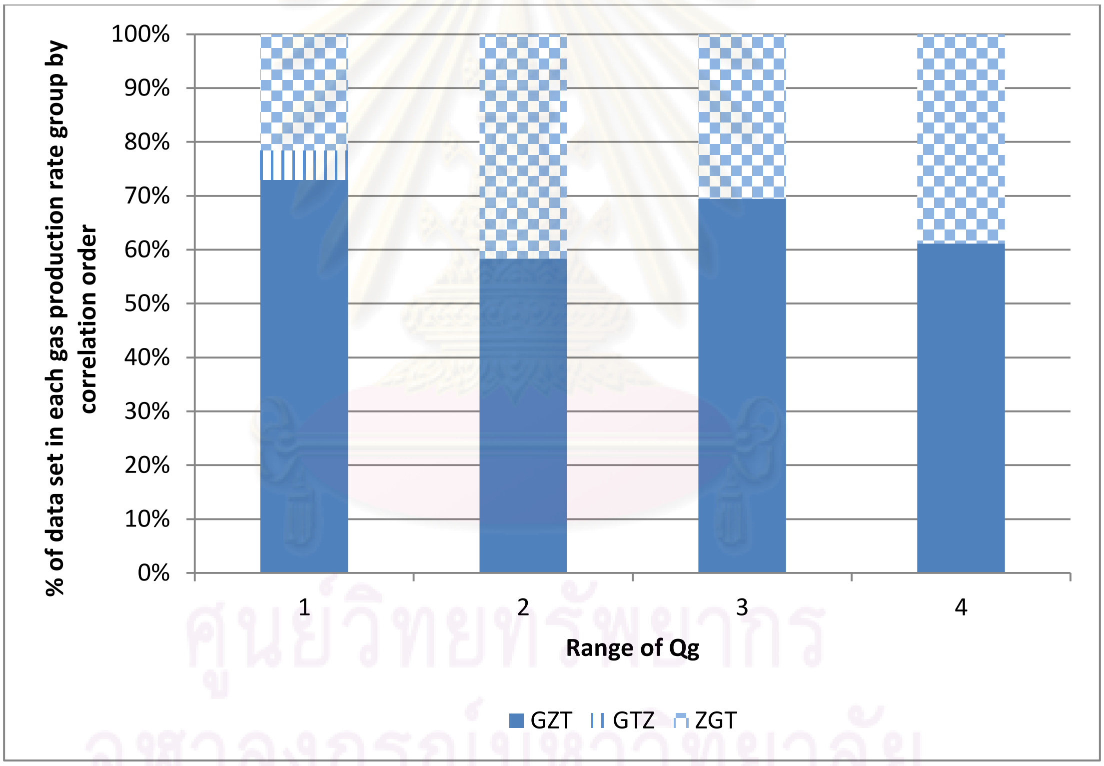


Figure 5.9: Details of critical flowrate data for moderate-high to high H_l range with high gas production rate (classified by gas production rate)

Even though liquid production rate is not directly mentioned in this section, it still plays an important role in this production scenario because its value is high and range of data is wide as the results of moderate-high to high liquid holdup range and high gas production rate. Number of data set that Guo's correlation predicts the highest critical rate is high as the results of high liquid production rate (66.90% of the entire data sets in this section). However, predicted values of Zhou's correlation are significantly increased as the results of an increase in liquid holdup value (which is indicated by the constraint of section 5.1.5). In details, the data sets that Turner's correlation can predict higher critical flowrate than Zhou's correlation stay in the first gas production rate group and percentage of them is small (1.38% of the entire data sets in this section).

5.1.5.2 Classified by liquid holdup

In this section, the data sets that have the value of liquid holdup in moderate-high to high range and gas production rate greater than 1.5 MMscf/d are categorized by liquid holdup. Four groups of liquid holdup classified by median and quartiles are set. Range of liquid holdup for the first group is 0.0300 to 0.0451. The ranges of liquid holdup at 0.0452 to 0.0713, 0.0714 to 0.0991 and 0.0992 to 0.2352 are set as second, third and fourth range respectively. Results of this section are shown in Figure 5.10.

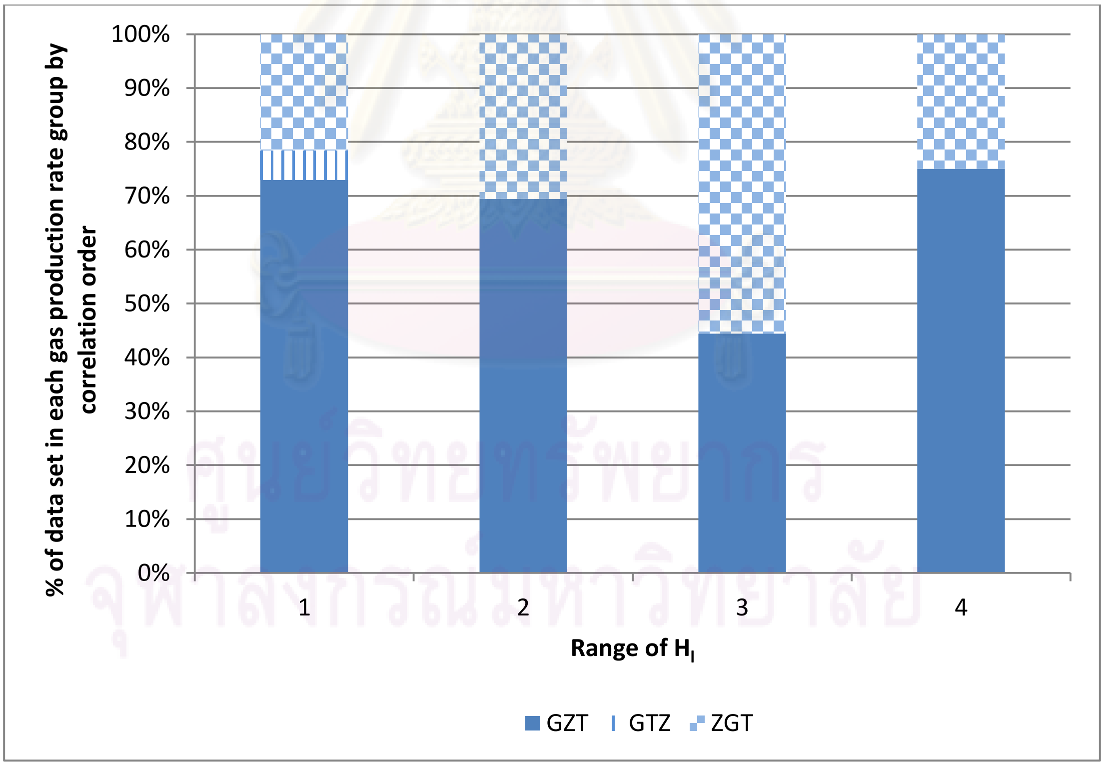


Figure 5.10: Details of critical flowrate data for moderate-high to high H_l range with high gas production rate (classified by liquid holdup)

High liquid holdup is the condition that favors Zhou’s correlation because number of data set that Zhou’s correlation predicts the highest critical flowrate is significant higher than the percentage of section 5.1.1 to 5.1.4. In details, the percentages of the data sets that Zhou’s correlation predicts the highest critical flowrate for section 5.1.1 to 5.1.5 are 2.78 %, 2.75%, 5.76%, 15.09% and 33.10% respectively. However, number of data set that Zhou’s correlation predicts the highest critical flowrate in highest liquid holdup group (0.0992 to 0.2352) is decreased. It can be described as liquid and gas production rate in this section is high. High gas production rate forces liquid production rate to have very high value in order to have high liquid holdup. This very high liquid production rate makes higher predicted critical flowrate from Guo’s correlation than Zhou’s correlation. Therefore, number of data that Guo’s correlation predicts highest critical flowrate is more than Zhou’s correlation in highest liquid holdup group (75% of the data sets in the highest liquid holdup value group). Turner’s correlation has no influences on this case because high liquid holdup and liquid production rate are not a favorable condition for Turner’s correlation.

In this section, influences of liquid holdup on critical flowrate are analyzed. Production data sets are classified into five production conditions in order to apply critical flowrate correlation to them. For each production condition, input data are classified and sorted in order to separate production conditions into small range by the concept of median and quartile because data distribution for input data are not a normal distribution. For each production condition, not only the analysis of predicted critical flowrates from each correlation, well status, which is predicted by critical flowrate and gas production rate, is also analyzed. Results and conclusions from this section are summarized as

1.) Guo’s correlation usually predicts the highest critical flowrate in every production condition. Guo’s correlation has a strong point on liquid production rate because it takes liquid production rate into critical flowrate calculation. For Guo’s correlation, liquid production rate has a direct relationship with predicted critical flowrate resulting in high number of data set that Guo’s correlation predicts the highest critical flowrate in high liquid production rate case.

Zhou’s correlation takes liquid holdup as a parameter in order to calculate critical flowrate. Therefore, for high liquid holdup value in each production condition, Zhou's correlation can predict the highest critical flowrate. However, high liquid holdup value usually has high liquid production rate which is a favorable condition for Guo's correlation in order to predict high critical flowrate. In many cases, Guo's correlation can predict higher critical flowrate than Zhou's correlation even though liquid holdup is high.

Turner's correlation is the correlation that has the least sensitive on variation in production condition because it does not take any production conditions into their calculation. Only the values of fluid properties are required for Turner's correlation. Therefore, variations in production conditions do not have any significant effects on Turner's correlation. Moreover, the amount of liquid production does not play any effects on Turner's correlation which means required gas production rate in order to unload the well that produce 1 bbl/d of liquid or 1,000 bbl/d of liquid is the same. This conclusion is not consistent with others as Kumar [11] mentioned in his study that the amount of liquid should play a role on critical flowrate. However, prediction of critical flowrate from Turner's correlation is the highest in low liquid holdup and gas production rate because of low value of production data makes a low predicted value by other correlations. Since production data act as an addition to Guo's and Zhou's correlation, low production data means less additional to those correlations and predicted values from those correlations are less than Turner's correlation.

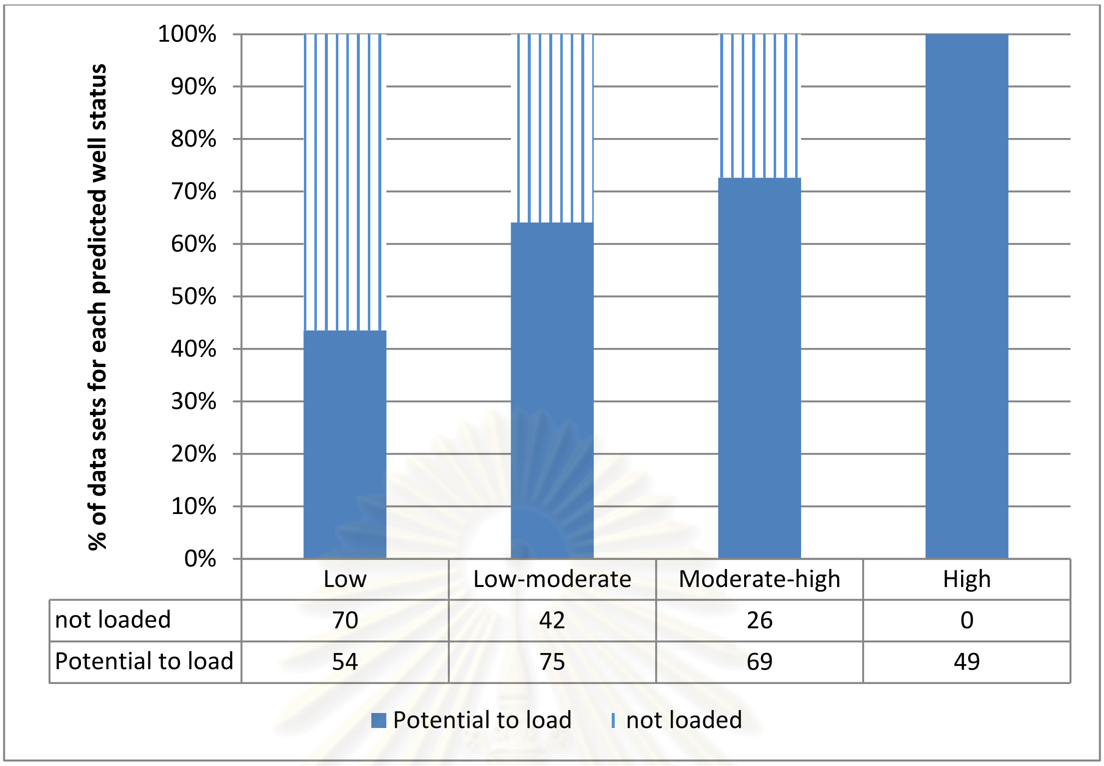
2.) Liquid production rate proves itself as an important parameter on predicted critical flowrate value form each correlation. In high liquid production rate condition, Guo's correlation is a recommended for conservative options because it usually predicts the highest critical flowrate. On the other hand, Turner's correlation is a better choice for quick estimation of critical flowrate because required parameters for Turner's are the lowest among selected correlations for this study. Moreover, simplicity of Turner's correlation suits quick estimation situation unlike a requirement of numerical iteration for Guo's correlation or additional calculation for liquid holdup for Zhou's correlation.

5.2) Well Status Analysis

One of the ultimate goals for liquid loading determination is prediction of well status. In this study, well status is determined by the comparison between gas production rate and predicted critical flowrate. However, there are several procedures to determine well status. For instance, liquid loading can be detected by the presence of liquid slug at surface which is indicated that flow regime in the well is no longer annular-mist flow regime resulting in predicted well status as loaded condition. Moreover, the actual well status data are not available for this study. Thus, well status in this study is defined as “potential to load” and “not loaded” statuses. When gas production rate is less than critical flowrate, the status of the well is indicated as “potential to load” condition and vice versa. In this section, the condition that provides a clear separation of potential to load and not loaded conditions is clarified. To achieve that objective, screened field data are used as the input data of this section. However, in order to consolidate the differences between each critical flowrate correlation, only screened field data which have the same predicted well status by all of selected correlations are classified as the input data of this section. Gas production rate is selected as primary screening criteria in order to clarify the clear separation of potential to load and not loaded conditions. Gas production rate at 1.5 MMscf/d, which is a median of entire gas production rate, is used as primary criteria. Variation in screening criteria can be applied in term of reducing gas production rate value or adding other screening criteria in the case that 1.5 MMscf/d gas production rate cannot provide clear conclusions.

5.2.1) Primary screening criteria

As mentioned earlier, gas production rate is an important parameter of well status prediction. Gas production rate at 1.5 MMscf/d, which is the median of the entire gas production rate data, is selected as the first criteria in order to determine the condition that provides a clear separation of well status prediction. The results in this section are presented in the percentage of potential to load and not loaded conditions for the data that have gas production rate less than 1.5 MMscf/d. Moreover, additional classification of the input data by liquid holdup is applied to investigate the influences of liquid holdup to predicted well status. The results of this section are shown in Figure 5.11.



	Low	Low-moderate	Moderate-high	High
not loaded	70	42	26	0
Potential to load	54	75	69	49

Figure 5.11: Predicted well status for gas production rate less than 1.5 MMscf/d

Considering Figure 5.11, Numbers of the potential to load and not loaded data sets for each liquid holdup range are showed at the bottom of the chart. The proportion of loaded data sets is increased with the increase in liquid holdup. In details, the percentages of potential to load data sets are 43.55 % for low liquid holdup range, 64.10 % for low-moderate liquid holdup range, 72.63% for moderate-high liquid holdup range and 100% for high liquid holdup range. Considering the data sets that have gas production rate less than 1.5 MMscf/d, a change in liquid holdup usually originated by a change in liquid production rate because the distribution of gas production rate for the data sets that have gas production rate less than 1.5 MMscf/d is small in comparison with liquid production rate. Therefore, an increase in liquid holdup usually originated by an increase in liquid production rate. As summarized in section 5.1, an increase in liquid production rate is the factor that generates the higher predicted critical flowrate. An increase in predicted critical flowrate makes the higher chance that well status is predicted as potential to load condition. Thus, the percentage of potential to load condition is increased with an increase in liquid holdup.

However, it cannot be concluded that gas well which has gas production rate less than 1.5 MMscf/d will suffer loaded condition because the percentages of not loaded condition data sets especially for low liquid holdup range are high. Therefore, modification of primary screening criteria is necessary in order to archive the condition that provides a clear separation of well status prediction. The details of modified criteria are analyzed and discussed in section 5.2.2.

5.2.2 Modification of primary screening criteria

As summarized in section 5.2.1, gas production rate less than 1.5 MMscf/d cannot provide a clear separation of well status prediction. Therefore, modification of primary screening criteria, which is gas production rate at 1.5MMscf/d, is performed. Modification of primary criteria is made by the reduction of gas production rate and addition of other parameters to primary criteria. Considering the additional parameters to primary constraint cases, several conditions can be concluded as the condition that provides a clear separation of predicted well status. Thus, gas production rate is set as a constant at 0.75 MMscf/d in order to minimize the uncertainties in the analysis. With the constant in gas production rate, only the variation in additional parameters is the factor that makes the clear conclusion for predicted well status. FTP, liquid production rate and liquid holdup are the parameters that selected to generate the modified criteria by addition of parameter to primary screening criteria.

5.2.2.1 Reduction of gas production rate

In this section, a reduction in gas production rate is selected procedure to modify the criteria. The reduction in gas production rate affects the predicted well status because it has a higher chance that predicted critical flowrate is higher than gas production rate resulting in potential to load condition. For this section, gas production rate is reduced until it reaches the value that every predicted well status is potential to load. However, numbers of the data sets that classified into each gas production rate value is reduced with a reduction in gas production rate. Thus, the numbers of data sets that classified into each gas production rate value are presented in Table 5.2. The percentages of potential to load and not loaded conditions at each reduced gas production rate are recorded. The results of this section are presented in Figure 5.12.

