CHARACTERIZATION OF CRITICAL GAS FLOW RATE TO PREVENT LIQUID LOADING

by

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Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Petroleum Engineering)

MAY 2013

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Petroleum Engineering Programme

Universiti Teknologi PETRONAS

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(PETROLEUM ENGINEERING)

Approved by,

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MAY 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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LIM PEI WEN

ABSTRACT

This report presents the research completed for the Final Year Project entitled 'Characterization of Critical Gas Flow Rate to Prevent Liquid Loading'. The project is aimed to develop a work flow that predicts critical gas flow rate (minimum required gas flow rate) to prevent liquid loading based on the published literature and to analyse effects of temperature, pressure, conduit size, producing depth and inclination on the critical gas flow rate. Turner et al Model and Guo et al Model are selected to be developed in the work flow. Liquid loading is a very common problem in mature gas wells. Hence, it is required to check for the occurrence of the liquid loading problem. It is hoped that by having this project, a better prediction and hence management of the liquid loading problem can be yielded. Scope of study of the current project includes estimation of presence of liquid loading problem by estimating critical gas flow rate to prevent liquid loading and to conduct sensitivity studies for effects of temperature, pressure, conduit size, producing depth and inclination on critical gas flow rate. Fluid characterization is performed by using the necessary fluid properties inputs based on that stated in the papers. In this report, literature review is conducted on the introduction to critical gas flow rate and available models in predicting critical gas flow rates. Project methodology and activities have been planned and the milestones for this project have been designed. The equations included in the work flow and flow charts of the work flow are also included in the report. This report presents the work flow (spread sheet) with two functions, which are estimating critical gas flow rate and performing sensitivity study. The analyses of the results from both functions are also included in this report. It is found that prediction of critical gas flow rate by the Turner et al Model is lower than that of the Guo et al Model at most of the time. Outcomes of the sensitivity studies demonstrate that critical gas flow rate will be increased if temperature is reduced; pressure is increased; conduit size is increased; producing depth is increased or inclination is reduced. In conclusion, the project has been successfully completed and it is hoped that the work flow can be applied in the industry.

ACKNOWLEDGEMENT

First and foremost, I would like to thank Universiti Teknologi PETRONAS (UTP) for coordinating the final year project and providing guidance in completing this final year project which is part of the requirement for Bachelors of Engineering (Hons.) in Petroleum Engineering in the university.

Secondly, a million thanks to my helpful supervisor, Mr. Mohammad Amin Shoushtari for his supervisions and encouragements. He is willing to sacrifice his valuable time to discuss about my project and give advices when I faced problems in conducting the project. With his guidance and endless support, I am able to complete the project successfully and confidently. His hard work is much indeed appreciated. A paper is not enough for me to express support and guidance I received from him in these two semesters.

Also, I would like to thank Miss Lye Yan Ching and Mr Joachim Wan for becoming my discussion partners in solving problems regards to the project. Finally, I would like to express my heartfelt gratitude to my family and friends for their endless supports and suggestions in helping me to complete this project.

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ABBREVIATIONS AND NOMENCLATURES

A	Tubing cross-sectional area (ft^2)
a_g	Parameter a for Guo et al Model (-)
A_z	Parameter A for Turner et al Model (-)
b_g	Parameter b for Guo et al Model (-)
B_z	Parameter B for Turner et al Model (-)
c_g	Parameter c for Guo et al Model (-)
C_d	Drag coefficient (-)
C_z	Parameter C for Turner et al Model (-)
D	Producing depth (ft)
d_g	Parameter d for Guo et al Model (-)
D_h	Hydraulic diameter (ft)
d_t	Tubing inner diameter (inch)
d_{to}	Tubing inner diameter (inch)
d_{to}	Tubing outer diameter (inch)
D_z	Parameter D for Turner et al Model (-)
e_g	Parameter e for Guo et al Model (-)
E_k	Gas specific kinetic energy (lb_f-ft/ft^3)
E_{km}	Minimum kinetic energy required to transport liquid drops (lb_f-ft/ft^3)
E_z	Parameter E for Turner et al Model (-)
f_g	Parameter f for Guo et al Model (-)
F_z	Parameter F for Turner et al Model (-)
k_v	Coefficient of Turner Equation (-)
m_g	Parameter m for Guo et al Model (-)
N_{Re}	Dimensionless Reynolds Number (-)
n_g	Parameter n for Guo et al Model (-)
P	Pressure (lbf/ft^2)
P_{av}	Average pressure (psia)
P_{hf}	Wellhead pressure (psia)
P_{pc}	Pseudo critical pressure (-)
P_{pr}	Pseudo reduced pressure (-)
P_{wf}	Surface pressure (psia)
P_{wh}	Wellhead pressure (psia)
Q_c	Condensate make (bbl/d)
Q_g	Gas production day (scf/d)
Q_{gm}	Minimum required gas flow rate for liquid removal (MMscf/d)
Q_o	Condensate make (bbl/d)
Q_s	Solid make (ft^3/d)
Q_w	Water make (bbl/d)
S_g	Gas specific gravity (-)
S_o	Condensate gravity (-)

S_s	Solid specific gravity (-)
S_w	Water specific gravity (-)
T_{av}	Average temperature (°R)
T_{pc}	Pseudo critical temperature (-)
T_{pr}	Pseudo reduced temperature (-)
T_{pz}	Producing zone temperature (°R)
T_{wf}	Surface temperature (°R)
T_{wh}	Wellhead temperature (°R)
V_g	Gas velocity required to transport liquid drops (ft/s)
V_{gc}	Critical gas velocity required to transport liquid drops (ft/s)
V_{gm}	Minimum gas velocity required to transport liquid drops (ft/s)
V_{sl}	Terminal settling velocity (ft/s)
V_{tr}	Transport velocity (ft/s)
Z	Gas compressibility factor (-)
Z'	Gas compressibility factor in computing gas density (-)
γ_c	Condensate gravity (-)
γ_g	Gas specific gravity (-)
γ_s	Solid specific gravity (-)
γ_w	Water specific gravity (-)
ε	Tubing wall roughness (ft)
θ	Hole inclination (rad)
ρ_g	Gas density (lbm/ft^3)
ρ_l	Liquid density (lbm/ft^3)
σ	Interfacial tension (dynes/cm)

CHAPTER 1

INTRODUCTION

This chapter covers background of study, problem statement, objectives, scope of study, and relevancy and feasibility of the project. In background of study, introductions of liquid loading, gas well deliquification and gas well deliquification techniques are included.

1.1 Background of Study

1.1.1 Liquid Loading

Liquid loading is a common problem as gas wells may produce some liquids as production begins. Water coning, aquifer water, water produced from another zone, free formation water, water of condensation and hydrocarbon condensates are the source of liquids in producing gas wells [1]. The liquids which are not removed will be accumulated in the bottom of the well tubing [2]. The liquids will not be able to be lifted by the well on its own [3]. This phenomenon is known as liquid loading [4]. Lea, Nickens and Wells define liquid loading as inability of the produced gas to remove the produce liquids from the wellbore [1] while Hearn states that liquid loading is a phenomenon that take places when the flow rate of the produced gas is reduced to a velocity where the fluids can no longer be lifted [5]. Figure 1 summarises how liquid loading happens.

Liquid loading occurs when the gas flow velocity decreases and the gas flow does not have sufficient energy to carry liquids up to the surface. This is caused by depletion of reservoir pressure after a period of production. As the pressure drops to a critical point, liquids tend to accumulate at the bottomhole of the well which result in a change of flow regime. The mist-flow regime of the gas well (the flow regime that is usually observed at the beginning of the production) may change to annular flow regime and lastly slug flow regime [6]. As the gas production rate is further decreased due to increasing liquid accumulation at the bottomhole, the flow regime might become bubbly flow regime. Figure 2 depicts the flow regimes in gas wells producing liquid.

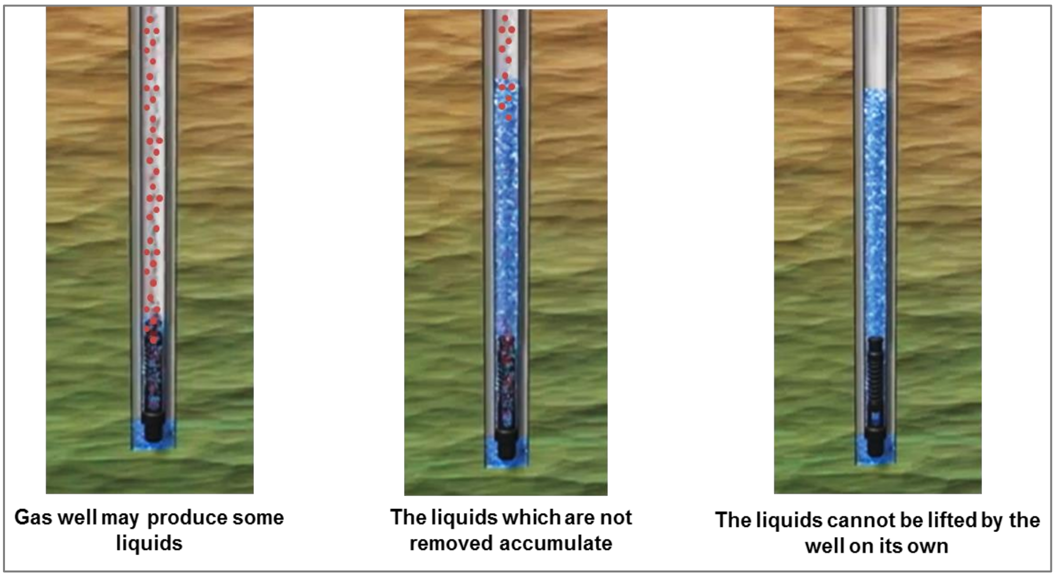


Figure 1 How Liquid Loading Happens? [7]

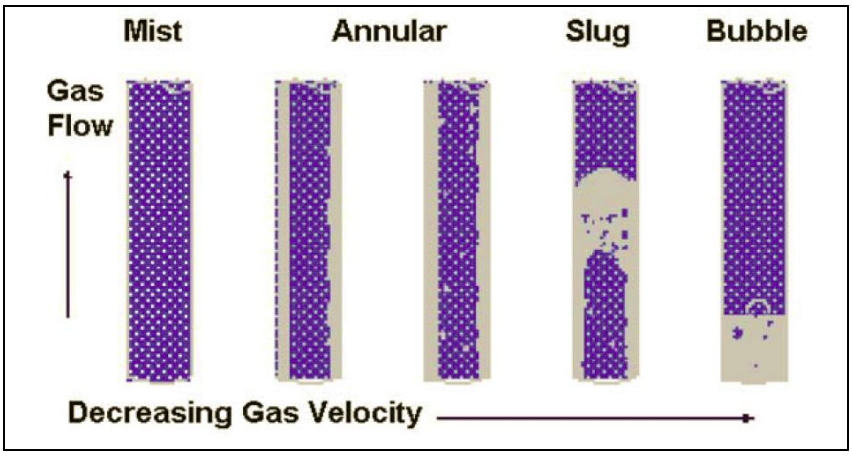


Figure 2 Flow Regimes in Gas Wells Producing Liquids [8]

Amount of liquid produced influences the speed of the subsequent loading up process [2]. The accumulated liquid (liquid hold up) in the wellbore will increase as time passes. This affects the gas relative permeability and causes additional backpressure on the formation which in turn increases the flowing bottom hole pressure and reduces the gas production rate [4], [9]. The increased backpressure may increase the risk of formation damage [10]. If problem of liquid loading is not solved, increasing amount of accumulated liquid will result in reduction of the relative permeability to gas, in which eventually there will be adequate energy to balance the available reservoir energy. In this case, the well may die [11]. In the end, production may be stopped which is followed by higher operating cost and expenditures. Figure 3 summarizes the effects of liquid loading.

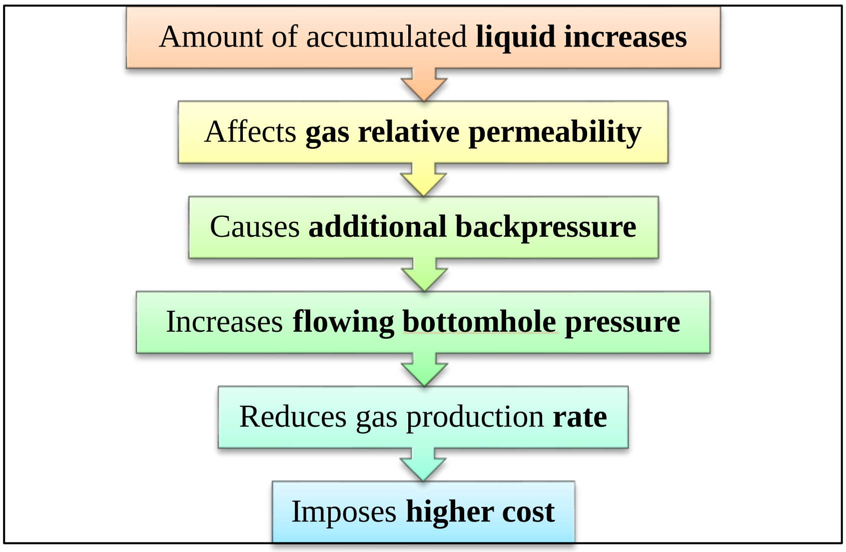


Figure 3 Effects of Liquid Loading

Identification of liquid loading problem is not easy as it is not clear to be observed. However, Guo, Ghalambor and Xu state that there are a few symptoms to check for liquid loading problems (onset of liquid slugs at the surface of the well, increasing difference between the tubing and casing pressure with time, sharp changes in gradient on a flowing pressure survey and sharp drops in a production decline curve) [6].

1.1.2 Gas Well Deliquification

Deliquification is the process of removing associated liquids, which could be water, oils or condensates from the wellbore and reservoir to the surface [9]. Veeken and Belfoid stated that the prediction of the time of liquid loading and selection of the best deliquification techniques are the two important components in ensuring successful tail-end production from gas wells [13]. They also proposed that ultimate recovery of the wells can be improved by 1 to 10% through deliquification.

Deliquification techniques must be cost-effective in long run where they are applied with minimum requirements for intervention, monitoring and optimization [14].

1.1.3 Gas Well Deliquification Techniques

Gas well deliquification techniques can be classified based on well's natural energy deliquifying systems (velocity strings, well cycling and venting, plunger lift, surfactant/former, and pit blow-downs) and energy-adding deliquifying systems (beam pump, sucker rod pump, electric submersible pump, progressing cavity pump, hydraulic pump, compression, swabbing, gas lift and down-hole separation/reinjection) [4], [9]. The techniques can be also grouped in terms of surface techniques (venting, intermitting, soaping, chemical injection, gas lift, and compression) and subsurface techniques (velocity strings, pumping unit, electrical submersible pumps and plunger lift) [2]. Basically, gas well deliquification techniques work based on four principles, which are [14]:

- Increasing actual gas rate above minimum gas rate
- Reducing minimum gas rate below actual gas rate
- Reducing hydrostatic component of pressure drop
- Removing liquids

1.2 Problem Statement

Liquid loading is a very common problem in mature gas wells. It is problematic and unfavourable as it reduces the gas production rates and increases the operating cost and expenditure. It may cease the production if the problem is prolonged which results in workover cost.

It is necessary to predict the occurrence of liquid loading in gas wells. There is a need to check the **onset of liquid loading** to know the point where liquid loading might occur in a gas well. Hence, a proper estimation of the minimum required gas flow rate (critical gas flow rate) for liquid removal is required to prevent liquid loading problem.

On top of that, it is required to know the **effect of parameters** (such as temperature, pressure, conduit size, producing depth and inclination) on the onset of liquid loading. Thus, proper sensitivity studies for these parameters on critical gas flow rate are needed to be carried out.

At the moment, there is no work flow (spread sheet) available that combines estimation of critical gas flow rates by using different models and section to conduct sensitivity studies. Hence, this project aims to develop an Excel-based work flow that combining both functions by using the developed effects. This project is worked with hopes to have a better management of the liquid loading problem.

1.3 Objectives

The objectives of this project are:

- To develop a work flow that predicts minimum required gas flow rate (critical gas flow rate) to prevent liquid loading based on the published literature.
- To analyse effects of temperature, pressure, conduit size, producing depth and inclination on the critical gas flow rate.

1.4 Scope of Study

The overall study plan includes conducting researches on the theories of liquid loading, gas well deliquification and gas well deliquification techniques; studying prediction of critical gas flow rate to prevent liquid loading problem; reviewing available models on prediction of minimum required gas flow rate for liquid removal; understanding the mathematical formulation of the chosen models developed by the researchers; getting familiar with Microsoft Excel; developing a spread sheet to predict critical gas flow rate to prevent liquid loading; and performing sensitivity studies to study effects of temperature, pressure and tubing inner diameter on critical gas flow rate.

This project focuses in predicting liquid loading by estimating the minimum required gas flow rate for liquid elimination in gas wells and performing sensitivity studies. Fluid characterization is to be performed by gas specific gravity, water specific gravity, solid specific gravity, condensate gravity, liquid density, interfacial tension, water production rate, solid production rate, condensate production rate, and major liquid (whether the major liquid is water or condensate). The necessary inputs of the spread sheet may be obtained from production historical data, well completion data or fluid analysis report. Other inputs, such as surface (or wellhead) temperature, surface (or wellhead) pressure, tubing outer diameter, tubing inner diameter, tubing wall roughness, hole inclination, and producing depth, may be extracted from production operational data.

1.5 Relevancy of the Project

This project is relevant as liquid loading is a common problem in gas well production which is part of the Petroleum Engineering. Prediction of occurrence of liquid loading in gas well is important in ensuring production optimisation. Two models developed by researches are used to calculate the minimum required gas flow rate for liquid removal in gas well. A spread sheet that checks the occurrence of liquid loading by calculating critical gas flow rate will be developed. It will be useful providing estimations of critical gas flow rate. Besides, effects of the parameters (chosen to be included in sensitivity studies) on critical gas flow rate can be determined. Furthermore, this spread sheet can be used during hydrocarbon production by carefully checking the critical has flow rate. Through this modelling work, it is hoped that a better management of liquid loading can be achieved.

1.6 Feasibility of the Project

With careful planning and full commitment in conducting this research, the project can be completed in two semesters. In FYP I, it is required for the author to study theories and literature reviews on existing models that predict critical flow rate, followed by familiarization of the selected models and Microsoft Excel. In FYP II, the focus should be on developing the two selected models into a spread sheet by using Microsoft Excel and to run sensitivity studies on a few parameters that affect the critical gas flow rate. Validation of the spread sheet is to be done by comparing results calculated by the models that are included in the spread sheet with the papers and books, followed by analysis and interpretation of the results. The cost for this project is affordable as only Microsoft Excel is needed to complete the project.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the author compiled literature review conducted on critical velocity and critical gas flow rate to prevent liquid loading problem in gas wells. Also, published models used to predict critical gas flow rate are reviewed and summarized.

2.1 Critical Velocity and Critical Gas Flow Rate

Critical velocity is the gas production velocity that keeps the liquid droplets from falling and accumulating in the bottom hole. Barry defines critical velocity as the minimum gas velocity in the tubing that is required to move liquids up and out of the wellbore [2]. Hearn describes critical velocity as the velocity at which liquids would have the tendency to fall instead of rise [5].

