Title: Li and Turner Modified model for Predicting Liquid Loading in Gas Wells

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Abstract

Background Liquid loading of gas wells causes production difficulty and reduces ultimate recovery from these wells. Several authors proposed different models to predict the onset of liquid loading in gas wells, but the results from the models often show discrepancies. Turner's et al. (J Pet Technol, 1969) critical model was developed based on the assumption that the droplet is a sphere and remains spherical all through the entire wellbore. On the other hand, Li's model was developed based on the assumption the liquid droplets are flat in shape and remains same all through the wellbore. However, it is a well-known fact that the droplet alternates between spherical and flat during production operation. Invariably, the Turner's model and the Li's model would not be able to predict correctly the critical rate required to lift that droplet which is because the droplet deformation was not taken into account during the development of the models.

Materials and methods In this work, a new improved model is developed and incorporated into Ms-Excel program to predict liquid loading in gas wells. In the new model, a deformation coefficient "C" is introduced to cater for the deformation of the liquid droplet along the wellbore and in turn be able to predict correctly the critical rate when the droplet varies from the spherical shape to the flat shape.

Results Results from the analysis carried out revealed 35% error on from Turner's model, 26% error on Li's model, whereas the new model yielded 20% error.

Conclusion The new developed software and model proved to be more accurate in predicting onset of liquid loading.

Keywords Predicting liquid loading in gas wells · Liquid loading · Gas production · Ms-Excel program · New improved model · Turner model · Li model · Gas wells · Production challenges in gas wells

List of symbols

ρ_l	Liquid density, lbm/ft ³
ρ_g	Gas density, lbm/ft ³
σ	Interfacial tension, dynes/cm
P	Pressure, lbf/ft ²
D_H	Hydraulic diameter, ft
A	Cross-sectional area of conduit, ft ²
T	Temperature, °R
z	Gas compressibility factor
S_g	Specific gravity of gas
S_o	Specific gravity of produced oil
S_w	Specific gravity of produced water

S_s	Specific gravity of produced solid
Q_g	Gas production rate, Mscf/D
Q_o	Oil production rate, B/D
Q_w	Water production rate, B/D
Q_s	Solids production rate, ft ³ /day
p_{hf}	Wellhead flowing pressure, psia
Q_{gm}	Minimum gas flow rate required to transport liquid drops, Mscf/D
E_{km}	Minimum kinetic energy required to transport liquid drops, lbf-ft/ft ³
V_{crit-S}	Critical velocity Luan's model
V_{crit-W}	Critical velocity Wang's model
V_{crit-L}	Critical velocity Li's model
V_{crit-N}	Critical velocity Nosseir's model
V_{crit-T}	Critical velocity Turner's model
V_{crit-C}	Critical velocity Coleman's model
$V_{crit-new}$	Critical velocity new model
We	Webers number
Re	Reynolds number

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ρ	Density, lb/cu ft
v	Flow velocity, ft/s

Introduction

Background of study

Natural gas can be simply defined as a naturally occurring mixture of light hydrocarbons consisting mainly of methane but also contains varying amounts of heavier alkanes and other impurities such as carbon dioxide, hydrogen sulphide, helium, nitrogen and water. Natural gas exists in reservoir in different thermodynamic states; as dry gas, wet gas and as retrograde condensate. Although natural gas consumption in Nigeria is quite small compared to some countries such as the US, natural gas production is faced with variety of challenges one of which is the issue of liquid loading. Liquid loading, in a nutshell can be defined as the accumulation of liquid or water in the wellbore due to insufficient gas velocity to evacuate the liquid phase which is co-produced with the gas resulting in reduction or complete cessation of gas production. These usually occur due to depletion of the reservoir pressure and at this stage the gas produced is unable to lift the liquid produced alongside it, to the surface and at such causing an accumulation of the liquid in the wellbore, and overtime as the liquid accumulates it builds up a high hydrostatic pressure in the wellbore thereby preventing further production of gas. Liquid loading leads to the premature death of a gas well which becomes a financial loss to the operating company.

The liquid content in the gas come from a variety of sources either in liquid form or in vapour form depending on the prevailing well conditions, some sources are; free water present in the formation produced alongside the gas, water condensate and hydrocarbon condensate which enter the well as vapour but while travelling up the tubing condenses, in a case where the well completion is an open one, water or other liquid can flow from other zones into the well bore, in a case where there is an aquifer below the gas zone.

Liquid loading is not always easy to predict and recognize because a thorough diagnostic analysis of the well data needs to be done but accurate prediction of the problem is vitally important for taking timely measures to solve the problem. There are some symptoms also which can help predict a gas well which is under attack such as the onset of liquid slugs at the surface of the well, increasing difference between the tubing and casing pressures with time, sharp changes in gradient on a flowing pressure survey and sharp drops in production decline curve.

In a bid to predict the onset of liquid loading early which has been identified as the key step in salvaging the liquid loading problem, various investigators over the years have

come up with models and methods to predict liquid loading in gas wells, the pioneer been Turner et al. (1969) subsequently other predictions came up most based on the foundation principle of Turner et al. (1969). Some of these models were better, some worse, but the various models used for the predictions had their merits and demerits. The Turner model and other models used in predicting liquid loading are included in subsequent sections.

After detection of liquid accumulation in the well, few solutions have been discovered to solve the problem of liquid loading in gas wells over the years and they have proved really helpful. These include foaming of the liquid water which can enable the gas to lift water from the well, the use of reduced tubing diameter and the heating the wellbore to the prevent further condensation, the use of plunger lift which is an intermittent artificial lift method which uses the energy of the gas reservoir to produce the liquid collected at the bottom of the hole, the use of gas lift method which involves injection of gas into the well from another source in other to increase gas production the use of the beam pumping which is a method commonly used in the oil industry to solve liquid loading in wells loaded with liquid hydrocarbon.

Statement of problem

From the above definition of liquid loading, it is clear that it is problematic to gas wells, ranging from decreasing the gas well production rate to completely preventing gas production from the well. However, if liquid loading can be predicted accurately and on time a suitable solution can be put together to combat it. This prediction in question is the primary aim of this study and research, due to the fact that the predicting methods at various points and times show various discrepancies, coming up or developing a better prediction mechanism will go a long way in saving maybe hundreds of petroleum gas wells which would have shut down prematurely due to liquid loading.

Aim of the study

This study aims at developing a new model for predicting critical velocity rate for gas wells building on the premise of Turner et al. (1969) and Li et al. (2001). The model developed would then be incorporated into an Ms-Excel-based program.

Significance of study

As was earlier stated, that early detection of liquid loading in gas wells helps the production team prepare a suitable technique and method to tackle the problem at its early stage before it aggravates. On the completion of this study,

software which when provided with the necessary data has the ability to predict liquid loading status of a given well will be developed.

Materials and methods

This research work was done on a three-phase scale:

1. Gathering of the various prediction model, evaluating their errors and choosing the better one.
2. Discover the merit and demerit of the chosen model and improve on it.
3. Finally build it into an excel platform for easy usage.

Predicting liquid loading

Liquid load-up in gas wells is not always obvious; therefore, a thorough diagnostic analysis of well data needs to be carried out to adequately predict the rate at which liquids will accumulate in the well. Although this subject has been studied extensively but the results from previous investigators and the most commonly applied model in the industry still has a high degree of inaccuracy, especially in predicting the minimum gas flow rate required to prevent liquid loading into the well bore (Adesina et al. 2013).

Turner's model

For the removal of gas well liquids, Turner et al. (1969) proposed two physical models: (1) the continuous film model (2) and entrained drop movement model.

The continuous film model Turner et al. (1969) were of the opinion that since liquid film accumulation on the walls of a conduit during two-phase gas/liquid flow is inevitable due to the impingement of entrained liquid drops and the condensation of vapours. He also suggested that the annular liquid film must keep moving upwards along the conduit walls to keep a gas well from loading up, and in the same vain the minimum gas flow rate necessary to accomplish this is of primary importance in the prediction of liquid loading. The analysis technique used involves describing the profile of the velocity of a liquid film moving upward on the inside of a tube. The major shortcoming of this model was its inability to clearly define between the adequate and inadequate rates when it was analysed with field data.