Table 5.2: Numbers of the data sets for each gas production rate value

Gas production rate (MMscf/d)	Number of data sets
≤ 0.48	143
≤ 0.5	155
≤ 0.75	221
≤ 1	259
≤ 1.25	318
≤ 1.5	385

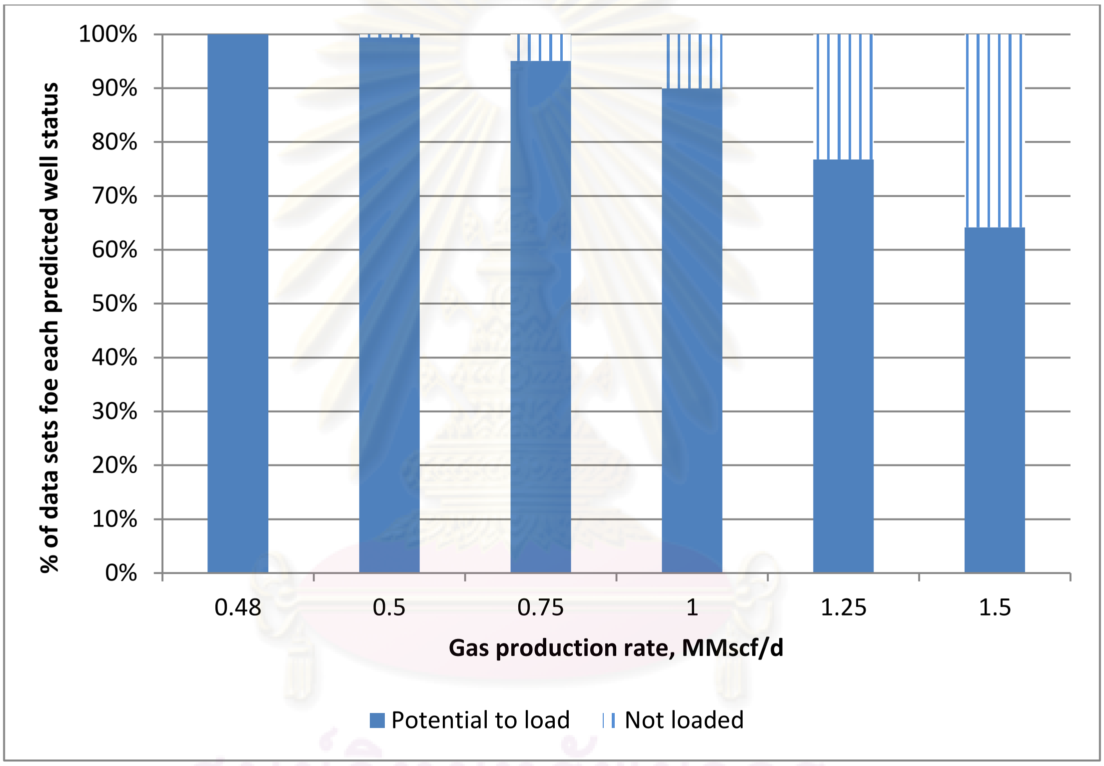


Figure 5.12: Predicted well status of reduction of gas production rate case

Considering Figure 5.12, percentages of not loaded condition are continuously decreased with decreasing in gas production rate. In details, percentages of not loaded condition for the data sets that have gas production rate less than 1.5 MMscf/d (in other words, primary criteria) is 35.84%. The percentages of not loaded condition for the data sets that have gas production rate less than 1.25, 1, 0.75 and 0.5 MMscf/d are 23.27%, 10.04%, 4.98% and 0.65% respectively. However, the reduction of gas production rate continues until it reaches the gas production rate that every predicted well status is potential to load at 0.48 MMscf/d. When the acceptable and primary constraints are compared, gas production rate has to be very low in order to achieve the condition that provides a clear separation of predicted well status. Thus, only gas production rate may not be an appropriate alternative for well status prediction because it eliminates a significant number of loaded data sets.

5.2.2.2 Addition of flowing tubing pressure

The second modified screening criteria is an addition of FTP as the secondary criteria. The influence of flowing tubing pressure plays a role on predicted critical flowrate in term of compressibility of gas. With the same driven energy from the reservoir, a higher FTP system will have less gas velocity because gas is heavier by an increase in FTP. Thus, a higher FTP system will require more critical flowrate in order to flow gas at the same critical velocity as lower FTP system. As mentioned earlier, gas production rate is set at less than 0.75 MMscf/d and only the variation in the value of flowing tubing pressure is the factor that provides the clear separation of predicted well status. Nevertheless, numbers of data sets that classified into each flowing tubing pressure value are reduced with an increase in flowing tubing pressure value. Thus, numbers of the data sets that classified into each flowing tubing pressure value are presented in Table 5.3. The results of this section are shown in Figure 5.13.

Table 5.3: Numbers of the data sets for each flowing tubing pressure value

Flowing tubing pressure (FTP), psia	Number of data sets
> 485	84
> 450	98
> 400	118
> 350	142
> 300	149
> 250	187
No FTP constraint	221

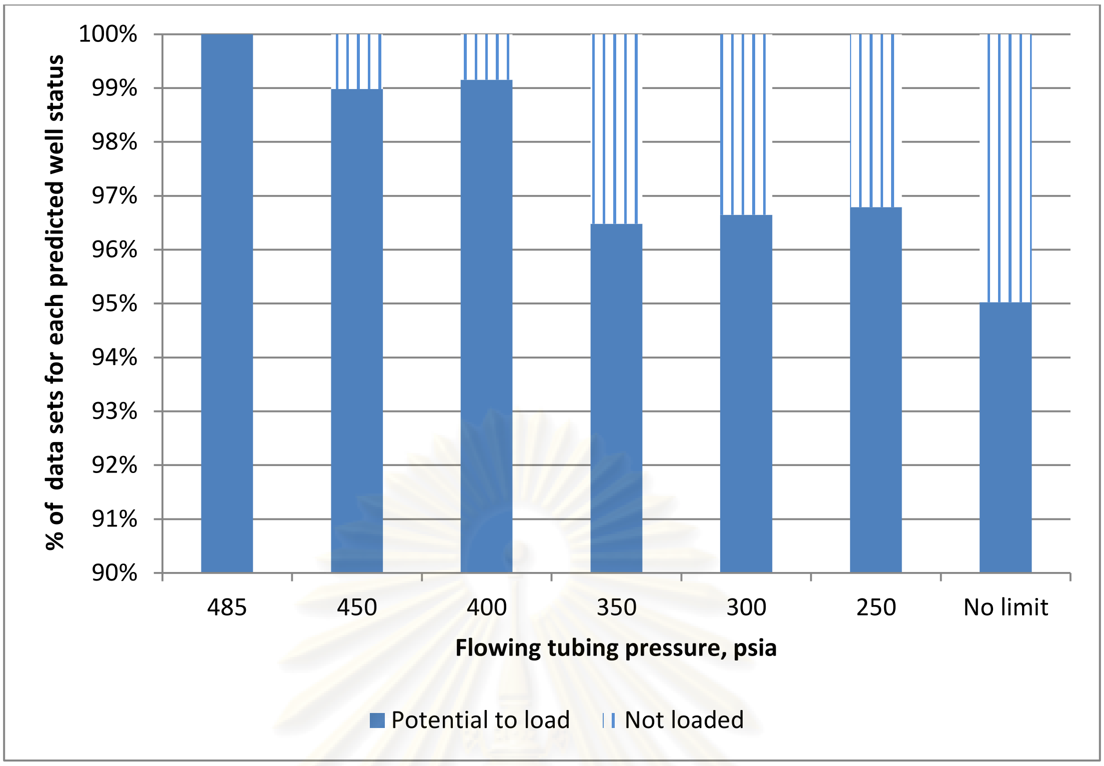


Figure 5.13: The comparison of well status between each FTP value case

Considering Figure 5.13, the “No limit” column represents that percentages of potential to load and not loaded data sets for every data set that has gas production rate less than 0.75 MMscf/d (in other words, the data sets in this column are not classified by FTP). The percentage of potential to load data sets is significantly increased when the data sets that have FTP less than 250 psia are eliminated. This conclusion is detected by a height of solid column of 250 psia column is higher than no limit column. However, percentages of potential to load data sets are slightly different for the cases of FTP values are 250, 300 and 350 psia as the results of only 1 not loaded data set different between those FTP values. Nevertheless, there is a significant difference in a percentage of potential to load data sets between 350 and 400 psia cases. Percentage of potential to load data sets is similar again when the data sets of 400 and 450 psia are compared. As discussed earlier, lower FTP system will have higher gas velocity if the same gas production rate systems are compared. Higher gas velocity creates a higher chance that gas velocity is higher than critical velocity resulting in not loaded condition. On the other hand, percentages of not loaded condition are decreasing with an increase in FTP. However, the condition that gives a clear separation of predicted well status is gas production rate less than 0.75 MMscf/d and FTP is higher than 485 psia while only gas production rate less than

0.75 MMscf/d cannot provide a clear separation. Thus, addition of FTP to gas production rate provides another alternative to evaluate the condition that clearly predicts well status.

5.2.2.3 Addition of liquid production rate

The third modified criteria is an addition of liquid production rate as the secondary criteria. Liquid production rate is proved as the most important parameter for the predicted values of critical flowrate correlation. In this case, same gas production rate as section 5.2.2.2, which is less than 0.75 MMscf/d, is set in order to minimize the deviation between the results of section 5.2.2.2 and this section. Similar to section 5.2.2.1, the data sets that classified into each liquid production rate value are decreasing with a decrease in liquid production rate. Thus, numbers of the data sets that classified into each flowing tubing pressure value are presented in Table 5.4. Same pattern of results is another similarity of section 5.2.2.2 and this section which is presented in Figure 5.14.

Table 5.4: Numbers of the data sets for each liquid production rate value

Liquid production rate, bbl/d	Number of data sets
< 3	7
< 50	92
< 100	137
< 200	177
< 300	192
< 500	204
No liquid production rate constraint	221

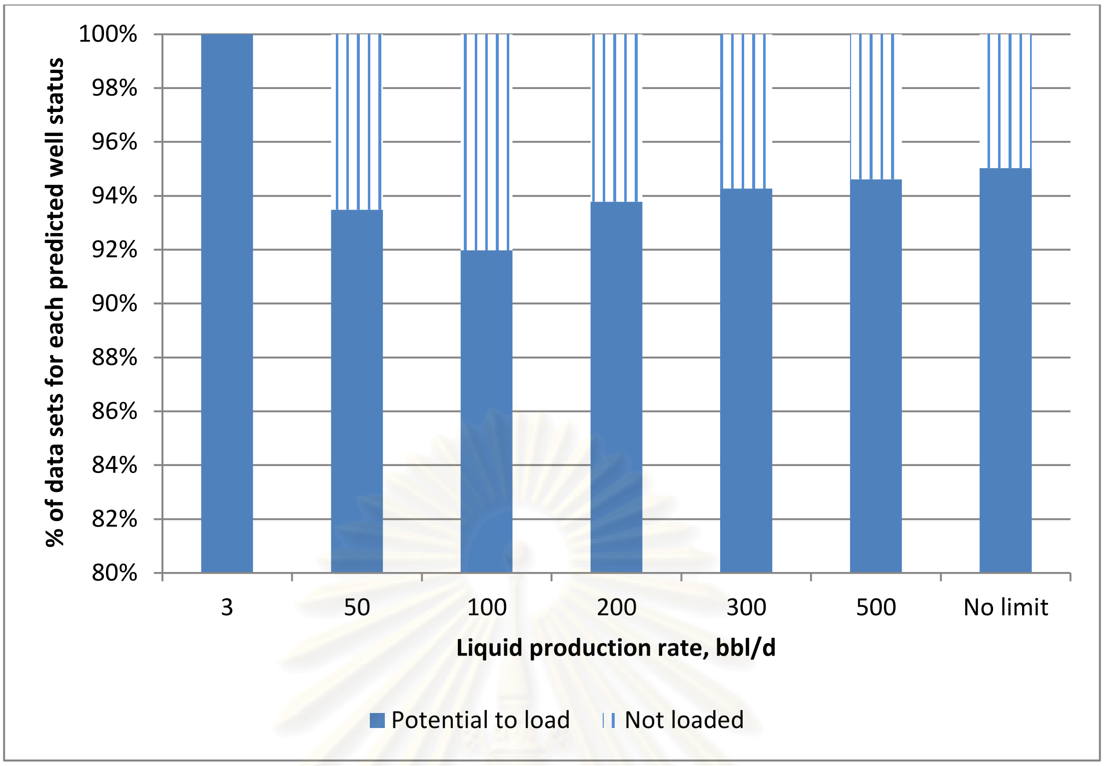


Figure 5.14: The comparison of well status between each liquid production rate case

Considering Figure 5.14, percentages of potential to load data sets are slightly decreased with a decrease in liquid production rate from no limit group to 100 bbl/d group because of an increase in eliminated data as the results of a modification of secondary criteria. As discussed in section 5.1, an increase in liquid production rate causes a higher critical flowrate. Thus, a reduction of liquid production rate makes a lower critical flowrate resulting in higher chance of not loaded well status. Nevertheless, percentage of potential to load data sets is increased when the data sets of liquid production rate less than 50 bbl/d and 100 bbl/d are compared. The variation of liquid production rate from 50 bbl/d to 100 bbl/d does not generate a significant difference in predicted critical flowrate. The proportion of not loaded to potential to load data sets having liquid production rate between 50 bbl/d to 100 bbl/d is higher than other eliminated data sets of modified secondary criteria. We further decrease liquid production rate to 3 bbl/d in order to get a clear separation of predicted well status. Together with 3 bbl/d liquid production rate, majority of the data are eliminated in order to reach 0% of not loaded condition resulting in only 7 data sets that classified into that group. In comparison with the results of section 5.2.2.2, which are presented in Figure 5.13, number of the data sets for the condition that provides a clear separation of predicted well status to the entire potential to load data sets is 84 data sets. Thus, determination of the condition that provides a clear separation of predicted well status by FTP is more appropriate than liquid production rate because the number of data sets that FTP can provide a clear separation of predicted well status is higher than liquid production rate.

5.2.2.4 Addition of liquid holdup

The fourth modified criteria is an addition of liquid holdup as the secondary criteria constraint. Liquid holdup is considered as an important parameter of this study. In this section, same gas production rate as section 5.2.2.2 and 5.2.2.3, which is less than 0.75 MMscf/d, is set in order to minimize the deviation between the results of section 5.2.2.2 5.2.2.3 and this section. Similar to section 5.2.2.1 to 5.2.2.3, there are several data sets eliminated when the values of liquid holdup are changed which is summarized in Table 5.5. Similar pattern of results is applied to this section which is presented in Figure 5.15.

Table 5.5: Numbers of the data sets for each liquid holdup value

Liquid holdup	Number of data sets
< 0.0005	2
< 0.01	55
< 0.03	121
< 0.05	136
< 0.1	178
< 0.2	209
No liquid holdup constraint	221

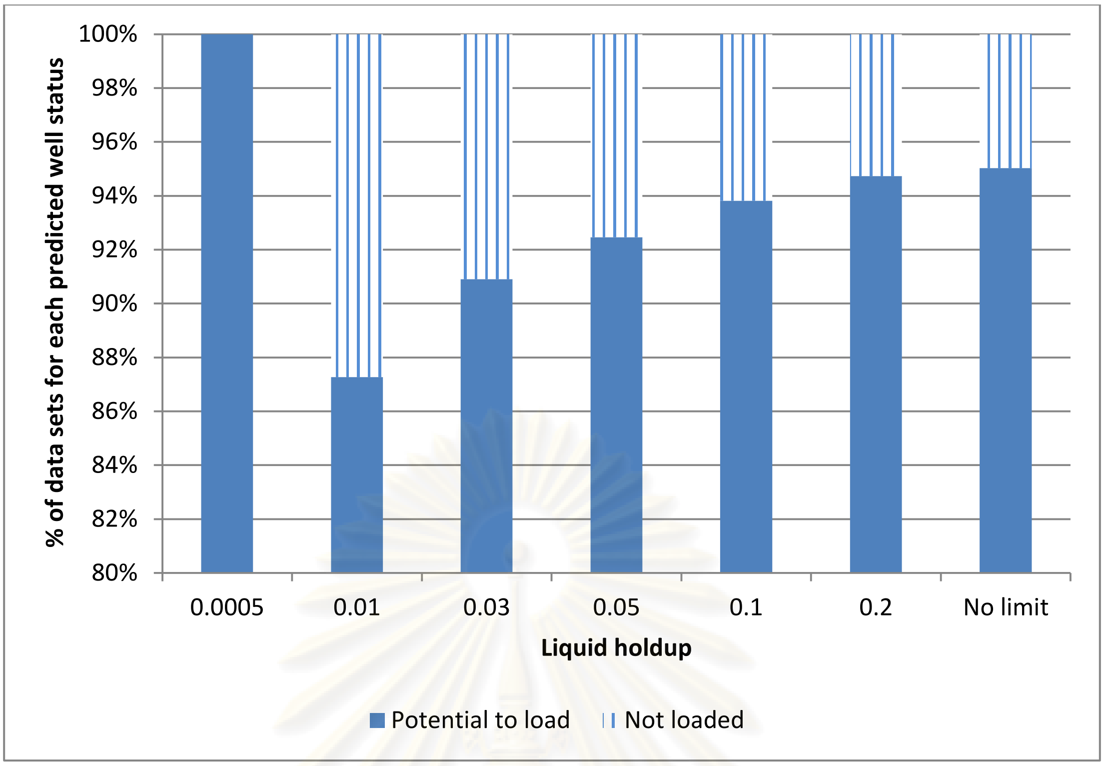


Figure 5.15: The comparison of well status between each liquid holdup case

Considering Figure 5.15, the percentages of potential to load data sets are decreasing with a decrease in liquid holdup value. Similar to section 5.2.2.3, the condition that provides a clear separation of predicted well status, which is liquid holdup at 0.0005, is the condition that has very low value. Since the condition that gives a clear separation of predicted well status has a very low liquid holdup value, only a small fraction of the entire data is classified into that condition. In details, there are only 2 data sets that have liquid holdup less than 0.0005. Similar to liquid production rate, it can be concluded that liquid holdup is not a proper parameter to determine the prediction of well status.

Determination of well status is one of the most important priorities for liquid loading study. Well status is determined by the comparison of gas production rate and predicted critical flowrate. The results of well status are potential to load and not loaded conditions. Definition of potential to load condition is that the predicted critical flowrate is higher than gas production rate and vice versa. The objective of this section is to find the conditions that provide a clear separation of potential to load and not loaded data sets. The results and conclusions of well status analysis are summarized as

Gas production rate is selected as a primary screening criteria in order to separate potential to load condition out of not loaded condition.. At the beginning, gas production rate at1.5 MMscf/d, which is the median of entire gas production rate data, is selected as a primary constraint. It provides a decent separation of potential to load and not loaded conditions because the majority of the data sets that have gas production rate greater than 1.5 MMscf/d are predicted as not loaded condition. However, it cannot provide a clear separation of loaded and not loaded data sets. Thus, modifications of this criteria are performed to determine the condition that provides a clear separation of predicted well status.

The modification of primary constraint is separated into two options which are the reduction of gas production rate and addition of other parameters as the secondary criteria. Considering the first option, gas production rate at 0.48 MMscf/d is the condition that gives a clear separation of predicted well status. In details, if gas production rate is less than 0.48 MMscf/d, predicted well status is potential to load for every data set. For the addition of other parameters cases, three parameters, which are FTP, liquid production rate and liquid holdup, are selected. Combinations of each additional parameter and gas production rate generate new criteria which is used to determine the condition that provides a clear separation of predicted well status. Considering addition of other parameters to primary screening criteria cases, gas production rate of them is 0.75 MMscf/d because gas production rate less than 0.75 MMscf/d cannot provide a clear separation of predicted well status. Together with gas production rate at 0.75 MMscf/d, all of additional parameters can provide a condition that gives a clear separation of predicted well status. However, the values of liquid production rate and liquid holdup that can predict a certain well status are very low. Therefore, liquid production rate and liquid holdup are not proper parameters for well status prediction.

