AN IMPROVED MODEL FOR THE PREDICTION AND MITIGATION OF LIQUID LOADING IN VERTICAL GAS WELLS

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ABSTRACT

The phenomenon of liquid loading is a dominant limitation in developed gas fields globally. Apparently, all gas wells will experience this depleting process in the subsequent phases of their production. The primary problem in dealing with liquid loading is the issue of forecasting its occurrence and accurately determining its onset. This paper is focused on developing an improved model for accurately predicting liquid loading in vertical gas wells as the available models often show variations.

In this paper, an improved model for predicting liquid loading was developed on the hypothesis that the liquid droplet is disk-shaped and retains its configuration throughout the wellbore. The developed model was established on the fundamental principles of Turner's model but offers better prediction than the former. The model was validated with Turner's well data using the commercial Microsoft statistical tool Excel®. The actual critical velocities and critical flowrates of 106 wells from Turner's data set were compared with the evaluated critical velocities and flowrates from the new model and the existing Turner's and Li's models.

The error analysis carried out on the models showed that the models predicted the liquid loading status of the wells with average relative errors of 15.48%, 26.29% and 35.71%, with the improved model having the least error. The results obtained from this analysis indicate an improvement over the Turner's and Li's models. The improved model was applied to field data from Stubb Creek field in the Niger Delta to validate the efficiency of the model in detecting the liquid loading status of four (4) gas wells. The results obtained showed that the improved model detected the liquid loading status of the wells with the least percentage error of 10%. The analysis obtained using the data collected from Stubb Creek field revealed that the improved model gave a more accurate detection of liquid loading than the existing Turner's and Li's models. The improved model can be applied to gas wells with well head pressures lower than 500 psia and liquid/gas ratios within the ranges of (1-130 bbl/MMscf) to ensure the existence of a mist flow regime in the gas wells. The developed equations can also be applied in gas wells where annular flow regime and other flow geometries exist.

It has been theoretically established that liquid loading is an issue bound to occur in all natural gas wells during their productive life. Therefore, the results of this study will be beneficial to the industry as it would enable the early detection and mitigation of liquid loading. The resultant effect of the early detection of liquid loading is its possible avoidance and increase in gas recovery rate.

INTRODUCTION

Liquid loading or accumulation in gas wells occurs when the gas phase lacks sufficient energy to remove liquids from the wellbore on a continuous basis. The build-up of liquid creates additional backpressure in the formation, limiting well productivity and, in rare cases, causing the death of gas wells. In recent years, several authors have proposed different mathematical models to calculate the gas velocity and flow rate required to keep gas wells unloaded.

(R. Turner et al., 1969) were the authors to analyze and determine the minimal gas-flow rate required to avoid liquid loading. Their theories and equations formed the foundations of the Turner's model, and the model was used to predict the terminal velocity and critical production rate of gas wells. Subsequently (R. Turner et al., 1969) concluded that the entrained-droplet model significantly underestimated the well's critical rates, so they modified the droplet model by 20%.

They discovered that by adjusting the model by 20%, the model considered majority of their well scenarios. These wells are constructed on Turner's model with a 20% upward modification, referred to in this work as Turner's modified model. (Coleman et al., 1991) later indicated that by utilizing the droplet model, they were able to achieve a good correlation with their actual field data without any adjustments. The contrast between Turner's and Coleman's model results, according to (Nosseir et al., 2000), was that both models neglected the flow-regime requirements for their individual data sets.

A pressure differential exists between the fore and apt regions of a liquid droplet when it is entrained in a high-velocity gas stream, according to (Li et al., 2002). They argued that a model should be developed to determine the critical flow rate required to keep gas wells unloaded while considering the impact of droplet deformation. Gas wells can function at sub-critical rates, according to (Sutton et al., 2003), who reviewed the methodologies for investigating this phenomena. (Guo et al., 2006) presented a comprehensive technique to predict the optimal gas-production rate for the continual removal of water and oil from gas wells using the minimum kinetic energy criterion and a four-phase-flow model.

(Guo et al., 2006) proposed a method for predicting the minimal gas-production rate required to eliminate water and oil from gas wells continuously. (Wang and Liu, 2007) claimed that droplets in gas wells are disk-shaped for specific ranges of the dimensionless number, establishing the disk-shaped-droplet model to ensure the lowest production rate in gas wells. In relation with gas velocity, (Zhou & Yuan, 2010) observed that the quantity of liquid in the gas stream (liquid holdup) is also a crucial element for liquid loading, which provided some further advancement on Turner's criterion.