Entrained drop movement model (spherical shape droplet model) The existence of liquid drops in the gas stream presents a different problem in fluid mechanics, namely, that of determining the minimum rate of gas flow that will lift the drops out of the well (Turner et al. 1969). In a bid to do this,

Turner et al. proposed a model to calculate the minimum gas flow velocity necessary to remove liquid drops from a gas well which is based on the sole principle of a freely falling particle in a fluid medium (by a transformation of coordinates, a drop of liquid being transported by a moving gas stream becomes a free falling particle and the same general equations apply as shown in Fig. 1). The minimum gas flow velocity necessary to remove liquid drop is given by the following equation:

$$V_{\text{crit-Tunadjusted}} = 1.593 \frac{\sigma^{1/4}(\rho_L - \rho_g)^{1/4}}{\rho_g^{1/2}}. \quad (1)$$

Turner et al. (1969) discovered that the drop model prediction in most cases was too low and he blamed this on the values of critical weber number and drag coefficient used in the development of the model and also on the fact that the mathematical development predicts stagnation velocity, which must be exceeded by some finite quantity to guarantee removal of the largest droplets. Analysis of the Turner's data reveals that the total contribution of these factors requires an upward adjustment of approximately 20%. Mapping Turner's calculated model against actual test data (as shown in Fig. 2) reveals large discrepancies at lower flowrates; hence adjusted droplet model is given by the following equation to accommodate these discrepancies:

$$V_{\text{crit-T}} = 1.92 \frac{\sigma^{1/4}(\rho_L - \rho_g)^{1/4}}{\rho_g^{1/2}}, \quad (2)$$

$$q_{\text{crit-T}} = \frac{3060PV_{\text{crit-T}}A}{T_z}. \quad (3)$$

Coleman model

Coleman et al. (1991) made use of the Turner model but validated with field data of lower reservoir and wellhead

Fig. 1 Entrained droplet movement (Turner et al. 1969)

Fig. 2 Turner et al. model-calculated minimum flow rates mapped against the test flow rates (Guo et al. 2006)

flowing pressure all below approximately 500 psia. Coleman et al. (1991) discovered that a better prediction could be achieved without a 20% upward adjustment to fit field data with the following expressions:

$$V_{\text{crit-C}} = 1.593 \left[\frac{\sigma(\rho_L - \rho_g)}{\rho_g^2} \right]^{\frac{1}{4}}, \quad (4)$$

$$q_{\text{crit-C}} = \frac{3060PV_{\text{crit-C}}A}{T_z}. \quad (5)$$

Li's model (flat-shaped droplet model)

Li et al. (2001) in their research posited that Turner and Coleman's models did not consider deformation of the free falling liquid droplet in a gas medium, and furthermore, contended that as a liquid droplet is entrained in a high velocity gas stream, a pressure difference exists between the fore and aft portions of the droplet leading to its deformation and its shape changes from spherical to convex bean with unequal sides (flat) as shown in Fig. 3.

Spherical liquid droplets have a smaller efficient area and need a higher terminal velocity and critical rate to lift them to the surface. However, flat-shaped droplets have a more efficient area and are easier to be carried to the wellhead. This lead to the formulation of the following expression:

$$V_{\text{crit-L}} = \frac{0.7241\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}}, \quad (6)$$

$$q_{\text{crit-L}} = \frac{3060PV_{\text{crit-L}}A}{T_z}. \quad (7)$$

Fig. 3 a Flat-shaped droplet model. b Shape of entrained droplet moving in high velocity gas (Li et al. 2001)

Nosseir's model

Nosseir et al. (2000) focused his study mainly on the impact of flow regime and changes in flow conditions on gas well loading. Their work was similar to that of Turner but the difference between the both was that Turner did not consider the effect of flow regime on the drag coefficient (used in the derivation stage), and thereby making use of the same drag coefficient (0.44) for laminar, transient and turbulent flows. Nosseir derived the critical flow equations by assuming drag coefficient value of 0.44 for Reynolds number (Re) 2×10^5 to 10^4 and for Re value greater than 10^6 he took the drag coefficient value to be 0.2. Representation of the critical velocity equation by Nosseir's model is summarized as:

$$V_{\text{crit-N}} = 1.938 \left[\frac{\sigma(\rho_l - \rho_g)}{\rho_g^2} \right]^{\frac{1}{4}}, \quad (8)$$

$$q_{\text{crit-N}} = \frac{3060PV_{\text{crit-N}}A}{T_z}. \quad (9)$$

Disk-shaped droplet model

Some authors consider that the four dimensionless numbers, Reynolds, Morton, Eotvos, and Weber (especially the first two parameters), are always used to characterize the shape of bubbles or droplets moving in a surrounding fluid or continuous phase (Hinze 1955; Youngren and Acrivos 1976; Acharya et al. 1977). Wang and Liu (2007) were of the opinion that for typical oilfield condition, the Reynolds number

ranges from 10^4 to 10^6 , and the Morton number for low viscosity liquid in gas wells is possibly between 10^{-10} and 10^{-12} . For the given ranges of the dimensionless numbers, they found that most of the entrained droplets in gas well are disk shaped. Similar to flat-shaped droplets proposed by Li et al. (2001), the disk-shaped droplets have a more efficient area and are more easily carried to the wellhead. For the disk-shaped droplets, the drag coefficient C_d is close 1.17. Wang's expressions can be summarized as follows:

$$V_{\text{crit-W}} = 0.5213 \left[\frac{\sigma(\rho_l - \rho_g)}{\rho_g^2} \right]^{1/4}, \quad (10)$$

$$q_{\text{crit-W}} = \frac{3060PV_{\text{crit-W}}A}{T_z}. \quad (11)$$

Guohua and Shunli's model

In this work, Guohua and Shunli (2012) carried out reviews on various models spotting their merit and shortcomings but paid much attention to the Turner's model (spherical shaped droplet model) and Li's model (flat shaped droplet model).

$$q_{\text{crit-S}} = \frac{3060PV_{\text{crit-S}}A}{T_z}, \quad (13)$$

Guo's model

Guo et al. (2006) were of the opinion that although various investigators have suggested several methods of predicting liquid loading but the results from these methods often show discrepancies and are not easy to use due to the difficulties with prediction of the bottom hole pressure in multiphase flow.

Guo et al. (2006) formulated a closed form analytical equation for predicting the minimum gas flow rate for the continual removal of liquid from the gas well. He did this by substituting the Turner et al.'s entrained drop movement model (for predicting minimum gas velocity for the continual removal of liquid from the gas well) into the kinetic energy equation to obtain the minimum kinetic energy the gas must possess in order to keep the well unloaded. The final stage of his work was to apply the minimum kinetic energy equation to the four phase mist flow model in gas wells to obtain the equation for predicting the minimum gas flow rate which can be solved using numerical method (Newton Raphson) or the go seek function built in the MS Excel. Below is a summary of Guo's model:

$$b \left[6.46 \times 10^{-13} \frac{S_g T Q_{\text{gm}}^2}{A^2 E_{\text{km}}} - p_{\text{hf}} \right] + \frac{1 - 2bm}{2} \ln \left| \frac{\left[6.46 \times 10^{-13} \frac{S_g T Q_{\text{gm}}^2}{A^2 E_{\text{km}}} + m \right]^2 + n}{(P_{\text{hf}} + m)^2 + n} \right| \\ - \frac{m + \frac{b}{c}n - bm^2}{\sqrt{n}} \left[\tan^{-1} \left[\frac{6.46 \times 10^{-13} \frac{S_g T Q_{\text{gm}}^2}{A^2 E_{\text{km}}} + m}{\sqrt{n}} \right] - \tan^{-1} \left[\frac{P_{\text{hf}} + m}{\sqrt{n}} \right] \right] = a(1 + d^2 e)L, \quad (14)$$

Using experimental results from Awolusi (2005) and Wei et al. (2007) (both though did different experiments came out with the same conclusion), Guohua and Shunli (2012) discovered that the Turner's model overestimated the probability of the occurrence of liquid loading in gas wells and Li's model underestimated after a plot of critical gas flow rate was done against flow tubing pressure, for measured flow rates and calculated flow rates from Turner's and Li's model.