Nevertheless, there are some significant notifications concluded by the production data that used in this study. Since the production data of this study is the actual data of the wells located in Gulf of Thailand, usual procedures that applied to the well play a role on production data. For instance, there is usually more than one producing layers which are drilled through for one producing well. Thus, additional perforations are performed when production from other perforated layers are declined. Therefore, well status is hardly stays in potential to load condition for long period as the results of additional gas flowrate from newly-perforated layer. Moreover, fluid properties data required in critical flowrate determination are hardly available in every production well. As mentioned in chapter IV that fluid properties show a strong function to predicted critical flowrate, applying only critical flowrate correlations in field practice is not an ideal solution to evaluate liquid loading problem.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

In this study, prediction of liquid loading has been investigated through liquid droplet model which was proposed by Turner. Critical flowrate is selected as a primary tool to predict liquid loading of this study. In order to calculate critical flowrate, three correlations which are Turner's correlation, Guo's correlation and Zhou's correlation are selected because each correlation has their own concepts of development. Another important parameter of this study is liquid holdup because it is usually mentioned in multiphase flow but hardly mentioned in liquid loading consideration. This study selects actual production data of the wells located in Gulf of Thailand to investigate the prediction of liquid loading. The results from this study can be summarized as follow:

1.) Gas specific gravity is the fluid properties that have the most influences on liquid loading consideration because it has the widest range of possible values. Moreover, gas specific gravity is the one that has the highest impact on predicted values of critical flowrate correlations.

2.) Guo's correlation is the one that usually predicts the highest critical flowrate in any production conditions. Predicted values of Turner's correlation is closed to Guo's correlation in low liquid production rate condition but the differences between predicted values of Turner's and Guo's correlation is increased with the increase in liquid production rate. On the other hand, the differences in predicted values of Zhou's and Guo's correlation are opposite to Turner's and Guo's correlation.

3.) Liquid production rate is proved as the most important parameters of critical flowrate because it affects each critical flowrate correlation in different manners. Moreover, variation in liquid production rate is the one that has the most influences on predicted critical flowrate.

4.) Gas production rate is the most important parameter of well status prediction. However, together with gas production rate, FTP can be used to provide the condition for well status prediction while liquid production rate and liquid holdup are not the proper parameters for well status prediction because it requires very low values of them to provide a condition that can be used to predict well status.

5.) For the gas production wells with producing some liquid located in Gulf of Thailand, they should have liquid loading problem if gas production rate is lower than 0.48 MMscf/d. If flowing tubing pressure is considered together with gas production rate, liquid loading problem should occur when gas production rate is lower than 0.75 MMscf/d and flowing tubing pressure is greater than 485 psia.

One advantage of this study is the calculation model generated using a simple spreadsheet program. The program can be developed into user-friendly interface that suits any users. Moreover, it can be integrated into other petroleum industry programs such as reservoir simulation program in order to help petroleum engineer make proper decisions on each production scenario. Moreover, results and conclusions of this study can provide a decent range of critical flowrate which petroleum engineers can observe an actual behavior of the well and make an adjustment in order to estimate a proper correlation for any particular wells.

Similar to several studies, this study can be used as a reference for future study on liquid loading. The recommendation for future study is to apply the different values of fluid properties because this study selects to apply a constant value of each fluid property for every production data set. As summarized in chapter IV, the values of fluid properties play a strong role on predicted critical flowrate. Moreover, values of fluid properties can be varied by depletion stages. Thus, applying another fluid properties value should provide validating results from this study.

References

[1] Turner, R.G., Hubbard, M.G. and Dukler, A.E.: Analysis and Prediction of Minimum Flow Rate for the Continuous Removal of Liquid from Gas Wells. SPE 2198 presented at SPE Gas Technology Symposium held in Omaha, NE, USA., September 1968.

[2] Solomon, F.A., Falcone, G. and Teodoriu, C.: Critical Review of Existing Solutions to Predict and Model Liquid Loading in Gas Well. SPE 115933 presented at SPE Annual Technical Conference and Exhibition held in Denver, CO, USA., September 2008.

[3] Ilobi, M. I. and Ikoku, C.U.: Minimum Gas Flow Rate for Continuous Liquid Removal in Gas Wells. SPE 10170 presented at the 56th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineer of AIME, held in San Antonio, TX, USA., October 1981.

[4] Lea, J.F., Nickens, H.V. and Wells, M.R.: Gas Well Deliquification. 2nd ed. Gulf Drilling Guide. MA, USA.: Elsevier Inc., 2008.

[5] Coleman, S.B., Clay, H.B., McCurdy, D.G. and Norris, H. L., III: A New Look at Predicting Gas-Well Load-Up. SPE 20280 presented at Journal of Petroleum Technology (March, 1991). 329-333.

[6] Nosseir, M.A., Darwich, T.A., Sayyouh, M.H. and El Sallaly, M.: A New Approach for Accurate Prediction of Loading in Gas Wells Under Different Flowing Conditions. SPE 66540 presented at SPE Production Operations Symposium held in Oklahoma City, OK, USA., March 1997.

[7] Allen, H.S.: Philos. Mag. (1900) **50**, 323.

[8] Poe, B.D. Jr.: Optimized Tubing String Design Modeling for Improved Recovery. presented at SPE Annual Technical Conference and Exhibition held in San Antonio, TX, USA., September 2006.

[9] Li, M., Li, S.L. and Sun, L.T.: New View on Continuous-Removal Liquids from Gas Wells. presented at SPE Permian Basin Oil and Gas Recovery Conference, Midland, TX, USA., May 2001.

[10] Guo, B., Ghalambor, A., and Xu, C.: A Systematic Approach to Predicting Liquid Loading in Gas Wells. presented at SPE Production and Operations Symposium held in Oklahoma City, OK, USA., April 2005.

[11] Kumar, N.: Improvements for Flow Correlations for Gas Wells Experiencing Liquid Loading. presented at SPE Western Regional Meeting held in Irvine, CA, USA., April 2005.

[12] Zhou, D. and Yuan, H.: New Model for Gas Well Loading Prediction. presented at SPE Production and Operations Symposium held in Oklahoma City, OK, USA., April 2009.

[13] Sutton, R.P., Cox, S.A., Lea, J.F., Rowlan, O.L.: Guidelines for the Proper Application of Critical Velocity Calculations. presented at SPE Production and Operations Symposium held in Oklahoma City, OK, USA., April 2009.

[14] Beggs, H.D.: Production Optimization Using NODAL^{TM} Analysis. Tulsa: OGCI Publications Oil & Gas Consultants International Inc., 1991.

[15] McCain, W.D. Jr.: The Properties of Petroleum Fluids. 2nd ed. Tulsa: PennWell Publishing Company, 1990.

[16] El-Banbi, A.H., Fattah, K.A. and Sayyouh, M.H: New Modified Black-Oil Correlations for Gas Condensate and Volatile Oil Fluids. presented at SPE Annual Technical Conference and Exhibition held in San Antonio, TX, USA., September 2006.

[17] Standing, M.B.: A Pressure-Volume-Temperature Correlation for Mixture of California Oils and Gases., Drilling and Production Practice, API, 1957, pp. 275-287.

[18] Rowe, A.M. Jr. and Chou, J.C.S.: Pressure-Volume-Temperature-Concentration Relation of Aqueous NaCl Solutions. presented at Journal of Chemical Engineering (1970) **15**, 61

[19] Sutton, R.P.: An Improved Model for Water-Hydrocarbon Surface Tension at Reservoir Conditions. presented at SPE Annual Technical Conference and Exhibition held in New Orleans, LA, USA., October 2009.

Appendices

Appendix A

Production data and critical flowrate of each production well

Well A-1

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-1, 1	593	0.95	0	75	92	0.0170	1.587	1.690	1.517
A-1, 2	464	0.50	0	14	96	0.0048	1.402	1.452	1.169
A-1, 3	1644	3.99	113	11	115	0.0206	2.543	2.713	2.724
A-1, 4	1615	3.85	91	15	116	0.0179	2.520	2.679	2.629
A-1, 5	1628	3.65	81	12	131	0.0167	2.499	2.646	2.573
A-1, 6	1253	4.80	76	13	162	0.0094	2.153	2.268	1.794
A-1, 7	1129	5.79	81	2	156	0.0067	2.058	2.163	1.715
A-1, 8	1326	3.46	54	0	123	0.0085	1.462	1.553	1.218
A-1, 9	1230	3.17	56	1	120	0.0091	2.207	2.313	1.839
A-1, 10	1161	2.70	45	0	114	0.0080	1.384	1.463	1.153
A-1, 11	1138	2.44	45	1	110	0.0088	2.144	2.241	1.787
A-1, 13	962	2.36	8	0	117	0.0014	1.263	1.311	1.052
A-1, 14	942	2.33	25	0	118	0.0042	1.249	1.305	1.041
A-1, 15	910	2.27	17	0	121	0.0028	1.226	1.275	1.021
A-1, 17	739	3.34	32	0	155	0.0029	1.079	1.125	0.899
A-1, 20	760	2.32	5	11	131	0.0020	1.733	1.791	1.444

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-1, 21	682	2.18	4	29	125	0.0039	1.652	1.720	1.377
A-1, 23	695	1.78	1	14	110	0.0022	1.689	1.747	1.407
A-1, 32	293	0.06	76	0	85	0.1339	0.728	0.792	0.881
A-1, 34	294	0.41	21	26	107	0.0130	1.109	1.176	0.995
A-1, 39	273	0.71	89	19	104	0.0167	1.072	1.176	0.979
A-1, 45	271	0.12	0	101	82	0.0779	1.089	1.208	1.119
A-1, 56	415	0.18	0	14	88	0.0118	1.337	1.386	1.207
A-1, 62	275	0.42	35	12	81	0.0123	1.098	1.166	0.980
A-1, 67	276	0.13	0	38	100	0.0290	1.081	1.146	1.032
A-1, 71	277	0.11	0	37	100	0.0333	1.083	1.147	1.045
A-1, 76	275	0.12	3	0	86	0.0029	0.705	0.724	0.588
A-1, 81	287	0.30	0	31	91	0.0109	1.111	1.172	0.983
A-1, 85	266	0.25	5	39	86	0.0173	1.075	1.146	0.985
A-1, 89	212	0.26	18	59	84	0.0234	0.962	1.060	0.892
A-1, 94	209	0.02	2	20	82	0.0793	0.957	1.011	0.962
A-1, 95	209	0.10	0	13	84	0.0100	0.956	1.001	0.796
A-1, 96	377	0.30	0	8	84	0.0037	1.280	1.323	1.066
A-1, 98	208	0.23	0	30	83	0.0099	0.954	1.015	0.795
A-1, 99	216	0.13	10	10	84	0.0129	0.971	1.021	0.864

Well A-2

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-2, 1	500	0.11	10	0	90	0.0186	0.942	0.977	0.962
A-2, 2	652	1.26	0	247	93	0.0452	1.661	1.910	1.781
A-2, 3	396	0.54	115	418	112	0.1294	1.279	1.696	1.415
A-2, 4	380	0.54	116	363	109	0.1139	1.256	1.641	1.371
A-2, 5	290	0.31	38	93	86	0.0449	1.122	1.271	1.113
A-2, 6	280	0.31	0	32	87	0.0106	1.102	1.171	0.972
A-2, 7	1673	3.63	71	168	83	0.0406	2.634	2.922	3.179
A-2, 8	876	2.39	108	178	110	0.0391	1.890	2.148	2.056
A-2, 9	1705	3.47	179	91	81	0.0505	2.662	2.955	3.335
A-2, 10	1066	5.11	207	169	150	0.0301	2.011	2.301	2.151
A-2, 11	1022	3.69	300	31	136	0.0364	1.993	2.244	2.179
A-2, 12	1037	1.92	35	106	96	0.0283	2.075	2.254	2.217
A-2, 15	271	0.59	0	8	93	0.0014	1.078	1.124	0.898
A-2, 19	489	0.90	76	3	87	0.0175	1.451	1.550	1.374
A-2, 22	403	0.47	39	0	89	0.0137	0.849	0.898	0.815
A-2, 24	437	0.37	182	0	104	0.0822	0.872	1.005	1.061
A-2, 25	428	0.12	11	13	97	0.0324	1.346	1.408	1.340
A-2, 36	275	0.37	0	13	80	0.0036	1.099	1.151	0.916
A-2, 43	1209	1.53	73	296	96	0.0996	2.234	2.573	2.868
A-2, 44	727	0.94	51	283	104	0.0888	1.735	2.034	2.019
A-2, 45	374	1.17	128	392	126	0.0597	1.229	1.629	1.267
A-2, 46	377	0.92	65	290	117	0.0469	1.179	1.482	1.180
A-2, 53	277	0.25	61	0	91	0.0274	0.705	0.764	0.716

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-2,54	278	0.25	150	10	95	0.0686	1.090	1.240	1.110
A-2, 55	277	0.03	37	13	103	0.1574	1.080	1.156	1.164
A-2, 58	204	0.34	74	85	116	0.0360	0.918	1.081	0.871

Well A-3

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-3, 1	730	1.22	47	0	100	0.0116	1.122	1.185	1.091
A-3, 2	638	2.17	124	0	115	0.0150	1.038	1.137	1.043
A-3, 3	543	2.23	99	0	123	0.0099	0.954	1.035	0.795
A-3, 4	577	2.16	110	0	110	0.0121	0.993	1.083	0.955
A-3, 5	610	1.67	20	21	117	0.0058	1.575	1.648	1.312
A-3, 6	598	1.98	35	38	114	0.0086	1.564	1.658	1.303
A-3, 7	283	0.74	16	19	100	0.0052	1.095	1.157	0.912
A-3, 8	608	1.19	22	8	102	0.0062	1.593	1.659	1.327
A-3, 9	305	1.16	55	7	105	0.0067	1.131	1.208	0.943
A-3, 10	573	1.23	21	10	104	0.0058	1.544	1.610	1.287
A-3, 11	575	1.16	12	5	104	0.0034	1.547	1.603	1.289
A-3, 12	582	1.10	5	2	107	0.0015	1.552	1.601	1.294
A-3, 13	583	1.19	16	10	107	0.0051	1.554	1.616	1.295
A-3, 15	582	0.92	102	8	102	0.0280	1.559	1.672	1.568
A-3, 16	557	1.00	7	5	106	0.0026	1.521	1.572	1.267

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-3, 22	2003	3.46	196	39	119	0.0527	2.779	3.034	3.566
A-3, 23	1680	3.15	145	42	134	0.0389	2.530	2.735	2.993
A-3, 24	1532	3.40	134	60	137	0.0340	2.417	2.617	2.761
A-3, 25	1376	3.32	154	77	129	0.0370	2.311	2.527	2.638
A-3, 26	645	0.76	14	12	88	0.0086	1.660	1.728	1.383
A-3, 27	1790	4.88	374	35	95	0.0583	2.690	3.021	3.459
A-3, 28	941	6.35	376	365	180	0.0414	1.850	2.279	2.016
A-3, 29	821	5.45	304	291	182	0.0341	1.728	2.092	1.813
A-3, 30	738	3.80	269	232	179	0.0370	1.644	1.963	1.722
A-3, 31	333	0.80	144	362	127	0.0747	1.159	1.523	1.203
A-3, 32	311	0.09	57	0	85	0.0758	0.750	0.805	0.864
A-3, 44	273	0.15	0	18	117	0.0120	1.060	1.108	0.982
A-3, 49	244	0.16	30	0	121	0.0187	0.645	0.678	0.620
A-3, 50	290	0.30	132	17	90	0.0559	1.118	1.254	1.127
A-3, 51	2170	4.03	297	357	54	0.0892	3.045	3.469	4.417
A-3, 52	1239	2.16	43	326	133	0.0737	2.191	2.500	2.692
A-3, 53	775	3.42	114	466	169	0.0475	1.697	2.084	1.839
A-3, 54	686	2.67	162	485	169	0.0596	1.599	2.015	1.748
A-3, 56	402	0.26	8	0	92	0.0051	0.846	0.872	0.705
A-3, 57	319	0.05	7	0	102	0.0183	0.748	0.771	0.732
A-3, 58	265	0.81	135	98	106	0.0294	1.054	1.252	1.044
A-3,64	209	0.27	4	0	88	0.0013	0.615	0.633	0.512
A-3, 65	316	0.27	230	21	97	0.1081	1.159	1.355	1.236
A-3, 82	205	0.36	3	128	83	0.0270	0.947	1.098	0.885
A-3, 84	203	0.25	12	28	83	0.0123	0.943	1.013	0.834

Well A-4

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
A-4, 2	2354	4.14	277	102	80	0.0801	3.089	3.451	4.441
A-4, 3	2337	4.08	235	120	80	0.0754	3.079	3.433	4.377
A-4, 4	2166	3.51	148	105	88	0.0584	2.995	3.245	3.955
A-4, 5	924	8.52	241	126	186	0.0157	1.825	2.056	1.761
A-4, 6	1517	5.26	53	154	112	0.0223	2.454	2.674	2.639
A-4, 7	1068	5.03	123	89	161	0.0176	1.996	2.167	1.982
A-4, 8	671	3.30	176	62	173	0.0192	1.577	1.741	1.526
A-4, 9	679	2.56	160	56	159	0.0227	1.604	1.760	1.585
A-4, 10	557	2.38	192	52	161	0.0227	1.453	1.619	1.414

Well A-5

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
A-5, 1	1575	7.15	319	48	156	0.0321	1.606	1.800	1.818
A-5, 2	1975	7.89	124	18	99	0.0574	1.868	2.013	2.439
A-5, 3	665	8.30	182	33	191	0.0070	1.031	1.146	0.859
A-5, 4	1425	4.17	152	30	150	0.0248	1.538	1.664	1.656
A-5, 5	1625	1.83	99	18	117	0.0408	1.681	1.795	2.001
A-5, 6	1515	2.55	75	26	132	0.0237	1.606	1.707	1.737
A-5, 7	1215	4.15	108	32	159	0.0164	1.415	1.517	1.408

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-5, 8	475	4.49	51	30	192	0.0034	0.873	0.931	0.727
A-5, 9	535	2.77	48	32	174	0.0061	0.938	0.999	0.782
A-5, 10	365	0.57	37	30	123	0.0167	0.810	0.868	0.749
A-5, 11	1745	3.33	206	19	114	0.0464	1.742	1.904	2.141
A-5, 12	1665	2.63	180	18	129	0.0492	1.684	1.827	2.062
A-5, 13	1415	2.42	138	17	126	0.0360	1.563	1.682	1.785
A-5, 14	1135	4.79	159	26	150	0.0177	1.380	1.498	1.381
A-5, 15	1335	3.73	144	24	123	0.0241	1.524	1.647	1.660
A-5, 16	675	6.52	173	3	192	0.0075	1.038	1.134	0.865
A-5, 17	945	5.19	144	36	156	0.0132	1.257	1.369	1.190
A-5, 18	1245	1.89	85	0	129	0.0230	0.940	1.011	1.106
A-5, 19	895	3.61	60	0	162	0.0062	0.783	0.829	0.653
A-5, 20	515	5.15	85	7	183	0.0038	0.915	0.976	0.762
A-5, 21	475	4.92	77	8	183	0.0034	0.879	0.937	0.732
A-5, 22	615	4.20	75	14	180	0.0053	1.000	1.062	0.834
A-5, 23	595	4.16	72	0	179	0.0043	0.635	0.678	0.529
A-5, 24	855	2.06	77	17	144	0.0157	1.209	1.282	1.165
A-5, 25	515	3.04	91	13	171	0.0072	0.923	0.992	0.769
A-5, 26	855	0.35	31	8	114	0.0373	1.239	1.290	1.336
A-5, 27	415	2.32	82	36	174	0.0084	0.828	0.906	0.690
A-5, 28	435	2.07	96	30	173	0.0106	0.848	0.929	0.755
A-5, 29	465	2.00	89	28	168	0.0109	0.880	0.957	0.787
A-5, 30	435	1.48	65	66	168	0.0149	0.852	0.939	0.783
A-5, 31	815	1.09	70	0	124	0.0213	0.772	0.824	0.845
A-5, 32	385	0.46	38	113	141	0.0460	0.819	0.927	0.828