According to various studies, Turner's adjusted model is more suitable for evaluating critical rate in wells with flowing tubing wellhead pressures of 800 psia or greater (Dousi et al., 2006; Hutlas & Granberry, 1972; Ilobi & Ikoku, 1981; Libson & Henry, 1980; Solomon et al., 2008). (Turner's model (also known as Coleman's model) is considered to be more effective in determining liquid loading in gas wells with wellhead pressures below 500 psia (Coleman et al., 1991; R. G. Turner et al., 1969).

However, when the rate of production is less than Turner's minimum production rate, a percentage of gas wells continue to produce without load up; this behavior is common in low-pressure gas wells. Turner's modified model and Turner's model both considered spherical-droplet mobility in the tubing, which is inconclusive. Despite the fact that the flat-shaped droplet model accounts for droplet deformation (Li et al., 2002), we discovered that virtually all gas wells have experienced liquid loading conditions before attaining Li's critical production rate. Li's model falls far short of the application's expectations.

The primary problem in dealing with liquid loading is the issue of forecasting its occurrence and accurately determining its onset (Liu et al., 2017; Ming & He, 2017). There are currently different models for detecting liquid loading but the results that are obtained from the current models often show variations (Fadairo et al., 2015). Hence, the need for a reliable model which is the need for this research.

This study is aimed at developing a mathematical model that will be adapted to detect liquid loading early in natural gas wells. In this paper, we will study liquid loading with a view to determining the onset of liquid loading. Thus, to develop a mathematical model to calculate the critical rate and critical velocity required to unload gas wells. The developed model will be validated with field data from Stubb Creek in the Niger Delta. The model will then be compared with the existing Turner’s and Li’s models to evaluate the performance of each model. The results of this study will be beneficial to the industry as it would enable the early detection and mitigation of liquid loading. The resultant effect of the early detection of liquid loading is its possible avoidance and increase in gas recovery rate.

METHODOLOGY

Analysis of Existing models

(Luan & He, 2012) discovered in his investigation that Turner’s model overestimates the possibility of the existence of liquid loading in gas wells while Li’s model underestimates it. Turner’s and Li’s models are respectively depicted in Equations 1 and 2.

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

$$V_{crit-L} = 0.7241\left[\frac{\sigma(\rho_l - \rho_g)}{\rho_g^2}\right]^{1/4} \qquad Eqn\ 2$$

An improved model for the calculation of the critical gas velocity needed to eliminate the liquid droplets from the well bore is developed in this study. The Model will be applied in gas wells having low well head pressures of about 500 psia or below.

Development of the New model

The process of predicting the smallest gas flow rate desired to eliminate all the droplets of liquids from the well bore is a major problem in fluid mechanics. This prevailing issue is due to the existence of liquid bubbles trapped in the gas phase. The theory of particle mechanics is an important phenomenon that may be applied in the computation of the required minimum gas flowrate because the liquid droplet is a particle whose motion is relative to that of the fluid in a gravitational field.

Figure 1 illustrates a falling particle in a multiphase fluid medium. At the instance at which the drag forces of the freely falling particle equals its gravitational force, then the particle attains terminal velocity. Therefore, the terminal velocity is a major determinant of the physical and chemical properties of the freely falling particle. Two important features of the fluid phase which are the density and viscosity, are also reliant on the terminal velocity of the freely falling particle.

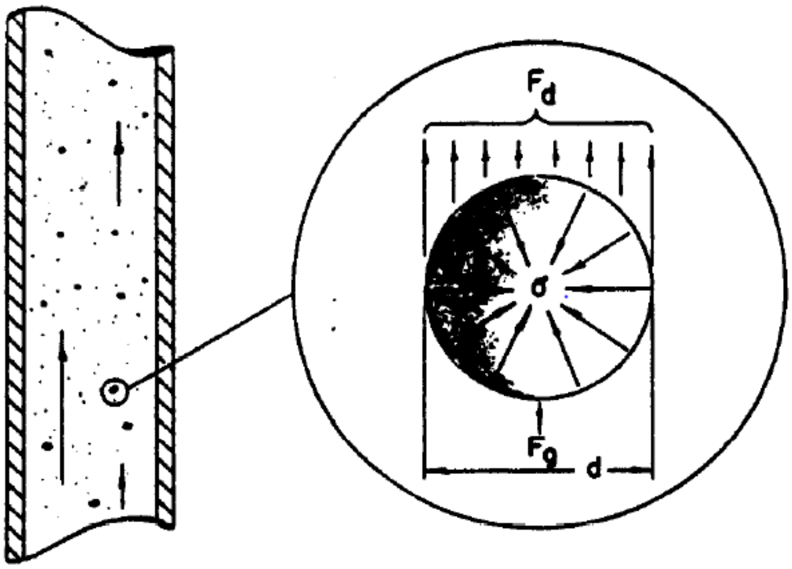

Figure 1 - Illustration of the movement of a liquid droplet that has been trapped in a gas (R. Turner et al., 1969).