Guohua and Shunli (2012) came up with a dimensionless parameter of loss factor S which he introduced to his new model and using data from Coleman's work. This loss factor S ranges from zero to unity (the larger it is, the closer the calculated results are to Turner's model and if zero the new model matches Li's model). Luan compared results from his work with Turner and Li and discovered that his was more accurate. Summary of Luan model given below:

$$V_{\text{crit-S}} = V_{\text{crit-L}} + 0.83 \times (V_{\text{crit-T}} - V_{\text{crit-L}}), \quad (12)$$

$$a = \frac{15.33S_s Q_s + 86.07S_w Q_w + 86.07S_o Q_o + 0.01879S_g Q_g}{TQ_g} \cos(\theta), \quad (14a)$$

$$b = n = \frac{c^2 e}{(1 + d^2 e)^2} \frac{0.2456Q_s + 1.379Q_w + 1.379Q_o}{TQ_g}, \quad (14b)$$

$$c = \frac{4.712 \times 10^{-5} T Q_g}{A}, \quad (14c)$$

$$d = \frac{Q_s + 5.615(Q_w + Q_o)}{86400A}, \quad (14d)$$

$$e = \frac{f}{2gD_H \cos(\theta)}, \quad (14e)$$

$$f = \left[\frac{1}{1.74 - 2 \log \left[\frac{2\varepsilon}{D_H} \right]} \right]^2, \quad (14f)$$

$$m = \frac{cde}{1 + d^2e}, \quad (14g)$$

$$n = \frac{c^2e}{(1 + d^2e)^2}. \quad (14h)$$

Nodal analysis

Nodal analysis can be used to estimate the onset of liquid loading in gas wells with more accuracy since it considers the complete flow path of fluids from reservoir to wellhead (Nallaparaju et al. 2012). In nodal analysis, the system is divided into two subsystems at a certain location called nodal point. The first subsystem takes into account inflow from reservoir to nodal point (IPR), while the other subsystem considers outflow from the nodal point to the surface (TPR). The curves formed by this relation on the pressure–rate graph are called the inflow curve and the outflow curve, respectively. The point where these two curves intersect denotes the optimum operating point where pressure and flow rate are equal for both of the curves. Turner's critical rate prediction in relation with the IPR and TPR curves can be used to predict liquid loading.

In a study carried out by Nallaparaju et al. 2012, we observe that Turner's critical rate model was plotted with IPR and TPR for a Well with a given initial static reservoir pressure of 3281 psi and Tubing head pressure of 1500 psi as shown in Fig. 4 above. The point at which the Turner's curve meets with the IPR curve represent the minimum flowrate to prevent liquid loading (10MMSCFD), whereas the optimum operating flowrate for the well is around 75MMSCFD. The

Fig. 4 IPR and TPR overlap with Turner (Nallaparaju et al. 2012)

farther the operating point from the minimum flowrate, the lower the tendency for liquid loading to occur.

Zhou model

Turner et al. (1969) entrained droplet model is the most popular model in predicting liquid loading in gas wells (Zhou and Yuan 2009). However, there were still quite a few wells that could not be covered even after a 20% upward adjustment (Turner et al. 1969). By studying the droplet model and liquid film mechanisms, Zhou came up with a new model.

In his work, he studied the force balance on a single liquid droplet, which are the upward drag force, F_D ; the upward buoyant force, F_B ; and downward gravity force, F_G , which

Fig. 5 Encountering two liquid droplets in turbulent gas stream

Fig. 6 Liquid loading when liquid droplet number reaches a threshold value (Zhou and Yuan 2009)

for unloading to be possible and for the droplets to move upwards ($F_D + F_B$) must be greater than F_G otherwise the droplet will accelerate downwards. The Turner et al. (1969) droplet model was based on the balance of these forces ($F_D + F_B = F_G$).

Zhou argued that Turner et al. (1969) based his model on force balance on a single liquid droplet, but which in a gas stream, there are more than one as shown above (droplets A and B in Fig. 5). And further argued that if a turbulent flow existed in the gas stream, due to the irregularity of the flow droplets will encounter each other and coalesce will occur as in Fig. 6 below forming a droplet AB (A + B). This newly formed droplet in a situation the gas stream does not have enough energy to lift the droplet it starts falling and may scatter into smaller droplets 1, 2, 3 and the cycle goes on and on for similar larger droplets and these leads to an accumulation of liquid down hole.

Zhou and Yuan (2009) were of the opinion that if there are more liquid droplets in the gas stream, the chance of the process of liquid droplet encountering, coalescing, falling and scattering increases (Fig. 6). As the number of liquid droplets in a gas stream, called liquid droplet concentration increases to a threshold value β , the process of droplets encountering, coalescing, falling and scattering will continue and bring those liquid droplets down to the well bottom. The liquid droplet concentration in a gas stream is defined by

$$H_1 = \frac{\text{Liquid superficial velocity}}{\text{Gas superficial velocity} + \text{liquid superficial velocity}} = \frac{V_{sl}}{V_{sg} + V_{sl}} \quad (15)$$

Zhou and Yuan (2009) concluded that if liquid droplet concentration is above the threshold value, then the new model can be used but below the threshold value Turners model is used. Summary of Zhou model:

$$V_{\text{crit-Z}} = V_{\text{crit-T}} = 1.593 \frac{[\sigma(\rho_l - \rho_g)]^{1/4}}{\rho_g^{1/2}} \quad \text{for } H_1 \leq \beta, \quad (16)$$

$$V_{\text{crit-Z}} = V_{\text{crit-T}} + \ln \frac{H_1}{\beta} + \alpha \quad \text{for } H_1 > \beta, \quad (17)$$

$$Q \left(\frac{Mc_f}{D} \right)_{\text{crit-Z}} = \frac{3060PV_{\text{crit-Z}}A}{TZ} \quad (18)$$

Experimental works on liquid loading

A series of experiments have been designed by Awolusi (2005) and Wei et al. (2007) which were done separately.

Fig. 7 Critical rate against flow tubing pressure (Awolusi 2005)

The primary aim of their work was to investigate and evaluate discrepancies in the previous works on critical gas velocities required to keep liquid from accumulating. Which resulted to the discovery that Turner model prediction was high compared to the actual observed critical rate, while Li's model prediction was low compared to the actual observed critical rate as can be seen in Fig. 7 below.

Model development

As was earlier stated at the beginning of this chapter, we are aimed at developing a new model which can be used to calculate the critical rate and in turn predict the onset of liquid loading in gas wells.

This new model was developed by combining the Turner critical rate model and the Li's critical rate model.

Theory

$$V_{\text{crit-T}} = 1.593 \left[\frac{\sigma(\rho_l - \rho_g)}{\rho_g^2} \right]^{1/4} \quad (19)$$

Fig. 8 Droplet shapes

Turner's critical model given above was developed based on the assumption that the droplet is a sphere and remains spherical all through the entire wellbore,

$$V_{\text{crit-L}} = \frac{0.7241\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}}. \quad (20)$$

On the other hand, Li's model above was developed based on the assumption that the liquid droplets are flat in shape and remains same all through the wellbore. Having considered the two above droplet shape, in a case where the droplet is neither spherical nor flat as can be observed in Fig. 8 invariably the Turner's model and the Li's model would not be able to predict correctly the critical rate required to lift that droplet which is because the droplet deformation was not taken into account during the development of the models. As the droplet travel up the wellbore they tend to deform and can take different shapes at different points in the well. For simplicity sake, the only droplet shapes consider in this paper are droplet shapes ranging from the spherical shape to the flat shape (Fig. 9).

In the new model, a deformation coefficient C is introduced to cater for the deformation of the liquid droplet along the wellbore and in turn be able to predict correctly the critical rate when the droplet varies from the spherical shape to the flat shape.