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-5, 33	395	0.61	46	151	160	0.0464	0.817	0.947	0.825
A-5, 34	485	0.50	43	103	153	0.0516	0.909	1.011	0.946
A-5, 35	415	0.49	41	0	144	0.0143	0.547	0.576	0.526
A-5, 36	455	0.45	35	108	136	0.0523	0.893	0.997	0.927
A-5, 37	415	0.45	40	52	150	0.0321	0.844	0.915	0.831
A-5, 38	465	0.42	29	0	133	0.0132	0.584	0.609	0.559
A-5, 39	795	1.32	194	564	158	0.1485	1.154	1.426	1.412
A-5, 40	1445	3.31	357	0	120	0.0610	1.015	1.150	1.483
A-5, 41	435	3.97	0	594	192	0.0235	0.836	1.073	0.800
A-5, 42	435	3.65	0	735	192	0.0314	0.836	1.117	0.820
A-5, 43	365	2.62	0	547	195	0.0274	0.765	0.989	0.733

Well A-6

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
A-6, 1	2235	3.24	200	8	78	0.0562	2.012	2.203	2.704
A-6, 2	445	6.24	152	24	183	0.0051	0.851	0.951	0.709
A-6, 3	435	5.15	160	4	183	0.0057	0.842	0.934	0.701
A-6, 4	1065	4.35	174	34	141	0.0204	1.348	1.476	1.370
A-6, 5	1965	0.64	106	21	99	0.1375	1.864	2.003	2.757
A-6, 6	685	4.52	157	35	151	0.0117	1.079	1.193	0.990
A-6, 7	685	4.49	152	35	160	0.0115	1.071	1.181	0.979

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
A-6, 8	1695	2.27	111	24	123	0.0395	1.706	1.830	2.032
A-6, 9	955	4.16	160	36	150	0.0180	1.269	1.389	1.256
A-6, 10	1565	2.50	99	14	135	0.0282	1.627	1.733	1.814
A-6, 11	1885	1.58	66	21	114	0.0404	1.806	1.921	2.201
A-6, 12	495	4.59	106	29	186	0.0059	0.895	0.978	0.746
A-6, 13	1475	2.41	81	0	138	0.0202	1.010	1.086	1.184
A-6, 14	1435	2.41	81	21	111	0.0241	1.593	1.695	1.723
A-6, 15	575	4.60	85	25	183	0.0056	0.966	1.038	0.805
A-6, 16	1545	1.15	67	15	105	0.0430	1.657	1.757	1.980
A-6, 17	435	4.17	76	25	188	0.0043	0.838	0.905	0.699
A-6, 18	555	3.98	79	27	174	0.0059	0.956	1.027	0.796
A-6, 19	555	3.87	86	31	162	0.0067	0.965	1.043	0.804
A-6, 20	545	3.40	67	29	180	0.0062	0.943	1.009	0.786
A-6, 21	555	3.75	108	48	174	0.0092	0.956	1.051	0.796
A-6, 22	555	3.89	56	88	174	0.0080	0.956	1.051	0.796
A-6, 23	555	3.79	37	75	177	0.0063	0.953	1.033	0.794
A-6, 24	545	3.76	39	19	174	0.0034	0.947	0.996	0.789
A-6, 25	555	3.66	59	29	177	0.0053	0.953	1.017	0.794
A-6, 26	1205	1.99	66	24	125	0.0216	1.449	1.535	1.507
A-6, 27	535	3.59	56	30	160	0.0051	0.949	1.013	0.791
A-6, 28	535	3.56	65	32	156	0.0058	0.952	1.022	0.793
A-6, 29	515	2.76	53	30	173	0.0062	0.922	0.983	0.768
A-6, 30	1115	1.71	70	2	126	0.0191	1.394	1.467	1.415
A-6, 31	905	2.16	54	0	150	0.0093	0.795	0.840	0.662
A-6, 32	1055	1.63	79	0	129	0.0209	0.870	0.932	0.979

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
A-6, 33	455	2.43	42	24	174	0.0049	0.867	0.919	0.722
A-6, 34	445	2.39	40	9	171	0.0037	0.859	0.902	0.716
A-6, 35	455	2.41	42	21	174	0.0047	0.867	0.917	0.722
A-6, 36	865	0.68	37	23	150	0.0295	1.210	1.269	1.262
A-6, 37	415	2.08	37	21	174	0.0046	0.828	0.876	0.690
A-6, 38	415	1.78	48	30	171	0.0072	0.830	0.889	0.692
A-6, 39	475	1.67	42	30	144	0.0081	0.906	0.966	0.755
A-6, 40	455	1.18	47	28	159	0.0114	0.877	0.935	0.788
A-6, 41	675	0.56	39	0	126	0.0192	0.704	0.739	0.740
A-6, 42	455	0.64	32	27	150	0.0163	0.883	0.935	0.822
A-6, 43	415	0.62	36	30	141	0.0172	0.850	0.907	0.792
A-6, 44	415	0.62	36	28	153	0.0167	0.842	0.896	0.782
A-6, 45	415	0.60	37	26	156	0.0170	0.840	0.893	0.781
A-6, 46	435	0.52	35	12	138	0.0157	0.872	0.917	0.808
A-6, 47	455	0.45	35	25	144	0.0235	0.887	0.940	0.856
A-6, 48	515	0.59	40	24	135	0.0218	0.950	1.006	0.919
A-6, 49	485	0.74	41	0	138	0.0111	0.593	0.624	0.555
A-6, 50	465	0.58	32	0	132	0.0106	0.584	0.611	0.541
A-6, 51	575	5.76	274	11	189	0.0117	0.961	1.102	0.872
A-6, 52	555	5.62	269	0	188	0.0109	0.609	0.725	0.571
A-6, 53	535	5.18	266	0	193	0.0113	0.596	0.710	0.560
A-6, 54	535	5.61	270	0	192	0.0106	0.597	0.712	0.555
A-6, 55	480	4.20	169	0	188	0.0080	0.567	0.647	0.473
A-6, 56	495	4.20	127	0	188	0.0062	0.576	0.640	0.480
A-6, 57	435	1.48	36	84	160	0.0134	0.857	0.944	0.780

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
A-6, 58	385	0.96	100	104	147	0.0311	0.815	0.945	0.796
A-6, 59	375	1.11	89	0	156	0.0124	0.515	0.565	0.482
A-6, 60	385	0.60	64	0	144	0.0168	0.527	0.567	0.515
A-6, 61	385	0.61	73	0	144	0.0188	0.527	0.571	0.523
A-6, 62	385	0.61	71	0	150	0.0183	0.525	0.567	0.518
A-6, 63	385	0.45	49	0	144	0.0172	0.527	0.560	0.517
A-6,64	375	0.46	5	0	141	0.0017	0.522	0.533	0.435
A-6, 65	395	0.61	17	0	138	0.0046	0.536	0.555	0.447
A-6, 66	355	0.29	10	0	90	0.0051	0.530	0.546	0.442
A-6, 68	365	0.23	8	0	102	0.0053	0.532	0.547	0.443

Well B-1

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-1, 1	1465	2.42	160	16	85	0.0421	1.644	1.816	1.952
B-1, 2	2015	2.44	159	19	90	0.0571	1.900	2.095	2.495
B-1, 3	865	1.94	146	23	130	0.0300	1.229	1.367	1.289
B-1, 4	785	2.23	224	136	140	0.0481	1.163	1.407	1.271
B-1, 5	715	2.33	226	104	135	0.0391	1.116	1.343	1.181
B-1, 6	715	2.15	205	257	145	0.0566	1.107	1.410	1.216
B-1, 7	710	0.90	89	464	140	0.1415	1.108	1.476	1.332
B-1, 8	635	0.31	18	228	100	0.1584	1.085	1.301	1.309

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-1, 9	665	0.56	136	504	123	0.2241	1.088	1.504	1.356
B-1, 10	715	1.19	48	920	185	0.1781	1.073	1.608	1.304
B-1, 11	735	0.80	13	606	156	0.1743	1.112	1.515	1.365
B-1, 12	755	0.63	30	488	155	0.1880	1.128	1.479	1.401
B-1, 13	755	0.65	67	376	153	0.1626	1.129	1.437	1.385
B-1, 14	695	0.54	48	489	145	0.2056	1.092	1.456	1.352
B-1, 15	715	0.50	99	183	155	0.1349	1.098	1.308	1.311
B-1, 16	695	0.49	41	518	150	0.2285	1.087	1.461	1.358
B-1, 17	715	0.47	46	463	145	0.2223	1.099	1.449	1.375
B-1, 19	695	1.14	53	728	165	0.1509	1.074	1.544	1.287
B-1, 20	655	0.74	33	576	170	0.1673	1.040	1.431	1.244
B-1, 21	655	0.43	38	408	150	0.2027	1.056	1.372	1.292
B-1, 25	675	0.42	33	425	150	0.2157	1.072	1.394	1.325
B-1, 26	685	0.43	38	408	150	0.2100	1.080	1.395	1.335
B-1, 32	665	0.29	7	72	145	0.0635	1.068	1.159	1.176
B-1, 34	715	0.31	8	240	132	0.1753	1.119	1.328	1.377
B-1, 37	785	0.23	8	96	112	0.1171	1.191	1.308	1.439
B-1, 39	1335	7.38	251	16	127	0.0196	1.519	1.656	1.573
B-1, 40	1335	7.34	195	10	143	0.0152	1.499	1.612	1.489
B-1, 41	1085	8.26	210	8	155	0.0117	1.345	1.452	1.263
B-1, 42	295	0.88	8	208	115	0.0262	0.734	0.868	0.697
B-1, 43	265	0.76	12	456	127	0.0571	0.689	0.941	0.687
B-1, 44	915	4.21	133	0	102	0.0119	0.831	0.904	0.826
B-1, 45	1195	5.14	115	0	130	0.0110	0.922	0.992	0.918
B-1, 47	715	2.76	69	2	135	0.0076	1.116	1.165	0.930

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-1, 48	655	1.18	39	0	106	0.0089	0.705	0.736	0.588
B-1, 49	295	2.75	32	0	130	0.0014	0.468	0.488	0.390
B-1, 50	815	3.89	97	12	130	0.0093	1.194	1.262	0.995
B-1, 51	295	0.99	36	48	115	0.0097	0.734	0.793	0.612
B-1, 52	225	0.15	16	0	112	0.0099	0.415	0.429	0.346
B-1, 53	245	0.24	7	131	105	0.0499	0.675	0.772	0.665
B-1, 54	255	0.44	0	88	115	0.0185	0.683	0.750	0.626
B-1, 55	255	0.46	4	81	107	0.0172	0.688	0.753	0.628
B-1, 56	255	0.41	6	102	107	0.0244	0.688	0.767	0.644
B-1, 57	265	0.27	11	140	110	0.0525	0.699	0.801	0.694
B-1, 58	225	0.40	0	144	107	0.0291	0.646	0.748	0.609
B-1, 59	225	0.53	4	141	110	0.0224	0.645	0.746	0.596
B-1, 60	245	0.21	0	184	107	0.0736	0.674	0.796	0.681
B-1, 61	245	0.29	22	162	110	0.0552	0.672	0.791	0.666
B-1, 62	275	0.67	2	218	125	0.0324	0.703	0.839	0.675
B-1, 63	245	0.46	311	0	118	0.0646	0.431	0.555	0.470
B-1, 64	255	1.17	0	456	120	0.0355	0.680	0.931	0.654
B-1, 65	635	1.86	48	16	110	0.0088	1.075	1.125	0.896
B-1, 67	265	1.43	14	164	115	0.0122	0.696	0.811	0.619
B-1, 68	375	0.59	12	135	115	0.0338	0.827	0.922	0.815
B-1, 69	325	1.10	3	197	130	0.0214	0.760	0.883	0.713
B-1, 70	265	1.31	6	306	135	0.0229	0.684	0.863	0.638
B-1, 71	580	0.36	16	102	115	0.0668	1.024	1.105	1.122
B-1, 72	575	0.46	58	102	115	0.0718	1.020	1.117	1.123
B-1, 73	595	0.36	32	48	110	0.0489	1.042	1.101	1.111

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-1, 74	595	0.37	21	40	100	0.0365	1.051	1.102	1.090
B-1, 75	455	1.56	12	594	145	0.0616	0.887	1.175	0.932
B-1, 76	445	0.97	4	683	150	0.1046	0.874	1.190	0.956
B-1, 77	395	0.48	0	588	147	0.1519	0.826	1.110	0.918
B-1, 78	385	0.73	0	654	152	0.1132	0.812	1.120	0.879
B-1, 79	385	0.72	0	678	155	0.1183	0.810	1.126	0.879
B-1, 81	795	0.83	0	552	120	0.1637	1.190	1.461	1.486
B-1, 86	595	1.18	12	1272	160	0.1935	1.000	1.483	1.196

Well B-2

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-2, 1	1635	8.61	223	48	115	0.0206	1.688	1.878	1.806
B-2, 2	1115	8.42	374	60	174	0.0238	1.366	1.585	1.422
B-2, 3	755	5.60	200	80	180	0.0150	1.106	1.266	1.048
B-2, 4	695	4.89	229	86	190	0.0178	1.054	1.227	1.012
B-2, 5	685	4.38	177	96	168	0.0168	1.064	1.227	1.017
B-2, 6	715	4.43	149	96	176	0.0155	1.080	1.229	1.024
B-2, 7	665	4.38	172	80	173	0.0151	1.045	1.195	0.984
B-2, 8	615	4.03	142	64	168	0.0125	1.010	1.139	0.927
B-2, 11	685	3.05	163	76	184	0.0211	1.051	1.193	1.028
B-2, 12	695	2.78	71	48	180	0.0117	1.062	1.149	0.972

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-2, 13	625	2.24	72	72	183	0.0156	1.006	1.107	0.946
B-2, 14	615	2.17	94	78	182	0.0189	0.999	1.113	0.958
B-2, 15	635	1.65	158	0	163	0.0247	0.663	0.749	0.716
B-2, 16	835	1.66	39	58	150	0.0186	1.189	1.275	1.169
B-2, 17	675	1.79	64	66	172	0.0189	1.053	1.149	1.018
B-2, 18	595	1.86	76	66	193	0.0176	0.975	1.072	0.925
B-2, 20	655	1.43	34	45	175	0.0139	1.036	1.104	0.965
B-2, 21	625	1.51	154	78	172	0.0371	1.015	1.156	1.046
B-2, 22	625	1.40	43	48	165	0.0157	1.020	1.096	0.962
B-2, 23	615	1.40	49	49	164	0.0167	1.013	1.092	0.960
B-2, 24	625	1.27	52	52	160	0.0197	1.024	1.107	0.991
B-2, 25	655	0.79	19	32	150	0.0161	1.056	1.112	1.003
B-2, 26	645	0.87	20	32	155	0.0147	1.044	1.100	0.980
B-2, 27	645	0.86	29	36	150	0.0187	1.048	1.112	1.011
B-2, 29	585	0.76	27	24	145	0.0153	1.003	1.058	0.941
B-2, 30	685	0.40	16	0	100	0.0113	0.724	0.753	0.697
B-2, 31	635	0.78	16	24	103	0.0125	1.082	1.136	1.000
B-2, 32	635	0.44	6	0	90	0.0036	0.704	0.727	0.587
B-2, 33	615	0.26	9	0	90	0.0088	0.694	0.717	0.578
B-2, 34	595	0.67	19	0	100	0.0070	0.677	0.704	0.564
B-2, 35	365	0.48	16	88	97	0.0290	0.829	0.925	0.806
B-2, 36	305	0.55	36	138	110	0.0354	0.750	0.889	0.731
B-2, 37	330	0.50	12	72	98	0.0205	0.788	0.871	0.739
B-2, 38	375	0.54	16	31	115	0.0124	0.827	0.881	0.746
B-2, 39	675	7.72	1728	12	140	0.0596	1.081	1.672	1.186

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-2, 40	645	5.07	104	30	140	0.0069	1.057	1.154	0.881
B-2, 41	515	1.60	36	42	110	0.0097	0.971	1.045	0.809
B-2, 42	815	3.30	0	1405	175	0.1138	1.152	1.756	1.374
B-2, 47	635	0.34	42	70	140	0.0750	1.049	1.141	1.168
B-2, 48	1315	5.84	930	6	140	0.0807	1.492	1.741	1.870
B-2, 49	695	2.23	43	13	130	0.0070	1.105	1.139	0.921
B-2, 50	465	1.88	48	0	120	0.0049	0.590	0.612	0.492
B-2, 51	310	1.96	58	13	103	0.0046	0.760	0.798	0.634
B-2, 54	515	2.22	300	18	122	0.0296	0.961	1.076	0.959
B-2, 55	275	1.69	144	24	115	0.0111	0.709	0.782	0.627
B-2, 56	275	1.76	138	40	120	0.0112	0.706	0.784	0.624
B-2, 57	550	1.34	6	60	100	0.0100	1.011	1.048	0.906
B-2, 58	575	1.35	12	48	106	0.0096	1.028	1.062	0.857
B-2, 59	575	1.38	0	96	109	0.0146	1.025	1.074	0.959
B-2, 60	295	1.71	0	6	105	0.0004	0.740	0.750	0.617
B-2, 62	215	0.60	60	1	90	0.0090	0.642	0.672	0.535
B-2, 63	195	0.48	3	0	90	0.0005	0.395	0.398	0.329

Well B-3

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-3, 2	695	0.26	107	0	98	0.1065	0.731	0.816	1.002
B-3, 3	675	0.27	91	3	93	0.0889	1.125	1.220	1.298
B-3, 4	655	0.31	44	8	100	0.0431	1.101	1.170	1.174
B-3, 5	755	0.17	12	0	95	0.0217	0.762	0.795	0.834
B-3, 6	635	0.37	46	12	98	0.0389	1.087	1.160	1.143
B-3, 7	695	3.21	117	0	119	0.0104	0.718	0.805	0.680
B-3, 8	695	2.94	207	0	119	0.0200	0.718	0.849	0.763
B-3, 9	695	2.77	57	0	141	0.0059	0.705	0.758	0.588
B-3, 10	665	0.55	38	0	103	0.0188	0.712	0.757	0.748
B-3, 11	685	1.83	48	8	152	0.0085	1.078	1.143	0.898
B-3, 12	685	1.53	50	5	130	0.0101	1.097	1.164	0.989
B-3, 13	605	1.35	0	8	155	0.0013	1.012	1.047	0.843
B-3, 14	625	1.34	17	0	136	0.0033	0.672	0.701	0.560
B-3, 15	645	1.10	0	1	130	0.0002	1.066	1.098	0.888
B-3, 16	595	1.12	0	12	135	0.0024	1.020	1.060	0.850
B-3, 17	645	0.48	0	1	105	0.0005	1.088	1.124	0.907
B-3, 20	775	0.31	40	150	106	0.1529	1.189	1.336	1.475
B-3, 21	415	0.25	66	228	115	0.1567	0.869	1.070	0.981
B-3, 22	595	0.49	24	138	110	0.0691	1.042	1.171	1.149
B-3, 23	595	0.47	36	126	109	0.0724	1.043	1.170	1.156
B-3, 24	295	1.65	0	216	140	0.0141	0.719	0.881	0.648
B-3, 27	235	0.11	8	0	100	0.0071	0.429	0.443	0.357

