Effects of Model Coefficient Adjustments on Liquid Loading Prediction Accuracy of Critical Velocity Models

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Abstract: **The availability of variant critical velocity predicting models with their associated coefficients with each claiming superiority, it become difficult in choosing the most appropriate models for predicting liquid loading in gas wells. Whereas most of these models are identical in their constituent variables, their coefficients are quite different and so their predicting capabilities. Therefore, it becomes imperative that the impact of these coefficients in accurately predicting the critical velocity in gas wells be investigated. Five critical velocity models were investigated using a field data and their coefficients adjusted below and above 20% while monitoring how close their predictions are to the observed values. It was observed that Turner *et al.* and adjusted Turner *et al.* models, did not cause any appreciable change in loading prediction accuracy beyond 20% rather the liquid loading prediction accuracies for these models remains invariant at 35.71%. For Ruiquing and Huiqun's model, the prediction accuracy initially remains invariant between 28.57% and 60% increments but thereafter started decreasing. Li *et al.* model experienced a steady increase in prediction accuracy across the range of percentage increase whereas Coleman *et al.* model initially decreased mixed results. Its prediction accuracy initially decreased up to 40% model coefficient increment; and started increasing to 60% and stabilizes thereafter. This clearly shows that there exist an optimum range of conditions under which each model's application is optimum below or above which the accuracy of the predictions becomes unreliable. It is also pertinent to note that accuracy of these models would strongly be dependent on the reliability of observed data. Therefore, it is important to constantly investigate the critical velocity of each well over time since properties of wells changes and such investigations must be based on well specific cases rather field.**

Key words: **Gas wells, liquid loading, critical gas velocity, model coefficient, prediction accuracy.**

I. INTRODUCTION

Depending on the prevailing drive mechanism, gas wells are capable of producing for a considerable length of time. However, decline in production ensues due to either natural depletion since the resource is finite or due to wellbore or reservoir related problems. One common wellbore related problem that could inhibit efficient gas well production is the accumulation of liquids (water or condensates or both) in the wellbore. The accumulation of these liquids could be from direct incursion or condensation of heavier hydrocarbon fractions. The mechanism governing the process of liquid accumulation in wellbore is what is termed liquid loading in gas wells. And the consequences of liquid loading include: flow instability, killing of wells, abnormal surface measurements etc. (Ardhi, 2016).

Liquid loading is a multiphase flow phenomenon which is associated with flow regimes. Different flow regimes can occur in a well depending on the flow properties and well geometries but not at the same time. There is always a transition from one dominant from regime to another flow properties vary. At high flow rates, the flow regime begins with mist flow before turning annular. For annular flow, the gas usually flows in the middle of the tubing carrying liquid droplets, with liquid film flowing up the tubing wall (Khamehchi *et al.*, 2016). The prevalent flow regime during multiphase flow can still change depending on flow conditions (Bolujo *et al.*, 2017).

During multiphase flow in vertical pipes, the gas phase provides drag force that accelerates the liquid phase. In spite of that, the gas and liquid phase velocities will slightly differ (Bouw, 2017). The velocity difference is traceable to two reasons. The first is density differences between both phases and the second is non-uniform velocity profile or distribution that is generated by flowing fluids in pipe (Ardhi, 2016). The center of the pipe experiences a higher velocity than fluid closer to the wall. Also, the liquid phase can exist as droplets in the gas stream, as liquid film going up the tubing wall or as intermittent slug in the tubing (Ikoku, 1992).

Over time, the accumulating liquids can cause increased bottom hole pressures and continued reduction in drawdown between well and reservoir, which will eventually destabilize gas production. Sometimes, the well might produce for some time, but production usually occurs at reduced rates (Ruiquing and Huiqun, 2017). Dousi *et al.* (2006) described the reduced rates as the result of equilibrium established between quantity of liquid flowing down and quantity of liquid flowing into the wellbore. But the well may still die if the back pressure resulting from accumulating liquids rises above the sand face pressure.

One of the measures of managing liquid loading is through predicting its occurrence. This is carried out using critical velocity predicting models. Unfortunately, many of these models exist with diverse theories governing their development. Moreover, these critical velocity predicting models do not give consistent results when applied. This has led to a multiplicity of critical velocity models, with each model claiming unfulfilled superiority over the rest. Discrepancies among the models when compared with actual velocities could be a small percentage difference arising from the model coefficients. One way of improving the liquid loading prediction accuracy of critical velocity models is to adjust their model coefficients. Hence, in this study, the effects of model coefficient adjustments on the liquid loading prediction accuracy of critical velocity models were investigated.