Critical gas flow rate is the minimum gas flow rate that is needed to ensure continuous removal of liquids [3]. It can also be defined as the flow rate necessary to ensure that the associated liquids are entrained at a specific wellhead pressure for a certain production tubing size [9]. In short, it is the minimum gas flow rate that is needed to provide sufficient energy in removing liquid accumulated at bottomhole of a gas well. Turner states that liquid droplets will accumulate at the bottomhole if the flow rate is below the critical flow rate but the well production may not necessary be stopped if the flow rate is below the critical flow rate [15].

Prediction of critical gas flow rate is important. A liquid-loaded well can be deliquified by using external aid such as artificial lifts, but these methods require additional expenses and loss of production. Most of the time, the wells are completed without the consideration of liquid loading. Hence, an estimation of critical gas flow rate is important to enable the well to be continuously deliquify with its own energy without external aid [16].

2.2 Models for Predictions of Critical Gas Flow Rate to Prevent Liquid Loading

2.2.1 Turner et al Model [1], [6], [17], [18], [21]

This model was the first published work in predicting minimum gas flow rate to ensure continuous liquid removal from wellbore. Two mathematical models were developed by the authors to study liquid loading problem, which are film movement model and entrainment drop movement model (or droplet model). Film movement model studies the movement of liquid film along the walls of the pipe while the droplet model studies liquid droplets that entrained in high velocity gas core [19]. The authors compared calculated results from the two models with field data and concluded that the droplet model (Stokes Law) is the only mechanism that has significant effect in transporting liquid.

The authors stated that liquids in a well can only be carried by gas in the well up to surface up to a specific point. At that particular point, gas velocity is lower than the terminal slip velocity, and the flow rate is below the minimum required gas flow rate for liquid removal. In this model, it is taken that droplet weight acts downward while drag force from the gas acts upward. Critical velocity can be determined when the weight is the same as the drag force.

The assumptions employed in this model include use of drag coefficients for solid spheres (0.44); stagnation velocity; maximum drop diameter corresponding to critical Weber number of 30 (which is established for drops falling in air, not in compressed gas); neglecting of transport velocity; neglecting of multiphase flow pressure; constant turbulent flow regime (with Reynolds number between 10^4 to $2x10^5$) [16], [17], [20]; and fixed droplet sizes and shapes [11].

The equations used to compute critical gas flow rate to prevent liquid loading are shown next, assuming that k_v is 1.3 and C_d is 0.44.

Equation 1

$$V_{gm} = \frac{k_v\, \sigma^{1/4} \left(\rho_l - \rho_g\right)^{1/4}}{C_d^{1/4} \rho_g^{1/2}}$$

Equation 2

$$Q_{gm} = \frac{3.06P_{av}AV_{gm}}{T_{av}Z}$$

The authors suggested that in most instances wellhead conditions controlled the onset of liquid load-up and that liquid/gas ratios in the range of 1 to 130 bbl/MMscf did not influence the minimum lift velocity [11]. They realised that the droplet model underestimates minimum gas flow rates. Hence, a 20 per cent upward adjustment is made on the results calculated by the equations to match measured field data and to ensure thorough removal.

This model was validated with real well data where majority of the data have surface flowing pressure that is higher than 1000 psi. Nonetheless, the authors examined and concluded that their work can still be employed for wells with surface pressure as low as 5 to 800 psi.

2.2.2 Coleman et al Model [1], [6], [11], [19]

Coleman et al extended Turner et al's work. The authors verified the minimum flow rate required to keep low-pressure gas wells unloaded and compared calculated results with the previous work [19].

The authors chose to focus on liquid-loaded wells with lower reservoir pressures (wellhead flowing pressure is below 500psi). This is because they claimed that liquid loading problems are generally worsened as reservoir energy keeps decreasing. Water is to be taken as the primary source of liquid that is to be loaded in gas wells. Likewise in the Turner et al Model, if both water and liquid hydrocarbon are present, the denser water dominates the onset of load-up. According to the authors, if tubing/packer is at a significant distance from the completion interval, flowing conditions of the largest diameter segment should be used to predict the wellbore critical flow rate.

In this work, studies on liquid yield effects, liquid sources, verification that wellhead conditions control onset of load-up, and effects of temperature, gas/liquid gravities, wellbore diameter, and packer/tubing setting depth were conducted. From these studies, the authors defined the important variables (wellbore cross-sectional area and pressure) and less important variables (temperature, gas gravity and interfacial tension). Also, a liquid/gas ratio that is below 22.6 bbl/MMscf does not affect the onset of liquid loading problem.

Wellbore with smaller diameter normally has higher transport-gas velocities and this ensures that the droplets can be carried efficiently. Besides, the authors proposed that system upsets; well shut-ins and human intervention will cause liquids to be accumulated periodically in the lower portion of the wellbore. Also, a well with slugging flow regime may not be taken as the droplet model because a different transport mechanism is involved.

The results calculated from this model were compared with field data from critical rate tests and production chart data base. The same outcome as that obtained by the Turner et al Model is seen where wellhead conditions control the onset of liquid loading problem. Also, the comparisons made proved that produced liquid will being held up in the wellbore when droplet terminal velocity had been reached.

The authors concluded that the prediction of critical flow rate can be made accurately by using the Turner et al Model but without the 20% upward adjustment. Equation 3 is the critical gas velocity equation modified by Coleman et al from the Turner et al Model while critical gas flow rate can be computed with Equation 2.

Equation 3

$$V_{gm} = \frac{1.593\, \sigma^{1/4} \left(\rho_l - \rho_g\right)^{1/4}}{\rho_g^{1/2}}$$

2.2.3 Nosseir et al Model [6], [16], [21]

This paper presents an approach to estimate liquid loading problem in gas wells under different flowing conditions. The study is narrowed down to the changes in flow regimes and impacts of the changes on gas well liquid loading problem. Similarly to the Coleman et al Model, the authors extended the work of Turner et al.

The main physics of this model is force balance. The authors claimed that there are two major forces acting upon a droplet of liquid falling in a gas stream, which are a gas stream force that is attempting to drag the droplet upward and a gravitational force that pull the droplet downwards and [16]. The authors reviewed different analytical equations for different flow conditions. They concluded that flow regime can be determined from dimensionless Reynolds number, N_{Re} (N_{Re} that is less than 1 for a laminar flow; N_{Re} that is between 1 to 1000 for a transition flow; and N_{Re} that is between 1000 to 200000 for a turbulent flow). The distinction between transition flow and turbulent flow is the degree of turbulence. The transition flow is a gradually developing turbulence flow while the latter is a fully developed turbulence.

In this study, the authors also examined the assumption of the Turner et al Model in which the turbulent flow regime is normally found in liquid-loaded gas wells. They compared the results of the Turner et al Model with Exxon group's data and realised that the assumption made by Turner et al (N_{Re} of 10^4 to $2x10^5$) may not necessarily be fulfilled due to a wide range of pressures, temperatures and flow rates that may be encountered in gas wells. In developing the new model, the assumptions of hard, smooth, spherical droplet of liquid are still being applied but the authors developed two analytical droplet models. The models are designed for transition (Equation 4) and highly turbulent flow regime (Equation 5). Critical gas flow rate can be computed by using Equation 2.

Equation 4

$$V_g = \frac{14.6\ \sigma^{0.35}\left(\rho_l - \rho_g\right)^{0.21}}{\mu^{0.134}\rho_g^{0.426}}$$

Equation 5

$$V_g = \frac{21.3\ \sigma^{0.25}\left(\rho_l - \rho_g\right)^{0.25}}{\rho_g^{0.5}}$$

However, there is time when more than one flow regimes are present at the same time. Thus, the authors suggested making the calculations at the wellhead because that is the point where maximum gas slippage and gas velocity can be found. Also, they proposed that the liquid phase should be taken as water. The prediction made from removing water is certainly enough to remove oil because water is denser than oil.

More conservative results are obtained by using the new equations after flow regime is taken into considerations. When flow regime is ignored, the accuracy of the critical gas velocity equation is reduced as the drag coefficient cannot be identified appropriately based on shapes of the droplets. The authors concluded that their work improve the accuracy in predicting liquid loading problem as their work managed to reduce the error between available data and calculate results.

2.2.4 Lea and Nickens Model [6], [22]

In this work, the authors studied the problem of liquid accumulation in gas well, solution methods and modified the critical flow velocity equation of the Turner et al Model.

They substituted some values (obtained from assumptions) into Equation 1. Gas gravity of 0.6; gas compressibility factor of 0.9; temperature of 120 °F; interfacial tension of 20 dynes/cm for condensate and 60 dynes/cm for water; condensate density of 45 lbm/ft^3 and water density of 67 lbm/ft^{3}are inserted. The final equation after inserting the values is Equation 6. Critical gas flow rate can be computed with Equation 2.

Equation 6

$$V_{gc} = \frac{C_{gc}\left(\rho_l - 0.0031P_{tf}\right)^{0.25}}{\left(0.0031P_{tf}\right)^{0.5}}$$

In the paper, the assumptions, limitations, and conditions to use of this equation are not clearly mentioned. However, it is believes that the same assumptions, limitations and conditions to use of the Turner et al Model are applied in the current model. No information is provided by the authors if comparisons of the results are made.

2.2.5 Li et al Model [21], [23]

In this model, the authors developed new formulae for continuous removal of liquids from gas wells. A new assumption on deformation of liquid droplet is included in this model in which the liquid droplets entrained in gas wells are said to become flat. The authors studied the shape of a liquid droplet entrained in a high-velocity gas stream. From the study, they claimed that a droplet will be deformed under an applied force. According to the authors, the force is coming from the pressure difference existing between the fore and aft portions of the droplet when it is entrained in a high-velocity as stream. The shape of the droplet will be changed from spherical to a convex bean with unequal sides (flat shape).

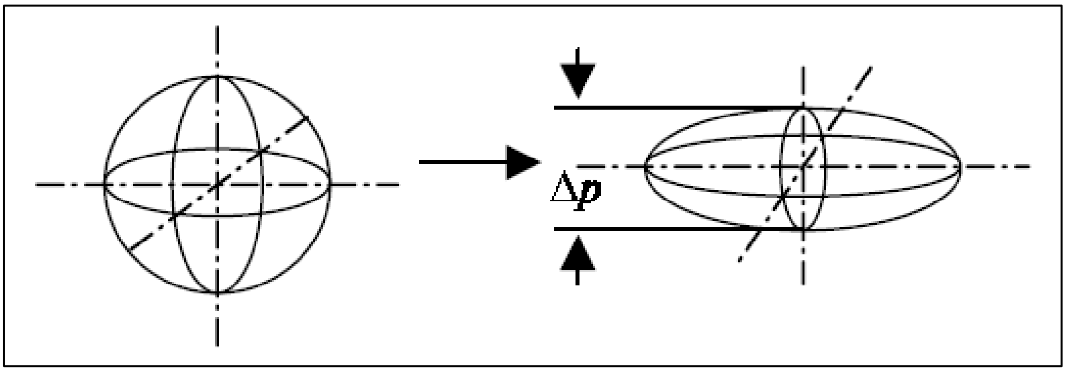


Figure 4 Shape of Entrained Drop Movement in the High-velocity Gas [23]

The effect of droplet shape on critical gas velocity is significant because efficient area of a droplet (that is held by gas) varies with shape. Smaller efficient area results in higher terminal velocity and thus critical rate to lift the droplet up to surface. A flattened droplet has a larger efficient area and thus it is relatively easier to be lifted up to the surface compared to a spherical droplet which has smaller efficient area. The required terminal velocity and critical rate are lower. Equation 7 is developed by the authors to compute critical gas velocity (SI units are to be used). Likewise in the previous models, critical gas flow rate is to be calculated by Equation 2 once critical gas velocity has been determined.

Equation 7

$$V_{gc} = \frac{2.5\ \sigma^{0.25}\left(\rho_l - \rho_g\right)^{0.25}}{\rho_g^{0.5}}$$

The authors compared results calculated by the new formulae with that of the Turner et al Model and field data. Their results are lower than that of the Turner et al Model but close to the practical production performance of China's gas wells with liquids. Thus, the current model has been validated. The differences of results calculated by the current model and the Turner et al Model are said to be caused by the shape of droplet assumed (flat shape in this model and spherical shape in the Turner et al Model) and drag coefficient used (1.00 is used for a flat shape in this model while 0.44 is used for a spherical shape in the Turner et al Model).

2.2.6 Guo et al Model [6], [18]

This model is a recent work in estimating minimum gas flow rate to prevent liquid loading. The model is created according to minimum kinetic energy theory and four-phase mist-flow model in gas wells. Based on minimum kinetic energy theory, gas kinetic energy must be larger than a minimum value to ensure transportation of liquid droplets from bottomhole up to surface. The four-phase mist-flow model (consists of four different phase, which are gas, oil, water and solid) employed in this model is important as it assures accurate prediction of pressure and fluid density (which is influenced by pressure).

In determining minimum kinetic energy, the minimum required gas velocity, V_{gm}, is equated to 1.2 times of the terminal settling velocity instead of summation of terminal settling velocity, V_{sl} and transport velocity, V_{tr}. This is because the Turner et al Model states that the transport velocity is 20 per cent of the terminal settling velocity. However, the transport velocity is hard to be determined as liquid production rate, geometry of the conduit and liquid volume fraction must be available. The transport velocity is treated as a constant that considers non-stagnation velocity, drag coefficients for solid spheres and the critical Weber number established for drops falling in air.

The authors proposed that the minimum required gas flow rate can be calculated by comparing gas specific kinetic energy, E_k with minimum kinetic energy required to transport liquid drops, E_{km}. An initial guess of Q_g is made to obtain E_k. The computed E_k is then compared with E_{km} (E_{km} can be calculated from Equation 8). If the E_k is higher than E_{km}, then Q_g should be reduced. The calculating steps are to be repeated until E_k is very close to E_{km}. To simplify this process, Equation 9 is developed by the authors to calculate the minimum required gas flow rate (which is determined at the last point of the mist flow regime or under the minimum unloaded condition). The critical gas flow rate to prevent liquid loading, Q_{gm}, can be obtained from Equation 9 with a numerical method such as Newton Raphson iteration technique.

Equation 8

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

Equation 9

$$b_g\left(P - P_{hf}\right) + \frac{1-2b_g m}{2}_g \ln\left|\frac{\left(P+m_g\right)^2 + n_g}{\left(P_{hf}+m_g\right)^2 + n_g}\right| - \frac{m_g + \frac{b_g}{c_g}n_g - b_g m_g^{\ 2}}{\sqrt{n_g}}\left[\tan^{-1}\left(\frac{P+m_g}{\sqrt{n_g}}\right) - \tan^{-1}\left(\frac{P_{hf}+m_g}{\sqrt{n_g}}\right)\right]$$
$$= a_g\left(1 + d_g^{\ 2} e_g\right)D$$

There are a few assumptions used in this model, which are V_{gm} that is approximate to 1.2 V_{sl} where V_{tr} is approximate to 0.2 V_{sl}; specific gravities of water, solid and condensate that are computed by taking water as 1; specific gravity of gas that is computed by taking gas as 1; a geothermal gradient of 0.01 °R/ft in calculating average temperature; and lastly the gas and condensate and/or water produced from the wells come from either tubing or annulus.

This model was validated against 106 test points (the same points used in the Turner et al Model). The comparison made shows that the current model gives more conservative results when compared to that of the Turner et al Model.

2.2.7 Summary of Review on Models for Predictions of Critical Gas Flow Rate to Prevent Liquid Loading

Turner et al Model [1], [6], [17], [18], [21] was the first work in the area of predicting minimum gas flow rate to prevent liquid loading. The authors presented an expression where gas density is the product of 0.0031 and pressure. Nonetheless, the method to calculate gas pressure in multiphase flow wellbore is not provided. It was validated with real well data (majority of the data have surface flowing pressure that is higher than 1000 psi) but it is proven that the model can also be used for wells with surface pressure as low as 5 to 800 psi.

Coleman et al [1], [6], [11], [19] modified the Turner et al Model by suggesting another constant value. Equation of Coleman et al Model is the same as the Turner et al Model but there is no 1.2 adjustment in the Coleman et al Model. This creates doubt as limitation of the droplet model and conditions to apply the 1.2 adjustment are not clearly defined [16]. Coleman et al developed their model by using data from surface tubing pressures that are below 1000 psi. Results from the Coleman et al Model is always less than that of the Turner et al's Model.

In Nosseir et al Model [6], [16], [21], flow regimes in a well are taken into considerations, which is said to improve the reliability of the prediction of critical gas flow rate. Dimensionless Reynolds number must be determined and flow regime of the flow must be identified before this model is used.

Leas and Nickens [6], [22] modified Turner et al Model with some assumptions but the new equation is still similar to that of Turner et al Model. However, the authors do not specify the assumptions and limitations of this model. Thus, it is considered that the same drawback of the Turner et al Model is still present.

Li et al [21], [23] added a new assumption where a liquid droplet tends to change shape due to the pressure difference and that a flattened droplet can be lifted easier up to the surface compared to a spherical droplet. The added consideration of deformation of droplet gives a different critical gas velocity equation.

Guo et al Model [6], [18] is one of the recent works on predicting minimum gas flow rate to prevent liquid loading. The basics of the model are the minimum kinetic energy criterion and 4-phase mist-flow model in gas wells. The authors proposed the kinetic energy theory and concluded that bottomhole conditions controls the controlling of liquid drop removal in gas wells but not top-hole conditions, which is contradicting with the Turner et al Model.

Both the Turner et al Model and the Coleman et al Model are famous and commonly used to determine the critical velocity and the corresponding rate [1], [15]. The critical rate calculated by the Coleman et al Model is 80 per cent of the critical rate calculated by the Turner et al Model [1].

The first five models (Turner et al Model, Coleman et al Model, Nosseir et al Model, Leas and Nicken Model and Li et al Model) have the same shortcoming. Transport velocity is ignored and multiphase flow pressure is not being considered [6]. The latest model of the six models reviewed, which is the Guo et al Model has an added advantage over the other models as it takes multiphase flow into considerations and its results are more conservative.

CHAPTER 3

METHODOLOGY AND PROJECT WORK

This chapter covers methodology and project work of this project. Research methodology that outlines overall work flow of this project, key milestones of the project, selection of models, flow chart showing the formulae used in the spread sheet, Gantt Chart showing the planned schedule of this project and tools required in the project are elaborated.