New model development

New critical velocity model

$$= \text{Li's critical velocity model} + \text{deformation coefficient} \times (\text{Turner's critical velocity model} - \text{Li's critical velocity model}), \quad (21)$$

$$V_{\text{crit-new}} = V_{\text{crit-L}} + C \times (V_{\text{crit-T}} - V_{\text{crit-L}}). \quad (22)$$

The deformation coefficient used in this work is adapted from Kelbaliyev and Ceylan (2007). Detailed derivation of the deformation coefficient can be found in "Appendix 5".

$$C = \frac{a_0}{b_0} = \frac{R(1 - \lambda_v We)}{R(1 + \lambda_v/2 We)}. \quad (23)$$

Using the experimental data from Raymond and Rosant (2000), λ_v is estimated as:

$$\lambda_v = \frac{1}{12} \left(1 - \frac{3 We}{25 Re} \right). \quad (24)$$

Weber's number can be obtained from

$$We = \frac{\rho \times v^2 l}{\sigma}, \quad (25)$$

Table 1 Summary of all assumptions used to prepare critical velocity rate for our new model

Parameters	Value	Unit
Condensate surface tension	20	Dynes/cm
Water surface tension	60	Dynes/cm
Condensate density	45	Lb/cu ft
Water density	67	Lb/cu ft
Gas specific gravity	0.6	
Wellhead temperature	580	Rankine

The condensate surface tension and density are used to calculate only when condensate is produced along with the gas

The water surface tension and density are used to calculate when only water is produced or when both water and condensate are produced along with the gas

Fig. 9 User interface for LOADCALC Software

whereas Reynolds number is obtained from

$$Re = \frac{QD_H}{\nu A}. \quad (26)$$

Computing the values of Table 1 into Eqs. (35) and (36), the value of C was calculated to be:

$$C = 2.261921523$$

$$V_{\text{crit-new}} = V_{\text{crit-L}} + 2.261921523 \times (V_{\text{crit-T}} - V_{\text{crit-L}}),$$

$$V_{\text{crit-new}} = \frac{0.7241\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}} + 2.261921523 \times \left[\frac{1.593\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}} - \frac{0.7241\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}} \right],$$

$$q_{\text{crit-new}} = \frac{3060PV_{\text{crit-new}}A}{Tz} = \text{Critical flow rate.} \quad (27)$$

The derivation of the Turner and Li models is shown in “Appendix 1”.

Software development

After the new model was developed, the new model and other related correlations were converted to computer codes and built into an excel platform leading to the development of a new software LOADCALC. The computer codes used for the development of LOADCALC are shown in appendix D.

LOADCALC features

LOADCALC software is colourful software and it is user friendly and consists of various sections;

- Wellbore data section
- Fluid properties section
- Introductory section
- Flow parameter section
- Output section
- Analysis section

Results

In order to be able to compute the critical rate using the new model and also compare with the critical rate from Turner and Li, the Turner et al. (1969) data on liquid loaded wells were utilised. Turner published important parameters which influence critical liquid loading rate calculation such as producing depth, wellhead pressures, liquid gas rate, fluid properties, tubing inner/outer diameter, casing diameter and also

Fig. 10 Crossplot of test flowrate against critical flowrate using Li's model

information on the well flow rate and status (loaded up, near load up and unloaded) at time of test was also included in the database. These data are shown in “Appendix 3”.

Assumptions

All assumptions are summarized in Table 1 below;

Calculated parameters

Due to the large amount of database, the calculations for the below parameters are done using an excel sheet.

Parameters

- Gas density
- Production area
- Compressibility factor

The results for the calculated parameters, formulas, correlations used in calculation are all stated and outlined in “Appendix 2”.

Fig. 11 Crossplot of test flowrate against critical flowrate using Turner model

Fig. 12 Crossplot of test flowrate against critical flowrate using New model

Critical velocity results

Using the production data from the 105 gas wells, assumed parameters and calculated parameter, an excel sheet was used to compute the critical rate for.

- The new critical velocity model.
- The Turner critical velocity model.
- The Li's critical velocity model.

The results from the different critical velocity models are tabulated in “Appendix 2”.

When the measured flow rate from the different gas wells was plotted against the critical flow rates from the different models in the above table, the following figures were obtained, Figs. 10, 11, 12.

Discussion

The above figures are constructed in such a way that if a well's actual test flow rate equals its critical flow rate for liquid removal, the point will plot on the diagonal, so therefore for critical velocity model to be correct, the wells that are tested at conditions near load-up should plot near this diagonal. Wells that unload easily during a test should plot above the diagonal and those that do not unload should plot below the line. The ability of a given analytical model to achieve this data separation is a measure of its validity.

As can be seen from Figs. 10, 11 and 12 above the most data separation is achieved by the new model in Fig. 12 and in turn provides a better prediction.

Li's model as can be seen in Fig. 10 was not able to separate the loaded wells from the unloaded wells, almost all the points plotted above the diagonal line, suggesting that all the wells are unloaded which is not correct compared to the well status obtained from the different wells during test.

Turner model as can be seen in Fig. 11 predicted better than Li but majority of the loaded wells still plotted in the unloaded region above the diagonal line.

From Fig. 12, it can be observed that the new model prediction was quite better than Turner and Li due to the fact that most of the loaded wells plotted in the loaded region, most of the unloaded wells plotted in the unloaded region and the near load up wells plotted close to the diagonal.

Software test

To test the efficiency of the LOADCALC software, the well data from a loaded well, an unloaded well and a well which is near load up was collected and feed in the software.

The summary of the production data from the three different wells is shown in Table 2.

Table 2 Summary of the production data from the three different wells

Well status	Loaded up	Near load up	Unloaded
Producing depth (ft)	2250	6770	6180
Wellhead pressure (psia)	210	450	1117
Wellhead temperature (rankine)	580	580	580
Tubing ID (in.)	0	1.995	0
Tubing OD (in.)	2.375	0	2.878
Casing ID (in.)	6.276	0	6.184
Production configuration	Annular	Tubular	Annular
Specific gravity	0.6	0.6	0.6
Water density (lb/cu ft)	67	0	0
Water surface tension (dynes/cm)	60	0	0
Condensate density (lb/cu ft)	0	45	45
Condensate surface tension (dynes/cm)	0	20	20
Test flow rate (mcf/days)	470	442	5513
Critical flow rate(mcf/days)	2593.59	685.20	2928.38

Fig. 13 LOADCALC software interface showing loaded up test

Fig. 14 LOADCALC software interface showing near load up test

Fig. 15 LOADCALC software interface showing unloaded test

Loaded up test

See Fig. 13.

4.3 Near load up test

See Fig. 14.

Unloaded test

See Fig. 15.

As can be observed from the test figures above the results from the software matches with the test result in Table 2.

Conclusion

This paper presents a new empirical model that calculates the critical velocity and flowrate for low-pressure gas wells by taking into account droplet deformation coefficient. The new model is derived from a modification of Turner's model and Li's model. The Turner's critical model above was developed based on the assumption that the droplet is a sphere and remains spherical all through the entire wellbore. On the other hand, Li's model above was developed based on the assumption the liquid droplets are flat in shape and remains same all through the wellbore. By applying the deformation and elasticity theory, a dimensionless coefficient, C was obtained as a function of the gas Weber number and Reynolds number assuming the surface area of a particle increases after deformation, while the volume remains constant.

Comparative analysis of well test results obtained from 105 gas wells between the new model, Turner's spherical

model and Li's flat model reveal that droplet deformation plays an important role in the accuracy of prediction of critical flowrate for liquid loading. Error analysis carried out reveals that the new model predicted the onset of liquid loading in gas wells with the least error of 20%, whereas Turner's model had 26% error and Li, 35% error.

Finally, the recommended applicable range of the new model is when the wellhead pressure is less than 500 psia and the liquid/gas ratios are in the range of 1–130 bbl/MMscf, which is suggested by Turner et al. (1969) to ensure a mist flow in gas wells.

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Appendix 1

Development of the critical velocity models

Turner model

Since the liquid droplets are particles moving relative to a fluid in the gravitational field, particle mechanics may be employed to determine this minimum gas flow rate. A freely falling particle in a fluid medium will reach a terminal velocity, which is the maximum velocity it can attain under the influence of gravity alone, i.e. when the drag forces equal the accelerating forces. Terminal velocity is therefore a function of the size, shape and density of the particle and of the density and viscosity of the fluid medium.