II. METHODOLOGY

In order to evaluate the effects of model coefficients in accurately predicting the onset of liquid loading, five renown correlations were selected and investigated using a published data from Wang and Zhang (2010) as shown in Table 1. These are the Turner *et al.* (1969), Coleman *et al.* (1991), Li *et al.* (2014), Ruiquing-Huiqun (2017) and the Modified Tuner *et al.* (1969) models. The coefficients of these respective models were sensitized on and their performance in closely predicting the actual data evaluated using cross-plots. From the cross-plots, we delineate the regions of models predicting flow as loading, unloading and on critical flow. Thereafter, the models were ranked based on their performance.

Calculated or predicted critical velocities that fall below the diagonal under predicts the actual critical velocity, those above the diagonal over predicts the actual critical velocity and those on the diagonal accurately predicts the actual velocity. In terms of liquid loading, those below indicates or predicts that the well is already loaded with liquids, those above that the wells are unloading or not loaded while those on the diagonal indicates wells flowing at terminal velocities.

III. RESULTS AND DISCUSSION

In this section, results of analyses carried out with models investigated in this work are presented. Comparative analyses of the different models were made to identify the impact of model coefficients in accurately predicting liquid loading using estimated critical velocities and actual velocities.

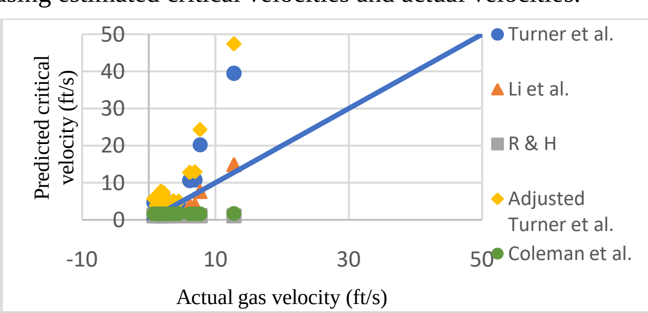

Figure 1: Actual gas velocities and predicted critical gas velocities for some gas wells without model coefficient adjustment

Figure 1 is a crossplot of actual against predicted gas velocities without any adjustments; this is used as a base case in determining the predictive capabilities of each model. From Figure 1, Turner *et al.* model critical velocity predictions showed that eleven (11) wells were above the diagonal, while three wells were on the diagonal with no well below the diagonal. For Li *et al.* model, eight (8) wells were on the diagonal, while one (1) well was above the diagonal and five (5) below it. For Ruiquing and Huiqun's model, nine (9) wells were below the diagonal, while five (5) wells were on the diagonal with no well above it. And the modified Turner *et al.* model, twelve (12) wells were found to be above the diagonal, with two (2) on the diagonal and none above it. For Coleman *et al.* model ten (10) were above the diagonal and two (4) were below it.

From Figure 1, it can also be deduced that in totality, more than 50% of the wells studied were not experiencing liquid loading. This is because most of the data points in Figure 1 are above the diagonal. Specifically, considering Turner *et al.* model, most of the gas wells studied were not loaded, since data points fell above the diagonal. While for Li *et al.* and Ruiquing and Huiqun's model, most data points fell below the diagonal signifying loaded conditions. However, Ruiquing and Huiqun's model data points were farthest from the diagonal.

Figure 2 represents the case where the model coefficients were adjusted by 20% upward. From Figure 2, it can be seen that there were obvious changes in the values of critical gas velocities predicted by the critical velocity models when the model coefficients were increased by 20%. Specifically, Turner *et al.* model critical velocity predictions showed that twelve (12) wells were found to be above the diagonal, with two (2) on the diagonal and none above it. For Li *et al.* model, eight (8) wells were above the diagonal, while no well on the diagonal and six (6) below it. For Ruiquing and Huiqun's model, ten (10) wells were below the diagonal, while three (3) wells were on the diagonal with one (1) well above it. And the modified Turner *et al.* model, all fourteen (14) wells were above the diagonal, and no well was either below or on the diagonal. For Coleman *et al.* model nine (9) were above the diagonal and three (3) were below it. This can be explained by the fact that since critical velocity is directly proportional to the model coefficient, increasing the model coefficient will surely lead to increase in predicted critical velocities.