3.1 Research Methodology

The overall work flow of this project includes preliminary research work, implementation stage, analysis of result and discussion stage and lastly report writing stage. The following flow chart summarizes the overall work flow of this project:

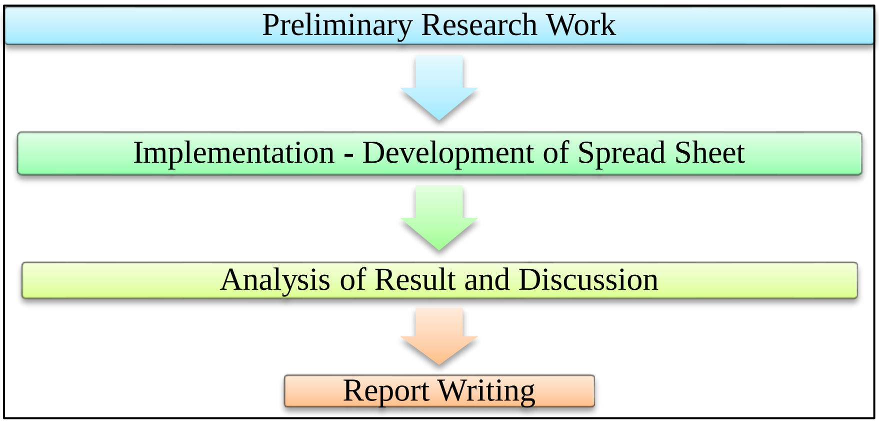


Figure 5 Overall Work Flow of the Current Project

<u>Preliminary Research Work</u>

Understanding fundamental theories of the topic (liquid loading problem, prediction of critical gas flow rate to prevent liquid loading, gas well deliquification, and gas well deliquification techniques), conducting literature review (prediction of minimum required gas flow rate for liquid removal and available prediction models), identifying tools needed (programme to design codes to model estimation of minimum required gas flow rate for liquid elimination), figuring out approaches to complete the project.

Implementation – Development of Spread Sheet

Getting familiar on how to use Microsoft Excel. The program is chosen due to its simplicity. It is able to code the models selected (equations of the models can be easily included by using Microsoft Excel). Furthermore, spread sheet and Microsoft Excel are always used by engineers (target users of this project) in different calculation and they are familiar with the spread sheet and Microsoft Excel. Also, Microsoft Excel has its added advantage in enabling the users to duplicate the data and results used in this project. The most important activity of this stage is to design and develop the spread sheet by using Microsoft Excel.

Equations to estimate critical gas flow rate to prevent liquid loading problem developed by Turner et al and Guo et al are included in the spread sheet. The models can act as an indicator of liquid loading problem. There are a few equations to be used to calculate parameters needed before proceed to the critical gas flow rate equations. All of the required equations in the spread sheet are described in Section 3.5 of this chapter. Sensitivity studies to examine effects of temperature, pressure, conduit size, producing depth and inclination are to be conducted.

Analysis of Results and Discussion

Validating the developed spread sheet by comparing the results with available data and the sources of the models (papers and books), discussing the outcomes of the results, drawing a conclusion of the study, determining if objectives are achieved.

Report Writing

Compiling all research outcomes, literature review, experimental works and findings into a final report.

3.2 Project Activities and Key Milestones

The project activities planned and key milestones identified for this project are described in the following sections.

FYP Briefing

The author is introduced to the FYP 1 course, scope of research and steps to initiate FYP.

FYP Topic Selection

The author is required to select a topic of interest which is feasible and can be completed within time allocated. The author identified liquid loading problem and prediction of minimum gas flow rate required for liquid removal to be studied in this project.

Preliminary Research Work

The author is required to study theories of liquid loading problem, prediction of critical gas flow rate for liquid removal, gas well deliquification and gas well deliquification techniques; review available models to estimate critical gas flow rate for liquid elimination and select most suitable models to be developed; plan the methodology and activity to be carried out. Outcomes of preliminary research work are compiled in Extended Proposal and Interim Report which have been submitted.

Proposal Defence

The author is required to present to the supervisor and an internal examiner to verbally report the progress of her project. In this activity, the author received feedbacks and suggestions to improve the project. The author had undergone the proposal defence.

Continuation of Project Work

The author is to study in depth the selected models on predicting critical gas flow rate, re-write the equations used in the model, get familiar with developing spread sheet by using Microsoft Excel, prepare and lastly submit the Interim Draft Report and Interim Report. The continuation of project work is compiled in Interim report.

Development and Validation of Spread Sheet

The two models selected are developed by using Microsoft Excel. A spread sheet in predicting minimum gas flow rate required to prevent liquid loading is developed. The spread sheet consists of two functions, which are estimation of minimum necessary gas flow rate for liquid removal and design of sensitivity studies. Effect of temperature, pressure, conduit size, producing depth and inclination are studied by developing the sensitivities study sections. Validation of the spread sheet is carried out by inputting the similar data provided in the papers.

Submission of Progress Report

The author is required to report progress of the project by drafting and completing the Progress Report. The Turner et al Model has been completed and compiled in the Progress Report.

Continuation of Project Work

The author is to complete the spread sheet for Guo et al Model. Similarly to the Turner et al Model, this model will be consisted of two functions, which are prediction of minimum required gas flow rate for liquid elimination and sensitivities studies.

Pre-SEDEX

The author is to prepare the presentation materials and poster for Pre-SEDEX upon completion of the spread sheet.

Submission of Draft Report, Dissertation and Technical Paper

The author is to start and finalise draft report, dissertation and technical paper upon completion of the spread sheet.

Oral Presentation

The author is to prepare the presentation materials and poster for Oral Presentation.

Submission of Hard-bounded Project Dissertation

The author will send the completed Project Dissertation to hard bound and submit the Project Dissertation.

3.3 Gantt Chart

Gantt Chart showing the study plan and schedule for each activity planned in this project is as below:

Table 1 Gantt Chart of FYP I and FYP II Project Implementation

Activities	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FYP 1														
FYP Briefing & Topic Selection														
Preliminary Research Work														
1. Fundamental theories														
2. Conducting literature review on available models and select the appropriate models														
3. Identifying steps and tools														
Preparation & Submission of Extended Proposal							●							
Proposal Defence														
1. Studying theories														
2. Getting familiar with the selected models														
3. Prepare for the Proposal Defence														
Project Work Continues														
1. To understand and rewrite equations used of the models														
2. Getting familiar with Microsoft Excel														
Preparation & Submission of Interim Draft Report													●	
Preparation & Submission of Interim Report														●
FYP 2														
Project Work Continues for development and validation of spread sheet														
Preparation and Submission of Progress Report								●						
Project Work Continues for development and validation of spread sheet, sensitivity study, analysis of results and conclusion drawing														
Pre-SEDEX (poster preparation)														
Preparation & Submission of Draft Report											●			
Preparation & Submission of Dissertation												●		
Preparation & Submission of Technical Paper												●		
Oral Presentation														
Submission of Project Dissertation														●

Legend: ■ Suggested period ● Date of Submission

3.4 Selection of Models

In current work, the Turner et al Model and the Guo et al Model are selected to develop the spread sheet for prediction of minimum required gas flow rate for liquid removal. The reasons on selection of models are elaborated next.

The Turner et al Model is selected although it was developed in 1969 because it gives results within an acceptable range of error. It is still commonly used until today. Compared to Coleman et al Model, it is recommended that Turner Model should be used as it is always better to go for the worst case scenarios. For similar inputs of a well, the Coleman et al Model always gives a lower result compare to that of the Turner et al Model. As a result, instead of being flow under the critical rate (calculated from the Turner et al Model), the well is said to be flow above the critical rate (calculated from the Coleman et al Model), which depicts no liquid loading problem [1]. Thus, the Turner et al Model is proposed to be used to estimate critical rate to transport liquid compared to the Coleman et al Model. The data provided in the paper [17], [18] can be used to validate the Turner et al Model in the produced spread sheet.

Dimensionless Reynolds number is compulsory to be available before using Nosseir et al Model. This might increase the burden as data to calculate the dimensionless Reynolds number may not be available. Hence, it is not chosen to be developed in the spread sheet. For Leas and Nicken Model, the authors modified the Turner et al Model and do not specify the assumptions and limitations of this model. Thus, it is not considered to be developed. Li et al Model takes deformation of droplet into account. Since all the models mentioned are extension of Turner et al Model based on different added inclusions, the Turner et al Model is chosen to be developed in the spread sheet. This is because a rough estimation of the critical gas flow rate is required and the Turner et al Model which is believed to give results with acceptable error but requires fewer inputs is recommended.

On the other hand, the Guo et al Model is selected as it is a recent work in area of gas well liquid loading. It includes water and condensate as liquid phase in its correlation. Unlike the Turner et al Model, both water and condensate production rates are added in its correlation. This further improves the accuracy of the results. The data provided in the paper [6], [18] can be used to validate the Guo et al Model in the produced spread sheet.

Thus, these two models are selected and comparisons of the result will be made. The data and results are available on the papers of these models. The data would be useful in aiding the development of the spread sheet in the implementation stage.

3.5 Calculation Procedures and Assumptions

The project focuses on the calculation of minimum required gas flow rate to prevent liquid loading problem in gas wells by using the Turner et al Model and the Guo et al Model. The calculation procedures included in the developed spread sheet for both models are explained next.

3.5.1 Turner et al Model

Turner et al developed the following equations to calculate minimum gas flow rate required for liquid removal:

Equation 1

$$V_{gm} = \frac{1.3\ \sigma^{1/4} \left(\rho_l - \rho_g\right)^{1/4}}{C_d^{1/4} \rho_g^{1/2}}$$

Equation 2

$$Q_{gm} = \frac{3.06 P_{av} A V_{gm}}{T_{av} Z}$$

Turner et al suggested using the discharged coefficient, C_d of 0.44.

The equations for all parameters in Equation 1 and Equation 2 are as follow:

i. Equation for gas density, ρ_g (Dake) [20],

Equation 10

$$\rho_g = \frac{2.7 \gamma_g P_{wf}}{Z'\ T_{wf}}$$

ii. Equations for pseudo critical pressure, P_{pc} and pseudo critical temperature, T_{pc}:

The Standing's (1977) correlations is used to compute pseudo critical pressure and pseudo critical temperature when composition of a natural gas is not available [24]. For developing this spread sheet, these correlations are used so that composition of the natural gas is not a compulsory input for the spread sheet. The Standing's correlation (1977) for natural gas systems is:

Equation 11

$$P_{pc} = 677 + 15\gamma_g - 37.5\gamma_g^2$$

Equation 12

$$T_{pc} = 168 + 325\gamma_g - 12.5\gamma_g^2$$

iii. Equations for pseudo reduced pressure, P_{pr} and pseudo reduced temperature, T_{pr}:

Equation 13

$$P_{pr} = \frac{P_{av}}{P_{pc}}, where\ P_{av} = P_{wf}$$

Equation 14

$$T_{pr} = \frac{T_{av}}{T_{pc}}, where\ T_{av} = T_{wf}$$

iv. Equation for gas compressibility factor, Z:

The Brill and Beggs correlation (1974) is to be used to develop this spread sheet [18].

Equation 15

$$Z = A_z + \frac{1 - A_z}{e^{B_z}} + C_z P_{pr}^{D_z}$$

Equation 16

$$A_z = 1.39\left(T_{pr} - 0.92\right)^{0.5} - 0.36T_{pr} - 0.101$$

Equation 17

$$B_z = (0.62 - 0.23T_{pr})P_{pr} + \left(\frac{0.066}{T_{pr} - 0.86} - 0.037\right)P_{pr}^2 + \frac{0.32P_{pr}^6}{10^{E_z}}$$

Equation 18

$$C_z = 0.132 - 0.32\log T_{pr}$$

Equation 19

$$D_z = 10^{F_z}$$

Equation 20

$$E_z = 9(T_{pr} - 1)$$

Equation 21

$$F_z = 0.3106 - 0.49T_{pr} + 0.1824T_{pr}^2$$

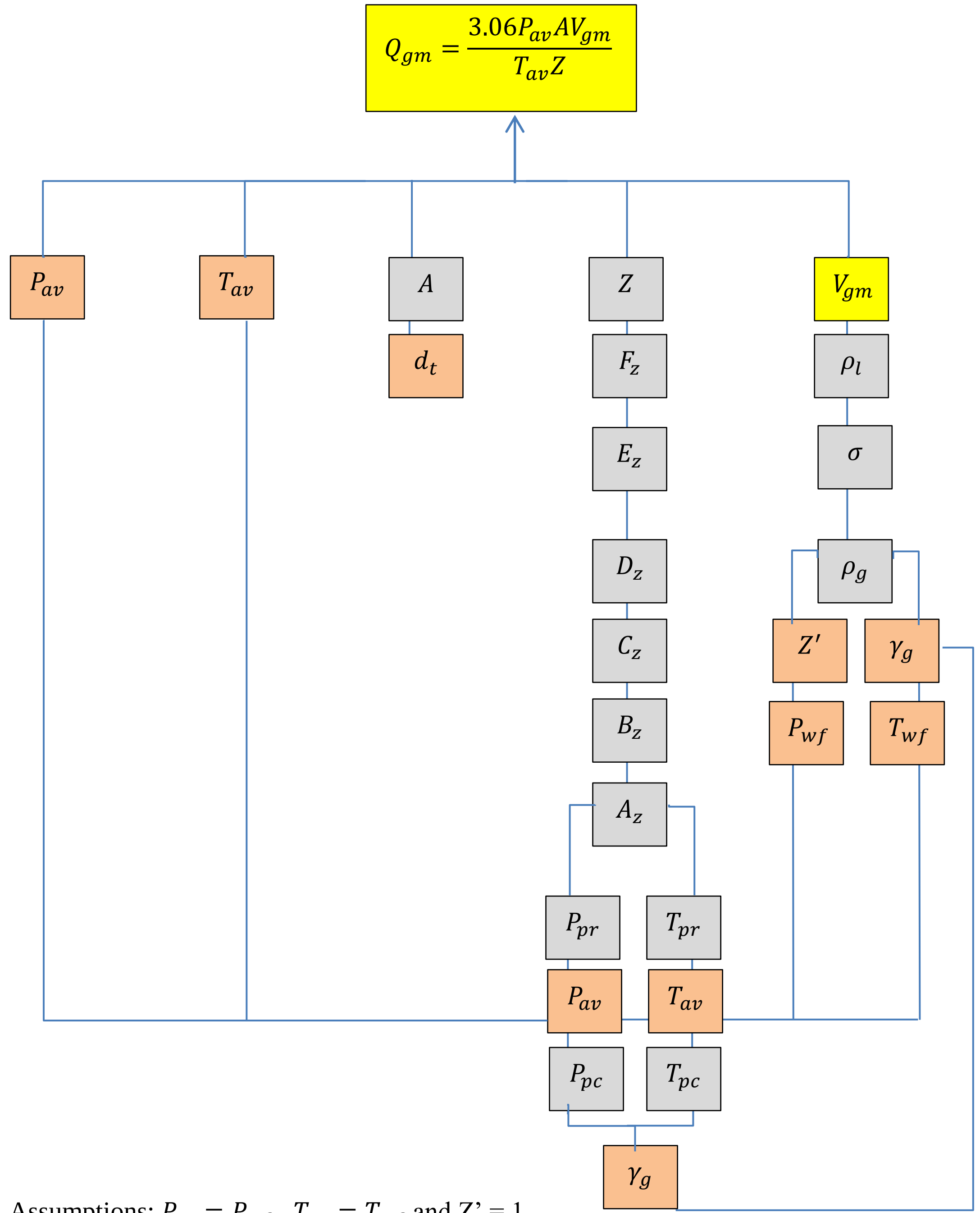
v. Equation for conduit cross-sectional area, A:

Equation 22

$$A = \frac{\pi\, d_t^2}{4 \times 144}$$

All the assumptions used in the Turner et al model are applied in the developed spread sheet. Also, assumptions and limitations of correlations used to reach final results (from Equation 10 to Equation 22) are also employed in the spread sheet. C_d of 0.44 is assumed. In addition, assumptions used in the Standing's Correlation and the Brill and Beggs correlation are included. If both water and condensate are present in a system, denser of the two should be used to proceed with determinations of surface tension and liquid density.

Figure below shows the overview of the parameters and program flow chart for Turner et al Model.



Assumptions: $P_{av} = P_{wf}$, $T_{av} = T_{wf}$ and Z' = 1

Legend: Results Inputs Working calculation

Figure 6 Overview of the Parameters and Program Flow Chart of the Turner et al Model

3.5.2 Guo et al Model

Guo et al developed the following equations to calculate minimum gas flow rate required for liquid removal:

Equation 9

$$b_g\left(P-P_{hf}\right)+\frac{1-2b_g m_g}{2}_g \ln\left|\frac{\left(P+m_g\right)^2+n_g}{\left(P_{hf}+m_g\right)^2+n_g}\right| - \frac{m_g+\frac{b_g}{c_g}n_g-b_g m_g{}^2}{\sqrt{n_g}}\left[\tan^{-1}\left(\frac{P+m_g}{\sqrt{n_g}}\right)-\tan^{-1}\left(\frac{P_{hf}+m_g}{\sqrt{n_g}}\right)\right]$$

$$=a_g\left(1+d_g{}^2 e_g\right)D$$

Equation 23

$$P = 6.46\times10^{-13}\frac{S_g T_{av} Q_{gm}^2}{A^2 E_{km}}$$

Equation 24

$$V_{gm} = 4.71\times10^{-5}\frac{T_{av} Q_{gm}}{A\ P}$$

The equations for all parameters in Equation 9, Equation 23 and Equation 24 are as follow:

i. Equation for minimum kinetic energy, E_{km}:

Equation 8

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

ii. Equation for hydraulic diameter, D_h:

Equation 25

$$D_h = \frac{(d_{to}-d_{ti})}{12}$$

iii. Equation for conduit cross-sectional area, A:

Equation 26

$$A = \frac{\pi\, d_{to}^2}{4\times144}$$

iv. Equation for producing zone temperature, T_{pz}:

Geothermal gradient is assumed to be 0.01°R/ft in computing T_{pz}.

Equation 27

$$T_{pz} = T_{wh} + 0.01(D)$$

v. Equation for average temperature, T_{av}:

T_{av} is assumed to be the average of T_{pz} and T_{wh}.

Equation 28

$$T_{av} = \frac{T_{pz} + T_{wh}}{2}$$

vi. Equation for heavy liquid-gas interfacial tension, σ:

Gas-condensate interfacial tension and gas-water interfacial tension are assumed to be 20 dynes/cm 60 dynes/cm. If major liquid of the system is water, the input of 'major liquid' will be 1; if the major liquid of the system is condensate, it will be -1. For simplification, an equation is used to determine the interfacial tension based on the input of 'major liquid'.

Equation 29

$$\sigma = \frac{(1 + major\ liquid)}{2}(60) + \frac{(1 - major\ liquid)}{2}(20)$$

vii. Equation for heavy liquid density, ρ_l:

The heavy liquid density is to be calculated from liquid specific gravity. Similarly to interfacial tension, the input of 'major liquid' is used to determine the heavy liquid density. Likewise, if major liquid of the system is water, the input of 'major liquid' will be 1; if the major liquid of the system is condensate, it will be -1. For simplification, an equation is used to determine the heavy liquid density based on the input of 'major liquid'.