A liquid that has been trapped in a gas stream and is being transported by it through a change in the coordinates of the trajectories of the gas stream becomes a falling particle (no gravitational effect) while on transit. The fundamental equations for terminal velocity can be applied to this scenario. Achieving the conditions at which the gas velocity equals the falling terminal velocity of the liquid bubble is possible. This condition can happen if the gas stream was moving at a velocity sufficient to ensure the liquid droplets remain in stable suspension. The restricting gas flow velocity necessary for the upward movement of liquid droplets out of the well bore is known as the terminal velocity of the droplets. This is because a further rise in the velocity of the gas medium would make the liquid bubbles move upwards.

$$V_t = \sqrt{\frac{2gm_p(\rho_p - \rho)}{\rho_\rho A_p C_d\, \rho}} \qquad Eqn\ 3$$

The general free settling equation which is illustrated in Equation 3 depicts the dependence of the terminal velocity on the densities of the fluid mediums and on the mass and the projected area of the freely falling particle. Following the fact that the surface tension acts to transform the liquid droplets into a spheroidal shape, Equation 3 can be re-written in terms of the diameter of the liquid droplets.

$$V_{new} = 6.55\sqrt{\frac{d(\rho_l - \rho_g)}{\rho_g C_d}} \qquad Eqn\ 4$$

Equation 4 illustrates that the larger the liquid droplets, the higher the terminal velocity, provided that all other things are equal. Therefore, the larger the liquid droplets, the higher the gas flow rate that is needed to successfully eliminate the droplets from the well bore. Hence, it is imperative to determine the diameter of the largest liquid droplets that can be found in a specific flow field. Another important parameter to calculate is the terminal velocity of the largest liquid droplets. The determination of the terminal velocity of the largest droplets of liquid would ensure the upward movement of all the liquid bubbles that are entrapped in the gas stream.

(R. Turner et al., 1969) established in his work that liquid droplets which are in relative motion to the gas stream are constrained by forces that acts to destroy the liquid droplets, whereas the surface tension of the droplets of liquids serves to ensure the coagulation of the liquid droplets.

The size and configuration of the bubbles of liquids can be estimated by the force of interaction between the velocity pressure and the surface tension pressure as recommended by (R. Turner et al., 1969). They hypothesized that an important parameter, which is the Weber number, can be depicted as the proportion of the velocity pressure to the surface tension pressure.

A relationship between the diameter of the liquid droplet and the Weber's number is represented by the equation below.

$$d = \frac{W_e \sigma g_c}{\rho_g V_{new}^2} \qquad Eqn\ 5$$

Where g_c can be described as the gravitational constant, which is given as 32.17 lbm/lbfs^2. The liquid droplets would be shattered if the Weber number outpaces a critical value. The Weber number for liquid droplet particles that were falling without any gravitational effect was found to be within the range of 20 – 30 by (R. Turner et al., 1969). The average of this value, which is 25, will be used for the derivation of the new model.

Substituting the equation for diameter into Equation 4, the terminal velocity then becomes:

$$V_{new} = \frac{13.629\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{C_d^{1/4}\rho_g^{1/2}} \qquad Eqn\ 6$$

Where σ is the surface tension in lbf/ft. When the surface tension is converted from 1 lbf/ft to 0.00006852 dyne/cm, the resulting expression is as thus:

$$V_{new} = \frac{1.24\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{C_d^{1/4}\rho_g^{1/2}} \qquad Eqn\ 7$$

(Wang and Liu, 2007) established that the Reynold's number for a typical oilfield condition is within the range of $10^4 – 10^6$, while the Morton's number for the low viscosity liquid in gas wells is within the range of 10^{-10} and 10^{-12}. According to (Wang and Liu, 2007) the liquid bubbles which are entrained in gas streams are usually disk-shaped, which is quite similar to flat-shaped models, for this range of Reynold's number. Disk-shaped liquid droplets have a drag coefficient close to 1.17.