By transformation of coordinates, a drop of liquid being transported by moving gas stream becomes a free falling particle and the same general equations apply.

$$V_t = 6.55 \sqrt{\frac{d(\rho_l - \rho_g)}{\rho_g C_d}}. \quad (28)$$

Turner determined that it is the antagonism of two pressures, the velocity pressure and the surface tension pressure that determines the maximum size a drop may attain. The ratio of these two pressures is the weber number. Hinze showed that if the weber number exceeded a critical value, a liquid drop would shatter. Weber number was found to be on the order of 20–30. If the larger of observed values is used, a relationship between the maximum drop diameter and the velocity of a liquid drop is obtained.

$$d_m = \frac{30\sigma g_c}{\rho_g V_t^2}. \quad (29)$$

Substituting the maximum diameter expression into Eq. 28, the terminal velocity equation becomes

$$V_t = \frac{1.3\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{C_d^{1/4} \rho_g^{1/2}}. \quad (30)$$

The drag coefficient is inflected by the drop shape and the drop Reynolds number, for spheres laboratory results shows that for a Reynolds number ranges of 1000 to 200,000 the drag coefficient is approximately constant and the drag coefficient of 0.44 was used resulting to

$$V_t = \frac{17.6\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}}. \quad (31)$$

Converting the surface tension from 1 lbf/ft to 0.00006852 dyne/cm equation becomes

$$V_t = \frac{1.593\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}}. \quad (32)$$

Fig. 16 Buoyancy, drag and gravity forces acting on a liquid droplet (Li et al. 2001)

Li's model

Li argued that a pressure difference exists between the fore and aft portion of a free falling droplet. The droplet is thus deformed, under the applied forces, from a sphere to a convex beam shown in Fig. 16 above.

Equating the gravity of a liquid droplet to the buoyancy and drag force, we obtain (in SI units)

$$\rho_l g V = \rho_g g V + 1/2 \rho_g v^2 s C_d. \quad (33)$$

As the droplets fall relative to the gas stream velocity, the pressure difference existing between the fore and aft portions, by Bernoulli, is expressed as

$$\Delta p = \frac{10^{-3} \rho_g v^2}{2}. \quad (34)$$

The condition for the balance of pressure and interfacial tension force is

$$\left(\frac{\Delta p}{10^{-3}} \right) s \Delta h + \sigma \Delta s = 0. \quad (35)$$

For a constant volume of the droplet, the following condition must be satisfied:

$$V = sh = \text{constant} \quad (36)$$

From equation A8, we obtain

$$\frac{\Delta p s}{10^{-3} \sigma} = \frac{\Delta s}{\Delta h}. \quad (37)$$

From Eq. 36, we have

$$\frac{\Delta s}{\Delta h} = -\frac{V}{h^2} = -\frac{sh}{h^2} = -\frac{s}{h} \quad (38)$$

By combining Eqs. 38 and 37, we calculate the thickness of the droplet as

$$h = \frac{10^{-3} \sigma}{\Delta p} \quad (39)$$

Substituting Δp from Eqs. 34 into 39, we have

$$h = \frac{2\sigma}{\rho_g v^2}. \quad (40)$$

Hence, s is estimated to be

$$s = \frac{\rho_g v^2 V}{2\sigma}. \quad (41)$$

Substituting Eqs. 41 into 33 and solving for $v = v_c$,

$$v_c = v = \sqrt[4]{\frac{4(\rho_l - \rho_g)g\sigma}{\rho_g^2 C_d}}. \quad (42)$$

For a typical field condition, the particle's Reynolds number ranges from 10^4 .

To 10^5 and the drag coefficient (C_d) is close to 1.0 for the shape considered. Hence, we have

$$v_c = 2.5 \frac{\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}}. \quad (43)$$

When converted to field units, we have

$$v_c = 0.7241 \frac{\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}}. \quad (44)$$

Appendix 2

LI's calculated		Turner's calculated		New model	
Critical velocity (ft/s)	Critical flow rate (mcf/days)	Critical velocity (ft/s)	Critical flow rate (mcf/days)	Critical velocity (ft/s)	Critical flow rate (mcf/days)
7.421352494	699.4091215	16.32677051	1538.680749	27.56470916	2597.77568
6.396371673	359.6368142	14.07184101	791.1910578	23.75768096	1335.778646
4.131293989	2118.908919	9.088732668	4661.541097	15.34463124	7870.143366
3.541108845	2462.936944	7.790341651	5418.39325	13.15253999	9147.947173
3.386080896	2572.339805	7.449284445	5659.076522	12.57672846	9554.29602
3.291364351	2644.010978	7.240910662	5816.751123	12.22492816	9820.500199
3.234436286	332.9551895	7.115670493	732.4922205	12.01348348	1236.676599
4.715188246	202.0876575	10.3732839	444.5872647	17.5133566	750.6027384
4.059829716	1265.103589	8.93151324	2783.192953	15.07919553	4698.902595
3.919333361	512.5407015	8.62242514	1127.575387	14.55735788	1903.700893
3.758126787	533.7705151	8.267775131	1174.28039	13.95859744	1982.553587
3.598854403	556.5083356	7.917380284	1224.302967	13.36702104	2067.007386
3.053296867	651.0725861	6.717168773	1432.341706	11.34068759	2418.242025
2.001478177	849.0393442	4.403196708	1867.863106	7.433977014	3153.53874
1.943962951	871.8746529	4.276664799	1918.100155	7.220351467	3238.354633
1.684472966	1417.688544	3.705793999	3118.87564	6.256542516	5265.640251
1.491075008	1100.566301	3.280323834	2421.215463	5.538215437	4087.771065
1.456080213	1122.729251	3.203336252	2469.973342	5.408236253	4170.089658
1.455257267	290.9181632	3.201525792	640.0119237	5.405179628	1080.540854
1.400981857	300.2324567	3.082121389	660.5031122	5.203587548	1115.136406
1.365227426	778.9730088	3.00346263	1713.719104	5.070786893	2893.29532
1.342980359	789.411588	2.954519697	1736.68369	4.988155872	2932.066743
1.21719954	799.768578	2.677805368	1759.468782	4.520975299	2970.535124
1.14102966	740.5246871	2.510233736	1629.133858	4.238061829	2750.488896
1.120325183	750.4774926	2.464684459	1651.029755	4.161160365	2787.456038
1.120009862	1127.752536	2.463990762	2481.024431	4.159989186	4188.747361
1.092491886	510.4162589	2.403451973	1122.901672	4.057780724	1895.810197
1.090396025	765.1843916	2.398841138	1683.384527	4.049996188	2842.08104
1.081265155	514.1588825	2.378753475	1131.13534	4.016081913	1909.711211
1.073654413	773.5731771	2.362010054	1701.839623	3.987813767	2873.23903
0.821584786	910.0832924	1.807463838	2002.158106	3.051565831	3380.270819
10.42094012	136.6487472	22.92578042	300.6234695	38.70590755	507.5467008
5.307834134	254.6612526	11.67708849	560.2477219	19.71458765	945.8738646
3.422057394	185.7565004	7.528431748	408.6591702	12.71035393	689.9448468
4.524866689	297.7395319	9.954581738	655.0187465	16.80645602	1105.877077
4.47176837	450.9070705	9.837766901	991.9831008	16.60923594	1674.778589
2.641855551	356.5982659	5.812009242	784.5063356	9.812494416	1324.492739
1.709903977	1399.141035	3.76174152	3078.071631	6.350999478	5196.750286