Equation 30

$$\rho_l = \frac{(1 + major\ liquid)}{2}(62.4 \times \gamma_w) + \frac{(1 - major\ liquid)}{2}(62.4 \times \gamma_c)$$

viii. Equations for parameters a_g, b_g, c_g, d_g, e_g, f_g, m_g, n_g and P:

Equation 31

$$a_g = \frac{15.33 S_s Q_s + 86.07 S_w Q_w + 86.07 S_o Q_o + 0.01879 S_g Q_g}{T_{av} Q_g} \cos(\theta)$$

Equation 32

$$b_g = \frac{0.2456 Q_s + 1.379 Q_w + 1.379 Q_o}{T_{av} Q_g}$$

Equation 33

$$c_g = \frac{4.712 \times 10^{-5} T_{av} Q_g}{A}$$

Equation 34

$$d_g = \frac{Q_s + 5.615 (Q_w + Q_o)}{86400 A}$$

Equation 35

$$e_g = \frac{f_g}{2 g D_h \cos(\theta)}$$

Equation 36

$$f_g = \left[\frac{1}{1.74 - 2 \log\left(\frac{2\varepsilon}{D_h} \right)} \right]^2$$

Equation 37

$$m_g = \frac{c_g d_g e_g}{1 + d_g^2 e_g}$$

Equation 38

$$n_g = \frac{c_g^2 e_g}{\left(1 + d_g^2 e_g\right)^2}$$

ix. Equation 9 is used to obtain the minimum required gas flow rate. This equation is developed under the minimum unloaded condition, which is the last point of the mist flow regime. It is to be solved by using a numerical method called Newton-Raphson iteration technique. Equation 39 shows the Newton-Raphson iteration technique [25].

Equation 39

$$x_{new} = x_{old} - \frac{f(x)}{f\prime(x)}$$

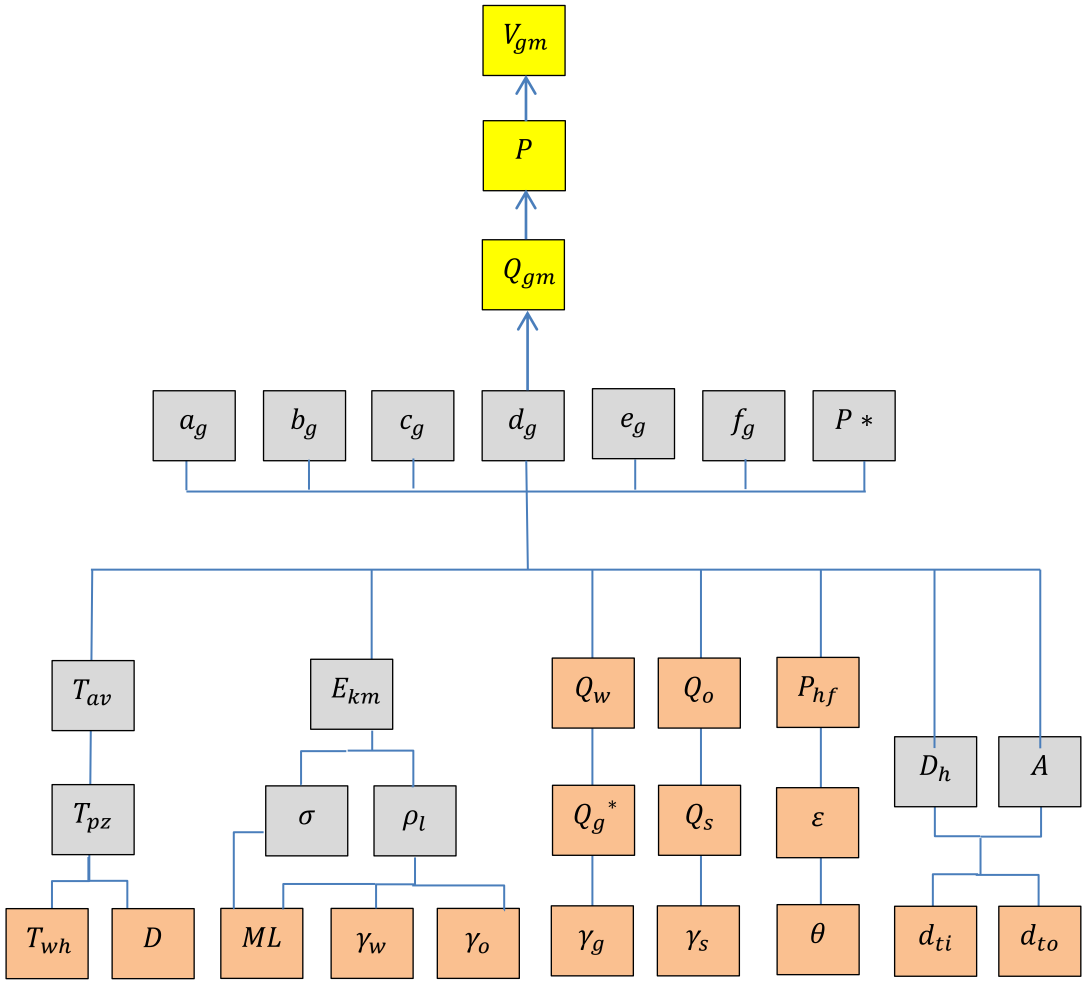
To use numerical method in solving an equation, an initial guess is needed. In this spread sheet, a constant initial guess of 1.1 scf/d and number of iteration of 20 are used. This initial guess is chosen as it is an unrealistically small gas flow rate. The calculated gas flow rate is not possible to fall under this value. A few trials have been used and the outcome shows that the objective function will reach to a value that is less than 0.1 in less than 10 iterations. Hence, it is concluded the initial guess of 1.1scf/d and 20 iterations are sufficient to reach a reliable final result.

x. Derivative of f(x) shown in Equation 39 can be determined by using the following. Here, *i* is taken as 1 because 1 scf/d is an unrealistically small gas flow rate which is more than sufficient to compare the results before and after a point [25].

Equation 40

$$f'(x) = \frac{f(x+i) - f(x-i)}{i}$$

All the assumptions used in the Guo et al model are applied in the developed spread sheet. Also, assumptions and limitations of correlations used to reach final results (Equation 23 to Equation 40) are also included in the spread sheet. If both water and condensate are present in a system, denser of the two should be chosen as major liquid and used to proceed with determinations of surface tension and liquid density. A geothermal gradient of 0.01°R/ft, gas-condensate interfacial tension of 20 dynes/cm and gas-water interfacial tension of 60 dynes/cm are assumed in this work. T_{av} will be obtained by averaging T_{pz} and $T_{wh.}$ Figure below shows the overview of the parameters and program flow chart for the Guo et al Model.



Note: ML = Major liquid;

Q_g^* = calculated Q_g at n^{th} iteration (with initial guess of 1.1scf/D);

P_{hf} = P_{wh};

P^* = calculated P at n^{th} iteration

Input inclination must be $0° \leq \theta < 90°$, or $270° < \theta \leq 360°$

Legend: Results Inputs Working calculation

Figure 7 Overview of the Parameters and Program Flow Chart for the Guo et al Model

3.6 Tool Required

In this project, the only tool required is Microsoft Excel. It will be used to create a spread sheet which includes the Turner et al Model and the Guo et al Model.

Excel is a spread sheet program in the Microsoft Office system which can be used to create and format workbooks for data analysis [26]. It is useful in data tracking, models building to analyse data, formulae writing to perform calculations on the data, and data presenting in a variety of professional looking charts.

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter will discuss the results for both objectives of the project which are firstly, to develop a work flow (spread sheet) to predict onset of liquid loading problem in gas wells by estimating critical gas flow rate and secondly, to run sensitivity study on several parameters to examine their effects on critical gas flow rate. Inputs are filled in into the spread sheet and results are analysed. The results of the Turner et al Model and the Guo et al Model are first shown, followed by comparison of the results obtained from the two models. Lastly, results of sensitivity studies are elaborated.

4.1 Development of Spread Sheet

Research papers and books on published works on critical gas flow rate to prevent liquid loading problem have been reviewed. From the six models reviewed, two models are carefully selected to produce a spread sheet to estimate onset of liquid loading problem in gas well by using Microsoft Excel. The spread sheet is developed based on the Turner et al Model and the Guo et al Model. The equations derived by the researchers are reviewed and included in the spread sheet. The series of equations included into this spread sheet are shown in Chapter 3. Assumptions used to develop the equations and related correlations are also applied in this spread sheet.

For this project, a spread sheet is modified and updated from the work completed by B. Guo and A. Ghalambor [18]. The design and flow of the spread sheet is modified from ‘Sand Modelling Spread Sheet’ by P.W. Lim and W.C. Kan for SPT Group [27]. There are four pages in the spread sheet. The first page contains guidelines on how to use the spread sheet and an input table for users to key in input data; the second page is the Turner et al Model page; the third page is the Guo et al Model page and the last page is Comparison page which shows input data (automatically linked from the first page) and final results of both models. Users are required to provide the necessary inputs in the correct required units in the first page of the spread sheet. The inputs will be automatically copied to the input data section in the model pages and comparison page. In other words, the inputs will be automatically linked to the second, third and fourth page. Legend of this spread sheet is:

■	Input Box
■ ■	Working Calculations. To be left untouched.
■	Final results.

Figure 8 Legend of the Spread Sheet

For both models, users can choose to proceed from the two functions developed in the spread sheet. The first function is calculation of critical gas flow rate to prevent liquid loading problem and the second function is to conduct sensitivity study. Temperature, pressure, conduit size, producing depth and inclination are the parameters chosen to be checked in sensitivity studies. Sensitivity studies of the first three parameters mentioned can be performed by both models while sensitivity studies of producing depth and inclination can only be conducted by using the Guo et al Model. Different inputs are required when the users are conducting different sensitivity studies. The necessary inputs and affected parameters when different sensitivity study is conducted are summarized in Table 2.

In all the sensitivity studies, liquid loading problem may occur in the well if minimum required gas flow rate for liquid removal is higher than the current flowing flow rate. Observations from graphs are useful in examining effects of temperature, pressure, conduit sizes, producing depth and inclination.

Table 2 Necessary Inputs and Affected Parameters for each Sensitivity Study

Necessary Inputs	Affected Parameters
Sensitivity Study of Temperature Available for the Turner et al Model and the Guo et al Model	
• 10 Temperature • 1 Pressure◊ • 1 Conduit Size◊ • 1 Current Flowing Flow Rate◊	• Turner et al Model: Varying the temperature will cause different gas compressibility factor, minimum required gas velocity, and minimum required gas flow rate. • Guo et al Model: Varying the temperature will cause different average temperature, minimum

	required gas glow rate, and minimum required gas flow velocity and bottomhole pressure.
Sensitivity Study of Pressure **Available for the Turner et al Model and the Guo et al Model**	
• 10 Pressure • 1 Temperature✧ • 1 Conduit Size✧ • 1 Current Flowing Flow Rate✧	• Turner et al Model: Varying the pressure will cause different gas compressibility factor, minimum required gas velocity, and minimum required gas flow rate. • Guo et al Model: Varying the pressure will cause different minimum required gas glow rate, and minimum required gas flow velocity and bottomhole pressure.
Sensitivity Study of Conduit Size **Available for the Turner et al Model and the Guo et al Model**	
• 10 Conduit Sizes • 1 Temperature✧ • 1 Pressure✧ • 1 Current Flowing Flow Rate✧	• Turner et al Model: Varying the conduit size will cause different cross-sectional area, minimum required gas velocity, and minimum required gas flow rate. • Guo et al Model: Varying the conduit size will cause different cross-sectional area and hydraulic diameter, minimum required gas glow rate, and minimum required gas flow velocity and bottomhole pressure.
Sensitivity Study of Producing Depth **Available for the Guo et al Model**	
• 10 Producing Depth • 1 Temperature✧ • 1 Pressure✧ • 1 Conduit Size✧ • 1 Current Flowing Flow Rate✧	• Guo et al Model: Varying the producing depth will cause different average temperature, minimum required gas glow rate, and minimum required gas flow velocity and bottomhole pressure.
Sensitivity Study of Inclination **Available for the Guo et al Model**	
• 10 Inclination • 1 Temperature✧ • 1 Pressure✧ • 1 Conduit Size✧ • 1 Current Flowing Flow Rate✧	• Guo et al Model: Varying the inclination will cause different minimum required gas glow rate, and minimum required gas flow velocity and bottomhole pressure.
*✧ indicates value maintained throughout the sensitivity study *Note: Temperature and pressure are from surface condition for the Turner et al Model and from wellhead condition for the Guo et al Model	

Necessary inputs of the spread sheet may be obtained from production historical data, well completion data, fluid analysis report or any relevant sources. The required inputs are summarized in Table 3.

Table 3 Necessary Inputs for the Spread Sheet

Parameters	Turner et al Model	Guo et al Model
Temperature, Pressure	✓ (Surface)	✓ (Wellhead)
Gas specific gravity *(by taking air as 1)*	✓	✓
Liquid density *(if both water and condensate are present, denser of the two should be used)*	✓	×
Interfacial tension *(if both water and condensate are present, denser of the two should be used)*	✓	×
Conduit size	✓	✓*
Hole inclination	×	✓
Water specific gravity, condensate gravity, solid specific gravity *(by taking water as 1)*	×	✓
Producing depth	×	✓
Production of water, condensate and solid	×	✓
Major liquid *(input as 1 for water and -1 for condensate)*	×	✓
*Conduit inner diameter, which is required to calculate hydraulic diameter, is always taken as zero.		

4.2 Critical Gas Flow Rate to Prevent Liquid Loading

The first function of the spread sheet is to calculate the critical gas flow rate and velocity for liquid removal by using the Turner et al Model and the Guo et al Model. This function can be known as creation of base cases as some of the inputs are to be brought forward into sensitivity study section in the spread sheet to perform sensitivity study. A set of inputs is utilized to demonstrate results of Turner et al Model and Guo et al Model. Inputs used are shown in Table 4.

Table 4 Inputs for the Turner et al Model and the Guo et al Model

Parameter	Symbol	Value	Units
Surface Temperature	T_{wf}	520	°R
Surface Pressure	P_{wf}	500	psia
Wellhead Temperature	T_{wh}	520	°R
Wellhead Pressure	P_{wh}	500	psia
Gas Specific Gravity	γ_g	0.6	(-)
Water Specific Gravity	γ_w	1.08	-
Condensate Gravity	γ_c	0.53764	-
Solid Specific Gravity	γ_s	2.65	-
Liquid Density (Heavy)	ρ_l	67.4	lbm/ft^3
Interfacial Tension	σ	60	dynes/cm
Conduit Outer Diameter	d_{to}	1.995	inch

Conduit Inner Diameter	d_{ti}	0.000	inch
Tubing Wall Roughness	ε	1.50E-05	inch
Hole Inclination	θ	0	degree
Producing Depth	D	6700	ft
Water Make	Q_w	8.6	bbl/day
Solid Make	Q_s	0	ft^3/day
Condensate Make	Q_c	0	bbl/day
Major liquid	-	1.000	-

Results calculated for both models are shown in the respective model page of the spread sheet. In addition, a comparison page is created so that results of both models can be viewed in a single page in the spread sheet. The calculated critical gas velocity required to transport liquid drops (V_{gm}) is 10.139 ft/s and the critical gas flow rate for liquid removal (Q_{gm}) is 0.701 MMscf/d by using the Turner et al Model. V_{gm} and Q_{gm} are 11.689 ft/s and 0.827 MMscf/d when the Guo et al Model is used. The Guo et al Model gives calculated bottomhole pressure as 589.756 psia. Bottomhole pressure calculation is not available for the Turner et al Model. Results calculated for both models are summarized in Table 5. Any flow rate for the well (with conditions as specified in Table 4) that is below the calculated Q_{gm} may lead to liquid loading problem.

Table 5 Results calculated for Both Models

	Turner et al Model	**Guo et al Model**
Minimum required gas velocity for liquid removal (ft/s)	10.139	11.689
Minimum required gas flow rate for liquid removal (MMscf/d)	0.701	0.827
Bottomhole pressure (psia)	Not Available	589.756

It was found that the results of the Guo et al Model are slightly higher than that of the Turner et al Model. Guo et al [6], [18] compared their results with the Turner et al Model's result with field data and concluded that their model provides results with higher accuracy. The differences between results calculated by the two models may be caused by several reasons. Firstly, both models have their own correlations. The Turner et al Model was developed from the entrainment drop movement model (or droplet model) while the Guo et al Model was developed from the minimum kinetic energy theory and the four-phase flow model.

Next, different assumptions are used in the models. In the Turner et al Model, drag coefficient and Weber number may be the reasons that result in lower critical flow rate. In developing the equations, Turner et al used drag coefficient which is allocated for solid sphere, but not oscillating liquid drops; and Weber number which was found experimentally from droplets falling in air but not for droplets moving in gas wells. These may be the reasons that lead to the less accurate results calculated from the Turner et al Model. In the Guo et al Model, the minimum kinetic energy theory and the four-phase mist-flow model (which comprises of gas, oil, water and solid phase) are believed to be the reasons that improve the accuracy of the results of Guo et al Model. On top of estimation of minimum gas velocity in the Turner et al Model, the Guo et al Model added minimum kinetic energy theory that is needed to lift liquid droplets in gas wells. The minimum kinetic energy theory has added advantage over the minimum gas velocity estimation of the Turner et al Model. The minimum kinetic energy equation not only includes minimum gas velocity, but also includes gas density to give prediction of minimum kinetic energy. Furthermore, the four-phase mist flow model takes gas, oil, water, and solid particles into account, which cannot be found in the Turner et al Model. This is believed to improve the accuracy of the Guo et al Model.

From the results, it is suggested that Guo et al Model should be used in predicting minimum required gas flow rate for liquid removal at all time. Furthermore, Guo et al [6], [18] state that results of their model is more conservative than that of the Turner et al Model when comparison of results with field data is made. Hence, it is recommended that the Guo et al Model should be used to predict critical gas flow rate to prevent liquid loading problem in gas well. However, in the case when only minimum data are available, Turner et al Model that requires fewer inputs can be used to give a rough prediction of onset of liquid loading problem. The Turner et al Model does not need inputs like specific gravities of water, condensate and solid, conduit wall roughness, hole inclination, producing depth, and production rates of water, solid and condensate.

4.3 Sensitivity Study

This is the second function of the developed spread sheet of this project. Sensitivity studies on five parameters have been run to examine the effect of the parameters on critical gas flow rate to prevent liquid loading problem in gas wells. The sensitivity studies section is included in the spread sheet of the current project (below the first function in each model page). The five selected parameters are temperature, pressure, conduit size, producing depth and inclination.

Both the Turner et al Model and the Guo et al Model can be used to perform sensitivity studies of the first three parameters aforementioned. However, sensitivity studies of producing depth and inclination can only be performed by using the Guo et al Model. When value of one variable is altered, the other parameters are kept constant and the effect of the change of the variable on critical gas flow rate is analysed. Thus, it is necessary to run base case (as shown in Section 4.2) before running the sensitivity studies. This is done because inputs, such as specific gravity (of water, solid and condensate), production rate (water, solid and condensate), conduit wall roughness, liquid density and surface tension, which are kept constant throughout the sensitivity studies, are needed to be carried forward from the input table into sensitivity study table.

In all sensitivity studies, input current flowing flow rate is compared against the calculated minimum required gas flow rate for each parameter, in which current flowing flow rate that is below the minimum required gas flow rate may lead to liquid accumulation in gas wells. In the last column of the sensitivity study table, the result of comparison between current flowing flow rate and calculated minimum required flow rate is returned in the form of ‘yes’ or ‘no’ to indicate probability of occurrence of liquid loading problem in gas well. A graph of current flowing flow rate and minimum gas flow rate is plotted in every sensitivity study section. The intersection point is the cut-off point where liquid loading problem may occur.