Substituting $C_d = 1.17$ into Equation 7 gives the following:

$$V_{CRIT-N} = \frac{1.1923\sigma^{1/4}(\rho_l - \rho_g)^{1/4}}{\rho_g^{1/2}} \qquad Eqn\ 8$$

Equation 8 is the desired model that will be employed to determine the critical velocity of the gas component required to transport the liquid bubbles from the wellbore up to the surface.

$$Q_{crit} = \frac{3060\ P\ V_{crit}\ A}{T\ Z} \qquad Eqn\ 9$$

The detection of the critical flow rate needed to carry all the liquid bubbles out of the well will be done using Equation 9. The data used for this study was gotten from (R. Turner et al., 1969) in their pioneering work on liquid loading in gas wells. The derived model in Equation 8 was run using the commercial Microsoft statistical tool Excel®.

RESULTS AND DISCUSSIONS

Results and Analysis

The newly developed model which is represented in Equation 8 was tested with Turner's data. The data also included some assumed parameters used by Turner in his work. This data set is illustrated in Table 1. The results gotten from the comparison of the correlations carried out between the new model and the two different models, Turner's model, and Li's model, are well illustrated in Table 2. Figures 2, 3 & 4 represent a graphical illustration of the plot of critical flow rate against the test flow rate of the three different models.

Table 1 - The assumed parameters used by Turner.

Parameter	Values	Unit
Surface tension of the Condensate	20	dynes/cm
Surface tension of water	60	dynes/cm
Density of the condensate	45	lb/cuft
Water density	65	lb/cuft
Gas specific gravity	0.6	-
Wellhead temperature	580	Rankine

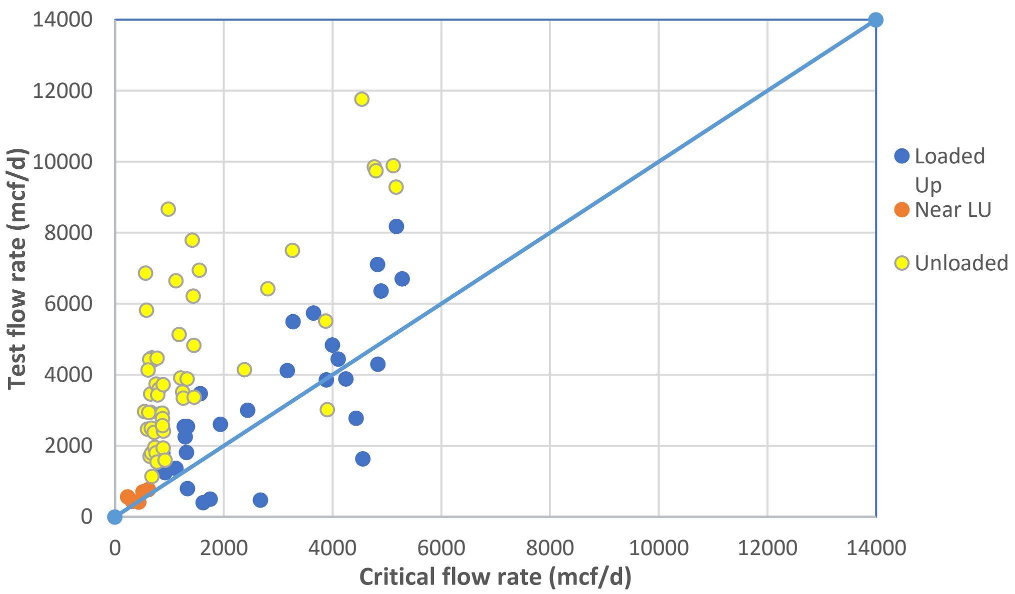

Figure 2 - A Cross plot of test flow rate against the critical flow rate using the developed model.