Well B-4

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-4, 2	695	2.06	0	1017	194	0.1127	1.051	1.610	1.217
B-4, 3	1135	4.93	128	1020	165	0.0903	1.364	1.928	1.677
B-4, 4	815	6.93	134	1638	172	0.0723	1.155	1.915	1.316
B-4, 5	1135	4.78	165	1032	172	0.0967	1.356	1.928	1.678
B-4, 6	865	5.70	206	1771	174	0.1011	1.187	1.986	1.412
B-4, 7	995	3.11	185	1521	176	0.1700	1.269	1.989	1.628
B-4, 8	675	0.15	26	36	90	0.0981	1.128	1.207	1.316
B-4, 9	635	0.22	4	37	92	0.0425	1.092	1.159	1.161
B-4, 10	635	2.51	0	1490	168	0.1225	1.026	1.739	1.188
B-4, 12	985	2.94	0	1440	160	0.1515	1.278	1.954	1.626
B-4, 13	625	0.34	5	390	118	0.2121	1.060	1.353	1.303
B-4, 15	615	0.22	0	48	100	0.0473	1.068	1.139	1.141
B-4, 17	335	0.49	49	997	120	0.2103	0.778	1.402	0.873
B-4, 19	605	0.55	20	378	110	0.1402	1.050	1.258	1.241
B-4, 20	545	0.42	24	528	162	0.2105	0.956	1.208	1.136
B-4, 22	585	0.43	24	564	110	0.2294	1.033	1.316	1.268
B-4, 23	245	0.24	54	420	105	0.1538	0.675	1.034	0.716
B-4, 24	245	0.21	0	146	95	0.0593	0.681	0.830	0.680
B-4, 25	775	1.95	0	1686	175	0.1988	1.124	1.874	1.403
B-4,27	215	0.18	37	270	93	0.1211	0.640	0.903	0.661

Well B-5

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-5, 1	2515	4.08	180	12	95	0.0467	2.092	2.289	2.775
B-5, 2	755	7.75	12	21	175	0.0012	1.110	1.153	0.925
B-5, 3	705	2.07	41	5	123	0.0064	1.119	1.170	0.933
B-5, 4	685	1.73	13	1	90	0.0023	1.136	1.173	0.946
B-5, 5	445	2.72	0	18	125	0.0011	0.892	0.925	0.743
B-5, 6	445	2.77	0	12	128	0.0007	0.889	0.918	0.741
B-5, 7	475	2.26	2	13	125	0.0012	0.921	0.952	0.767
B-5, 8	295	2.60	24	0	140	0.0011	0.464	0.484	0.387
B-5, 10	285	2.35	8	13	123	0.0010	0.717	0.750	0.597
B-5, 11	1135	4.91	51	720	165	0.0624	1.364	1.741	1.605
B-5, 12	665	1.59	0	512	160	0.0735	1.056	1.345	1.175
B-5, 13	685	1.29	0	468	143	0.0843	1.086	1.362	1.235

Well B-6

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-6, 2	765	2.16	14	8	110	0.0031	1.178	1.223	0.981
B-6, 3	635	1.50	12	36	100	0.0077	1.085	1.146	0.904
B-6, 4	745	1.59	6	0	100	0.0012	0.754	0.779	0.629
B-6, 5	1465	8.49	269	256	143	0.0345	1.567	1.854	1.781

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-6, 6	795	4.70	151	1056	193	0.0713	1.123	1.647	1.268
B-6, 7	795	4.70	151	1056	193	0.0713	1.123	1.647	1.268
B-6, 8	705	3.17	20	1168	192	0.0893	1.060	1.595	1.204
B-6, 9	795	3.07	44	1197	188	0.1068	1.127	1.673	1.326
B-6, 10	795	2.80	41	1284	193	0.1227	1.123	1.690	1.338
B-6, 11	715	3.16	119	1800	205	0.1394	1.057	1.769	1.250
B-6, 12	715	2.62	29	1413	197	0.1274	1.063	1.667	1.250
B-6, 13	1255	5.82	85	168	115	0.0206	1.489	1.676	1.548
B-6, 14	1175	5.51	69	108	135	0.0144	1.420	1.559	1.386
B-6, 19	735	0.94	188	0	175	0.0577	0.705	0.803	0.877
B-6, 24	695	1.95	56	80	130	0.0185	1.105	1.213	1.073
B-6, 25	315	1.29	72	48	93	0.0115	0.773	0.873	0.689
B-6, 26	265	2.50	0	132	137	0.0052	0.683	0.797	0.569
B-6, 27	265	2.17	36	90	133	0.0059	0.686	0.791	0.571
B-6, 28	245	2.06	12	60	130	0.0032	0.661	0.733	0.551
B-6, 29	265	1.82	16	80	123	0.0053	0.691	0.780	0.576
B-6, 30	265	1.51	12	48	130	0.0040	0.687	0.750	0.573
B-6, 31	315	1.41	12	72	137	0.0070	0.744	0.823	0.620
B-6, 32	275	1.51	8	56	125	0.0044	0.703	0.770	0.586
B-6, 33	255	1.41	0	56	114	0.0037	0.684	0.748	0.570
B-6, 34	235	1.14	0	52	113	0.0040	0.657	0.719	0.547
B-6, 35	685	2.81	16	60	112	0.0070	1.114	1.193	0.928
B-6, 36	335	2.76	18	66	113	0.0039	0.783	0.863	0.653
B-6, 37	625	1.24	11	36	105	0.0089	1.072	1.131	0.893
B-6, 38	625	1.26	11	33	100	0.0083	1.076	1.134	0.897

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-6, 39	655	1.23	12	32	100	0.0089	1.101	1.160	0.918
B-6, 40	685	1.01	28	24	98	0.0137	1.128	1.190	1.060
B-6, 42	725	0.90	21	27	85	0.0149	1.173	1.237	1.118
B-6, 43	315	1.43	24	74	98	0.0082	0.770	0.861	0.641
B-6, 44	315	1.08	18	64	108	0.0090	0.763	0.842	0.636
B-6, 45	275	1.08	18	54	90	0.0070	0.725	0.800	0.604
B-6, 46	595	1.31	0	53	80	0.0088	1.070	1.138	0.891
B-6, 47	260	0.93	0	60	90	0.0062	0.705	0.774	0.587
B-6, 48	265	0.72	0	61	90	0.0082	0.712	0.782	0.593
B-6, 49	255	0.83	6	56	95	0.0071	0.695	0.765	0.579
B-6, 50	265	0.60	0	53	90	0.0086	0.712	0.776	0.593
B-6, 51	255	0.61	0	56	150	0.0086	0.663	0.724	0.553
B-6, 52	255	0.61	0	362	87	0.0531	0.700	0.972	0.696
B-6, 53	260	0.39	0	47	87	0.0115	0.707	0.767	0.626
B-6, 54	235	0.34	20	51	83	0.0185	0.675	0.751	0.618
B-6, 55	235	0.34	20	40	83	0.0157	0.675	0.742	0.611
B-6, 57	735	7.61	134	281	180	0.0152	1.092	1.327	1.034
B-6, 58	695	6.83	398	732	180	0.0426	1.062	1.552	1.121

Well B-7

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-7, 1	1835	4.61	259	552	210	0.1106	1.659	2.062	2.256
B-7, 2	1765	4.37	265	552	215	0.1128	1.623	2.025	2.192
B-7, 3	1765	4.63	282	456	215	0.0984	1.623	1.995	2.155
B-7, 4	1765	4.59	261	286	212	0.0762	1.626	1.928	2.090
B-7, 5	1795	5.19	254	192	200	0.0577	1.653	1.918	2.058
B-7, 6	1715	4.82	211	168	208	0.0507	1.609	1.844	1.947
B-7, 7	865	6.22	213	120	225	0.0182	1.143	1.338	1.114
B-7, 8	765	6.69	128	94	200	0.0100	1.096	1.246	0.914
B-7, 9	715	6.07	86	74	200	0.0074	1.061	1.179	0.884
B-7, 10	885	6.24	116	81	165	0.0110	1.209	1.355	1.112
B-7, 11	735	5.30	66	65	198	0.0071	1.077	1.181	0.897
B-7, 12	735	4.75	0	48	190	0.0027	1.083	1.144	0.903
B-7, 13	715	1.90	0	40	190	0.0055	1.069	1.124	0.891
B-7, 15	665	3.08	0	40	175	0.0032	1.043	1.099	0.869
B-7, 16	595	2.89	45	48	178	0.0075	0.986	1.069	0.821
B-7, 17	615	2.67	78	48	172	0.0114	1.007	1.108	0.915
B-7, 18	625	2.23	66	16	170	0.0093	1.016	1.090	0.847
B-7, 19	715	1.48	50	24	157	0.0142	1.096	1.171	1.030
B-7, 20	735	1.38	46	24	145	0.0147	1.122	1.197	1.062
B-7, 21	665	1.62	62	30	160	0.0149	1.056	1.139	0.994
B-7, 22	705	1.65	57	31	158	0.0148	1.088	1.171	1.027
B-7, 23	655	1.55	59	32	155	0.0152	1.052	1.136	0.992
B-7, 24	615	0.39	54	0	110	0.0343	0.682	0.731	0.778

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-7, 25	595	0.51	59	0	105	0.0279	0.674	0.726	0.743
B-7, 26	635	0.35	47	0	100	0.0343	0.698	0.746	0.803
B-7, 27	635	0.27	43	0	100	0.0404	0.698	0.744	0.823
B-7, 28	615	0.32	26	0	105	0.0204	0.685	0.719	0.722
B-7, 29	605	0.30	25	0	98	0.0206	0.683	0.718	0.722
B-7, 30	605	0.33	36	0	95	0.0268	0.685	0.726	0.755
B-7, 31	2715	8.46	749	24	140	0.0934	2.091	2.477	3.106
B-7, 32	2715	8.24	185	0	160	0.0248	1.306	1.479	1.790
B-7, 33	2335	6.69	544	40	168	0.0777	1.912	2.225	2.641
B-7, 34	2315	6.86	534	44	168	0.0746	1.905	2.216	2.610
B-7, 35	2265	6.57	517	50	168	0.0746	1.886	2.193	2.572
B-7, 36	2195	6.39	486	60	168	0.0717	1.859	2.159	2.503
B-7, 37	2135	6.25	0	72	165	0.0090	1.839	1.968	1.533
B-7, 38	2015	5.74	0	180	136	0.0229	1.830	2.026	2.038
B-7, 39	2015	5.62	395	89	160	0.0661	1.797	2.081	2.357
B-7, 40	1535	6.98	467	133	185	0.0509	1.552	1.858	1.857
B-7, 41	675	2.40	236	0	193	0.0269	0.668	0.791	0.731
B-7, 42	665	3.17	151	200	178	0.0279	1.041	1.264	1.048
B-7, 43	665	3.09	147	252	168	0.0322	1.049	1.302	1.073
B-7, 44	635	3.03	139	205	170	0.0273	1.024	1.248	1.025
B-7, 45	585	1.40	48	264	145	0.0469	1.003	1.229	1.057
B-7, 46	615	1.55	21	192	150	0.0307	1.024	1.193	1.038
B-7, 47	595	1.49	13	183	158	0.0284	1.001	1.159	1.003
B-7, 48	595	1.49	13	183	158	0.0284	1.001	1.159	1.003
B-7, 49	245	1.99	84	180	158	0.0124	0.646	0.847	0.573

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-7, 50	245	2.00	58	198	155	0.0118	0.648	0.848	0.572
B-7, 51	2095	9.97	699	12	150	0.0585	1.844	2.165	2.400
B-7, 52	1715	9.36	610	10	170	0.0451	1.654	1.935	1.988
B-7, 53	865	6.28	414	197	203	0.0327	1.162	1.444	1.216
B-7, 54	735	4.49	162	0	210	0.0109	0.687	0.770	0.653
B-7, 56	715	4.11	280	744	220	0.0639	1.045	1.491	1.145
B-7, 57	695	2.87	273	312	220	0.0526	1.031	1.315	1.105
B-7, 58	715	2.78	651	768	220	0.1250	1.045	1.581	1.221
B-7, 59	695	9.45	296	69	185	0.0108	1.058	1.249	0.960
B-7, 60	665	2.36	464	644	215	0.1085	1.013	1.475	1.156
B-7, 61	665	1.88	247	792	215	0.1229	1.013	1.471	1.169
B-7, 62	595	2.10	158	795	212	0.0926	0.961	1.404	1.067
B-7, 63	715	2.58	117	368	176	0.0488	1.080	1.352	1.161
B-7, 64	565	1.74	42	760	198	0.0885	0.947	1.353	1.042
B-7, 65	565	1.59	49	703	194	0.0907	0.949	1.338	1.049
B-7, 66	595	1.73	0	702	190	0.0821	0.977	1.351	1.077
B-7, 67	585	1.74	42	672	195	0.0822	0.965	1.338	1.061
B-7, 68	595	1.61	50	608	193	0.0833	0.975	1.324	1.076
B-7, 69	565	0.13	0	8	109	0.0127	1.017	1.049	0.936
B-7, 70	535	0.13	9	8	92	0.0269	1.005	1.042	1.001
B-7, 71	395	1.01	18	778	165	0.1036	0.814	1.249	0.876
B-7, 72	475	1.21	0	720	195	0.0947	0.871	1.256	0.945
B-7, 73	315	1.98	0	808	210	0.0454	0.703	1.133	0.691
B-7, 74	465	1.22	16	600	190	0.0802	0.865	1.208	0.925
B-7, 75	515	1.11	16	520	185	0.0846	0.913	1.221	0.993

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-7, 76	415	1.07	16	545	195	0.0748	0.815	1.135	0.855
B-7, 77	275	1.59	20	261	190	0.0178	0.667	0.858	0.609
B-7, 78	335	1.38	24	420	184	0.0386	0.739	1.012	0.724
B-7, 79	335	1.26	16	604	190	0.0577	0.736	1.090	0.742
B-7, 80	305	1.50	16	596	200	0.0442	0.697	1.048	0.683
B-7, 81	255	1.14	6	408	185	0.0332	0.645	0.913	0.613
B-7, 82	265	0.98	12	492	184	0.0482	0.658	0.970	0.643
B-7, 83	275	0.97	22	416	165	0.0442	0.680	0.963	0.664
B-7, 84	265	1.12	13	435	165	0.0379	0.668	0.958	0.644
B-7, 85	285	1.01	22	553	170	0.0569	0.690	1.037	0.687
B-7, 86	295	1.09	14	418	165	0.0417	0.704	0.982	0.689
B-7, 87	295	1.24	12	390	160	0.0343	0.707	0.971	0.682
B-7, 88	285	1.30	12	335	168	0.0275	0.691	0.924	0.653
B-7, 89	265	1.21	12	336	163	0.0276	0.669	0.906	0.630
B-7, 90	265	1.09	13	364	174	0.0330	0.663	0.913	0.632
B-7, 91	275	0.95	12	344	165	0.0369	0.680	0.920	0.656
B-7, 92	265	0.90	14	327	152	0.0360	0.675	0.911	0.649
B-7, 93	1635	8.38	177	72	180	0.0192	1.605	1.785	1.678
B-7, 94	1585	7.84	152	72	182	0.0179	1.579	1.747	1.626
B-7, 95	735	6.89	90	196	178	0.0116	1.093	1.289	1.003
B-7, 96	645	4.83	70	206	196	0.0139	1.012	1.200	0.940
B-7, 97	915	4.47	54	224	183	0.0211	1.212	1.408	1.214
B-7, 98	865	2.82	56	238	180	0.0331	1.182	1.387	1.243
B-7, 99	635	5.67	129	234	202	0.0155	0.999	1.226	0.939
B-7, 100	615	4.46	28	163	170	0.0098	1.008	1.158	0.840

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-7, 101	615	2.94	42	198	183	0.0186	0.998	1.172	0.956
B-7, 102	635	2.67	48	192	180	0.0212	1.016	1.190	0.989
B-7, 103	635	2.66	46	192	180	0.0211	1.016	1.190	0.989
B-7, 104	615	2.95	18	198	180	0.0166	1.000	1.165	0.946
B-7, 105	655	2.39	36	78	186	0.0119	1.027	1.125	0.939
B-7, 106	635	2.26	37	177	174	0.0222	1.021	1.183	1.000
B-7, 107	735	2.01	31	132	162	0.0221	1.107	1.242	1.097
B-7, 108	605	0.97	46	266	130	0.0684	1.033	1.263	1.135
B-7, 110	575	1.80	40	378	160	0.0476	0.983	1.264	1.032
B-7, 111	315	3.10	18	396	185	0.0154	0.716	1.002	0.651
B-7, 112	315	3.36	30	396	200	0.0147	0.708	0.994	0.640
B-7, 113	565	2.25	57	156	190	0.0201	0.952	1.107	0.913
B-7, 114	235	0.49	12	66	132	0.0139	0.646	0.732	0.578
B-7, 116	265	0.74	14	80	130	0.0125	0.687	0.784	0.612
B-7, 117	245	0.46	6	198	130	0.0388	0.661	0.840	0.637
B-7, 119	665	1.47	80	12	115	0.0168	1.095	1.182	1.050
B-7, 120	715	1.91	52	13	137	0.0098	1.114	1.184	0.928
B-7, 121	715	5.63	87	20	142	0.0055	1.110	1.203	0.925
B-7, 122	595	2.24	104	24	145	0.0137	1.012	1.114	0.939
B-7, 123	555	1.59	98	35	152	0.0184	0.972	1.077	0.927
B-7, 124	555	1.56	99	61	157	0.0222	0.968	1.090	0.941
B-7, 125	635	1.23	69	49	142	0.0236	1.047	1.149	1.036
B-7, 126	595	1.46	91	43	150	0.0215	1.008	1.115	0.981
B-7, 127	575	0.98	36	42	110	0.0176	1.024	1.108	0.979
B-7, 128	295	0.16	0	32	122	0.0216	0.730	0.780	0.682

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-7, 129	555	1.10	26	58	115	0.0160	1.003	1.091	0.945
B-7, 130	615	0.33	13	2	112	0.0113	1.057	1.097	0.964
B-7, 131	595	0.26	7	1	102	0.0075	1.049	1.085	0.874
B-7, 132	575	0.39	1	1	90	0.0012	1.043	1.076	0.869
B-7, 133	595	0.26	2	1	100	0.0027	1.051	1.084	0.876
B-7, 134	545	0.25	0	7	135	0.0056	0.977	1.010	0.814
B-7, 135	545	0.23	7	1	102	0.0077	1.005	1.040	0.837
B-7, 137	555	0.20	0	6	95	0.0061	1.020	1.056	0.850
B-7, 138	535	0.24	5	0	85	0.0046	0.651	0.673	0.543