Sets of inputs are used to run sensitivity study with the spread sheet developed. Inputs used, calculated results and plotted graphs will be discussed next.

4.3.1 Sensitivity Study of Temperature

In this sensitivity study, different temperature values are used to study effect of temperature on minimum required gas flow rate for liquid removal. The required input temperatures for both models are not the same. Surface temperatures must be the inputs for the Turner et al Model while wellhead temperatures must be the inputs for the Guo et al Model. Ten different temperatures (from 500 °R to 1400 °R with increment of 100 °R each), pressure of 500 psia (surface pressure for the Turner et al Model and wellhead pressure for the Guo et al Model), conduit size of 1.995 inch and current flowing flow rate of 0.5 MMscf/d are filled in in the sensitivity study table. Other input data are the same as in Table 4. The calculated critical gas flow rates are shown in the sensitivity study table (See Table 6 for the Turner et al Model and Table 7 for the Guo et al Model).

From the sensitivity study tables, the results of the Turner et al Model are varying from 0.724 MMscf/d to 0.387 MMscf/d while the results of the Guo et al Model are ranging from 0.844 MMscf/d to 0.492 MMscf/d. The first four input surface temperature (from 500 °R to 800 °R) is concluded by the Turner et al Model to have liquid loading problem in the well. However, all the input wellhead temperatures, except the last value (1400 °R) are predicted by the Guo et al Model to have liquid loading problem in the well.

Figure 9 is the graph for the Turner et al Model and Figure 10 is the graph for the Guo et al Model. Increasing temperature will result in lower critical flow rate. However, there is a slight difference between both lines. Line of the Turner et al Model tends to become straight from temperature of 1000 °R and above whereas line of the Guo et al Model tends to show linear relationship in lower temperature (less than 700 °R). From Figure 9, it can be concluded that surface temperature below 880 °R will result in potential liquid loading problem in the well. From Figure 10, wellhead temperature below 1340 °R may lead to liquid loading problem in the well.

In the Turner et al Model, the input surface temperature is used to compute pseudo reduced temperature to get gas compressibility factor, gas density before calculating minimum required gas flow rate. In the Guo et al Model, the input wellhead temperature is firstly used to compute producing zone temperature. Average temperature is computed from the wellhead temperature and producing zone temperature. It is used to calculate parameter a_g, b_g, c_g, and P before computing the critical gas flow rates. The difference of use of input temperature for both models is believed to be the reason that causes the difference of calculated results by both models. The temperature inputs required by the Turner et al Model are surface temperatures whereas the temperature inputs needed by the Guo et al Model are wellhead temperatures. These may explain the reason in which the cut-off point of the Guo et al Model (1400 °R) is higher than that of the Turner et al Model (880 °R); and higher critical gas flow rate of the Guo et al Model than the Turner et al Model.

It is concluded that both the Turner et al Model and the Guo et al Model give lower critical gas flow rates when temperature is increased. In other words, reduction of temperature must be controlled (at surface if the Turner et al Model is used and at wellhead if the Guo et al Model is used) during hydrocarbon production to prevent worsening of liquid loading problem and ensure continuous liquid removal in gas well. The differences of results calculated by the two models are due to the inputs of differences temperatures in the respective correlations.

4.3.2 Sensitivity Study of Pressure

In this sensitivity study, different pressure values are used to study effect of pressure on minimum required gas flow rate for liquid removal. The required input pressures for both models are not the same. Surface pressures must be the inputs for the Turner et al Model while wellhead pressures must be the inputs for the Guo et al Model. Ten different pressures (from 100 psia to 1900 psia with increment of 200 psia each), temperature of 520 °R (surface temperature for the Turner et al Model and wellhead temperature for the Guo et al Model), conduit size of 1.995 inch and current flowing flow rate of 0.5 MMscf/d are filled in in the sensitivity study table (See Table 8 for the Turner et al Model and Table 9 for the Guo et al Model). Other input data are the same as in Table 4.

From the sensitivity study tables, the results of the Turner et al Model are varying from 0.295 MMscf/d to 1.643 MMscf/d while the results of the Guo et al Model are varying from 0.387 MMscf/d to 1.595 MMscf/d. The first input pressure, 100 psia, is concluded by both Turner et al Model and Guo et al Model that there is no liquid loading problem in the well. Results of other input pressures show that liquid loading problem may occur in the well.

A graph of current flowing flow rate and minimum gas flow rate for various pressures is plotted. Likewise, the intersection point is the cut-off point where liquid accumulation may occur. Figure 11 is the graph for the Turner et al Model and Figure 12 is the graph for the Guo et al Model. Both graphs demonstrate same pattern. Increasing pressure will result in higher critical flow rate. From Figure 11, it is shown that surface pressure above 260 psia will result in potential liquid loading problem in the well. From Figure 12, wellhead pressure above 180 psia may lead to liquid loading problem in the well.

In the Turner et al Model, the input surface pressure is used to compute pseudo reduced pressure to get gas compressibility factor, gas density before calculating minimum required gas flow rate. In the Guo et al Model, the input wellhead pressure is to be applied in the four-phase mist flow model in estimating minimum required gas flow rate. Uses of pressure in correlations of both the models are not the same. This is believed to be the reason on the differences of calculated results by both models. The difference roles of pressure in the correlations is believed to to cause a lower cut-off point of the Guo et al Model (180 psia) than that of the Turner et al Model (260 psia).

It is concluded that both Turner et al Model and Guo et al Model give higher critical gas flow rates when pressure is increased. Increment of pressure must be controlled during hydrocarbon production to prevent liquid loading problem and also increasing amount of liquid accumulated. The differences of results calculated by the two models are due to the difference pressures used in the respective correlations.

4.3.3 Sensitivity Study of Conduit Size

In this sensitivity study, different conduit sizes are used to study effect of conduit sizes on minimum required gas flow rate for liquid removal. Ten different conduit sizes (from 1.315 inch to 6.625 inch), temperature of 520 °R (as surface temperature for the Turner et al Model and wellhead temperature for the Guo et al Model), pressure of 500 psia (as surface pressure for the Turner et al Model and wellhead pressure for the Guo et al Model) and current flowing flow rate of 0.5 MMscf/d are filled in in the sensitivity study table (See Table 10 for the Turner et al Model and Table 11 for the Guo et al Model). Note that the input sizes are defined as tubing diameters in the Turner et al Model and tubing outer diameters in the Guo et al Model (tubing inner diameters are always taken as 0 in this model as they are required to compute hydraulic diameter). Other input data are the same as in Table 4.

From the sensitivity study tables, the results of the Turner et al Model are varying from 0.305 MMscf/d to 7.735 MMscf/d while the results of the Guo et al Model are changing from 0.364 MMscf/d to 8.990 MMscf/d. From the Turner et al Model, it is shown that if conduit size larger than 1.660 inch is used, liquid loading problem probably will occur. However, results of the Guo et al Model depict that conduit size larger than 1.315 inch may lead to liquid accumulation in gas well.

A graph of current flowing flow rate and minimum gas flow rate for conduit sizes is plotted. Similarly, the intersection point is the cut-off point where liquid loading problem may occur. Figure 13 is the graph for the Turner et al Model and Figure 14 is the graph for the Guo et al Model. Both graphs demonstrate same pattern. Increasing conduit sizes will increase critical gas flow rate. From Figure 13, it is demonstrated that conduit that is larger than 1.7 inch will result in potential liquid loading problem in the well. From Figure 14, conduit larger than 1.5 inch may lead to liquid loading problem in the well.

In the Turner et al Model, the input conduit size is only used to calculate cross-sectional area to determine minimum required gas flow rate. In the Guo et al Model, the input conduit size is to be employed to calculate hydraulic diameter and cross-sectional area before using them in the four-phase mist flow model to obtain minimum required gas flow rate. Type of pressures input and uses of pressure in correlations of both the models are not the same. The cut-off point of the Turner et al Model (≈1.7 inch) is higher than that of the Guo et al Model (≈1.5 inch). This probably is caused by difference uses of conduit size and times of the conduit size used in correlations in both models.

It is concluded that both Turner et al Model and Guo et al Model give higher critical gas flow rates when conduit size is increased. Critical gas flow rate is to be increased by approximately 80% to 90% when the conduit size is increased by four times. Hence, appropriate conduit size should be carefully selected before hydrocarbon production to prevent liquid loading problem to be occurred. The differences of results calculated by the two models are due to the differences of uses of conduit sizes in the respective correlations.

4.3.4 Sensitivity Study of Producing Depth

This sensitivity study can be only performed by using the Guo et al Model. In this sensitivity study, different producing depths are used to study effect of producing depth on minimum required gas flow rate for liquid removal. Ten different producing depths (from 2000 ft to 20000 ft with increment of 2000 ft each), wellhead temperature of 520 °R, wellhead pressure of 500 psia, conduit outer diameter of 1.995 inch, conduit inner diameter of 0 inch and current flowing flow rate of 0.830 MMscf/d are filled in in the sensitivity study table (See Table 12). Other input data are the same as in Table 4.

From the sensitivity study table, the calculated minimum required gas flow rates are ranging from 0.798 MMscf/d to 0.890 MMscf/d. The sensitivity study shows that producing depth that is larger than 6000 ft may lead to liquid loading in gas well. A graph of current flowing flow rate and minimum gas flow rate for various producing depth is plotted. Likewise, the intersection point is the cut-off point where liquid loading problem may occur. Figure 15 is the graph for sensitivity study of producing depth by the Guo et al Model. From the graph, it is shown that increasing producing depth will increase critical gas flow rate. The line is almost linear. Cut-off point of the graph is found to be 7200 ft. This depicts that liquid loading problem may occur in the well if producing depth is larger than 7200 ft. From this sensitivity study, it is said that producing depth can affect the critical gas flow rate. This is because the input producing depth is to be employed to calculate average temperature and objective function before using the two calculated values in determining the minimum required gas flow rate.

In conclusion, critical gas flow rate is higher when producing depth is increased. Hence, producing depth should be input carefully when users want to use the Guo et al Model to compute critical gas flow rate. The increment of 2000 ft gives approximately 0.01 MMscf/d increment in critical gas flow rate. Thus, if producing depth is not available, users can input a rough estimation of producing depth in order to proceed with calculation of critical gas flow rate by using the Guo et al Model.

4.3.5 Sensitivity Study of Inclination

Similarly to producing depth, this sensitivity study can be only performed by using the Guo et al Model. In this sensitivity study, different inclination angles are used to study effect of inclination on minimum required gas flow rate for liquid removal. Ten different inclination angles (from 0° to 80° with increment of 10° each and 89°), wellhead temperature of 520 °R, wellhead pressure of 500 psia, conduit outer diameter of 1.995 inch, conduit inner diameter of 0 inch and current flowing flow rate of 0.800 MMscf/d are filled in in the sensitivity study table (See Table 13). Other input data are the same as in Table 4.

From the sensitivity study table, the calculated minimum required gas flow rates are ranging from 0.827 MMscf/d to 0.769 MMscf/d. The sensitivity study computed result shows that inclination that is smaller than 60° may lead to liquid loading problem in gas well. A graph of current flowing flow rate and minimum gas flow rate for various inclinations is plotted. The intersection point is the cut-off point where liquid accumulation may occur. Figure 16 is the graph for sensitivity study of inclination by the Guo et al Model. From the graph, it is shown that increasing inclination angle will reduce critical gas flow rate. Cut-off point of the graph is found to be 56°. This depicts that liquid loading problem may occur in the well if inclination angle is smaller than 56°. From this sensitivity study, it is said that inclination can affect the critical gas flow rate. This is because the input inclination is to be used to calculate constant a and constant e which are necessary in determining the minimum required gas flow rate.

In conclusion, critical gas flow rate reduces when inclination is increased. Hence, inclination should be input carefully when users want to use the Guo et al Model to compute critical gas flow rate. However, the increment of 10° reduces the critical gas flow rate by about 0.01 MMscf/d. Thus, if inclination is not available, users can input a rough estimation of inclination in order to proceed with calculation of critical gas flow rate by using the Guo et al Model.

Table 6 Sensitivity Study Table of Temperature by the Turner et al Model

Surface temperature, °R	Current flowing flow rate, MMscf/d	Pseudo reduced temperature, (-)	Gas density, lbm/ft^3	A_z, (-)	B_z, (-)	C_z, (-)	D_z, (-)	E_z, (-)	F_z, (-)	Z, (-)	Mini-mum required gas velocity, ft/s	Mini-mum required gas flow rate, MMscf/d	Liquid Loading
500	0.5	1.395	1.620	0.355	0.270	0.086	0.959	3.552	-0.018	0.912	9.940	0.724	Yes
600	0.5	1.674	1.350	0.503	0.199	0.060	1.003	6.063	0.001	0.955	10.900	0.632	Yes
700	0.5	1.953	1.157	0.609	0.140	0.039	1.120	8.573	0.049	0.977	11.782	0.572	Yes
800	0.5	2.232	1.013	0.688	0.086	0.020	1.335	11.084	0.125	0.988	12.602	0.529	Yes
900	0.5	2.510	0.900	0.748	0.033	0.004	1.698	13.594	0.230	0.994	13.372	0.496	No
1000	0.5	2.789	0.810	0.795	-0.018	-0.011	2.307	16.105	0.363	0.998	14.100	0.469	No
1100	0.5	3.068	0.736	0.832	-0.068	-0.024	3.345	18.615	0.524	1.003	14.793	0.445	No
1200	0.5	3.347	0.675	0.860	-0.117	-0.036	5.177	21.126	0.714	1.010	15.454	0.424	No
1300	0.5	3.626	0.623	0.880	-0.166	-0.047	8.555	23.636	0.932	1.018	16.088	0.404	No
1400	0.5	3.905	0.579	0.895	-0.215	-0.057	15.091	26.146	1.179	1.025	16.698	0.387	No

Table 7 Sensitivity Study Table of Temperature by the Guo et al Model

Wellhead temperature, °R	Current flowing flow rate, MMscf/d	Average temperature, °R	Minimum required gas flow rate, MMscf/d	Bottomhole pressure, psia	Minimum required gas velocity, ft/s	Liquid Loading
500	0.5	533.5	0.844	592.851	11.446	Yes
600	0.5	633.5	0.766	579.407	12.616	Yes
700	0.5	733.5	0.706	569.769	13.690	Yes
800	0.5	833.5	0.658	562.529	14.687	Yes
900	0.5	933.5	0.618	556.893	15.621	Yes
1000	0.5	1033.5	0.585	552.380	16.504	Yes
1100	0.5	1133.5	0.557	548.686	17.342	Yes
1200	0.5	1233.5	0.533	545.607	18.142	Yes
1300	0.5	1333.5	0.511	543.001	18.908	Yes
1400	0.5	1433.5	0.492	540.767	19.645	No

Table 8 Sensitivity Study Table of Pressure by the Turner et al Model

Surface pressure, psia	Current flowing flow rate, MMscf/d	Pseudo reduced pressure, (-)	Gas density, lbm/ft^3	A_z, (-)	B_z, (-)	C_z, (-)	D_z, (-)	E_z, (-)	F_z, (-)	Z, (-)	Minimum required gas velocity, ft/s	Minimum required gas flow rate, MMscf/d	Liquid Loading
100	0.5	0.149	0.312	0.389	0.044	0.080	0.963	4.054	-0.016	0.986	22.778	0.295	No
300	0.5	0.446	0.935	0.389	0.143	0.080	0.963	4.054	-0.016	0.956	13.121	0.526	Yes
500	0.5	0.743	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.701	Yes
700	0.5	1.041	2.181	0.389	0.379	0.080	0.963	4.054	-0.016	0.891	8.549	0.858	Yes
900	0.5	1.338	2.804	0.389	0.517	0.080	0.963	4.054	-0.016	0.860	7.521	1.006	Yes
1100	0.5	1.636	3.427	0.389	0.669	0.080	0.963	4.054	-0.016	0.831	6.787	1.148	Yes
1300	0.5	1.933	4.050	0.389	0.834	0.080	0.963	4.054	-0.016	0.806	6.228	1.283	Yes
1500	0.5	2.230	4.673	0.389	1.014	0.080	0.963	4.054	-0.016	0.785	5.783	1.412	Yes
1700	0.5	2.528	5.296	0.389	1.209	0.080	0.963	4.054	-0.016	0.768	5.419	1.533	Yes
1900	0.5	2.825	5.919	0.389	1.420	0.080	0.963	4.054	-0.016	0.755	5.113	1.643	Yes

Table 9 Sensitivity Study Table of Pressure by the Guo et al Model

Wellhead pressure, psia	Current flowing flow rate, MMscf/d	Wellhead pressure, lbf/ft^2	Minimum required gas flow rate, MMscf/d	Bottomhole pressure, psia	Minimum required gas velocity, ft/s	Liquid Loading
100	0.5	14400	0.387	129.098	24.983	No
300	0.5	43200	0.645	359.398	14.973	Yes
500	0.5	72000	0.827	589.756	11.689	Yes
700	0.5	100800	0.975	819.921	9.913	Yes
900	0.5	129600	1.103	1049.899	8.761	Yes
1100	0.5	158400	1.218	1279.681	7.935	Yes
1300	0.5	187200	1.322	1509.238	7.307	Yes
1500	0.5	216000	1.419	1738.521	6.808	Yes
1700	0.5	244800	1.510	1967.465	6.400	Yes
1900	0.5	273600	1.595	2195.987	6.057	Yes

Table 10 Sensitivity Study Table of Conduit Size by the Turner et al Model

Conduit diameter, inch	Current flowing flow rate, MMscf/d	Tubing cross-sectional area, ft^2	Gas density, lbm/ft^3	A_z, (-)	B_z, (-)	C_z, (-)	D_z, (-)	E_z, (-)	F_z, (-)	Z, (-)	Minimum required gas velocity, ft/s	Minimum required gas flow rate, MMscf/d	Liquid Loading
1.315	0.5	0.009	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.305	No
1.660	0.5	0.015	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.486	No
1.900	0.5	0.020	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.636	Yes
2.375	0.5	0.031	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.994	Yes
2.875	0.5	0.045	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	1.457	Yes
3.500	0.5	0.067	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	2.159	Yes
4.000	0.5	0.087	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	2.820	Yes
4.500	0.5	0.110	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	3.569	Yes
5.563	0.5	0.169	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	5.454	Yes
6.625	0.5	0.239	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	7.735	Yes

Table 11 Sensitivity Study Table of Conduit Size by the Guo et al Model

Conduit outer diameter, in	Conduit inner diameter, in	Current flowing flow rate, MMscf/d	Cross-sectional area, ft^2	Minimum required gas flow rate, MMscf/d	Bottomhole pressure, psia	Minimum required gas velocity, ft/s	Liquid Loading
1.315	0.0	0.5	0.009	0.364	606.481	11.527	No
1.660	0.0	0.5	0.015	0.575	595.583	11.632	Yes
1.900	0.0	0.5	0.020	0.751	591.120	11.675	Yes
2.375	0.0	0.5	0.031	1.167	585.720	11.729	Yes
2.875	0.0	0.5	0.045	1.706	582.439	11.762	Yes
3.500	0.0	0.5	0.067	2.523	579.889	11.788	Yes
4.000	0.0	0.5	0.087	3.291	578.464	11.802	Yes
4.500	0.0	0.5	0.110	4.161	577.329	11.814	Yes
5.563	0.0	0.5	0.169	6.348	575.381	11.834	Yes
6.625	0.0	0.5	0.239	8.990	573.669	11.852	Yes