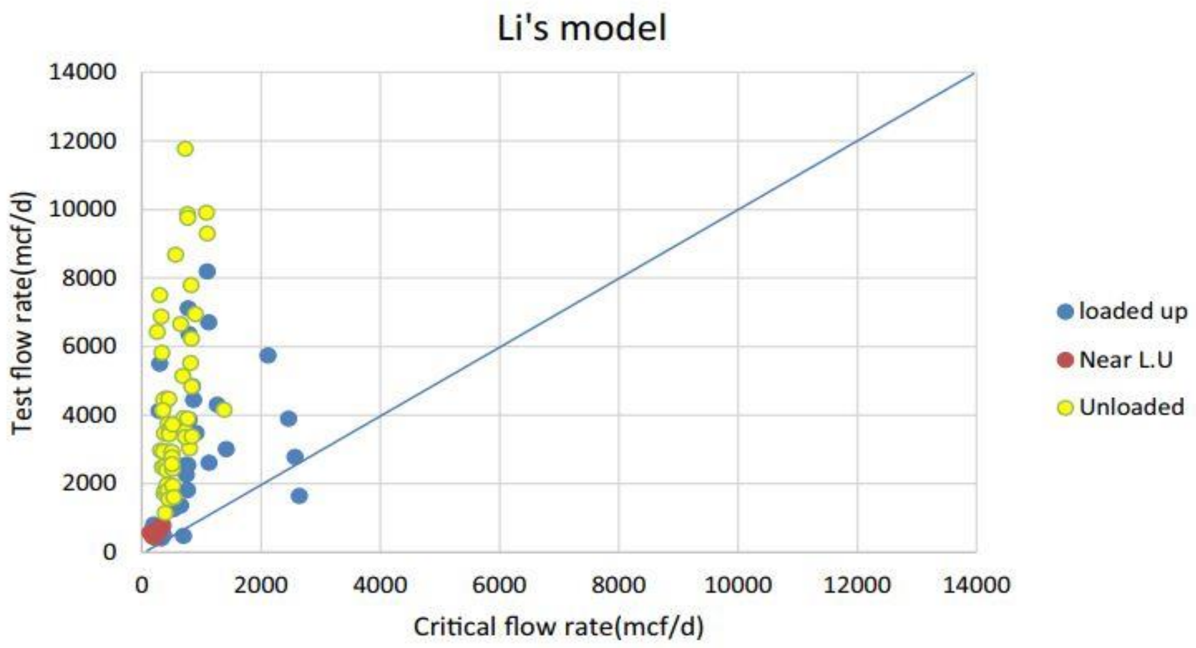

Figure 3 - A Cross plot of test flow rate against the critical flow rate using Li's model.

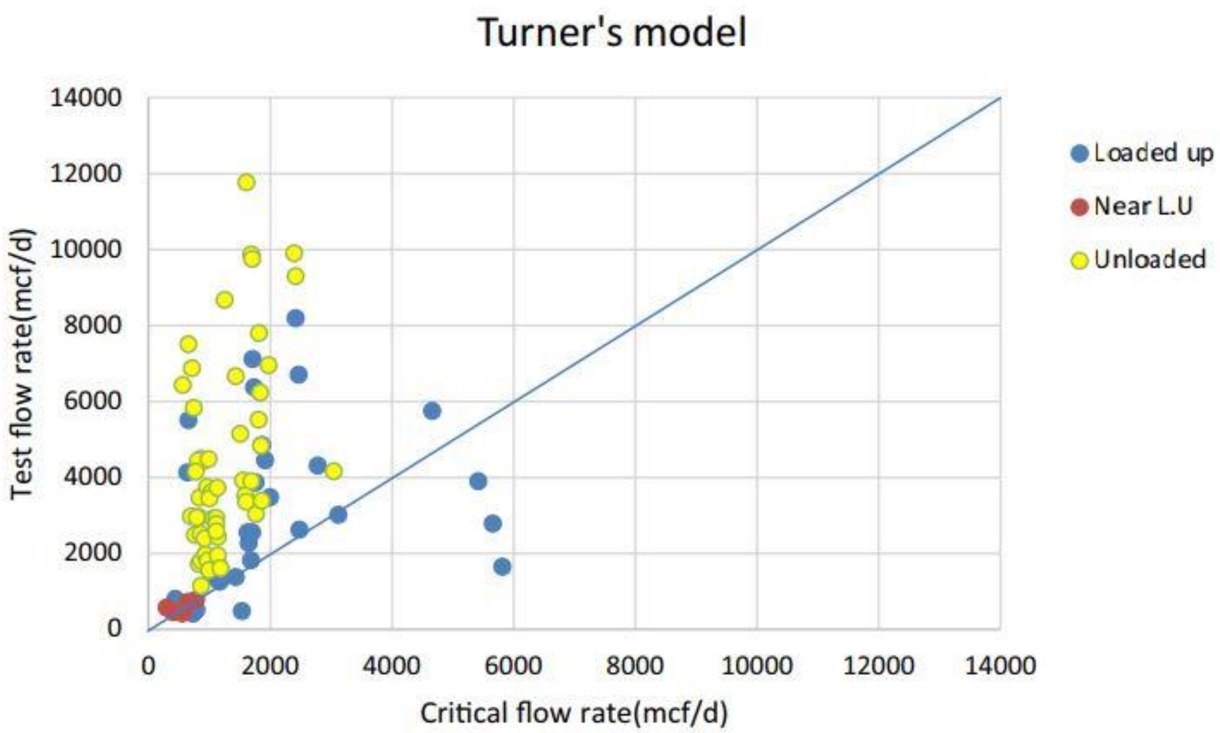

Figure 4 - A Cross plot of test flow rate against the critical flow rate using Turner's model.