Well B-8

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-8, 1	1615	8.42	375	0	120	0.0291	1.068	1.288	1.384
B-8, 2	715	7.20	0	34	138	0.0012	1.113	1.174	0.928
B-8, 3	755	2.27	0	16	90	0.0020	1.191	1.244	0.992
B-8, 4	745	1.86	6	16	90	0.0034	1.183	1.240	0.986
B-8, 6	745	0.83	2	4	90	0.0021	1.183	1.227	0.986
B-8, 9	665	0.52	0	8	105	0.0038	1.105	1.147	0.921
B-8, 10	675	0.53	20	0	95	0.0105	0.722	0.758	0.686
B-8, 11	635	0.48	6	0	95	0.0033	0.701	0.727	0.584
B-8, 12	625	0.53	12	0	98	0.0059	0.694	0.723	0.579

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-8, 13	655	0.45	13	0	92	0.0078	0.714	0.745	0.595
B-8, 14	735	0.33	5	0	90	0.0046	0.756	0.785	0.630
B-8, 15	700	0.24	1	1	82	0.0023	1.156	1.196	0.963
B-8, 16	675	0.26	0	1	90	0.0010	1.128	1.166	0.940
B-8, 20	815	7.17	136	68	115	0.0092	1.209	1.348	1.008
B-8, 21	815	5.07	114	45	120	0.0102	1.204	1.318	1.096
B-8, 22	685	4.67	147	72	145	0.0127	1.084	1.221	1.005
B-8, 23	685	2.85	57	24	145	0.0078	1.084	1.152	0.903
B-8, 24	645	2.70	45	0	145	0.0045	0.678	0.715	0.565
B-8, 25	655	2.12	52	15	133	0.0083	1.071	1.132	0.892
B-8, 26	655	2.08	43	15	123	0.0073	1.080	1.138	0.900
B-8, 27	655	1.91	46	16	125	0.0085	1.078	1.138	0.898
B-8, 28	645	1.92	16	32	125	0.0062	1.070	1.125	0.892
B-8, 29	675	1.73	44	12	135	0.0088	1.085	1.141	0.904
B-8, 30	655	1.58	54	0	155	0.0092	0.677	0.718	0.565
B-8, 31	285	2.79	35	20	138	0.0022	0.708	0.760	0.590
B-8, 32	285	1.91	0	16	127	0.0009	0.714	0.746	0.595
B-8, 33	215	1.36	0	416	126	0.0238	0.622	0.908	0.575
B-8, 34	245	1.41	0	360	125	0.0226	0.664	0.915	0.616
B-8, 35	310	1.57	0	12	125	0.0009	0.746	0.783	0.622
B-8, 36	265	1.56	18	0	112	0.0013	0.450	0.474	0.375
B-8, 37	265	1.52	36	0	102	0.0026	0.454	0.490	0.379
B-8, 38	285	1.51	27	1	108	0.0022	0.726	0.773	0.605
B-8, 39	255	1.35	36	0	110	0.0028	0.443	0.478	0.369
B-8, 41	1545	5.71	155	0	120	0.0172	1.047	1.143	1.195

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-8, 42	895	8.55	188	12	155	0.0086	1.225	1.324	1.021
B-8, 43	615	3.59	59	6	140	0.0046	1.032	1.078	0.860
B-8, 44	635	2.39	37	0	133	0.0041	0.679	0.706	0.566
B-8, 45	345	1.46	24	8	105	0.0031	0.800	0.845	0.667
B-8, 46	355	1.55	0	32	115	0.0027	0.804	0.852	0.670
B-8, 47	355	0.40	0	8	105	0.0026	0.811	0.842	0.676
B-8, 48	375	0.26	36	0	85	0.0212	0.547	0.581	0.555
B-8, 49	305	0.29	44	0	78	0.0189	0.498	0.536	0.489
B-8, 50	295	1.28	24	42	132	0.0059	0.724	0.791	0.603
B-8, 51	265	0.29	0	8	101	0.0027	0.705	0.734	0.587
B-8, 53	475	2.08	10	712	138	0.0576	0.911	1.288	0.958
B-8, 54	535	1.85	14	650	147	0.0665	0.959	1.305	1.033
B-8, 55	255	0.44	5	32	113	0.0080	0.684	0.728	0.570
B-8, 56	275	0.96	489	257	160	0.0789	0.683	1.031	0.695
B-8, 57	255	0.50	214	403	130	0.1084	0.674	1.009	0.699
B-8, 58	275	0.52	6	270	120	0.0514	0.706	0.895	0.701

Well B-9

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-9, 3	1555	9.27	341	45	200	0.0259	1.545	1.776	1.676
B-9, 4	1165	1.07	309	48	198	0.1376	1.347	1.562	1.729

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-9, 5	1215	9.61	348	48	198	0.0202	1.375	1.606	1.401
B-9, 6	915	8.65	230	42	185	0.0116	1.210	1.388	1.122
B-9, 7	585	7.09	174	48	174	0.0074	0.981	1.137	0.817
B-9, 8	605	6.17	99	24	170	0.0049	1.000	1.102	0.833
B-9, 9	585	5.10	93	32	160	0.0058	0.991	1.097	0.826
B-9, 10	575	3.08	0	48	165	0.0033	0.979	1.044	0.816
B-9, 11	585	3.01	41	24	160	0.0050	0.991	1.063	0.826
B-9, 12	655	1.79	51	24	158	0.0109	1.050	1.128	0.952
B-9, 13	615	2.10	38	28	150	0.0076	1.024	1.098	0.853
B-9, 14	635	1.23	8	0	128	0.0017	0.682	0.707	0.568
B-9, 15	625	1.69	26	30	140	0.0080	1.041	1.111	0.867
B-9, 16	695	2.55	21	54	113	0.0078	1.121	1.212	0.934
B-9, 17	675	2.74	21	24	112	0.0043	1.106	1.174	0.922
B-9, 18	665	2.77	22	54	90	0.0070	1.119	1.214	0.933
B-9, 19	665	0.29	1	0	85	0.0010	0.724	0.748	0.603
B-9, 20	255	2.46	37	78	110	0.0046	0.686	0.805	0.572
B-9, 21	275	0.77	18	168	103	0.0243	0.716	0.895	0.674
B-9, 22	625	1.23	148	1	110	0.0306	1.067	1.191	1.089
B-9, 23	645	1.15	128	0	115	0.0290	0.695	0.788	0.778
B-9, 24	255	1.44	92	304	130	0.0260	0.674	0.981	0.633
B-9, 25	275	1.34	18	174	127	0.0145	0.702	0.880	0.633
B-9, 27	295	1.50	18	150	117	0.0122	0.733	0.894	0.654
B-9, 28	255	0.86	11	34	85	0.0051	0.701	0.769	0.584
B-9, 29	255	0.73	10	26	100	0.0048	0.692	0.750	0.577
B-9, 30	255	0.73	100	35	95	0.0187	0.695	0.822	0.639

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-9, 31	245	0.71	129	11	95	0.0196	0.681	0.807	0.627
B-9, 32	255	0.63	48	0	90	0.0080	0.451	0.495	0.376
B-9, 33	245	0.62	48	0	95	0.0078	0.440	0.483	0.367

Well B-10

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
B-10, 1	1475	7.49	683	10	157	0.0537	1.555	1.846	1.876
B-10, 2	935	7.06	198	16	190	0.0116	1.218	1.337	1.129
B-10, 3	765	7.40	153	1	185	0.0066	1.109	1.201	0.924
B-10, 4	775	3.63	86	108	175	0.0159	1.124	1.248	1.075
B-10, 5	795	4.67	212	72	197	0.0192	1.120	1.269	1.094
B-10, 6	795	3.01	149	348	170	0.0480	1.143	1.405	1.243
B-10, 7	715	2.07	51	192	175	0.0309	1.081	1.234	1.108
B-10, 9	945	3.12	98	450	168	0.0591	1.245	1.505	1.418
B-10, 10	1015	2.48	80	120	130	0.0308	1.328	1.454	1.423
B-10, 11	905	3.48	106	152	168	0.0255	1.219	1.359	1.251
B-10, 12	855	3.67	66	144	170	0.0185	1.184	1.305	1.162
B-10, 13	815	3.80	87	120	175	0.0170	1.152	1.268	1.115
B-10, 14	735	3.02	43	125	170	0.0154	1.100	1.202	1.044
B-10, 15	755	1.71	23	96	125	0.0195	1.156	1.243	1.137
B-10, 16	655	3.14	24	96	150	0.0094	1.056	1.138	0.880

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
B-10, 17	535	2.39	18	132	150	0.0125	0.956	1.054	0.873
B-10,18	495	2.28	48	186	138	0.0189	0.930	1.069	0.884
B-10, 19	475	2.11	48	192	142	0.0201	0.908	1.049	0.865
B-10, 20	295	1.35	11	162	128	0.0139	0.726	0.843	0.655

Well C-1

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-1, 1	1825	2.30	930	0	147	0.2352	1.106	1.415	2.123
C-1, 2	1865	5.30	1056	0	150	0.1341	1.115	1.443	1.967
C-1, 3	1895	5.40	840	0	164	0.1094	1.111	1.399	1.892
C-1, 4	1895	5.20	722	46	172	0.1038	1.731	2.053	2.379
C-1, 5	1815	5.80	739	73	180	0.0949	1.686	2.017	2.264
C-1, 6	1815	6.50	716	126	138	0.0879	1.741	2.103	2.345
C-1, 7	1795	6.40	669	147	145	0.0855	1.722	2.077	2.301
C-1, 8	1615	7.70	622	414	145	0.0796	1.639	2.069	2.124
C-1, 9	1705	6.40	534	342	136	0.0851	1.693	2.086	2.244
C-1, 10	1675	5.80	533	355	136	0.0926	1.679	2.076	2.243
C-1, 11	1605	6.00	554	511	137	0.1010	1.644	2.094	2.202
C-1, 12	1685	6.10	506	506	125	0.0991	1.698	2.143	2.301
C-1, 13	1445	6.10	546	668	145	0.1011	1.555	2.046	2.035
C-1, 14	1305	5.10	495	605	205	0.0992	1.415	1.849	1.783

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-1, 15	1115	4.20	515	957	223	0.1312	1.295	1.825	1.630
C-1, 16	1115	3.60	714	909	138	0.1630	1.381	1.984	1.823
C-1, 17	1090	4.90	685	743	128	0.1109	1.377	1.938	1.740
C-1, 18	1105	4.80	556	833	223	0.1106	1.290	1.795	1.591
C-1, 19	1095	5.10	578	868	135	0.1077	1.372	1.943	1.726
C-1, 20	1095	4.80	363	1089	130	0.1123	1.378	1.971	1.744
C-1, 21	1075	4.40	359	1078	132	0.1182	1.363	1.953	1.729
C-1, 22	935	3.30	444	1332	132	0.1612	1.275	1.953	1.630
C-1, 23	955	3.50	432	1296	150	0.1526	1.269	1.922	1.611
C-1, 24	465	1.50	323	1828	136	0.2010	0.903	1.740	1.051
C-1, 25	515	5.00	229	915	140	0.0428	0.946	1.489	0.976
C-1, 26	525	5.10	459	1453	144	0.0698	0.952	1.701	1.028
C-1, 27	595	5.10	531	1593	150	0.0864	1.008	1.788	1.126
C-1, 28	595	4.30	422	1690	137	0.0998	1.018	1.814	1.156
C-1, 29	2255	3.10	144	24	100	0.0477	1.984	2.161	2.579
C-1, 30	2065	6.40	174	38	115	0.0272	1.882	2.063	2.179
C-1, 31	2015	6.60	252	48	140	0.0361	1.825	2.028	2.193
C-1, 32	1995	7.30	187	19	144	0.0227	1.811	1.974	2.007
C-1, 33	1895	7.40	179	37	148	0.0221	1.762	1.927	1.930
C-1, 34	1845	7.10	199	41	145	0.0249	1.745	1.917	1.943
C-1, 35	1815	6.70	223	56	160	0.0299	1.711	1.894	1.953
C-1, 36	1740	6.70	248	28	154	0.0287	1.686	1.863	1.903
C-1, 37	1715	5.80	227	31	143	0.0304	1.688	1.863	1.925
C-1, 38	1685	6.00	248	28	140	0.0309	1.678	1.859	1.915
C-1, 39	1590	7.60	278	32	158	0.0260	1.610	1.795	1.768

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-1, 40	1465	8.70	327	21	168	0.0237	1.537	1.728	1.644
C-1, 41	1465	8.80	296	44	165	0.0227	1.541	1.732	1.638
C-1, 42	1405	8.80	316	56	169	0.0238	1.506	1.707	1.603
C-1, 43	1405	8.70	376	83	168	0.0294	1.507	1.740	1.655
C-1, 44	1315	9.10	320	163	175	0.0272	1.452	1.699	1.563
C-1, 45	1315	7.30	398	170	177	0.0396	1.450	1.723	1.642
C-1, 46	1315	8.40	594	198	173	0.0478	1.455	1.794	1.690
C-1, 47	1285	8.20	480	135	175	0.0377	1.436	1.720	1.611
C-1, 48	1225	8.90	467	181	185	0.0348	1.393	1.687	1.534
C-1, 49	1215	8.70	556	139	175	0.0380	1.398	1.705	1.559
C-1, 50	1195	8.60	581	173	175	0.0408	1.387	1.713	1.557
C-1, 51	1185	8.10	649	162	119	0.0461	1.444	1.810	1.666
C-1, 52	1165	7.80	714	178	180	0.0515	1.365	1.726	1.571
C-1, 53	1705	3.70	180	66	104	0.0438	1.737	1.925	2.115
C-1, 54	1190	2.00	36	1092	135	0.1997	1.428	1.952	1.954
C-1, 55	1065	2.00	27	1104	170	0.1828	1.317	1.825	1.728
C-1, 58	715	5.70	8	377	195	0.0176	1.065	1.294	1.023
C-1, 59	715	5.00	290	2126	190	0.1149	1.069	1.879	1.246
C-1, 60	715	5.00	290	2128	182	0.1150	1.075	1.892	1.256
C-1, 61	695	4.40	174	2309	198	0.1278	1.048	1.875	1.227
C-1, 65	715	6.10	580	1352	150	0.0800	1.103	1.702	1.253
C-1, 66	815	5.00	1253	139	155	0.0855	1.171	1.587	1.362
C-1, 67	815	5.70	242	970	153	0.0617	1.172	1.617	1.319
C-1, 68	795	5.10	312	803	160	0.0624	1.152	1.563	1.291
C-1, 70	355	0.10	200	10	96	0.2360	0.818	0.930	0.937

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-1, 71	265	0.10	41	97	95	0.1231	0.708	0.803	0.748
C-1, 72	275	0.10	25	137	92	0.1439	0.723	0.834	0.776
C-1, 73	265	0.10	4	188	92	0.1589	0.710	0.840	0.764
C-1, 74	255	0.10	0	96	96	0.0831	0.694	0.770	0.711

Well C-2

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-2, 1	2315	5.66	182	46	74	0.0366	2.051	2.281	2.583
C-2, 2	2175	4.66	86	21	92	0.0200	1.964	2.123	2.178
C-2, 3	1785	6.26	181	40	102	0.0251	1.778	1.967	1.995
C-2, 4	1315	6.56	106	26	119	0.0107	1.518	1.642	1.425
C-2, 5	1115	6.55	133	23	125	0.0108	1.396	1.522	1.300
C-2, 6	1115	6.24	163	28	123	0.0138	1.398	1.542	1.352
C-2, 7	665	4.36	20	13	126	0.0020	1.085	1.136	0.904
C-2, 8	515	4.36	14	10	132	0.0011	0.953	0.994	0.794
C-2, 9	515	4.11	6	6	130	0.0006	0.954	0.988	0.795
C-2, 10	785	3.93	47	38	125	0.0067	1.178	1.263	0.981
C-2, 11	355	3.78	53	43	132	0.0036	0.793	0.879	0.661
C-2, 12	315	2.16	49	41	122	0.0052	0.754	0.838	0.628
C-2, 13	315	2.14	16	24	112	0.0023	0.760	0.813	0.634
C-2, 14	315	1.80	14	18	110	0.0022	0.762	0.809	0.635

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-2, 15	305	1.74	25	47	108	0.0049	0.751	0.827	0.626
C-2, 16	295	1.71	12	28	106	0.0027	0.740	0.794	0.617
C-2, 17	205	1.60	47	25	110	0.0037	0.616	0.691	0.513
C-2, 18	205	1.26	30	55	102	0.0053	0.620	0.710	0.517
C-2, 19	235	1.13	7	16	100	0.0018	0.665	0.707	0.554
C-2, 20	375	1.70	87	36	94	0.0108	0.842	0.947	0.751
C-2, 22	235	0.20	132	0	106	0.0607	0.427	0.510	0.462

Well C-3

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-3, 1	2575	6.22	219	39	72	0.0419	2.155	2.436	2.842
C-3, 2	1925	6.18	161	18	115	0.0225	1.822	2.011	2.020
C-3, 3	1715	7.67	232	26	120	0.0232	1.720	1.936	1.886
C-3, 4	1495	7.94	151	17	138	0.0129	1.589	1.747	1.550
C-3, 5	1485	7.85	173	19	135	0.0147	1.587	1.759	1.585
C-3, 6	1215	8.40	141	27	145	0.0098	1.431	1.580	1.193
C-3, 7	1195	7.96	138	26	145	0.0100	1.420	1.566	1.183
C-3, 8	615	4.77	58	86	150	0.0072	1.024	1.157	0.853
C-3, 9	485	4.84	150	150	154	0.0117	0.908	1.133	0.821
C-3, 10	375	3.35	42	168	142	0.0088	0.808	0.994	0.673
C-3, 11	335	3.17	50	202	143	0.0100	0.764	0.980	0.672

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-3, 12	335	2.87	29	163	140	0.0084	0.765	0.943	0.638
C-3, 13	275	2.01	29	163	136	0.0098	0.697	0.878	0.580
C-3, 14	275	1.04	3	29	123	0.0032	0.704	0.761	0.587

Well C-4

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-4, 1	1415	3.02	36	326	105	0.0598	1.590	1.865	1.961
C-4, 2	815	2.72	89	31	95	0.0143	1.230	1.340	1.175
C-4, 3	275	1.48	41	7	106	0.0036	0.715	0.771	0.595
C-4, 4	355	1.34	19	5	107	0.0026	0.810	0.851	0.675
C-4, 5	295	1.25	22	6	108	0.0027	0.739	0.782	0.615
C-4, 6	275	1.07	26	4	104	0.0032	0.716	0.760	0.597
C-4, 7	255	1.08	14	2	103	0.0015	0.690	0.725	0.575
C-4, 8	245	1.06	20	4	103	0.0023	0.677	0.718	0.564
C-4, 9	205	1.66	22	2	100	0.0012	0.621	0.663	0.517
C-4, 10	245	1.00	10	6	100	0.0016	0.678	0.715	0.565
C-4, 11	195	0.64	4	5	86	0.0011	0.613	0.646	0.511
C-4, 12	195	0.55	6	6	96	0.0017	0.608	0.643	0.507
C-4, 13	215	0.43	2	3	90	0.0010	0.642	0.671	0.535
C-4, 14	475	3.23	52	31	110	0.0049	0.933	1.014	0.777
C-4, 15	495	3.74	55	29	128	0.0044	0.937	1.016	0.781