Table 12 Sensitivity Study Table of Producing Depth by the Guo et al Model

Producing depth, ft	Current flowing flow rate, MMscf/d	Producing zone temperature, °R	Average temperature, °R	Minimum required gas flow rate, MMscf/d	Bottomhole pressure, psia	Minimum required gas velocity, ft/s	Liquid Loading
2000	0.830	540.000	530.000	0.798	526.366	12.107	No
4000	0.830	560.000	540.000	0.810	553.110	11.922	No
6000	0.830	580.000	550.000	0.822	580.204	11.747	No
8000	0.830	600.000	560.000	0.834	607.552	11.584	Yes
10000	0.830	620.000	570.000	0.845	634.953	11.432	Yes
12000	0.830	640.000	580.000	0.856	662.171	11.292	Yes
14000	0.830	660.000	590.000	0.865	688.989	11.165	Yes
16000	0.830	680.000	600.000	0.874	715.217	11.051	Yes
18000	0.830	700.000	610.000	0.882	740.694	10.950	Yes
20000	0.830	720.000	620.000	0.890	765.293	10.860	Yes

Table 13 Sensitivity Study Table of Inclination by the Guo et al Model

Inclination, °	Current flowing flow rate, MMscf/d	Inclination, rad	Minimum required gas flow rate, MMscf/d	Bottomhole pressure, psia	Minimum required gas velocity, ft/s	Liquid Loading
0	0.800	0.000	0.827	589.756	11.689	Yes
10	0.800	0.175	0.826	588.443	11.702	Yes
20	0.800	0.349	0.823	584.561	11.741	Yes
30	0.800	0.524	0.818	578.268	11.804	Yes
40	0.800	0.698	0.812	569.821	11.892	Yes
50	0.800	0.873	0.805	559.559	12.000	Yes
60	0.800	1.047	0.797	547.881	12.127	No
70	0.800	1.222	0.787	535.222	12.270	No
80	0.800	1.396	0.778	522.024	12.424	No
89	0.800	1.553	0.769	509.872	12.571	No