LI's calculated		Turner's calculated		New model	
Critical velocity (ft/s)	Critical flow rate (mcf/days)	Critical velocity (ft/s)	Critical flow rate (mcf/days)	Critical velocity (ft/s)	Critical flow rate (mcf/days)
1.556999679	274.7512183	3.425356288	604.4450915	5.783075706	1020.492886
1.499996768	1095.037664	3.299951458	2409.052616	5.571353022	4067.236365
1.475833132	1110.124946	3.246792128	2442.244219	5.481603401	4123.274202
1.403547149	299.7808064	3.087764962	659.509494	5.213115669	1113.458867
1.369620827	776.9387388	3.013127989	1709.243766	5.087105051	2885.739546
1.348429142	434.714034	2.966506868	956.3588679	5.008393976	1614.633711
1.34746222	787.2900433	2.964379665	1732.01635	5.004802591	2924.186809
1.135442959	743.1923023	2.497943148	1635.002538	4.217311462	2760.397068
1.129647046	1120.7564	2.485192299	2465.633124	4.19578403	4162.762009
1.127202887	1122.525143	2.479815217	2469.524309	4.186705829	4169.331549
1.121590491	749.8640298	2.467468101	1649.680154	4.165860025	2785.177488
1.08818154	511.8490824	2.393969333	1126.053844	4.041771052	1901.132052
1.076379387	772.1999559	2.36800492	1698.818574	3.997934981	2868.138553
1.060167742	521.2849112	2.332339749	1146.812407	3.937720986	1936.179016
0.828289561	906.3740504	1.822214156	1993.997876	3.076468996	3366.493791
2.069910537	823.3000487	4.553746009	1811.237367	7.688151451	3057.936733
1.943055426	317.051904	4.274668269	697.5054317	7.216980699	1177.607927
1.756986123	347.0319721	3.865320942	763.4607535	6.525874028	1288.961195
2.550365894	396.0331763	5.610734525	871.2620492	9.472679569	1470.963592
1.729666199	1385.031745	3.805217863	3047.031583	6.424401181	5144.34495
2.488292397	405.1319773	5.474174545	891.2791601	9.242123494	1504.758753
1.678272973	257.464428	3.692154187	566.4146304	6.233514235	956.2855403
1.630809828	370.5014663	3.587736578	815.0929925	6.057224563	1376.132608
1.599159534	376.8453131	3.518106805	829.0492801	5.939667668	1399.695199
1.584225405	379.9067787	3.485252133	835.7844198	5.884198678	1411.066227
1.574311494	381.9637827	3.463441805	840.3097719	5.847376003	1418.706441
2.279657719	570.3090674	5.015184016	1254.664196	8.467203527	2118.266662
2.276833029	439.3267218	5.008969777	966.5066536	8.456711942	1631.766356
1.535862442	390.1324084	3.378854952	858.2805229	5.704566866	1449.046705
1.519721278	393.6544503	3.343344836	866.0289177	5.644614654	1462.128425
1.516458703	394.3731698	3.336167261	867.6100809	5.632496656	1464.797924
1.511372749	1088.058447	3.324978303	2393.69853	5.613606187	4041.313852
1.493290761	1099.188691	3.285198429	2418.18476	5.546445282	4082.654289
1.471562939	732.1496788	3.237397821	1610.709071	5.465742864	2719.382077
2.110573533	470.2398351	4.643203477	1034.514649	7.839183713	1746.585182
1.413206941	418.3594754	3.109016236	920.3792905	5.248994485	1553.8889
1.405757846	299.3925111	3.092628433	658.6552551	5.221326734	1112.016644
1.392656745	325.8187734	3.063806374	716.7923022	5.172666058	1210.170213
1.38625049	769.3187759	3.049712788	1692.480058	5.148871666	2857.437149
2.046960152	483.1548332	4.503255796	1062.927288	7.602908137	1794.554627
1.385191945	425.3032698	3.04738402	935.6554464	5.144939975	1579.679842
1.374747968	774.5759431	3.024407558	1704.045681	5.106148501	2876.963548
1.32615174	339.0168546	2.9174972	745.8277163	4.925650286	1259.191099
1.323415957	441.3164356	2.911478551	970.8839689	4.915488919	1639.156637
1.955275567	653.633251	4.301552242	1437.975099	7.262369277	2427.752957
1.290926191	450.1400415	2.840001964	990.2956583	4.794814024	1671.929657
1.282960346	452.3468883	2.822477325	995.1506602	4.765226936	1680.126423
1.893367226	517.1644348	4.165355602	1137.747472	7.032426634	1920.874564
1.890328167	517.8808064	4.158669756	1139.32347	7.021138828	1923.535343

LI's calculated		Turner's calculated		New model	
Critical velocity (ft/s)	Critical flow rate (mcf/days)	Critical velocity (ft/s)	Critical flow rate (mcf/days)	Critical velocity (ft/s)	Critical flow rate (mcf/days)
1.268325947	456.4463974	2.790282052	1004.169467	4.710871218	1695.352997
1.257046614	353.6829155	2.765467832	778.0926451	4.668977031	1313.664418
1.845859692	686.9283921	4.060840339	1511.223489	6.85597209	2551.419214
1.226248479	360.5449216	2.697712783	793.1888691	4.554585259	1339.151578
1.80973596	537.5436438	3.981369126	1182.581169	6.721799758	1996.567906
1.208624311	804.1004949	2.658940101	1768.998879	4.489124812	2986.624918
1.787904127	705.8110894	3.933339696	1552.764902	6.640711016	2621.554147
1.175099571	724.545081	2.585186599	1593.979166	4.36460577	2691.13675
1.162399661	730.4436077	2.557247147	1606.955762	4.317435212	2713.045314
1.105630712	506.0805299	2.432357028	1113.363188	4.106581521	1879.706244
1.10253258	507.0985587	2.425541224	1115.602823	4.095074307	1883.487451
1.100054031	507.9149264	2.420088484	1117.398809	4.085868371	1886.519639
1.080199508	770.279937	2.376409082	1694.594586	4.012123842	2861.007135
1.074300103	516.4981552	2.363430555	1136.281675	3.990212017	1918.399839
1.474301242	825.382891	3.243422012	1815.819563	5.475913587	3065.672916
1.451895651	835.1698762	3.19413033	1837.35066	5.39269377	3102.024161
1.437724503	841.4514938	3.162954197	1851.170045	5.340058679	3125.355617
1.426234667	846.5968816	3.137676874	1862.489756	5.297382631	3144.46684
0.843677721	897.8268281	1.856067683	1975.194223	3.133624365	3334.747328

Appendix 3

Turner's data

Producing depth (ft)	Wellhead pressure (psi)	Condensate gravity (API)	Condensate make (bbl/MM)	Water make (bbl/MM)	Tubing ID (in.)	Tubing OD (in.)	Casing ID (in.)	Test flow rate (Mcf/D)	Well status during test
6529	108	64.3	9.6	12.4	2.041			568	Near L.U
2250	210	0	0	24		2.375	6.276	470	Loaded up
3077	280	0	0	28		2.375	4.974	500	Loaded up
3278	315	50	10	0	7.386			5740	Loaded up
6739	400		0	18	1.995			417	Near L.U
3278	422	50	10	0	7.386			3890	Loaded up
6770	450	61	11.3	0	1.995			442	Near L.U
3278	459	50	10	0	7.386			2780	Loaded up
3278	484	50	10	0	7.386			1638	Loaded up
5080	500	50	14	0		2.375	4.974	400	Loaded up
7200	500	0	0	5		2.375	4.052	800	Loaded up
6700	540	70.8	10.5	10.5	1.995			712	Near L.U
7531	552	54.9	25.1	22.3	2.441			1607	Near L.U
6776	660	0	0	3.5		2.375	6.276	4300	Loaded up
7531	704	54.9	31.6	40.8	2.441			1313	Loaded up
6404	725	63.8	6	0	2.441			775	Near L.U
7531	760	54.9	46.1	45.1	2.441			1247	Loaded up
7531	822	54.9	26.7	26.3	2.441			1356	Loaded up
7531	1102	54.9	26.1	23.8	2.441			1365	Loaded up