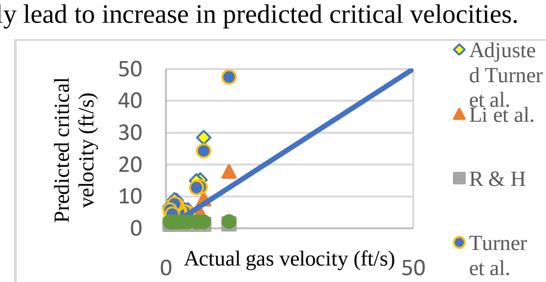

Figure 2: Actual and predicted critical gas velocities for some gas wells with 20% model coefficient increment

Table 1: Gas well production data (Wang and Zhang, 2010)

Well no	Depth (ft)	Gas rate (cuft/d)	Water rate (cuft/d)	Gas relative density	Water relative density	Wellhead Temp. (^oR)	Bottom Hole Temp. (^OR)	Wellhead Pressure (psia)	Bottom Hole Pressure (psia)
1	10696.06	1871960	2277.097	0.574	1.0433	494	553.2	2958.775	4017.553
2	10696.06	1165560	1015.266	0.574	1.0433	493	682.8	3493.965	4674.575
3	10696.06	1059600	507.6330	0.547	1.0433	492	686.4	4371.445	5684.039
4	8268.120	2295800	6961.824	0.575	1.0255	503	652.2	1079.083	1897.097
5	8268.120	1836640	4786.254	0.575	1.0255	501	664.8	1084.884	1908.700
6	8268.120	1412800	4206.102	0.575	1.0255	500	670.2	1058.777	1902.899
7	8268.120	1236200	5511.444	0.575	1.0255	499	668.4	1016.716	1908.700
8	7644.730	847680	7251.900	0.575	1.0255	495	645.0	1305.342	2517.860
9	7644.730	706400	6526.710	0.584	1.0378	495	643.2	1258.930	2552.669
10	9186.800	706400	5076.330	0.575	1.0378	495	672.0	723.7396	1660.685
11	9186.800	353200	1638.929	0.575	1.0363	495	666.6	1213.968	2058.089
12	10696.06	1589400	1740.456	0.574	1.0363	484	682.8	2377.173	3467.859
13	9383.660	671080	7106.862	0.578	1.0290	491	684.6	636.7168	1535.952
14	9186.800	706400	4786.254	0.575	1.0363	490	675.6	932.5943	1743.357

Table 2: Comparison of actual well loading status and predicted status according to different models for some gas wells without model coefficient adjustment

Well No	Actual u (ft/s)	Test status	Turner *et al.* (ft/s)	Predicted status	Li Min *et al.* (ft/s)	Predicted status	R & H (ft/s)	Predicted status	Coleman *et al.* (ft/s)	Predicted status
1	6.926653	Unloaded	10.82126	Unloaded	4.103715	Loaded	1.125116	Loaded	1.67894	Loaded
2	7.663945	Unloaded	20.32107	Unloaded	7.710393	Unloaded	1.125116	Loaded	1.67894	Loaded
3	12.77473	Loaded	39.51649	Unloaded	14.94643	Unloaded	1.170408	Loaded	1.746504	Loaded
4	4.437402	Unloaded	4.164331	Critical	1.576984	Loaded	1.123477	Loaded	1.676494	Loaded
5	3.680706	Unloaded	4.275281	Unloaded	1.620926	Loaded	1.123477	Loaded	1.676494	Loaded
6	2.876586	Unloaded	4.314879	Unloaded	1.632463	Loaded	1.123477	Loaded	1.676494	Loaded
7	2.517900	Unloaded	4.330788	Unloaded	1.640232	Loaded	1.123477	Loaded	1.676494	Loaded
8	2.126886	Loaded	6.238865	Unloaded	2.366160	Critical	1.123477	Loaded	1.676494	Loaded
9	1.791889	Loaded	6.397043	Unloaded	2.419050	Unloaded	1.108832	Loaded	1.654648	Loaded
10	1.272125	Loaded	3.574672	Unloaded	1.354813	Unloaded	1.123477	Critical	1.676494	Unloaded
11	0.765296	Loaded	4.798408	Unloaded	1.813752	Unloaded	1.123477	Unloaded	1.676494	Unloaded
12	6.137798	Unloaded	10.63885	Unloaded	4.023668	Loaded	1.125116	Loaded	1.67894	Loaded
13	1.138725	Unloaded	3.188429	Unloaded	1.210644	Unloaded	1.118573	Critical	1.669179	Unloaded
14	1.328331	Loaded	3.805669	Unloaded	1.441239	Unloaded	1.123477	Loaded	1.676494	Unloaded

Table 2 above shows the comparison of actual well loading status and predicted status according to different models for some gas wells without model coefficient adjustment. From the table, the predicted liquid loading statuses for the different models studied were classified into three (3) namely: loaded, unloaded and critical conditions. Hence, from Table 2, it can be deduced that Turner *et al.* model without any model adjustments had seven (7) predictions that corresponded with test status of the wells, giving a prediction accuracy of 50%. Li *et al.* model had only two (2) predictions that corresponded with test status of the wells, giving a prediction accuracy of about 14.29%. And Ruiquing and Huiqun's model had five (4) predictions that corresponds with test status of the wells, giving a prediction accuracy of about 20.57%. Coleman *et al.* model equally had five (4) predictions that corresponds with test status of the wells, giving a prediction accuracy of about 20.57%.