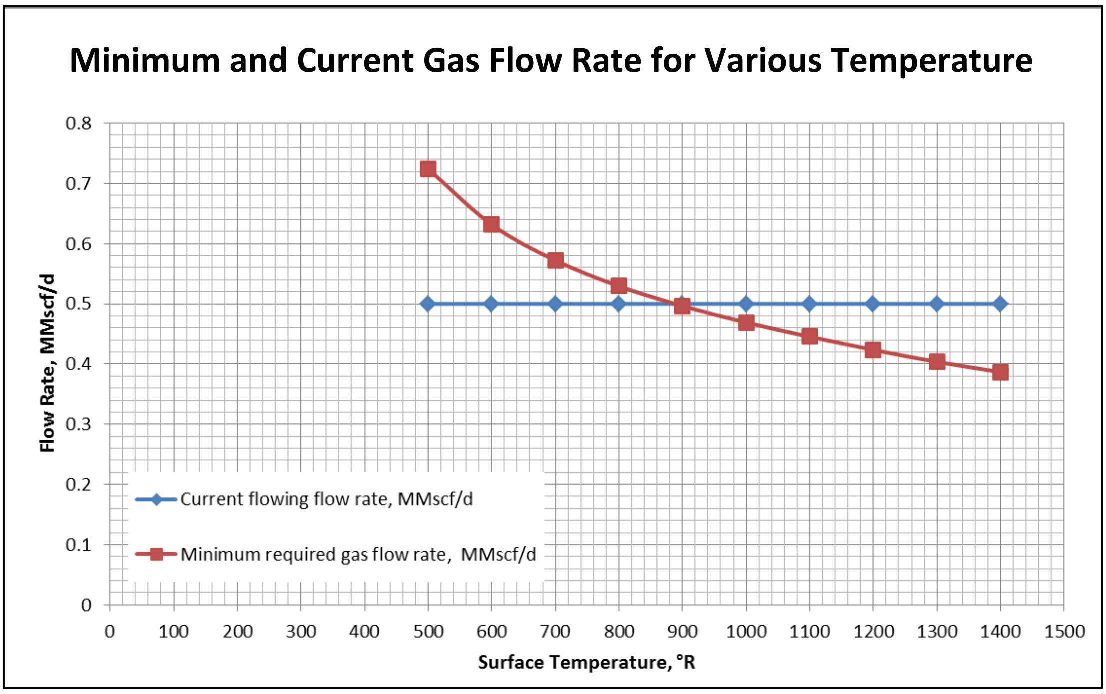


Figure 9 Graph of Sensitivity Study of Temperature by the Turner et al Model

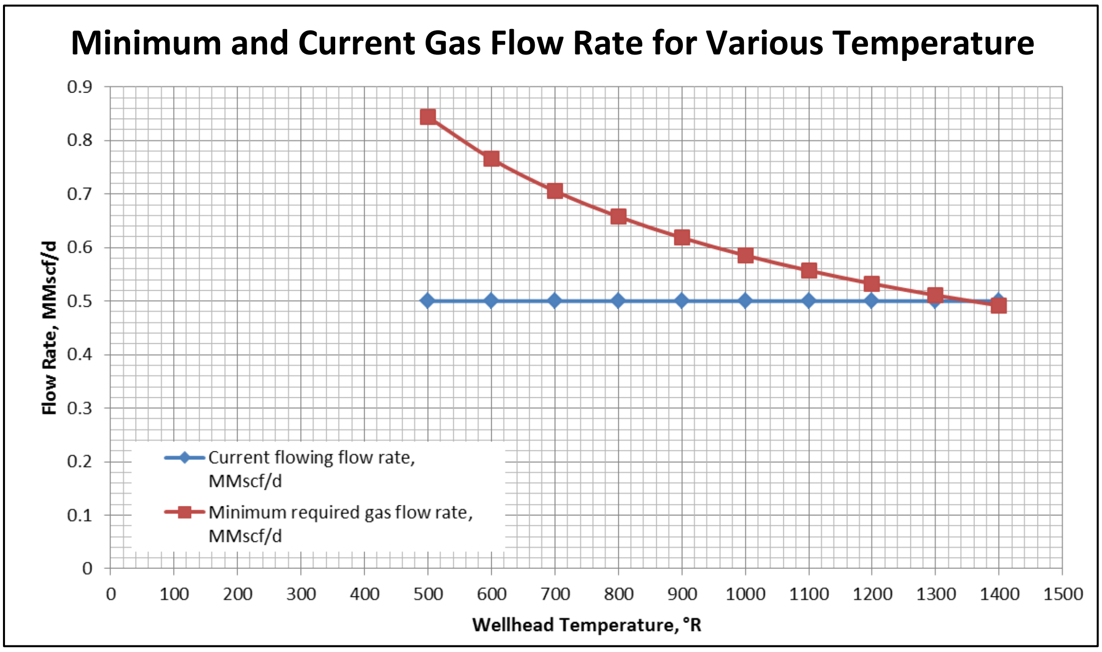


Figure 10 Graph of Sensitivity Study of Temperature by the Guo et al Model

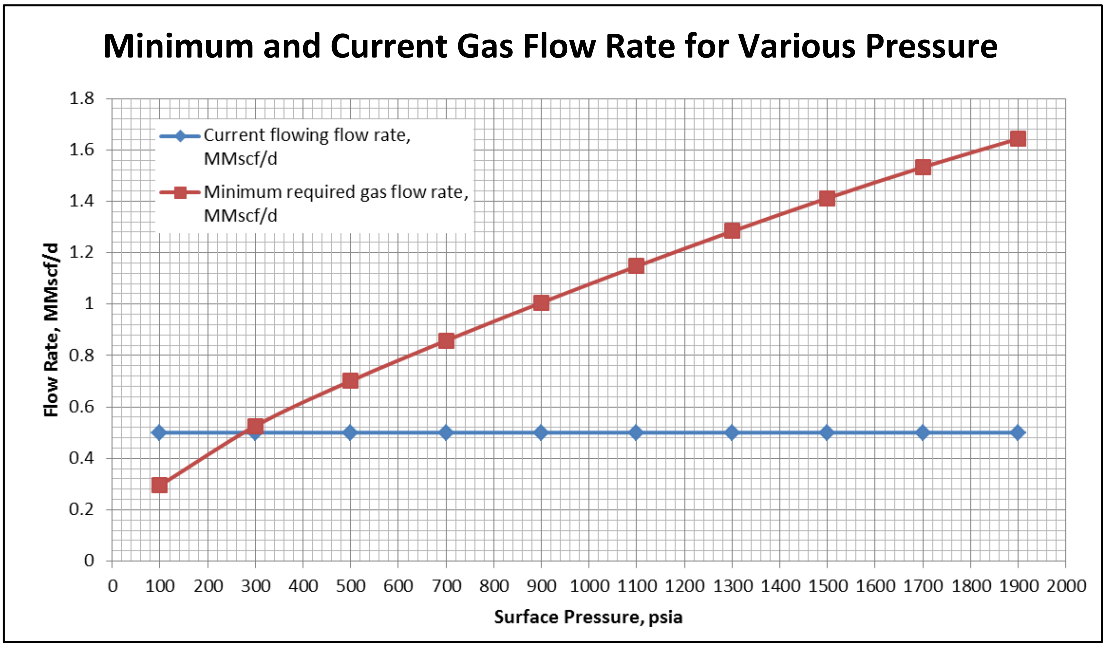


Figure 11 Graph of Sensitivity Study of Pressure by the Turner et al Model

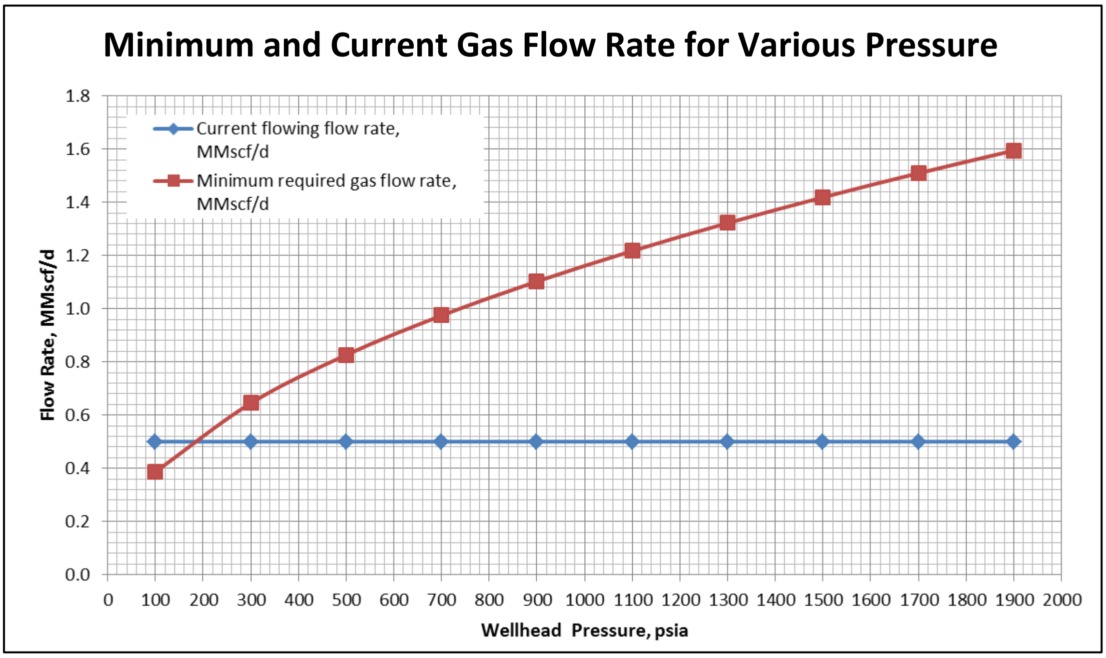


Figure 12 Graph of Sensitivity Study of Pressure by the Guo et al Model

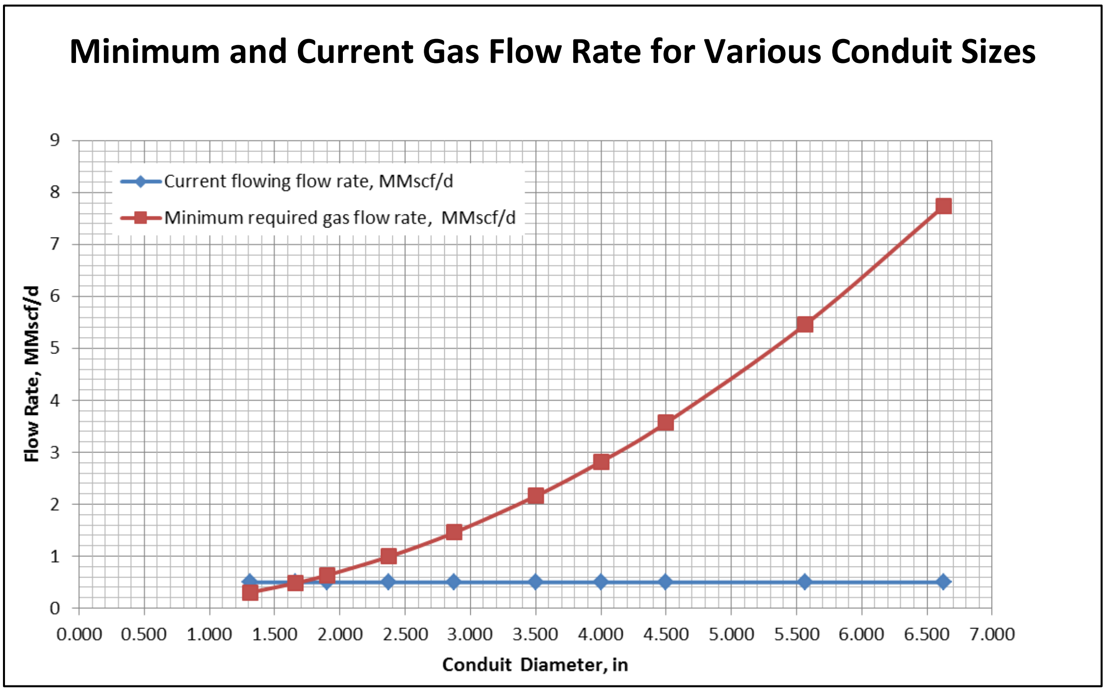


Figure 13 Graph of Sensitivity Study of Conduit Size by the Turner et al Model

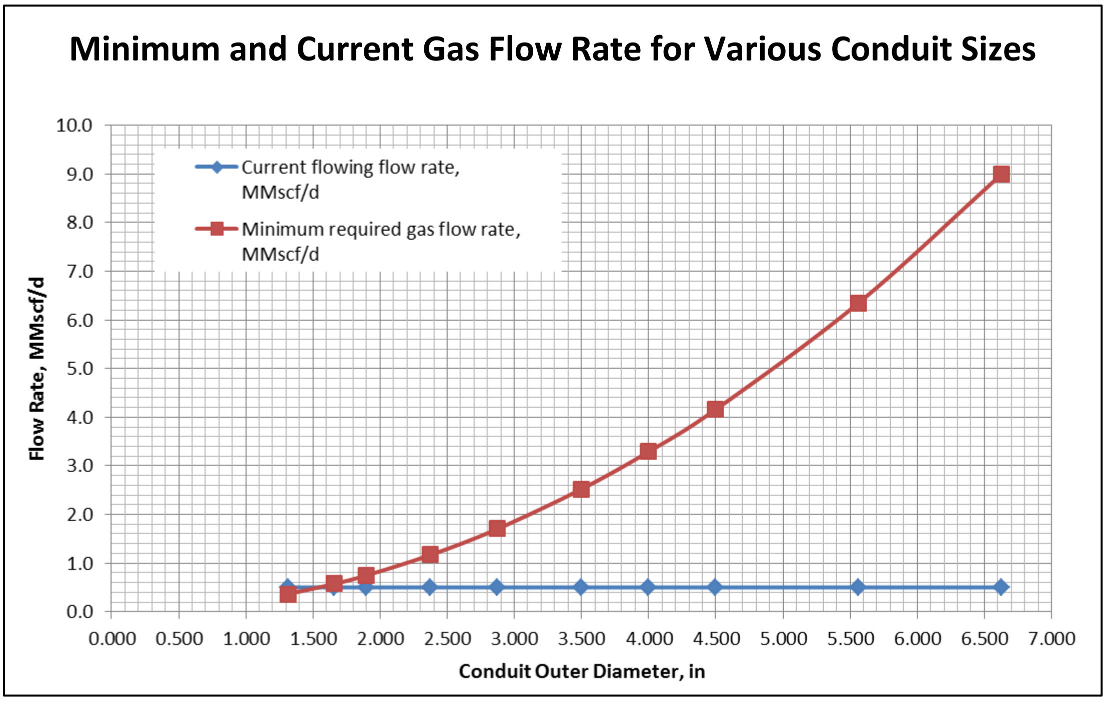


Figure 14 Graph of Sensitivity Study of Conduit Size by the Guo et al Model

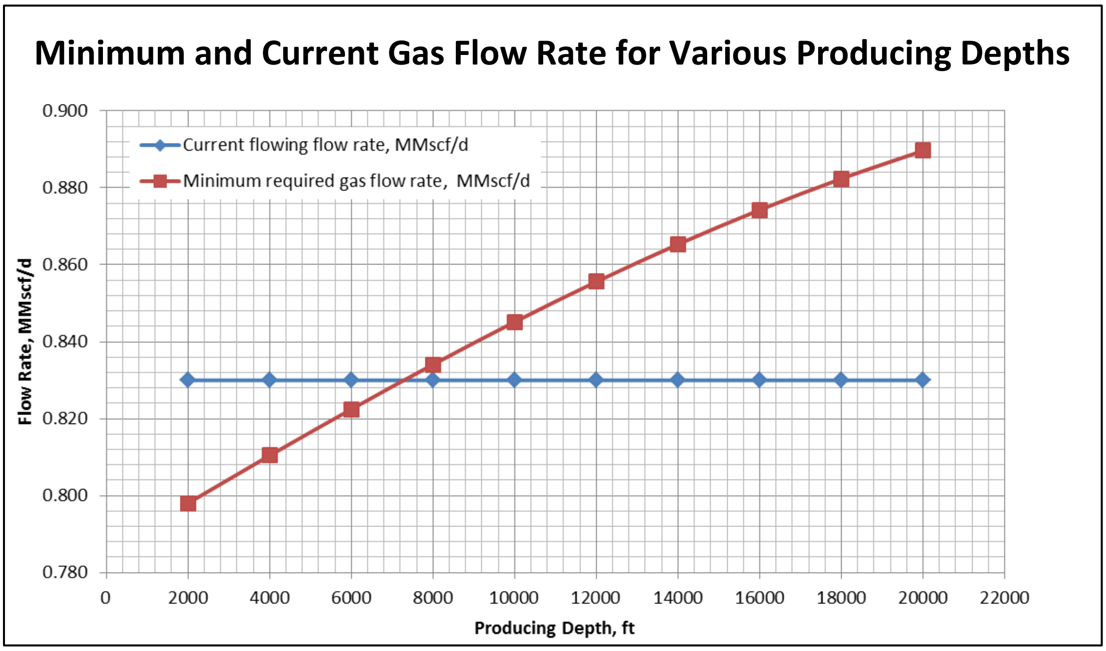


Figure 15 Graph of Sensitivity Study of Producing Depth by the Guo et al Model

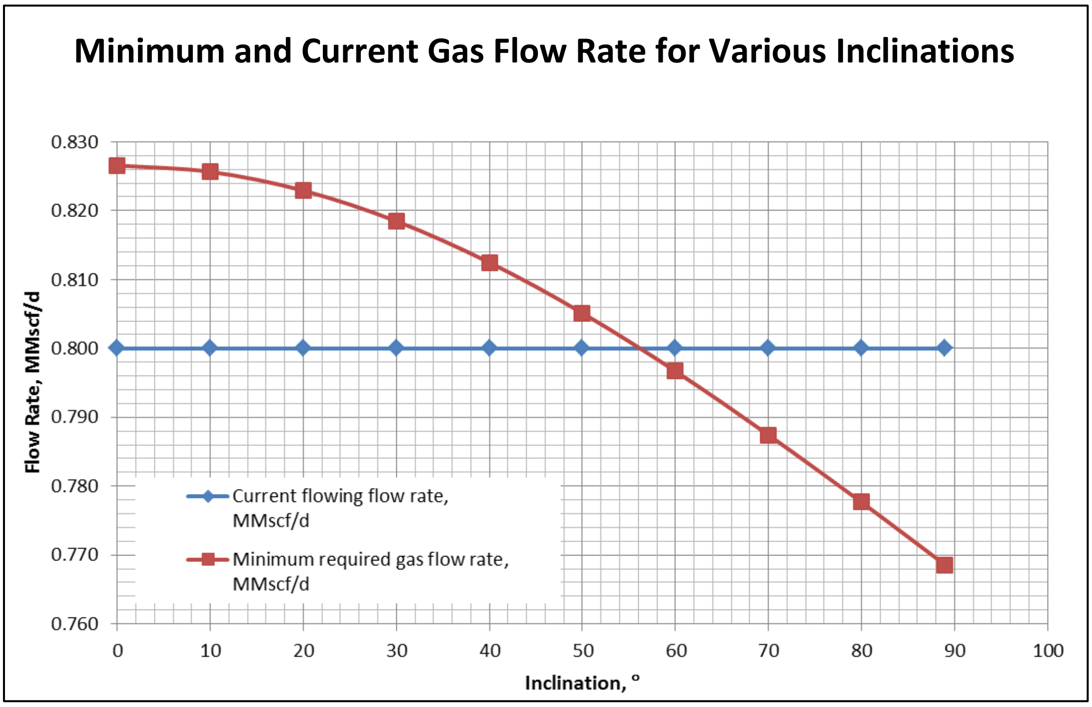


Figure 16 Graph of Sensitivity Study of Inclination by the Guo et al Model

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The whole project can be summarized as follow:

- A work flow that predicts critical gas flow rate to prevent liquid loading and to conduct sensitivity study by Turner et al Model and Guo et al Model was developed.
    - For the set of inputs utilized, the critical gas velocity and flow rate calculated by the Turner et al Model (10.139 ft/s and 0.701 MMscf/d) is lower than that of the Guo et al Model (11.689ft/s and 0.827 MMscf/d).
- Through sensitivity studies, effects of parameters (temperature, pressure, conduit size, producing depth and inclination) on the critical gas flow rate were obtained.
    - Critical gas flow rate will be increased if temperature is reduced; pressure is increased; conduit size is increased; producing depth is increased or inclination is reduced.
    - For the sets of inputs utilized, the cut-off points (and critical gas flow rates) obtained for the Turner et al Model are 880°R (0.724 to 0.387 MMscf/d), 260 psia (0.295 to 1.643 MMscf/d) and 1.7 inches (0.305 to 7.735 MMscf/d); while the cut-off points (and critical gas flow rates) obtained for the Guo et al Model are 1340°R (0.844 to 0.492 MMscf/d), 180 psia (0.387 to 1.595 MMscf/d), 1.5 inches (0.364 to 8.990 MMscf/d), 7200 ft (0.798 to 0.890 MMscf/d), and 56° (0.827 to 0.769 MMscf/d).
- It is hoped that through this project, a better insight of prediction of liquid loading problem in gas wells can be yielded. Hopefully the project and the work flow will be beneficial and can be applied in the industry.
- The objectives of the project have been achieved. Therefore, the project can be considered as successfully completed.

5.2 RECOMMENDATIONS

The project can be further improved to have deeper study in liquid loading problem. For expansion and continuation, a few works have been highlighted and proposed:

- It is suggested to include other models on prediction of critical gas flow rates.
- It is recommended to include gas well deliquification techniques after the prediction of liquid loading in gas well. Occurrence of liquid loading in a gas well can be checked by using the spread sheet of the current project. After that, the spread sheet can be further developed by includes different gas well deliquification techniques.
- Different criteria in selecting suitable gas well deliquification techniques can be added.
- Also, mathematical models of different techniques can be further included to check well performances after unloading by those techniques.
- Upon completion of static and steady-state model, it is recommended to develop dynamic and non-steady state models of the techniques.

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barger%2Fpublic_html%2FSelected_papers%2FLiquid%2520Loading.doc&ei=nbr3UdOZJczRrQfQjoCgAw&usg=AFQjCNG5KtmT70RLr55596M6c22wsxeSrg&sig2=crULi1DKqtue_Es8gId_RA&bvm=bv.49967636,d.bmk

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APPENDICES

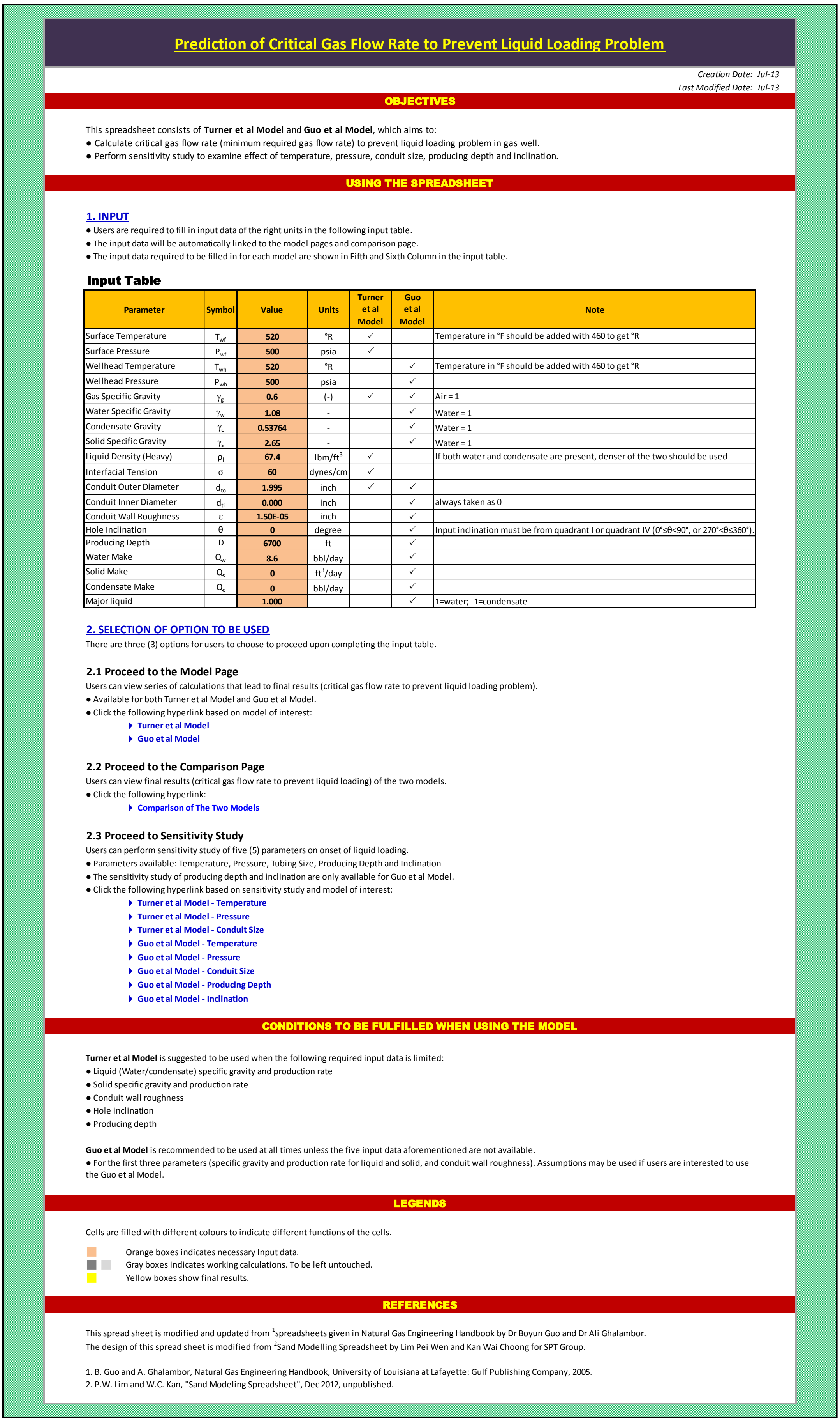
Appendix 1

The four pages of the spread sheet developed are shown in this section.

The home page with input table is shown in Figure 17. The input table will be automatically linked to the second, third and fourth page of the spread sheet. Names and symbols of the necessary parameters are included in the first two columns; the automatically-linked values and units of the parameters can be found in the third and fourth column, requirements of the inputs for both models are shown in the following columns and the last column is named as 'Note' column where notes such as 'specific gravity by assuming air equals to one' can be added in this column.

Figure 18 and Figure 19 demonstrate the Turner et al Model while Figure 20 and Figure 21 shows the Guo et al Model. First function is the prediction of critical flow rate and second function is the sensitivity study section.

In Figure 22, a comparison page which links the calculated critical flow rates from Figure 18 and Figure 20 is shown.



Prediction of Critical Gas Flow Rate to Prevent Liquid Loading Problem

Creation Date: Jul-13
Last Modified Date: Jul-13

OBJECTIVES

This spreadsheet consists of **Turner et al Model** and **Guo et al Model**, which aims to:
- Calculate critical gas flow rate (minimum required gas flow rate) to prevent liquid loading problem in gas well.
- Perform sensitivity study to examine effect of temperature, pressure, conduit size, producing depth and inclination.

USING THE SPREADSHEET

1. INPUT

- Users are required to fill in input data of the right units in the following input table.
- The input data will be automatically linked to the model pages and comparison page.
- The input data required to be filled in for each model are shown in Fifth and Sixth Column in the input table.

Input Table

Parameter	Symbol	Value	Units	Turner et al Model	Guo et al Model	Note
Surface Temperature	T_{wf}	520	°R	✓		Temperature in °F should be added with 460 to get °R
Surface Pressure	P_{wf}	500	psia	✓		
Wellhead Temperature	T_{wh}	520	°R		✓	Temperature in °F should be added with 460 to get °R
Wellhead Pressure	P_{wh}	500	psia		✓	
Gas Specific Gravity	γ_g	0.6	(-)	✓	✓	Air = 1
Water Specific Gravity	γ_w	1.08	-		✓	Water = 1
Condensate Gravity	γ_c	0.53764	-		✓	Water = 1
Solid Specific Gravity	γ_s	2.65	-		✓	Water = 1
Liquid Density (Heavy)	ρ_l	67.4	lbm/ft^3	✓		If both water and condensate are present, denser of the two should be used
Interfacial Tension	σ	60	dynes/cm	✓		
Conduit Outer Diameter	d_{to}	1.995	inch	✓	✓	
Conduit Inner Diameter	d_{ti}	0.000	inch		✓	always taken as 0
Conduit Wall Roughness	ε	1.50E-05	inch		✓	
Hole Inclination	θ	0	degree		✓	Input inclination must be from quadrant I or quadrant IV ($0°\leq\theta<90°$, or $270°<\theta\leq360°$).
Producing Depth	D	6700	ft		✓	
Water Make	Q_w	8.6	bbl/day		✓	
Solid Make	Q_s	0	ft^3/day		✓	
Condensate Make	Q_c	0	bbl/day		✓	
Major liquid	-	1.000	-		✓	1=water; -1=condensate

2. SELECTION OF OPTION TO BE USED

There are three (3) options for users to choose to proceed upon completing the input table.

2.1 Proceed to the Model Page

Users can view series of calculations that lead to final results (critical gas flow rate to prevent liquid loading problem).
- Available for both Turner et al Model and Guo et al Model.
- Click the following hyperlink based on model of interest:
  - **Turner et al Model**
  - **Guo et al Model**

2.2 Proceed to the Comparison Page

Users can view final results (critical gas flow rate to prevent liquid loading) of the two models.
- Click the following hyperlink:
  - **Comparison of The Two Models**

2.3 Proceed to Sensitivity Study

Users can perform sensitivity study of five (5) parameters on onset of liquid loading.
- Parameters available: Temperature, Pressure, Tubing Size, Producing Depth and Inclination
- The sensitivity study of producing depth and inclination are only available for Guo et al Model.
- Click the following hyperlink based on sensitivity study and model of interest:
  - **Turner et al Model - Temperature**
  - **Turner et al Model - Pressure**
  - **Turner et al Model - Conduit Size**
  - **Guo et al Model - Temperature**
  - **Guo et al Model - Pressure**
  - **Guo et al Model - Conduit Size**
  - **Guo et al Model - Producing Depth**
  - **Guo et al Model - Inclination**

CONDITIONS TO BE FULFILLED WHEN USING THE MODEL

Turner et al Model is suggested to be used when the following required input data is limited:
- Liquid (Water/condensate) specific gravity and production rate
- Solid specific gravity and production rate
- Conduit wall roughness
- Hole inclination
- Producing depth

Guo et al Model is recommended to be used at all times unless the five input data aforementioned are not available.
- For the first three parameters (specific gravity and production rate for liquid and solid, and conduit wall roughness). Assumptions may be used if users are interested to use the Guo et al Model.

LEGENDS

Cells are filled with different colours to indicate different functions of the cells.

Orange boxes indicates necessary Input data.
Gray boxes indicates working calculations. To be left untouched.
Yellow boxes show final results.

REFERENCES

This spread sheet is modified and updated from [1]spreadsheets given in Natural Gas Engineering Handbook by Dr Boyun Guo and Dr Ali Ghalambor.
The design of this spread sheet is modified from [2]Sand Modelling Spreadsheet by Lim Pei Wen and Kan Wai Choong for SPT Group.

1. B. Guo and A. Ghalambor, Natural Gas Engineering Handbook, University of Louisiana at Lafayette: Gulf Publishing Company, 2005.
2. P.W. Lim and W.C. Kan, "Sand Modeling Spreadsheet", Dec 2012, unpublished.

Figure 17 First Page of the Developed Spread Sheet – Home and Input Page

Turner et al Model

INPUT DATA REQUIRED

Parameter	Symbol	Value	Units	Note
Surface Temperature	T_{wf}	520.000	°R	
Surface Pressure	P_{wf}	500.000	psia	
Gas Specific Gravity	γ_g	0.600	(-)	Air = 1
Liquid Density (Heavy)	ρ_l	67.400	lbm/ft^3	
Interfacial Tension	σ	60.000	dynes/cm	
Tubing Outer Diameter	d_{to}	1.995	inch	

Critical Gas Production Rate to Prevent Liquid Loading

This is to calculate Turner velocity and the minimum gas flow rate required for liquid removal.

Average Temperature	T_{av}	520.000	°R	
Average Pressure	P_{av}	500.000	psia	
Pseudo Critical Temperature	T_{pc}	358.500	°R	
Pseudo Critical Pressure	P_{pc}	672.500	psia	
Pseudo Reduced Temperature	T_{pr}	1.450	(-)	
Pseudo Reduced Pressure	P_{pr}	0.743	(-)	
Gas Density	ρ_g	1.558	lbm/ft^3	Assuminng z = 1
Tubing Cross-sectional Area	A	0.022	ft^2	
Parameter A	A_z	0.389	(-)	
Parameter B	B_z	0.254	(-)	
Parameter C	C_z	0.080	(-)	
Parameter D	D_z	0.963	(-)	
Parameter E	E_z	4.054	(-)	
Parameter F	F_z	-0.016	(-)	
Gas Compressibility Factor	Z	0.923	(-)	
Terminal Settling Velocity	V_{gm}	10.139	ft/s	
Minimum Gas Flow Rate	Q_{gm}	0.701	MMscf/d	

The minimum gas velocity required to transport liquid drops is : 10.139 ft/s
The minimum required gas flow rate for liquid removal is : 0.701 MMscf/d

Gas flow rate below the calculated minimum gas flow rate may lead to liquid accumulation at the bottomhole.

Figure 18 Second Page of the Developed Spread Sheet - First Function of the Turner et al Model

SENSITIVITY STUDY (TEMPERATURE)

This is to examine the terminal settling velocity and the minimum gas flow rate required for liquid removal for a range of surface temperature.

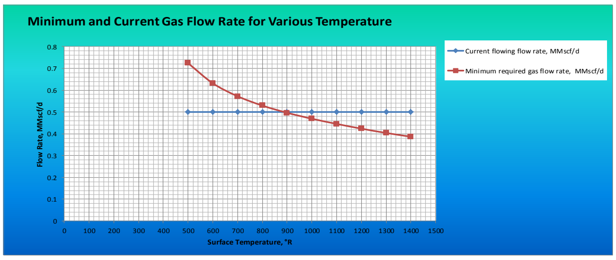
User can choose to fill in ten (10) different surface temperature for one (1) surface pressure, one (1) conduit size and one (1) current flowing flow rate of interest for this sensitivity study in the Orange boxes.

Assuming z = 1 in computing gas density.