Producing depth (ft)	Wellhead pressure (psi)	Condensate gravity (API)	Condensate make (bbl/MM)	Water make (bbl/MM)	Tubing ID (in.)	Tubing OD (in.)	Casing ID (in.)	Test flow rate (Mcf/D)	Well status during test
6180	1117	67	10.3	0		2.875	6.184	5513	Unloaded
6180	1184	67	10.3	0		2.875	6.184	4843	Loaded up
6180	1245	67	10.3	0		2.875	6.184	4441	Loaded up
5294	1246	71	0.9	0	1.995			2965	Unloaded
5294	1480	71	0.9	0	1.995			2473	Unloaded
7546	1509	52.2	4.1	0.6	1.75			4485	Unloaded
5515	1520	65	13.1	0	3.958			4150	Unloaded
5515	1550	65	13.1	0	3.958			3551	Questionable
7639	1575	53.5	3.3	1	1.75			4410	Unloaded
5515	1590	65	13.1	0	3.958			3009	Loaded up
6850	1600	65	26.7	0		4.5	6.184	6423	Unloaded
5234	1680	71.7	54.1	0	1.995			4439	Unloaded
5294	1737	71	0.9	0	1.995			1712	Unloaded
8162	1765	56.7	7.7	0	1.995			2949	Unloaded
5234	1784	71.7	54.1	0	1.995			3460	Unloaded
6850	1818	65	26.7	0		4.5	6.184	4998	Questionable
7346	1835	52.7	27.8	0.4	1.995			8672	Unloaded
7546	1839	52.2	4.1	0.6	1.75			3742	Unloaded
5234	1861	71.7	54.1	0	1.995			2502	Unloaded
5234	1895	71.7	54.1	0	1.995			1797	Unloaded
5294	1902	71	30.9	0	1.995			1138	Unloaded
6031	1913	62.5	24.8	0		2.875	6.184	9897	Unloaded
6031	1938	62.5	24.8	0		2.875	6.184	9039	Questionable
5962	1953	65	31.8	0		2.875	6.184	9289	Unloaded
6031	1958	62.5	24.8	0		2.875	6.184	8185	Loaded up
5962	1993	65	31.8	0		2.875	6.184	8210	Questionable
5934	2003	70	3.7	0		3.5	6.184	11,767	Unloaded
5962	2040	65	31.8	0		2.875	6.184	6702	Loaded up
6850	2042	65	26.7	0		4.5	6.184	4124	Loaded up
7639	2104	53.5	3.3	1	1.75			3598	Unloaded
8162	2149	56.7	7.7	0	1.995			2385	Unloaded
5725	2169	70	2.5	0		4.5	6.184	7504	Unloaded
5725	2175	70	2.5	0		4.5	6.184	6405	Questionable
5725	2182	70	2.5	0		4.5	6.184	5501	Loaded up
7475	2205	52.4	3.4	0	1.75			6871	Unloaded
5934	2223	70	3.7	0		3.5	6.184	9860	Unloaded
7546	2224	52.2	4.1	0.6	1.75			2910	Unloaded
6995	2226	65	17.9	0	1.995			1959	Unloaded
5906	2256	67.5	15.1	0		3.5	6.184	9747	Unloaded
5906	2271	67.5	15.1	0		3.5	6.184	8406	Questionable
5906	2284	67.5	15.1	0		3.5	6.184	7109	Loaded up
6995	2335	65	17.9	0	1.995			1116	Questionable
5934	2338	70	3.7	0		3.5	6.184	8057	Questionable
5934	2352	70	3.7	0		3.5	6.184	6361	Loaded up
7475	2406	52.4	3.4	0	1.75			5820	Unloaded
8162	2415	56.7	7.7	0	1.995			1804	Unloaded
7346	2421	52.7	27.8	0.4	1.995			6654	Unloaded
7753	2527	52.6	5.5	0	1.995			4471	Unloaded
8162	2556	56.7	7.7	0	1.995			1550	Unloaded

Producing depth (ft)	Wellhead pressure (psi)	Condensate gravity (API)	Condensate make (bbl/MM)	Water make (bbl/MM)	Tubing ID (in.)	Tubing OD (in.)	Casing ID (in.)	Test flow rate (Mcf/D)	Well status during test
7546	2574	52.2	4.1	0.6	1.75			1943	Unloaded
7639	2582	53.5	3.3	1	1.75			2423	Unloaded
7753	2611	52.6	5.5	0	1.995			3436	Unloaded
7475	2655	52.4	3.4	0	1.75			4140	Unloaded
7346	2705	52.7	27.8	0.4	1.995			5136	Unloaded
7475	2783	52.4	3.4	0	1.75			2939	Unloaded
7639	2814	53.5	3.3	1	1.75			1596	Unloaded
7810	2823	52.2	5	0		2.375	4.974	3863	Loaded up
7810	2862	52.2	5	0		2.375	4.974	3024	Unloaded
7346	2884	52.7	27.8	0.4	1.995			3917	Unloaded
8840	3025	60	54.8	0	2.441			3517	Unloaded
11,355	3092	55	117.6	0	2.441			3351	Unloaded
8840	3212	60	54.8	0	2.441			2547	Loaded up
11,355	3245	55	117.6	0	2.441			2503	Questionable
11,416	3280	56.4	130.8	0	2.992			4095	Questionable
11,416	3295	56.4	130.8	0	2.992			3264	Questionable
11,417	3330	56.4	113.5	0	2.441			2915	Questionable
11,355	3338	55	117.6	0	2.441			2261	Loaded up
11,416	3340	56.4	130.8	0	2.992			2611	Loaded up
11,200	3434	61	37.4	0	1.995			2926	Unloaded
11,390	3455	55	104.3	0	1.995			2769	Unloaded
11,426	3472	55	106.9	0	1.995			2572	Unloaded
11,426	3525	55	106.9	0	1.995			1792	Loaded up
11,417	3540	56.4	113.5	0	2.441			1814	Loaded up
11,390	3556	55	104.3	0	1.995			2069	Questionable
11,200	3607	61	37.4	0	1.995			1525	Loaded up
8690	3615	60	68.3	0	2.441			3890	Unloaded
8690	3644	60	68.3	0	2.441			3182	Questionable
11,340	3660	58	36.8	0	1.995			3726	Unloaded
8690	3665	60	68.3	0	2.441			2542	Loaded up
11,340	3773	58	36.8	0	1.995			2494	Questionable
8963	4575	43.9	7.5	1.4	1.995			7792	Unloaded
8963	4786	43.9	7.5	1.4	1.995			6221	Unloaded
8963	4931	43.9	7.5	1.4	1.995			4830	Unloaded
8963	5056	43.9	7.5	1.4	1.995			3376	Unloaded
11,850	7405	67.5	10.8	0	2.441			6946	Unloaded
11,850	7950	67.5	10.8	0	2.441			4896	Questionable
11,850	8215	67.5	10.8	0	2.441			3472	Loaded up

Appendix 4

LOADCALC PROGRAM CODES

```
Sub program_code_for_LOADCALC_software()
```

```
'program codes for the welcome message
```

```
Dim yourMsg As String
```

```
yourMsg = "Welcome to the LOADCALC platform for predicting liquid loading in gas wells. Click OK to continue"
```

```
MsgBox yourMsg, vbOK
```

```
'program codes for the input section of the software
```

```
Dim prodCONFIG As String
```

```
prodCONFIG = InputBox("ENTER PRODUCTION CONFIGURATION, FOR TUBING PRODUCTION ENTER 'T', FOR ANNULAR PRODUCTION ENTER 'A'", "PRODUCTION CONFIGURATION", "Enter T or A")
```

```
Range("d3").Value = prodCONFIG
```

```
TubingID = InputBox("ENTER THE TUBING INNER DIAMETER IN INCHES. CLICK OK TO CONTINUE", "TUBING INNER DIAMETER", "inches")
```

```
Range("d4").Value = TubingID
```

```
TubingOD = InputBox("ENTER THE TUBING OUTER DIAMETER IN INCHES. CLICK OK TO CONTINUE", "TUBING OUTER DIAMETER", "inches")
```

```
Range("d5").Value = TubingOD
```

```
CasingID = InputBox("ENTER THE CASING INNER DIAMETER IN INCHES. CLICK OK TO CONTINUE", "CASING INNER DIAMETER", "inches")
```

```
Range("d6").Value = CasingID
```

```
PRODUCINGDEPTH = InputBox("ENTER THE PRODUCING DEPTH IN FEET", "PRODUCING DEPTH", "feet")
```

```
Range("d7").Value = PRODUCINGDEPTH
```

```
WATERDENSITY = InputBox("ENTER THE WATER DENSITY IN LB/CUFT, IF WATER IS PRODUCED ALONG WITH THE GAS, ELSE CLICK OK TO CONTINUE", "WATER DENSITY", "0")
```

```
Range("d9").Value = WATERDENSITY
```

```
WATERGASINTERFACIALTENSION = InputBox("ENTER THE WATER GAS INTERFACIAL TENSION IN DYNES/CM, IF WATER IS PRODUCED ALONG WITH THE GAS, ELSE CLICK OK TO CONTINUE", "WATER GAS INTERFACIAL TENSION", "0")
```

```
Range("d10").Value = WATERGASINTERFACIALTENSION
```

```
CONDENSATEDENSITY = InputBox("ENTER THE CONDENSATE DENSITY IN LB/CUFT, IF CONDENSATE IS PRODUCED ALONG WITH THE GAS, ELSE CLICK OK TO CONTINUE", "CONDENSATE DENSITY", "0")
```

```
Range("D11").Value = CONDENSATEDENSITY
```

```
CONDENSATEGASINTERFACIALTENSION = InputBox("ENTER THE CONDENSATE GAS INTERFACIAL TENSION IN DYNES/CM, IF CONDENSATE IS PRODUCED ALONG WITH THE GAS, ELSE CLICK OK TO CONTINUE", "CONDENSATE GAS INTERFACIAL TENSION", "0")
```

```
Range("D12").Value = CONDENSATEGASINTERFACIALTENSION
```