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-4, 16	535	2.76	11	5	127	0.0012	0.975	1.012	0.812
C-4, 17	535	3.47	54	27	128	0.0050	0.974	1.051	0.812
C-4, 18	495	3.48	50	27	130	0.0044	0.936	1.010	0.780
C-4, 19	505	3.33	32	7	128	0.0024	0.947	0.997	0.789
C-4, 20	495	3.42	58	14	128	0.0042	0.937	1.007	0.781
C-4, 21	495	3.26	48	16	127	0.0039	0.938	1.004	0.782
C-4, 22	425	3.55	45	15	133	0.0029	0.866	0.928	0.722
C-4, 23	435	3.29	45	15	130	0.0032	0.878	0.940	0.732
C-4, 24	415	3.24	45	15	132	0.0031	0.857	0.919	0.714
C-4, 25	415	3.34	49	16	132	0.0033	0.857	0.922	0.714
C-4, 26	415	3.21	42	14	134	0.0029	0.855	0.914	0.713
C-4, 27	395	3.24	48	16	135	0.0032	0.834	0.898	0.695
C-4, 28	375	3.26	27	9	134	0.0017	0.813	0.860	0.678
C-4, 29	375	3.25	18	10	134	0.0013	0.813	0.855	0.678
C-4, 30	395	3.15	27	9	135	0.0018	0.834	0.881	0.695
C-4, 31	435	3.02	48	16	134	0.0037	0.875	0.940	0.729
C-4, 32	435	2.69	33	27	130	0.0038	0.878	0.943	0.732
C-4, 33	415	2.89	41	13	130	0.0031	0.858	0.916	0.715
C-4, 34	405	2.92	31	17	130	0.0027	0.848	0.903	0.706
C-4, 35	395	2.74	26	26	130	0.0029	0.837	0.897	0.698
C-4, 36	375	2.74	34	31	130	0.0035	0.816	0.884	0.680
C-4, 37	365	2.76	40	32	127	0.0038	0.807	0.880	0.673
C-4, 38	365	2.76	40	32	125	0.0038	0.809	0.881	0.674
C-4, 39	325	2.65	30	30	127	0.0029	0.762	0.827	0.635
C-4, 40	335	2.46	28	28	126	0.0030	0.774	0.837	0.645

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-4, 41	345	2.51	27	27	128	0.0029	0.784	0.845	0.654
C-4, 42	335	2.68	7	41	125	0.0023	0.775	0.835	0.646
C-4, 43	335	2.19	10	38	128	0.0028	0.773	0.832	0.644
C-4, 44	355	2.96	11	46	124	0.0026	0.798	0.865	0.665
C-4, 45	355	2.68	11	46	126	0.0029	0.797	0.863	0.664
C-4, 46	340	2.59	12	48	126	0.0030	0.780	0.848	0.650
C-4, 47	340	2.59	12	48	126	0.0030	0.780	0.848	0.650
C-4, 48	335	2.30	25	30	127	0.0031	0.774	0.836	0.645
C-4, 49	335	2.37	24	24	125	0.0027	0.775	0.832	0.646
C-4, 50	325	2.19	12	12	127	0.0014	0.762	0.803	0.635
C-4, 51	325	2.31	6	6	126	0.0007	0.763	0.795	0.636
C-4, 52	315	2.36	9	3	127	0.0006	0.751	0.782	0.626
C-4, 53	315	2.42	24	24	128	0.0025	0.750	0.807	0.625
C-4, 56	315	2.36	20	13	125	0.0018	0.752	0.798	0.627
C-4, 57	315	2.33	23	15	127	0.0020	0.751	0.800	0.626
C-4, 58	335	2.17	29	19	125	0.0029	0.775	0.831	0.646
C-4, 59	335	1.59	32	21	126	0.0044	0.774	0.834	0.645
C-4, 60	325	2.19	17	18	125	0.0020	0.764	0.812	0.636
C-4, 61	365	2.26	10	8	124	0.0011	0.809	0.846	0.674
C-4, 62	325	2.26	8	8	125	0.0009	0.764	0.798	0.636
C-4, 63	305	1.87	6	6	122	0.0008	0.742	0.774	0.618
C-4, 65	315	2.00	15	15	122	0.0019	0.754	0.799	0.628
C-4, 66	315	1.78	30	13	122	0.0031	0.754	0.806	0.628
C-4, 67	315	1.89	17	9	122	0.0018	0.754	0.795	0.628
C-4, 68	335	1.68	16	8	120	0.0019	0.778	0.819	0.649

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-4, 69	315	1.89	14	8	122	0.0015	0.754	0.793	0.628
C-4, 70	315	1.99	6	3	124	0.0006	0.754	0.784	0.629
C-4, 71	315	1.89	21	12	122	0.0022	0.754	0.800	0.628
C-4, 72	295	1.93	14	7	122	0.0013	0.730	0.768	0.608
C-4, 73	295	1.95	20	16	122	0.0022	0.730	0.779	0.608
C-4, 74	285	1.75	33	27	122	0.0039	0.717	0.783	0.598
C-4, 75	295	0.87	31	25	120	0.0075	0.731	0.794	0.609
C-4, 76	305	0.73	25	21	120	0.0032	0.743	0.799	0.619
C-4, 77	315	1.67	19	13	120	0.0024	0.755	0.801	0.629
C-4, 78	315	1.86	22	18	120	0.0027	0.755	0.807	0.629
C-4, 79	285	1.91	10	8	123	0.0011	0.717	0.753	0.597
C-4, 80	285	1.89	9	7	125	0.0010	0.716	0.750	0.596
C-4, 81	365	1.68	22	14	120	0.0031	0.812	0.861	0.677
C-4, 82	365	1.30	23	13	115	0.0040	0.816	0.865	0.680
C-4, 83	375	1.26	14	11	116	0.0029	0.826	0.868	0.688
C-4, 84	355	1.44	13	6	120	0.0019	0.801	0.838	0.668
C-4, 85	395	1.64	16	21	116	0.0035	0.847	0.898	0.706
C-4, 86	295	1.58	14	18	120	0.0023	0.731	0.778	0.609
C-4, 87	295	1.65	12	12	122	0.0017	0.730	0.770	0.608
C-4, 88	275	1.45	12	10	122	0.0016	0.705	0.744	0.587
C-4, 89	275	1.53	3	3	187	0.0004	0.669	0.693	0.557
C-4, 90	275	1.62	8	7	124	0.0010	0.704	0.738	0.586
C-4, 91	275	1.41	6	6	120	0.0009	0.706	0.738	0.588
C-4, 92	295	1.38	21	11	116	0.0027	0.733	0.780	0.611
C-4, 93	295	1.36	11	7	115	0.0016	0.734	0.771	0.612

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-4, 94	265	1.21	10	4	106	0.0012	0.702	0.736	0.585
C-4, 95	275	1.25	10	10	116	0.0017	0.708	0.747	0.590
C-4, 96	285	1.36	26	22	116	0.0040	0.721	0.779	0.601
C-4, 97	285	1.38	18	18	116	0.0029	0.721	0.771	0.601
C-4, 98	285	1.20	7	7	116	0.0013	0.721	0.755	0.601
C-4, 99	275	1.11	9	9	118	0.0018	0.707	0.744	0.589
C-4, 100	295	1.08	7	7	116	0.0015	0.733	0.767	0.611
C-4, 101	275	1.25	7	5	114	0.0010	0.710	0.742	0.591
C-4, 102	275	1.19	6	5	113	0.0010	0.710	0.742	0.592
C-4, 103	275	1.14	8	6	113	0.0013	0.710	0.744	0.592
C-4, 105	280	0.97	3	2	112	0.0006	0.717	0.745	0.598
C-4, 106	255	1.03	5	4	110	0.0009	0.686	0.717	0.572
C-4, 107	235	0.72	3	2	110	0.0006	0.659	0.686	0.549
C-4, 108	235	0.98	8	6	108	0.0013	0.660	0.694	0.550
C-4, 109	235	0.73	3	3	107	0.0008	0.660	0.689	0.550
C-4, 110	225	0.72	4	3	91	0.0009	0.656	0.686	0.546
C-4, 111	225	0.47	5	11	102	0.0029	0.649	0.687	0.541
C-4, 112	255	1.68	8	4	114	0.0007	0.684	0.716	0.570
C-4, 113	355	1.85	18	6	122	0.0019	0.800	0.840	0.666
C-4, 115	295	1.34	61	15	127	0.0068	0.727	0.799	0.606
C-4, 116	275	1.67	115	76	129	0.0124	0.701	0.848	0.624
C-4, 117	285	1.69	64	46	128	0.0073	0.714	0.811	0.595
C-4, 118	265	0.80	7	5	128	0.0016	0.688	0.720	0.574
C-4, 119	265	1.78	9	7	122	0.0009	0.692	0.727	0.577
C-4, 120	275	1.77	5	4	124	0.0006	0.704	0.733	0.586

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
C-4, 121	275	1.68	24	260	128	0.0171	0.701	0.924	0.641
C-4, 122	255	1.62	10	14	127	0.0015	0.676	0.717	0.563
C-4, 123	295	1.48	46	38	127	0.0066	0.727	0.808	0.606
C-4, 124	285	1.37	12	12	127	0.0020	0.714	0.755	0.595
C-4, 125	255	1.61	15	10	128	0.0016	0.675	0.716	0.563
C-4, 126	255	1.64	12	12	126	0.0015	0.677	0.717	0.564
C-4, 127	295	1.56	21	21	128	0.0031	0.726	0.779	0.605
C-4, 128	265	0.85	488	400	162	0.0987	0.670	1.145	0.689
C-4, 129	235	0.35	232	284	145	0.1193	0.640	0.971	0.660
C-4, 130	235	0.31	220	268	110	0.1264	0.659	0.990	0.686

Well D-1

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
D-1, 2	2381	5.40	3	168	121	0.0272	1.999	2.204	2.364
D-1, 3	1457	10.79	32	648	219	0.0331	1.477	1.832	1.641
D-1, 4	1615	9.18	29	713	217	0.0463	1.554	1.931	1.836
D-1, 5	1030	10.54	52	1053	246	0.0387	1.227	1.711	1.325
D-1, 6	1566	5.85	16	732	211	0.0692	1.538	1.921	1.910
D-1, 7	1742	3.28	24	308	168	0.0618	1.669	1.907	2.104
D-1, 8	943	9.13	32	1368	244	0.0510	1.177	1.750	1.298
D-1, 9	1613	2.95	17	377	171	0.0742	1.606	1.869	2.046

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
D-1, 10	1446	2.34	31	395	177	0.0895	1.517	1.787	1.938
D-1, 11	1426	2.23	27	473	169	0.1065	1.517	1.822	1.978
D-1, 12	873	5.62	47	1952	250	0.1034	1.129	1.845	1.324
D-1, 14	664	2.82	56	1138	200	0.0948	1.023	1.550	1.157
D-1, 15	675	2.70	56	689	194	0.0651	1.036	1.412	1.135
D-1, 16	618	2.87	56	622	188	0.0518	0.997	1.351	1.058
D-1, 17	603	1.46	56	396	163	0.0656	1.004	1.270	1.092
D-1, 18	606	0.93	50	209	117	0.0601	1.045	1.227	1.138
D-1, 21	585	0.72	43	181	137	0.0645	1.010	1.168	1.098
D-1, 30	431	0.01	0	2	130	0.0309	0.874	0.897	0.863
D-1, 31	484	1.54	36	577	176	0.0670	0.892	1.232	0.946
D-1, 32	441	0.57	57	4	96	0.0191	0.910	0.969	0.864
D-1, 33	548	2.32	349	765	172	0.0919	0.951	1.451	1.052
D-1, 34	528	2.33	189	417	184	0.0502	0.925	1.241	0.964
D-1, 35	499	2.19	155	368	179	0.0438	0.903	1.189	0.925
D-1, 36	487	1.86	149	325	170	0.0456	0.899	1.165	0.923
D-1, 37	468	1.80	149	310	168	0.0440	0.883	1.143	0.900
D-1, 38	492	1.21	163	224	145	0.0578	0.922	1.151	0.971
D-1, 39	487	1.25	127	240	149	0.0523	0.914	1.136	0.953
D-1, 40	483	1.21	141	223	146	0.0534	0.912	1.133	0.953
D-1, 41	479	1.06	133	178	143	0.0520	0.911	1.105	0.949
D-1, 42	433	1.08	102	217	144	0.0469	0.866	1.069	0.885
D-1, 43	451	1.02	109	314	137	0.0667	0.889	1.147	0.941
D-1, 44	445	0.74	114	117	120	0.0518	0.896	1.052	0.929
D-1, 45	452	0.81	180	133	126	0.0648	0.898	1.092	0.951

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
D-1, 47	462	0.66	115	157	123	0.0691	0.910	1.090	0.972
D-1, 48	465	0.63	108	134	114	0.0653	0.920	1.085	0.980
D-1, 49	501	0.57	14	31	107	0.0150	0.960	1.014	0.894
D-1, 50	493	0.30	117	43	100	0.0961	0.958	1.075	1.066
D-1, 51	468	0.30	105	77	105	0.1013	0.930	1.061	1.032
D-1, 53	622	4.28	379	22/	191	0.0340	0.998	1.287	1.017
D-1, 54	517	2.60	220	319	180	0.0400	0.919	1.203	0.936
D-1, 55	497	2.56	203	374	183	0.0415	0.899	1.202	0.915
D-1, 56	537	2.01	205	383	167	0.0572	0.945	1.257	1.001
D-1, 57	552	1.93	170	328	171	0.0521	0.955	1.228	1.005
D-1, 58	542	2.03	161	295	176	0.0450	0.943	1.196	0.976
D-1, 59	465	2.09	131	266	177	0.0329	0.874	1.104	0.867
D-1, 60	486	1.74	261	93	166	0.0385	0.901	1.095	0.911
D-1, 61	500	1.57	127	177	162	0.0363	0.916	1.102	0.925
D-1, 62	496	1.82	125	182	171	0.0315	0.906	1.091	0.901
D-1, 63	506	1.57	146	151	160	0.0363	0.923	1.103	0.933
D-1, 64	491	0.26	113	287	169	0.2245	0.903	1.138	1.061
D-1, 65	470	1.91	89	576	153	0.0580	0.895	1.263	0.938
D-1, 66	479	3.69	145	294	166	0.0215	0.894	1.146	0.856
D-1, 67	471	0.86	109	131	137	0.0489	0.908	1.066	0.940
D-1, 68	457	0.30	79	106	120	0.0990	0.907	1.041	0.998

Well D-2

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
D-2, 8	528	0.49	0	12	91	0.0048	0.999	1.040	0.832
D-2, 9	510	0.49	1	0	97	0.0004	0.629	0.648	0.525
D-2, 10	500	0.53	0	5	90	0.0017	0.973	1.008	0.811
D-2, 20	415	0.64	0	25	95	0.0060	0.884	0.934	0.737
D-2, 21	389	0.66	0	28	90	0.0061	0.860	0.913	0.717
D-2, 24	714	8.15	683	104	173	0.0275	1.082	1.463	1.095
D-2, 25	610	5.93	302	69	186	0.0153	0.992	1.210	0.930
D-2, 26	543	3.45	213	52	172	0.0167	0.947	1.119	0.891
D-2, 27	498	2.19	157	46	164	0.0184	0.913	1.057	0.864
D-2, 28	487	0.76	112	49	127	0.0399	0.931	1.060	0.950
D-2, 29	478	1.12	106	115	138	0.0357	0.914	1.083	0.921
D-2, 30	470	1.37	108	161	144	0.0346	0.902	1.100	0.904
D-2, 31	434	1.10	92	131	143	0.0331	0.868	1.040	0.861
D-2, 32	442	0.68	83	117	120	0.0482	0.893	1.056	0.920
D-2, 33	428	0.53	9	22	111	0.0095	0.885	0.937	0.738
D-2, 34	460	0.12	59	13	168	0.1013	0.875	0.944	0.956
D-2, 35	497	0.57	7	1	106	0.0029	0.957	0.992	0.797
D-2, 36	486	0.55	18	18	105	0.0124	0.947	1.003	0.864
D-2, 38	495	0.10	0	43	102	0.0730	0.958	1.023	1.041
D-2, 39	471	0.10	7	55	99	0.0988	0.938	1.016	1.040

Well D-3

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
D-3, 1	442	0.96	0	15	99	0.0025	0.909	0.950	0.757
D-3, 2	900	4.35	487	14	160	0.0413	1.224	1.495	1.331
D-3, 3	565	4.97	419	23	175	0.0204	0.963	1.210	0.927
D-3, 5	574	2.65	258	0	149	0.0227	0.638	0.782	0.674
D-3, 6	495	1.61	147	24	130	0.0211	0.936	1.067	0.900
D-3, 7	460	1.28	115	59	126	0.0245	0.906	1.045	0.879
D-3, 11	509	2.49	200	28	129	0.0188	0.950	1.111	0.904
D-3, 12	556	2.16	181	59	138	0.0244	0.984	1.154	0.968
D-3, 13	550	1.95	180	92	135	0.0298	0.981	1.173	0.984
D-3, 14	543	1.95	154	65	136	0.0240	0.974	1.136	0.955
D-3, 15	483	1.27	149	31	119	0.0272	0.933	1.072	0.920
D-3, 16	483	1.28	149	31	119	0.0270	0.933	1.072	0.919
D-3, 17	459	0.18	0	5	101	0.0048	0.924	0.958	0.770
D-3, 18	450	0.41	54	0	94	0.0239	0.594	0.643	0.622
D-3, 20	410	1.08	148	63	124	0.0313	0.857	1.018	0.844
D-3, 21	410	1.08	148	63	124	0.0313	0.857	1.018	0.844
D-3, 22	408	1.10	134	67	123	0.0290	0.856	1.012	0.837
D-3, 23	400	0.71	108	57	121	0.0359	0.849	0.984	0.845
D-3, 24	407	1.00	58	35	100	0.0149	0.872	0.965	0.804
D-3,28	425	1.02	105	242	120	0.0526	0.875	1.132	0.906
D-3, 29	414	0.10	37	83	107	0.1604	0.874	0.991	0.990