Figure 3 is a plot of critical velocity versus well number for models without coefficient adjustment. From Figure 3, it can be seen that the curve representing Li *et al.* model was closest to the actual or test gas velocity trend line as recorded in the wells investigated. This was followed by both Turner *et al.* and adjusted Turner *et al.* models. The aforementioned models were able to closely imitate crest and troughs of the actual or test gas velocity trend line to varying degrees. For Turner*et al.* and adjusted Turner *et al.* models, the highest discrepancies between them and actual or test gas velocity trend line occurred in well numbers 3 and 12. While for Li *et al.* model, the highest discrepancies between it and actualor test gas velocity trend line occurred in well numbers 3 and 4. But, the curve for Coleman *et al.* and Ruiquing and Huiqun's poorly followed the actual or test gas velocity trend line. The model performed poorly in all the wells.

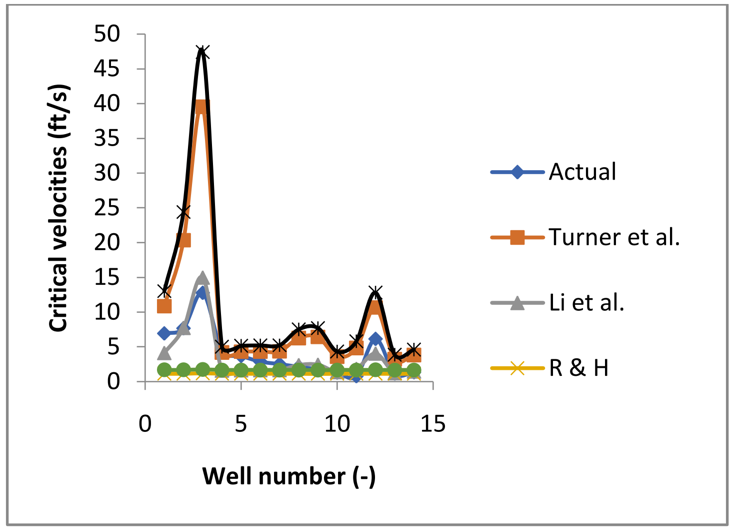

Figure 3: A plot of critical velocity versus well number for models without coefficient adjustment

Table 3: Comparison of actual well loading status and predicted status according to different models for some gas wells with 20% model coefficient increment

Well No	Actual u (ft/s)	Test status	Adjusted Turner *et al.* (ft/s)	Predicted status	Li Min *et al.* (ft/s)	Predicted status	R & H (ft/s)	Predicted status	Coleman *et al.* (ft/s)	Predicted status
1	6.926653	Unloaded	15.14976	Unloaded	4.924458171	Loaded	1.350139	Loaded	2.014728	Loaded
2	7.663945	Unloaded	28.44949	Unloaded	9.252471823	Unloaded	1.350139	Loaded	2.014728	Loaded
3	12.77473	Loaded	55.32309	Unloaded	17.93571881	Unloaded	1.404489	Loaded	2.095805	Loaded
4	4.437402	Unloaded	5.830063	Unloaded	1.892381147	Loaded	1.3481718	Loaded	2.011793	Loaded
5	3.680706	Unloaded	5.985393	Unloaded	1.945111453	Loaded	1.3481718	Loaded	2.011793	Loaded
6	2.876586	Unloaded	6.0408310	Unloaded	1.958955212	Loaded	1.3481718	Loaded	2.011793	Loaded
7	2.517900	Unloaded	6.0631031	Unloaded	1.968278372	Loaded	1.3481718	Loaded	2.011793	Loaded
8	2.126886	Loaded	8.7344111	Unloaded	2.839392588	Unloaded	1.3481718	Loaded	2.011793	Loaded
9	1.791889	Loaded	8.9558605	Unloaded	2.902859950	Unloaded	1.3305981	Loaded	1.985578	Unloaded
10	1.272125	Loaded	5.0045404	Unloaded	1.625775975	Unloaded	1.3481718	Unloaded	2.011793	Unloaded
11	0.765296	Loaded	6.7177711	Unloaded	2.176502743	Unloaded	1.3481718	Unloaded	2.011793	Unloaded
12	6.137798	Unloaded	14.894389	Unloaded	4.828401024	Loaded	1.3501393	Loaded	2.014728	Loaded
13	1.138725	Unloaded	4.4638003	Unloaded	1.452772819	Unloaded	1.3422873	Unloaded	2.003015	Unloaded
14	1.328331	Loaded	5.3279362	Unloaded	1.729487167	Unloaded	1.3481718	Critical	2.011793	Unloaded