SPECIFICGRAVITYOFGAS = InputBox("ENTER THE GAS SPECIFIC GRAVITY", "GAS SPECIFIC GRAVITY", "S.G")

Range("D13").Value = SPECIFICGRAVITYOFGAS

WELLHEADPRESSURE = InputBox("ENTER WELL HEAD PRESSURE IN PSIA", "WELLHEAD PRESSURE", "psia")

Range("N2").Value = WELLHEADPRESSURE

WELLHEADTEMPERATURE = InputBox("ENTER WELL HEAD TEMPERATURE IN DEGREE RANKINE", "WELL HEAD TEMPERATURE", "rankine")

Range("n3").Value = WELLHEADTEMPERATURE

TESTFLOWRATE = InputBox("ENTER GAS WELL TEST FLOW RATE IN MCF/D", "TEST FLOW RATE", "MCF/D")

Range("n4").Value = TESTFLOWRATE

Range("D22").GoalSeek goal:=Range("D34"), changingcell:=Range("D20")

Z = Range("D21").Value

GASDENSITY = (2.7 * SPECIFICGRAVITYOFGAS * WELLHEADPRESSURE) / (Z * WELLHEADTEMPERATURE)

Range("D14").Value = GASDENSITY

If WATERDENSITY = 0 Then

VCRITL = (0.7241 * (CONDENSATEGASINTERFACIALTENSION) ^ 0.25 * (CONDENSATEDENSITY - GASDENSITY) ^ 0.25) / (GASDENSITY) ^ 0.5

VCRITT = (1.593 * (CONDENSATEGASINTERFACIALTENSION) ^ 0.25 * (CONDENSATEDENSITY - GASDENSITY) ^ 0.25 / (GASDENSITY) ^ 0.5)

VCRITNEW = VCRITL + 2.261921523 * (VCRITT - VCRITL)

End If

If WATERDENSITY > 0 Then

VCRITL = (0.7241 * (WATERGASINTERFACIALTENSION) ^ 0.25 * (WATERDENSITY - GASDENSITY) ^ 0.25) / (GASDENSITY) ^ 0.5

VCRITT = (1.593 * (WATERGASINTERFACIALTENSION) ^ 0.25 * (WATERDENSITY - GASDENSITY) ^ 0.25 / (GASDENSITY) ^ 0.5)

VCRITNEW = VCRITL + 2.261921523 * (VCRITT - VCRITL)

End If

Range("n9").Value = VCRITNEW

If prodCONFIG = "T" Then

PIE = 3.142

AREA = (PIE * (TubingID / 12) ^ 2) / 4

QCRIT = (3060 * WELLHEADPRESSURE * VCRITNEW * AREA) / (WELLHEADTEMPERATURE * Z)

End If

```

If prodCONFIG = "A" Then
  PIE = 3.142
  AREA = (PIE * ((CasingID) / 12 - (TubingOD) / 12) ^ 2) / 4
  QCRIT = (3060 * WELLHEADPRESSURE * VCRITNEW * AREA) / (WELLHEADTEMPERATURE * Z)
  End If
  Range("n10").Value = QCRIT
  If Abs(QCRIT - TESTFLOWRATE) <= 100 Then
    WELLSTATUS = "THE WELL IS NEAR LOAD UP"
  End If
  If TESTFLOWRATE > QCRIT Then
    WELLSTATUS = "THE WELL IS UNLOADED"
  End If
  If TESTFLOWRATE < QCRIT Then
    WELLSTATUS = "THE WELL IS LOADED UP"
  End If
  Range("m15").Value = WELLSTATUS
End Sub

```

Appendix 5

Derivation of deformation coefficient, C for a droplet rising through gaseous medium

Generally, small droplets maintain their spherical forms, but larger ones assume different shapes such as ellipsoid, oblate ellipsoid, spherical cap or saucer shape during the rise motion (Kelbaliyev and Ceylan 2007).

From Fig. 17, the characteristic dimension (r) for the intermediate droplet can be estimated as

$$r = R[1 - \xi(\cos \theta)], \quad (45)$$

where R is the equivalent radius (the radius of spherical droplet having the same volume as the intermediate droplet) and $\xi(\cos \theta)$ is a function representing the surface curvature. Taylor and Acrivos, 1964 represented the function $\xi(\cos \theta)$ by

$$\xi(\cos \theta) = \lambda_v \times Ac \times Re^2 P_2(\cos \theta) - \frac{3}{70} \lambda_v \frac{11 + 10\gamma}{1 + \gamma} Ac^2 Re^3 P_3(\cos \theta) + \dots \quad (46)$$

where $\lambda_v = \varphi(\gamma)$.

Fig. 17 Schematic representation of ellipsoidal bubble deformation and the characteristic dimensions

For the case of liquid drops in gaseous medium $\gamma \rightarrow \infty$ and then $\lambda_v \rightarrow 5/48$. According to the deformation and elasticity theory, the relation between the deformation and the variation in the dimension could be given as (Landau and Lifshitz 1953):

$$\frac{1 - \Delta C}{\nu_p C - C_s} = -z \Delta a, \quad (47)$$

where v_p is the volume of the particle, a is the equivalent diameter of the particle, C_s is the stable deformation factor (maximum deformation or minimum aspect ratio), and z is the compressibility factor.

Equation (47) can be modified as

$$\lim_{\Delta a \rightarrow 0} \frac{\Delta C}{\Delta a} = \frac{dC}{da} = -v_p \times z(C - C_s). \quad (48)$$

For spherical particles, it can be written as

$$\frac{d\chi}{da} = -\frac{\pi a^3}{6} z(C - C_s), \quad (49)$$

$$C^{(a)} \Big|_{a \rightarrow 0} = 1. \quad (50)$$

A solution to Eq. (49) can be given as

$$C = C_s + (1 - C_s) \times \exp(-\beta a^4), \quad (51)$$

where $\beta = 1.475 \times 10^{-4} \cdot Mo^{-1/5}$, $C_s = 0.5 \times Mo^{1/8}$

However, the surface area of a particle increases after deformation, although the volume remains constant. If the drops or bubbles do not have sufficient surface energy, they undergo breakup after deformation. If the first term of Eq. (46) is sufficient to represent the surface curvature and if it is replaced by

$$We = Ac \times Re^2, \quad (52)$$

$$P_2(\cos \theta) = 0.5(3\cos^2 \theta - 1). \quad (53)$$

Then Eq. (46) can be written as

$$r = R \left[1 - \frac{\lambda_v}{2} We(3\cos^2 \theta - 1) \right]. \quad (54)$$

If $\theta = 0$ and $r = a_0$, then Eq. (54) can be rewritten as

$$a_0 = R(1 - \lambda_v We) \quad (55)$$

and if $\theta = \pi/2$ and $r = b_0$, then Eq. (54) can be written as

$$b_0 = R \left(1 + \lambda_v / 2 We \right). \quad (56)$$

Based on these radii, the shape deformation is defined as

$$C = \frac{a_0}{b_0} = \frac{R(1 - \lambda_v We)}{R(1 + \lambda_v / 2 We)}. \quad (57)$$

Using the experimental data from Raymond and Rosant (2000), λ_v is estimated as

$$\lambda_v = \frac{1}{12} \left(1 - \frac{3 We}{25 Re} \right). \quad (58)$$

Weber's number can be obtained from

$$We = \frac{\rho \times v^2 l}{\sigma}, \quad (59)$$

whereas Reynolds number is obtained from

$$Re = \frac{QD_H}{\nu A}. \quad (60)$$

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