The graphical illustrations plotted above are constructed in such a sequence that if the current test flow rate of the well is equivalent to the critical flow rate of the well for the removal of liquid droplets, the datum points will be constructed on the region of the slanted line. Hence, to ascertain the accuracy of a developed model for determining the critical velocity, the wells that are examined at specifications near load up should be constructed in the region of the slanted line. Contrastingly, in validation of the new model, it is required that the wells that unload with ease while the test is being carried out should be constructed in the segment above the slanted line, while the wells that do not unload easily will be plotted in the segment below the slanted line. The accuracy of this developed diagnostic model is a measure of its capacity to efficiently achieve this data segregation.

From a critical evaluation of the above graphical illustration, it can be deduced that the newly developed model gives the best data separation. This is clearly illustrated in Fig 2. The new model can therefore be said to provide the best prediction.

Discussion of Findings

Li's model, which is represented in Figure 3 did not have the capacity to accurately distinguish the loaded wells from the unloaded wells. Most of the data points were constructed in the region above the slanted line. This type of data separation delineates that all the wells are unloaded which is incorrect when juxtaposed with the well's status recorded from the different wells during the examination.

As earlier discussed, unloaded wells should plot above the diagonal line, loaded wells below it and wells near load up (Near L.U.) should plot in the region of the diagonal line. This pattern cannot be seen using Li's model. Thus, Li's model can be said to be a poor predictor of the existence of liquid loading in gas wells. This confirms the assertions of (Luan & He, 2012) who stated that Li's model underestimated the possibility of liquid loading occurrence in gas wells.

The Turner's model, which is represented in Figure 4 presented a more accurate prediction than Li's model. However, a good number of the loaded wells are still constructed in the unloaded segment which is above the slanted line. The loaded wells can also be seen to mix with the wells that were unloaded and situated in the unloaded region. This shows poor data separation and thus confirms the observations of (Coleman et al., 1991; Luan & He, 2012; Wei, 2007) who observed that Turner's model was not an accurate model for liquid loading detection as it overestimates the probability of occurrence of liquid loading.

From Figure 2, it can be recognized that the predictions given by the developed model was more accurate than that of Turner's model and Li's model by reason of the concept that majority of the loaded wells were constructed in the loaded segment, majority of the unloaded wells were constructed in the unloaded segment and finally the near load up wells were constructed in proximity to the diagonal line. Thus, aligning with the convention. The loaded wells that appear above the diagonal line for the new model can be seen to be more separated from the unloaded wells than what is observed from the other models. This is a good data separation, and it makes the newly developed model a better model for the accurate detection of liquid loading in gas wells compared to the existing Li's and Turner's model.

Turner's model was earlier reported to overestimate the possibility of liquid loading in gas wells while Li's model underpredicted the possibility of liquid loading occurrence in gas wells. The results depict that the critical rates and velocities gotten from the developed model are greater than the predictions of Li's model and lower than the predictions of Turner's model. Throughout the analysis, the new model gave values that were between the values predicted by the two existing models. This suggests an improvement over the existing Li's and Turner's models.

An error analysis was conducted on the three distinctive models to determine the average absolute relative errors of their predictions. The analysis revealed that the three models had absolute relative errors of 15.48%, 26.29% and 35.71% respectively, as presented in Table 2.

Table 2 - Comparison between current models and the developed model

Parameters	Turner's model	Li's model	New model
Geometry of the liquid droplet	spherical shape	flat shape	disk-shape
Drag Coefficient	0.44	1	1.14
Proposed formula for terminal velocity (v_{CRIT})	$v_{CRIT-T} = 1.593[\frac{\sigma(\rho_l-\rho_g)}{\rho_g^2}]^{\frac{1}{4}}$	$v_{CRIT-L} = 0.7241[\frac{\sigma(\rho_l-\rho_g)}{\rho_g^2}]^{\frac{1}{4}}$	$v_{CRIT-N} = 1.1923[\frac{\sigma(\rho_l-\rho_g)}{\rho_g^2}]^{\frac{1}{4}}$
Average absolute relative error	26.29%	35.71%	15.48%

The newly developed model has the least relative error. Evidently, when juxtaposed with Turner's and Li's models, the determined results of the developed model offered a more appropriate and reliable prediction. Finally, it is important to state that most of the data used for this analysis was gotten from wells under low-pressure conditions. Although it might be quite convincing theoretically, there is no substantial evidence to prove the existence of disk-shaped and flat-shaped liquid droplets in high-pressure gas wells. Hence, it is suggested that the developed model presented in this paper be applied to low pressure gas wells, especially well head pressure lower than 500 psia.