Well E-1

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
E-1, 1	796	1.50	936	0	123	0.1715	1.148	1.562	1.707
E-1, 2	824	1.50	616	0	122	0.1236	1.168	1.479	1.677
E-1, 3	605	1.40	318	1	118	0.0543	1.567	1.786	1.689
E-1, 4	549	1.20	83	59	109	0.0252	1.506	1.641	1.490
E-1, 5	291	1.50	107	52	123	0.0122	1.088	1.227	0.971
E-1, 6	583	1.30	73	47	108	0.0210	1.552	1.674	1.513
E-1, 7	285	1.30	73	25	116	0.0086	1.083	1.183	0.903
E-1, 8	280	1.30	49	43	111	0.0078	1.078	1.178	0.899
E-1, 9	542	0.60	8	46	96	0.0181	1.513	1.598	1.447
E-1, 10	284	1.10	90	52	104	0.0144	1.093	1.226	0.988
E-1, 11	286	1.10	47	30	103	0.0079	1.098	1.187	0.915
E-1, 12	240	0.90	17	33	92	0.0051	1.016	1.091	0.847
E-1, 13	1621	3.70	42	86	93	0.0212	2.573	2.767	2.776
E-1, 14	1628	4.90	27	109	92	0.0169	2.580	2.784	2.679
E-1, 15	862	3.90	410	161	156	0.0485	1.806	2.149	1.992
E-1, 16	794	4.10	10	0	157	0.0008	1.115	1.152	0.929
E-1, 18	635	3.90	55	39	163	0.0060	1.547	1.644	1.289
E-1, 19	772	3.50	1	1	149	0.0002	1.721	1.768	1.434
E-1, 21	1051	2.40	0	3	125	0.0005	2.038	2.105	1.698
E-1, 25	534	2.60	11	29	145	0.0031	1.441	1.507	1.201
E-1, 28	685	2.50	0	1	141	0.0001	1.634	1.678	1.362
E-1, 29	557	2.60	47	61	147	0.0090	1.469	1.578	1.224
E-1, 30	555	2.60	23	24	145	0.0039	1.469	1.538	1.224

Data No.	FTP (psia)	Gas rate (MMscf/d)	Oil rate (bbl/d)	Water rate (bbl/d)	Temperature (°F)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
E-1, 32	564	2.40	35	42	144	0.0070	1.482	1.571	1.235
E-1, 33	554	2.50	14	18	136	0.0028	1.479	1.539	1.232
E-1, 34	548	2.40	4	3	136	0.0006	1.471	1.514	1.226
E-1, 36	540	2.00	4	8	139	0.0012	1.457	1.503	1.214
E-1, 37	575	2.20	36	134	133	0.0166	1.510	1.667	1.429
E-1, 38	597	2.00	10	24	138	0.0039	1.531	1.595	1.276
E-1, 44	533	1.80	41	97	136	0.0154	1.451	1.584	1.357
E-1, 46	358	1.70	0	2	124	0.0002	1.204	1.240	1.004
E-1, 50	335	2.10	0	1	141	0.0001	1.149	1.182	0.958
E-1, 51	512	2.00	56	93	117	0.0146	1.445	1.587	1.343
E-1, 52	311	1.70	20	8	131	0.0021	1.117	1.168	0.931
E-1, 53	328	1.60	36	20	118	0.0046	1.159	1.232	0.966
E-1, 55	286	1.80	10	2	133	0.0008	1.070	1.109	0.891
E-1, 56	287	1.80	20	5	135	0.0016	1.070	1.118	0.891
E-1, 57	282	1.60	15	6	127	0.0015	1.068	1.114	0.890
E-1, 58	280	1.50	20	7	131	0.0020	1.060	1.110	0.884
E-1, 59	288	1.40	25	8	133	0.0027	1.073	1.127	0.894
E-1 ,62	269	1.50	7	2	119	0.0007	1.050	1.089	0.875
E-1, 67	266	1.00	11	3	107	0.0015	1.055	1.098	0.879
E-1, 68	272	1.00	3	2	101	0.0005	1.072	1.110	0.894
E-1, 69	258	0.40	12	2	94	0.0037	1.051	1.095	0.876

Appendix B

Sensitivity analysis of fluid properties data

1.) Sensitivity analysis on gas specific gravity (γ_g)

1.1) Production condition No.1: Low FTP and low liquid production rate, condensate properties case (315 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	50	0	0.0043	0.423	0.469	0.352
+20%	315	50	0	0.0043	0.440	0.483	0.367
+10%	315	50	0	0.0043	0.460	0.498	0.384
+5%	315	50	0	0.0043	0.471	0.507	0.393
Base case	315	50	0	0.0043	0.483	0.516	0.403
-5%	315	50	0	0.0043	0.496	0.526	0.416
-10%	315	50	0	0.0043	0.510	0.537	0.425
-20%	315	50	0	0.0043	0.541	0.562	0.451
-30%	315	50	0	0.0043	0.579	0.594	0.482

1.2) Production condition No.2: Low FTP and high liquid production rate, condensate properties case (315 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	375	0	0.0312	0.423	0.592	0.451
+20%	315	375	0	0.0312	0.440	0.607	0.466
+10%	315	375	0	0.0312	0.460	0.624	0.482
+5%	315	375	0	0.0312	0.471	0.634	0.491
Base case	315	375	0	0.0312	0.483	0.644	0.501
-5%	315	375	0	0.0312	0.496	0.656	0.512
-10%	315	375	0	0.0312	0.510	0.668	0.523
-20%	315	375	0	0.0312	0.541	0.696	0.549
-30%	315	375	0	0.0312	0.579	0.730	0.581

1.3) Production condition No.3: High FTP and low liquid production rate, condensate properties case (685 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	685	50	0	0.0093	0.617	0.677	0.514
+20%	685	50	0	0.0093	0.643	0.697	0.536
+10%	685	50	0	0.0093	0.672	0.719	0.560
+5%	685	50	0	0.0093	0.689	0.732	0.574
Base case	685	50	0	0.0093	0.706	0.746	0.589
-5%	685	50	0	0.0093	0.725	0.760	0.604
-10%	685	50	0	0.0093	0.746	0.777	0.621
-20%	685	50	0	0.0093	0.792	0.814	0.660
-30%	685	50	0	0.0093	0.848	0.860	0.707

1.4) Production condition No.4: High FTP and high liquid production rate, condensate properties case (685 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	685	375	0	0.0655	0.617	0.793	0.820
+20%	685	375	0	0.0655	0.643	0.814	0.842
+10%	685	375	0	0.0655	0.672	0.839	0.866
+5%	685	375	0	0.0655	0.689	0.853	0.880
Base case	685	375	0	0.0655	0.706	0.867	0.895
-5%	685	375	0	0.0655	0.725	0.883	0.910
-10%	685	375	0	0.0655	0.746	0.901	0.928
-20%	685	375	0	0.0655	0.792	0.940	0.966
-30%	685	375	0	0.0655	0.848	0.989	1.013

1.5) Production condition No.5: Low FTP and low liquid production rate, water properties case (315 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	0	50	0.0038	0.656	0.727	0.546
+20%	315	0	50	0.0038	0.683	0.748	0.569
+10%	315	0	50	0.0038	0.714	0.772	0.595
+5%	315	0	50	0.0038	0.730	0.786	0.609
Base case	315	0	50	0.0038	0.749	0.800	0.624
-5%	315	0	50	0.0038	0.768	0.816	0.640
-10%	315	0	50	0.0038	0.790	0.834	0.658
-20%	315	0	50	0.0038	0.838	0.873	0.698
-30%	315	0	50	0.0038	0.896	0.922	0.747

1.6) Production condition No.6: Low FTP and high liquid production rate, water properties case (315 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	0	375	0.0279	0.656	0.905	0.639
+20%	315	0	375	0.0279	0.683	0.929	0.661
+10%	315	0	375	0.0279	0.714	0.956	0.687
+5%	315	0	375	0.0279	0.730	0.971	0.701
Base case	315	0	375	0.0279	0.749	0.987	0.716
-5%	315	0	375	0.0279	0.768	1.005	0.732
-10%	315	0	375	0.0279	0.790	1.024	0.750
-20%	315	0	375	0.0279	0.838	1.069	0.790
-30%	315	0	375	0.0279	0.896	1.123	0.839

1.7) Production condition No.7: High FTP and low liquid production rate, water properties case (685 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	685	0	50	0.0082	0.959	1.047	0.799
+20%	685	0	50	0.0082	0.999	1.077	0.833
+10%	685	0	50	0.0082	1.045	1.112	0.871
+5%	685	0	50	0.0082	1.070	1.132	0.892
Base case	685	0	50	0.0082	1.097	1.153	0.914
-5%	685	0	50	0.0082	1.127	1.176	0.939
-10%	685	0	50	0.0082	1.158	1.201	0.965
-20%	685	0	50	0.0082	1.230	1.259	1.025
-30%	685	0	50	0.0082	1.316	1.330	1.097

1.8) Production condition No.8: High FTP and high liquid production rate, water properties case (685 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	685	0	375	0.0587	0.959	1.212	1.092
+20%	685	0	375	0.0587	0.999	1.245	1.125
+10%	685	0	375	0.0587	1.045	1.283	1.163
+5%	685	0	375	0.0587	1.070	1.304	1.184
Base case	685	0	375	0.0587	1.097	1.326	1.207
-5%	685	0	375	0.0587	1.127	1.351	1.231
-10%	685	0	375	0.0587	1.158	1.378	1.257
-20%	685	0	375	0.0587	1.230	1.439	1.317
-30%	685	0	375	0.0587	1.316	1.514	1.389

2.) Sensitivity analysis on condensate density (ρ_o)

2.1) Production condition No.1: Low FTP and low liquid production rate (315 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	315	50	0	0.0043	0.506	0.539	0.422
+10%	315	50	0	0.0043	0.495	0.528	0.413
+5%	315	50	0	0.0043	0.489	0.522	0.408
Base case	315	50	0	0.0043	0.483	0.516	0.403
-5%	315	50	0	0.0043	0.477	0.509	0.397
-10%	315	50	0	0.0043	0.470	0.503	0.392
-20%	315	50	0	0.0043	0.456	0.489	0.380

2.2) Production condition No.2: Low FTP and high liquid production rate (315 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	315	375	0	0.0312	0.506	0.670	0.521
+10%	315	375	0	0.0312	0.495	0.657	0.511
+5%	315	375	0	0.0312	0.489	0.651	0.506
Base case	315	375	0	0.0312	0.483	0.644	0.501
-5%	315	375	0	0.0312	0.477	0.637	0.496
-10%	315	375	0	0.0312	0.470	0.630	0.491
-20%	315	375	0	0.0312	0.456	0.615	0.479

2.3) Production condition No.3: High FTP and low liquid production rate (685 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	685	50	0	0.0093	0.741	0.780	0.618
+10%	685	50	0	0.0093	0.724	0.763	0.604
+5%	685	50	0	0.0093	0.716	0.755	0.596
Base case	685	50	0	0.0093	0.706	0.746	0.589
-5%	685	50	0	0.0093	0.697	0.736	0.581
-10%	685	50	0	0.0093	0.687	0.727	0.572
-20%	685	50	0	0.0093	0.665	0.706	0.554

2.4) Production condition No.4: High FTP and high liquid production rate (685 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	685	375	0	0.0655	0.741	0.903	0.924
+10%	685	375	0	0.0655	0.724	0.886	0.910
+5%	685	375	0	0.0655	0.716	0.877	0.902
Base case	685	375	0	0.0655	0.706	0.867	0.895
-5%	685	375	0	0.0655	0.697	0.858	0.887
-10%	685	375	0	0.0655	0.687	0.848	0.878
-20%	685	375	0	0.0655	0.665	0.826	0.861

3.) Sensitivity analysis on water density (ρ_w)

3.1) Production condition No.1: Low FTP and low liquid production rate (315 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	315	0	50	0.0038	0.784	0.838	0.654
+10%	315	0	50	0.0038	0.767	0.820	0.639
+5%	315	0	50	0.0038	0.758	0.810	0.632
Base case	315	0	50	0.0038	0.749	0.800	0.624
-5%	315	0	50	0.0038	0.739	0.790	0.616
-10%	315	0	50	0.0038	0.729	0.780	0.607
-20%	315	0	50	0.0038	0.707	0.757	0.589

3.2) Production condition No.2: Low FTP and high liquid production rate (315 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	315	0	375	0.0279	0.784	1.028	0.746
+10%	315	0	375	0.0279	0.767	1.008	0.731
+5%	315	0	375	0.0279	0.758	0.998	0.724
Base case	315	0	375	0.0279	0.749	0.987	0.716
-5%	315	0	375	0.0279	0.739	0.976	0.708
-10%	315	0	375	0.0279	0.729	0.965	0.700
-20%	315	0	375	0.0279	0.707	0.940	0.682

3.3) Production condition No.3: High FTP and low liquid production rate (685 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	685	0	50	0.0082	1.151	1.206	0.959
+10%	685	0	50	0.0082	1.125	1.181	0.938
+5%	685	0	50	0.0082	1.111	1.167	0.926
Base case	685	0	50	0.0082	1.097	1.153	0.914
-5%	685	0	50	0.0082	1.083	1.138	0.902
-10%	685	0	50	0.0082	1.067	1.123	0.890
-20%	685	0	50	0.0082	1.035	1.091	0.862

3.4) Production condition No.4: High FTP and high liquid production rate (685 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+20%	685	0	375	0.0587	1.151	1.382	1.251
+10%	685	0	375	0.0587	1.125	1.355	1.230
+5%	685	0	375	0.0587	1.111	1.341	1.219
Base case	685	0	375	0.0587	1.097	1.326	1.207
-5%	685	0	375	0.0587	1.083	1.311	1.195
-10%	685	0	375	0.0587	1.067	1.296	1.182
-20%	685	0	375	0.0587	1.035	1.262	1.155

4.) Sensitivity analysis on gas-condensate surface tension (σ_o)

4.1) Production condition No.1: Low FTP and low liquid production rate (315 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	50	0	0.0043	0.516	0.550	0.430
+20%	315	50	0	0.0043	0.506	0.539	0.421
+10%	315	50	0	0.0043	0.495	0.528	0.412
+5%	315	50	0	0.0043	0.489	0.522	0.408
Base case	315	50	0	0.0043	0.483	0.516	0.403
-5%	315	50	0	0.0043	0.477	0.509	0.397
-10%	315	50	0	0.0043	0.471	0.503	0.392
-20%	315	50	0	0.0043	0.457	0.489	0.381
-30%	315	50	0	0.0043	0.442	0.473	0.368

4.2) Production condition No.2: Low FTP and high liquid production rate (315 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	375	0	0.0312	0.516	0.681	0.529
+20%	315	375	0	0.0312	0.506	0.670	0.520
+10%	315	375	0	0.0312	0.495	0.657	0.511
+5%	315	375	0	0.0312	0.489	0.651	0.506
Base case	315	375	0	0.0312	0.483	0.644	0.501
-5%	315	375	0	0.0312	0.477	0.637	0.496
-10%	315	375	0	0.0312	0.471	0.630	0.491
-20%	315	375	0	0.0312	0.457	0.615	0.479
-30%	315	375	0	0.0312	0.442	0.598	0.467

4.3) Production condition No.3: High FTP and low liquid production rate (685 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
+30%	685	50	0	0.0093	0.754	0.795	0.629
+20%	685	50	0	0.0093	0.739	0.780	0.616
+10%	685	50	0	0.0093	0.723	0.763	0.603
+5%	685	50	0	0.0093	0.715	0.755	0.596
Base case	685	50	0	0.0093	0.706	0.746	0.589
-5%	685	50	0	0.0093	0.697	0.736	0.581
-10%	685	50	0	0.0093	0.688	0.727	0.573
-20%	685	50	0	0.0093	0.668	0.706	0.557
-30%	685	50	0	0.0093	0.646	0.684	0.538

4.4) Production condition No.4: High FTP and high liquid production rate (685 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner’s critical flowrate (MMscf/d)	Guo’s critical flowrate (MMscf/d)	Zhou’s critical flowrate (MMscf/d)
+30%	685	375	0	0.0655	0.754	0.919	0.935
+20%	685	375	0	0.0655	0.739	0.903	0.922
+10%	685	375	0	0.0655	0.723	0.886	0.909
+5%	685	375	0	0.0655	0.715	0.877	0.902
Base case	685	375	0	0.0655	0.706	0.867	0.895
-5%	685	375	0	0.0655	0.697	0.858	0.887
-10%	685	375	0	0.0655	0.688	0.848	0.879
-20%	685	375	0	0.0655	0.668	0.826	0.863
-30%	685	375	0	0.0655	0.646	0.802	0.844

5.) Sensitivity analysis on gas-water surface tension (σ_w)

5.1) Production condition No.1: Low FTP and low liquid production rate (315 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	0	50	0.0038	0.799	0.855	0.666
+20%	315	0	50	0.0038	0.784	0.838	0.653
+10%	315	0	50	0.0038	0.767	0.820	0.639
+5%	315	0	50	0.0038	0.758	0.810	0.632
Base case	315	0	50	0.0038	0.749	0.800	0.624
-5%	315	0	50	0.0038	0.739	0.790	0.616
-10%	315	0	50	0.0038	0.729	0.780	0.608
-20%	315	0	50	0.0038	0.708	0.757	0.590
-30%	315	0	50	0.0038	0.685	0.733	0.571

5.2) Production condition No.2: Low FTP and high liquid production rate (315 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	315	0	375	0.0279	0.799	1.046	0.758
+20%	315	0	375	0.0279	0.784	1.028	0.745
+10%	315	0	375	0.0279	0.767	1.008	0.731
+5%	315	0	375	0.0279	0.758	0.998	0.724
Base case	315	0	375	0.0279	0.749	0.987	0.716
-5%	315	0	375	0.0279	0.739	0.976	0.708
-10%	315	0	375	0.0279	0.729	0.965	0.700
-20%	315	0	375	0.0279	0.708	0.940	0.682
-30%	315	0	375	0.0279	0.685	0.913	0.663

5.3) Production condition No.3: High FTP and low liquid production rate (685 psia and 50 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	685	0	50	0.0082	1.172	1.230	0.976
+20%	685	0	50	0.0082	1.149	1.206	0.957
+10%	685	0	50	0.0082	1.124	1.181	0.937
+5%	685	0	50	0.0082	1.111	1.167	0.926
Base case	685	0	50	0.0082	1.097	1.153	0.914
-5%	685	0	50	0.0082	1.083	1.138	0.903
-10%	685	0	50	0.0082	1.069	1.123	0.891
-20%	685	0	50	0.0082	1.038	1.091	0.865
-30%	685	0	50	0.0082	1.004	1.056	0.836

5.4) Production condition No.4: High FTP and high liquid production rate (685 psia and 375 bbl/d)

Sensitivity value	FTP (psia)	Oil rate (bbl/d)	Water rate (bbl/d)	Liquid holdup	Turner's critical flowrate (MMscf/d)	Guo's critical flowrate (MMscf/d)	Zhou's critical flowrate (MMscf/d)
+30%	685	0	375	0.0587	1.172	1.407	1.269
+20%	685	0	375	0.0587	1.149	1.382	1.250
+10%	685	0	375	0.0587	1.124	1.355	1.229
+5%	685	0	375	0.0587	1.111	1.341	1.218
Base case	685	0	375	0.0587	1.097	1.326	1.207
-5%	685	0	375	0.0587	1.083	1.311	1.195
-10%	685	0	375	0.0587	1.069	1.296	1.183
-20%	685	0	375	0.0587	1.038	1.262	1.157
-30%	685	0	375	0.0587	1.004	1.225	1.129

Vitae

Sataporn Klaibanmai was born on December 22, 1983 in Nakhon Si Thammarat, Thailand. He received his B.Eng. in Environmental Engineering from the Faculty of Engineering, Kasetsart University in 2006. After graduation, he worked for Construction Company named GETEC for two years and then continued his studies in the Master of Petroleum Engineering program at the Department of Mining and Petroleum Engineering, Faculty of Engineering, Chulalongkorn University.