Surface pressure	500.000 psia	Pseudo reduced pressure	0.743 (-)
Conduit diameter	1.995 inch	Tubing cross-sectional area	0.022 ft^2

Surface temperature, °R	Current flowing flow rate, MMscf/d	Pseudo reduced temperature, (-)	Gas density, lbm/ft^3	A_z, (-)	B_z, (-)	C_z, (-)	D_z, (-)	E_z, (-)	F_z, (-)	Z, (-)	Minimum required gas velocity, ft/s	Minimum required gas flow rate, MMscf/d	Liquid Loading
500	0.5	1.395	1.620	0.355	0.270	0.086	0.959	3.552	-0.018	0.912	9.940	0.724	Yes
600	0.5	1.674	1.350	0.503	0.199	0.060	1.003	6.063	0.001	0.955	10.900	0.632	Yes
700	0.5	1.953	1.157	0.609	0.140	0.039	1.120	8.573	0.049	0.977	11.782	0.572	Yes
800	0.5	2.232	1.013	0.688	0.086	0.020	1.335	11.084	0.125	0.988	12.602	0.529	Yes
900	0.5	2.510	0.900	0.748	0.033	0.004	1.698	13.594	0.230	0.994	13.372	0.496	No
1000	0.5	2.789	0.810	0.795	-0.018	-0.011	2.307	16.105	0.363	0.998	14.100	0.469	No
1100	0.5	3.068	0.736	0.832	-0.068	-0.024	3.345	18.615	0.524	1.003	14.793	0.445	No
1200	0.5	3.347	0.675	0.860	-0.117	-0.036	5.177	21.126	0.714	1.010	15.454	0.424	No
1300	0.5	3.626	0.623	0.880	-0.166	-0.047	8.555	23.636	0.932	1.018	16.088	0.404	No
1400	0.5	3.905	0.579	0.895	-0.215	-0.057	15.091	26.146	1.179	1.025	16.698	0.387	No

Liquid removal may occur when the current flowing flow rate is above the minimum gas flow rate, for which below the minimum gas flow rate, liquid may accumulate.
Current flowing flow rate below the calculated minimum gas flow rate may lead to liquid loading problem.



SENSITIVITY STUDY (PRESSURE)

This is to examine the terminal settling velocity and the minimum gas flow rate required for liquid removal for a range of surface pressure.

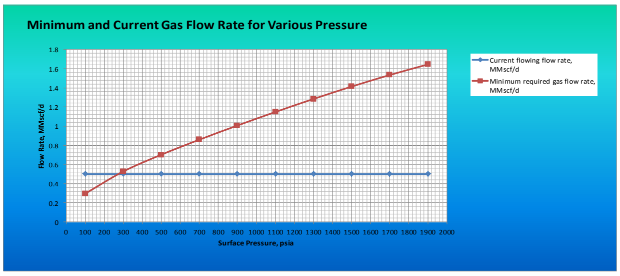
The user can choose to fill in ten (10) different surface pressure for one (1) surface temperature, one (1) conduit size and one (1) current flowing flow rate of interest for this sensitivity study in the Orange boxes.

Assuming z = 1 in computing gas density.

Surface temperature	520.000 °R	Pseudo reduced temperature	1.450 (-)
Conduit diameter	1.995 inch	Tubing cross-sectional area	0.022 ft^2

Surface pressure, psia	Current flowing flow rate, MMscf/d	Pseudo reduced pressure, (-)	Gas density, lbm/ft^3	A_z, (-)	B_z, (-)	C_z, (-)	D_z, (-)	E_z, (-)	F_z, (-)	Z, (-)	Minimum required gas velocity, ft/s	Minimum required gas flow rate, MMscf/d	Liquid Loading
100	0.5	0.149	0.312	0.389	0.044	0.080	0.963	4.054	-0.016	0.986	22.778	0.295	No
300	0.5	0.446	0.935	0.389	0.143	0.080	0.963	4.054	-0.016	0.956	13.121	0.526	Yes
500	0.5	0.743	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.701	Yes
700	0.5	1.041	2.181	0.389	0.379	0.080	0.963	4.054	-0.016	0.891	8.549	0.858	Yes
900	0.5	1.338	2.804	0.389	0.517	0.080	0.963	4.054	-0.016	0.860	7.521	1.006	Yes
1100	0.5	1.636	3.427	0.389	0.669	0.080	0.963	4.054	-0.016	0.831	6.787	1.148	Yes
1300	0.5	1.933	4.050	0.389	0.834	0.080	0.963	4.054	-0.016	0.806	6.228	1.283	Yes
1500	0.5	2.230	4.673	0.389	1.014	0.080	0.963	4.054	-0.016	0.785	5.783	1.412	Yes
1700	0.5	2.528	5.296	0.389	1.209	0.080	0.963	4.054	-0.016	0.768	5.419	1.533	Yes
1900	0.5	2.825	5.919	0.389	1.420	0.080	0.963	4.054	-0.016	0.755	5.113	1.643	Yes

Liquid removal may occur when the current flowing flow rate is above the minimum gas flow rate, for which below the minimum gas flow rate, liquid may accumulate.
Current flowing flow rate below the calculated minimum gas flow rate may lead to liquid loading problem.



SENSITIVITY STUDY (CONDUIT SIZE)

This is to examine the terminal settling velocity and the minimum gas flow rate required for liquid removal for a range of conduit size.

The user can choose to fill in ten (10) different tubing size for one (1) surface temperature, one (1) surface pressure and one (1) current flowing flow rate of interest for this sensitivity study in the Blue boxes.

Surface temperature	520.000 °R	Pseudo reduced temperature	1.450 (-)
Surface pressure	500 psia	Pseudo reduced pressure	0.743 (-)

Conduit diameter, in	Current flowing flow rate, MMscf/d	Tubing cross-sectional area, ft^2	Gas density, lbm/ft^3	A_z, (-)	B_z, (-)	C_z, (-)	D_z, (-)	E_z, (-)	F_z, (-)	Z, (-)	Minimum required gas velocity, ft/s	Minimum required gas flow rate, MMscf/d	Liquid Loading
1.315	0.5	0.009	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.305	No
1.660	0.5	0.015	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.486	No
1.900	0.5	0.020	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.636	Yes
2.375	0.5	0.031	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	0.994	Yes
2.875	0.5	0.045	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	1.457	Yes
3.500	0.5	0.067	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	2.159	Yes
4.000	0.5	0.087	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	2.820	Yes
4.500	0.5	0.110	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	3.569	Yes
5.563	0.5	0.169	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	5.454	Yes
6.625	0.5	0.239	1.558	0.389	0.254	0.080	0.963	4.054	-0.016	0.923	10.139	7.735	Yes

Liquid removal may occur when the current flowing flow rate is above the minimum gas flow rate, for which below the minimum gas flow rate, liquid may accumulate.
Current flowing flow rate below the calculated minimum gas flow rate may lead to liquid loading problem.

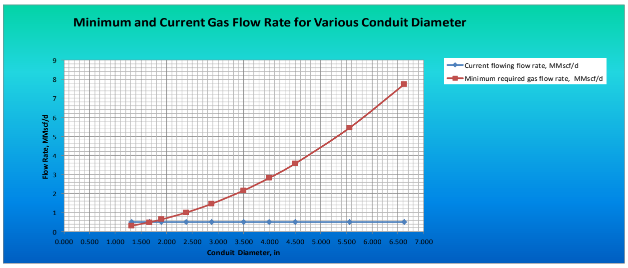


Figure 19 Second Page of the Developed Spread Sheet - Second Function of the Turner et al Model

Guo et al Model

INPUT DATA REQUIRED

Parameter	Symbol	Value	Units	Note
Gas Specific Gravity	γ_g	0.6	(-)	Air = 1
Water Specific Gravity	γ_w	1.08	(-)	Water = 1
Solid Specific Gravity	γ_s	2.65	(-)	Water = 1
Condensate Gravity	γ_c	0.53764	(-)	Water = 1
Conduit Outer Diameter	d_{to}	1.995	inch	
Conduit Inner Diameter	d_{ti}	0	inch	always taken as 0
Conduit Wall Roughness	ε	1.25E-06	ft	
Hole Inclination	θ	0	rad	input inclination must be $0° \le \theta < 90°$, or $270° < \theta \le 360°$
Producing Depth	D	6700	ft	
Wellhead Pressure	P_{wh}	72000	lbf/ft^2	
Wellhead Temperature	T_{wh}	520	°R	
Water Make	Q_w	8.6	bbl/day	
Solid Make	Q_s	0	ft^3/day	
Condensate Make	Q_c	0	bbl/day	
Major liquid	-	1.000	(-)	1=water; -1=condensate

Critical Gas Production Rate to Prevent Liquid Loading

This is to calculate minimum required gas production rate and velocity to prevent liquid loading problem.

Hydraulic Diameter	D_h	0.166	ft	
Conduit Cross-Sectional Area	A	0.022	ft^2	
Producing Zone Temperature	T_{pz}	587.000	°R	
Average Temperature	T_{av}	553.500	°R	
Heavy Liquid-Gas Interfacial Tension	σ	60.000	dynes/cm	60 for water; 20 for condensate
Heavy Liquid Density	ρ_l	67.392	lb/ft^3	From E11 or E13
Minimum Kinetic Energy	E_{km}	3.663	$lbf\text{-}ft/ft^3$	

Note: In Qg calculation, g is taken as 32.17 and P is handled in lbf/ft^2.

Iteration	i	1	20
Minimum Required Gas Flow Rate for Liquid Removal	Qg	1.100	826572.421
Function of Qg	f(Qg)	-10214.183	0.000
Minimum Required Gas Flow Rate for Liquid Removal (after)	Qg+1	2.100	826573.421
Function of Qg+1	f(Qg+1)	-5356.620	0.000
Minimum Required Gas Flow Rate for Liquid Removal (before)	Qg-1	0.100	826571.421
Function of Qg-1	f(Qg-1)	-112211.826	0.000
Derivative of function of Qg	f'(Qg)	53427.603	0.000

The minimum required gas flow rate for liquid removal is 0.827 **MMscf/d**
Bottomhole pressure is 589.756 **psia**
The minimum required gas velocity for liquid removal is 11.689 **ft/s**

Gas flow rate below the calculated minimum gas flow rate may lead to liquid accumulation at the bottomhole.

Figure 20 Third Page of the Developed Spread Sheet - First Function of the Guo et al Model

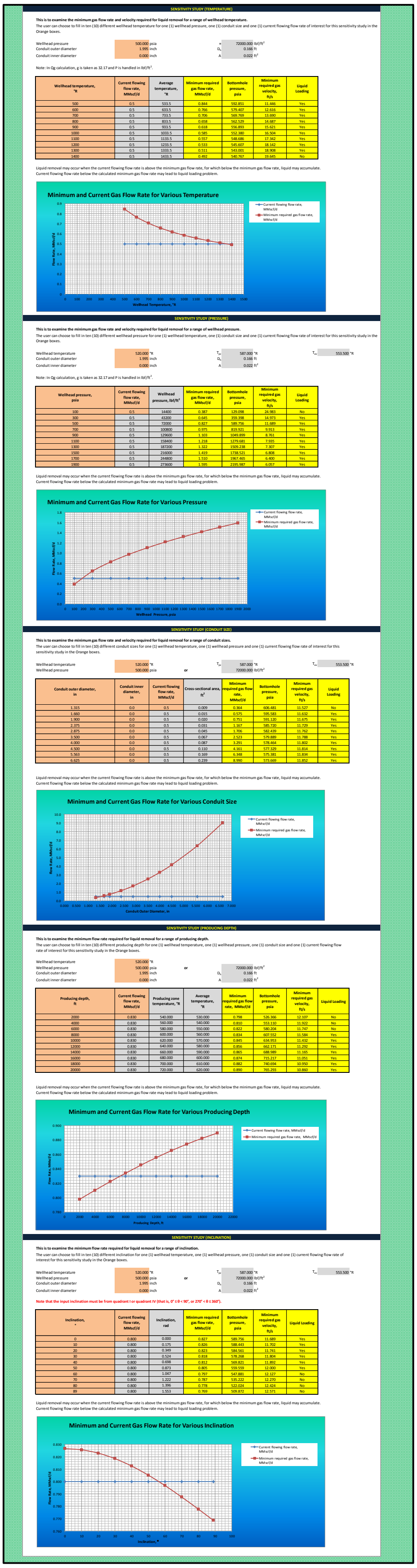
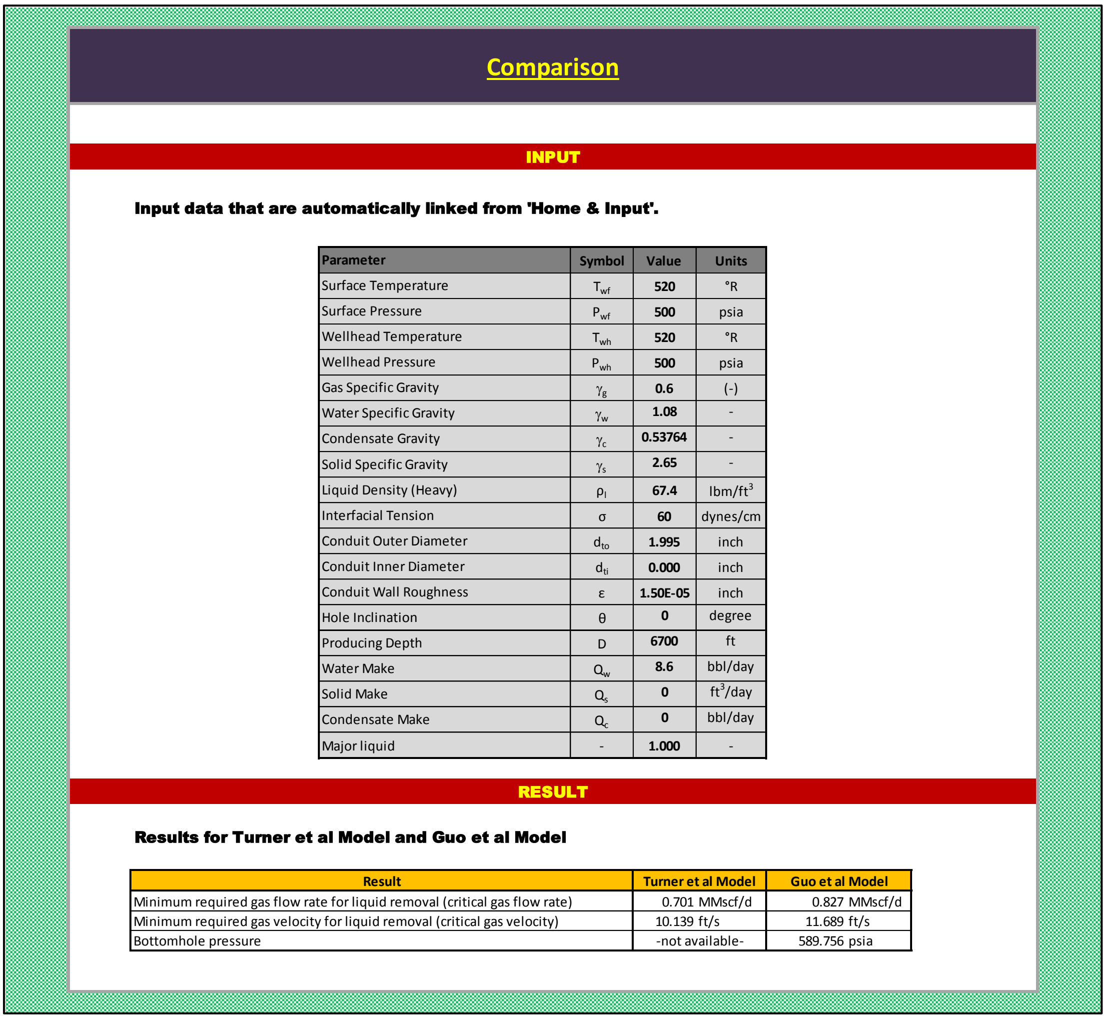


Figure 21Third Page of the Developed Spread Sheet - Second Function of the Guo et al Model



Comparison

INPUT

Input data that are automatically linked from 'Home & Input'.

Parameter	Symbol	Value	Units
Surface Temperature	T_{wf}	520	°R
Surface Pressure	P_{wf}	500	psia
Wellhead Temperature	T_{wh}	520	°R
Wellhead Pressure	P_{wh}	500	psia
Gas Specific Gravity	γ_g	0.6	(-)
Water Specific Gravity	γ_w	1.08	-
Condensate Gravity	γ_c	0.53764	-
Solid Specific Gravity	γ_s	2.65	-
Liquid Density (Heavy)	ρ_l	67.4	lbm/ft^3
Interfacial Tension	σ	60	dynes/cm
Conduit Outer Diameter	d_{to}	1.995	inch
Conduit Inner Diameter	d_{ti}	0.000	inch
Conduit Wall Roughness	ε	1.50E-05	inch
Hole Inclination	θ	0	degree
Producing Depth	D	6700	ft
Water Make	Q_w	8.6	bbl/day
Solid Make	Q_s	0	ft^3/day
Condensate Make	Q_c	0	bbl/day
Major liquid	-	1.000	-

RESULT

Results for Turner et al Model and Guo et al Model

Result	Turner et al Model	Guo et al Model
Minimum required gas flow rate for liquid removal (critical gas flow rate)	0.701 MMscf/d	0.827 MMscf/d
Minimum required gas velocity for liquid removal (critical gas velocity)	10.139 ft/s	11.689 ft/s
Bottomhole pressure	-not available-	589.756 psia

Figure 22 Fourth Page of the Developed Spread Sheet - Comparison Page

Appendix 2

The flow chart of the developed work flow is summarized in the figure below:

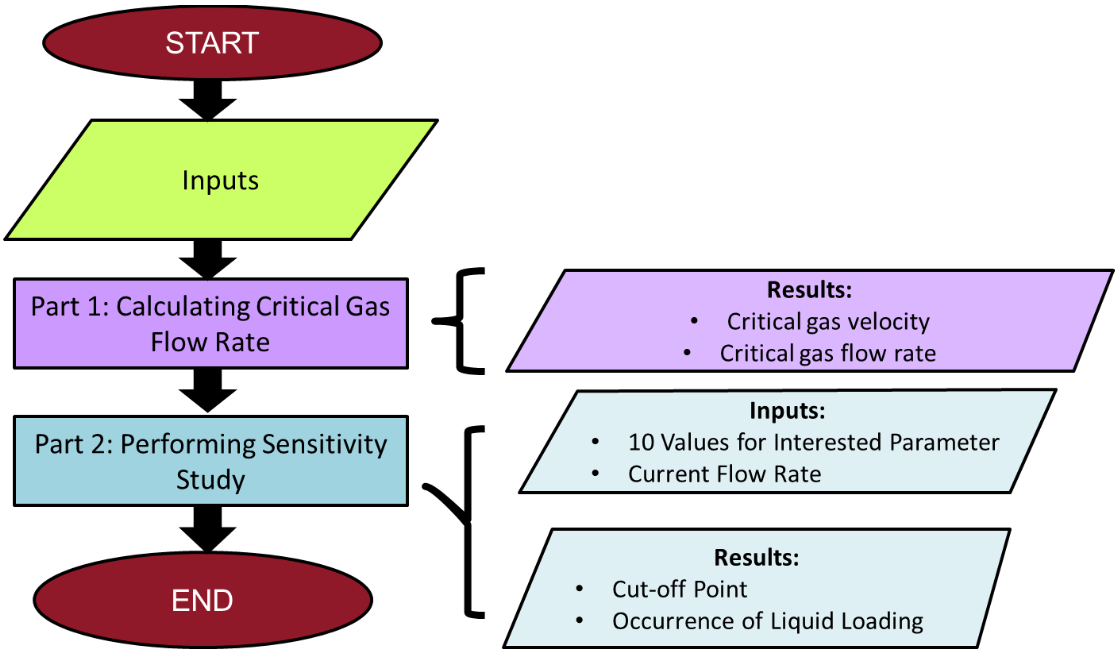


Figure 23 Flow Chart of the Developed Work Flow