Application of the developed model to field data

The data applied for the application of this model was gotten from Stubb Creek field in the Niger Delta. The data was used to verify the reliability and efficiency of the developed model on real life cases. The data was gotten from four wells (W1, W2, W3, W4) in the field. W1 and W4 were loaded wells while W2 and W3 were unloaded. The properties of the wells are as depicted in Table 3. The gas flow rates of the wells are converted into superficial gas velocity which is then employed to correlate with the predicted critical gas velocity determined from the existing models and the developed model as shown in Table 2. The results obtained from using the three models examined in this work on the field data are shown in Table 4. Table 5 represents the critical gas velocities calculated by Turner's model, Li's model, and the newly developed model respectively.

The criterion for analyzing the different models is as; thus, if the critical gas velocity of the gas is larger than the actual velocity of the gas stream, the well is assumed to be a loaded well. Contrastingly, if the critical gas velocity of the gas stream is lower than the actual velocity of the gas stream, it would be impossible for water to accumulate at the bottom hole region of the well. Thus, the well is assumed to be unloaded. The predicted critical gas flow rates of the existing models and the developed model are shown in Table 4.

If the well status predicted by the models is in accordance with the well's actual test status, then the determined results are correct. But if the well status predicted by the models is not in accordance with the well's current test condition, then the determined results are incorrect.

Table 3 – Stubb Creek field data.

Well label	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)	Condition of the well during test
W1	8500	1000	54.9	31.6	40.8	2.441			950	Loaded up
W2	7500	2500	52.7	27.8	0.4	1.995			1200	Unloaded
W3	6250	2200	62.5	24.8	0		2.875	6.184	2000	Unloaded
W4	6250	1500	62.5	24.8	0		2.875	6.184	1550	Loaded up

Table 4 - Field data result

	W1			W2			W3			W4		
	Qcrit	Error	Status	Qcrit	Error	Status	Qcrit	Error	Status	Qcrit	Error	Status
Turner's model	1345.374	42%	Loaded	1440.246	20%	Loaded	2549.202	27%	Loaded	2107.511	36%	Loaded
Li's model	611.5414	36%	Unloaded	654.6653	45%	Unloaded	1158.743	42%	Unloaded	957.9716	38%	Unloaded
New model	1006.96	6%	Loaded	1077.969	10%	Unloaded	1907.981	5%	Unloaded	1577.392	2%	Loaded

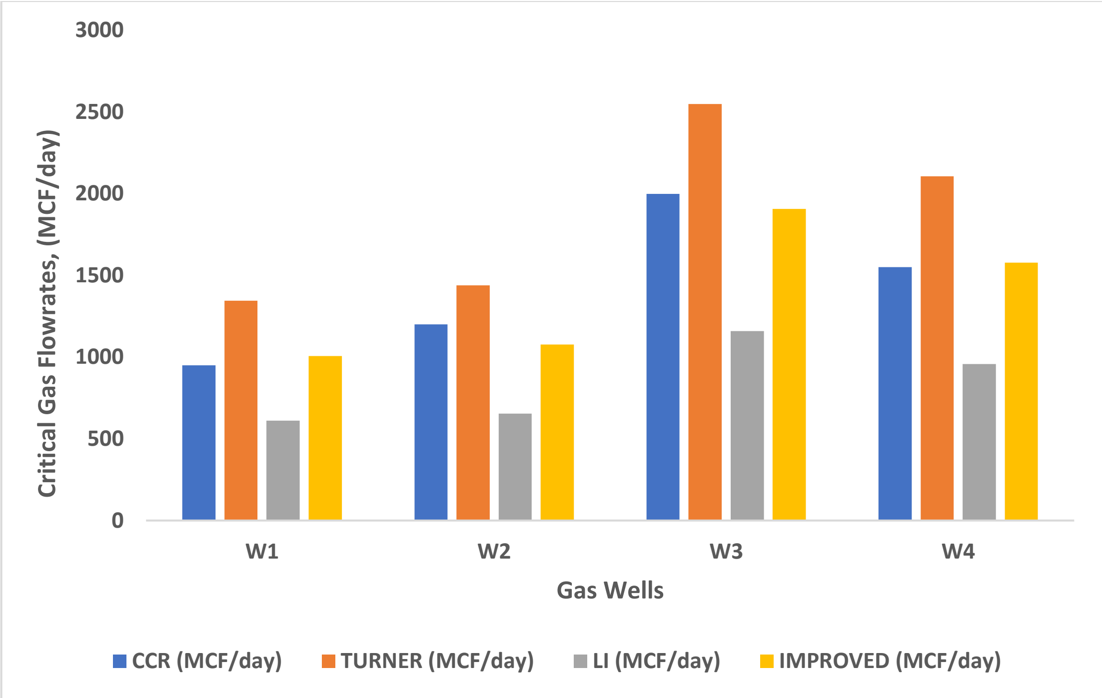

Figure 5 – Model Comparison of Critical Gas Flowrates

Table 5 - Comparison of the critical gas velocities using field data

Well Test Status		**Turner's model**		**Li's model**		**New Model**	
Wells	Current gas velocity (m/s)	Current gas velocity (m/s)	Percentage error	Current gas velocity (m/s)	Percentage error	Current gas velocity (m/s)	Percentage error
W1	5.5	7.0569	28.30%	3.2077	41.68%	5.2819	3.97%
W2	3.4	4.2131	23.91%	1.9151	43.67%	3.1533	7.26%
W3	2.6	3.0827	18.56%	1.4012	46.10%	2.3072	11.26%
W4	3	3.8494	28.30%	1.7497	41.67%	2.8811	3.96%

Correlation comparison results

From the result presented in Table 4, it can be clearly seen that when the Turner's model is used to determine the liquid loading status of the gas wells, W2 and W3 were predicted wrongly. Li's model correctly predicted the status of W2 and W3 but not W1 and W4. The new model on the other hand correctly predicted the status of all the four wells.

Also, the percentage error in the values of the critical flow rate as determined for the three models is seen to be least for the new model. It ranges from 20% to 42% for Turner's model, 36% to 45% for Li's model and 2% to 10% for the new model.

The correlation of the critical gas velocities determined by the three models is illustrated in Table 5. It shows that the improved model predicted the critical gas velocities of the wells with an accuracy greater than 90% in the four well cases. The result from the predictions shows considerable improvements over the Turner's model and the Li's model.

The error margin of the calculated results of the new model is approximately 10% for the critical flow rate and 11% for the critical velocity, which shows the accuracy of the developed model against the existing Turner and Li's models.

CONCLUSION AND RECOMMENDATION

Conclusion

The problem of liquid loading remains a dominant constraint in ensuring the viability of mature gas wells. When the menace of liquid loading is improperly managed, it could lead to a considerable reduction in gas production and subsequently lead to the abandonment of the well. Diagnosing liquid loading is a difficult process because the affected wells continue to produce over an extensive period without any appreciable impairment in their performance.

The primary problem in dealing with liquid loading is the issue of forecasting its occurrence and accurately determining its onset. The minimum flow conditions that are required to successfully transport the liquid droplets out of the well are those that will provide the appropriate gas velocity to transport the largest droplet of liquid that could exist in the well bore. This required velocity can be calculated based on the concept of particle and droplet dissociation mechanics. However, the available models for the prediction of liquid loading in vertical wells show discrepancies, thus necessitating the need for a better model.

An improved model for predicting liquid loading in vertical gas wells was developed in this work. The model was established on the fundamentals of Turner's pioneering model but offers better prediction than the base model. The developed model was validated with the data used in Turner's work. The results obtained from the analysis indicate an improvement over the Turner's and Li's models which were reported to respectively overpredict and underpredict the possibility of liquid loading in vertical gas wells.

Turner's model for calculating the critical gas velocity in gas wells was developed on the assumption that the liquid droplets are spherical in shape and remain spherical throughout the well bore. Contrarily, Li's model was developed based on the assumption that the liquid droplets are flat-shaped and maintain their shape throughout the well bore. The new model was developed on the assumption that the droplet is disk-shaped and remains the same throughout the well bore.

The developed model was further validated with field data from Stubb Creek field in the Niger delta. The field data was used to verify the accuracy of the developed model's earlier prediction with Turner's data. The error analysis carried out on the results obtained from the prediction carried out using Turner's data revealed the average absolute relative errors of the improved model, Turner's, and Li's model to be 15.48%, 26.29% and 35.71% respectively. The analysis carried out using the data collected from Stubb Creek field revealed that the new model gave a more accurate prediction of liquid loading than the existing Turner's and Li's models. Therefore, in the prediction of liquid loading occurrence in gas wells, the new model offers a better prediction than the existing Turner's and Li's models.

Recommendation

The following are the recommendations when using the developed model,

1. The new model is recommended to be applied to gas wells with well head pressures lower than 500 psia.
2. To achieve the accuracy of prediction with the new model, the model should be applied to gas wells with liquid/gas ratios within the ranges of (1-130 bbl/MMscf). The produced liquid may be water or condensate. This will ensure the existence of a mist flow regime in the gas wells.
3. The developed equations can also be applied in gas wells where annular flow regime and other flow geometries exist.

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