Table 3 shows a comparison of actual well loading status and predicted status according to different models for gas wells with 20% model coefficient adjustment. From the Table, it can be deduced that adjusting Turner *et al.* model coefficient upwards by 20% increased both the number of correct predictions and the prediction accuracy of Turner *et al.* model. The number of correct predictions and prediction accuracy increased from seven (7) and 50% to eight (8) and 57.14% respectively. This phenomenon agrees with the results achieved by Turner *et al.* (1969) who reported increase in liquid loading prediction accuracy upon increment of model coefficient by 20%.

Also, it was observed that increasing model coefficient by 20% did not affect the number of correct predictions by Li *et al.* model. Which suggests that a higher percentage adjustment might be needed to affect prediction accuracy. But, for Ruiquing and Huiqun's model, the number of correct predictions remained the same, corresponding to 28.57% in percentage accuracy. And for Coleman *et al.* the number of correct predictions actually reduced to three (3), corresponding to a prediction accuracy of 21.43 (%).

Moreover, it is obvious that 20% model coefficient adjustment does have significant effects on the gas well liquid loading prediction accuracy of Turner *et al.* model for the field data used in this study. In this case, it led to an increase in liquid loading prediction accuracy. While for Li *et al.* and Ruiquing and Huiqun's models, the 20% model increment however, did not affect prediction accuracy. Probably, higher percentage increment is needed to change prediction accuracy.

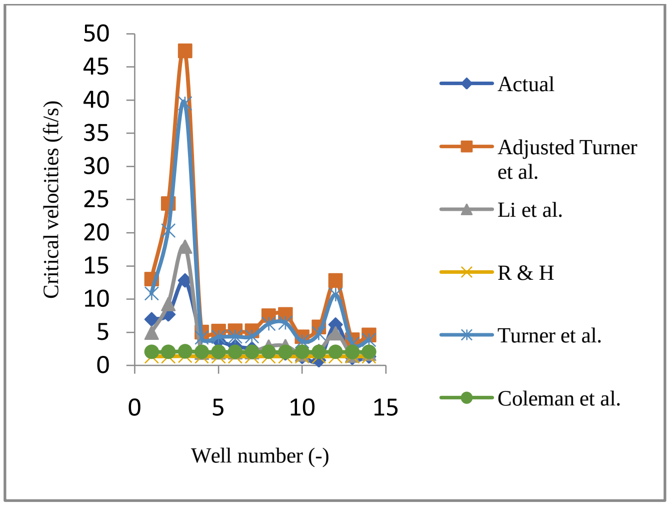

Figure 4: A plot of critical velocity versus well number for models with 20 % coefficient adjustment

From Figure 4, it can be seen that the trends for the models were similar to those captured in Figure 3. This implies that with 20% model coefficient increment, there were obvious changes in critical velocity predictions of the models. Although, the trend patterns attributed to each of them did not remarkably change.

Figure 5 shows the effects of different percentage increment on model coefficients on various critical gas models liquid loading prediction accuracy. From the figure, it is obvious that for Turner *et al.* and adjusted Turner *et al.* models, increasing model coefficient beyond 20% did not cause any appreciable change in loading prediction accuracy. Instead, the liquid loading prediction accuracies for these models remained constant at 35.71%. For Ruiquing and Huiqun's model, the prediction accuracy initially remained constant at 28.57% until 60% increment after which it started reducing. Li *et al.* model experienced a steady increase in prediction accuracy from 7.14% at 20% model coefficient increment to 42.86% at 80% model increment. But, Coleman *et al.* model showed mixed results: its prediction accuracy initially decreased up to 40% model coefficient increment. And started increasing thereafter, but stabilized again at 21.43%.

Figure 6 shows the effects of different percentage decrement on model coefficients on various critical velocity models liquid loading prediction accuracy. From Figure 6, it is obvious that decreasing the model coefficient for Ruiquing and Huiqun's model did not cause any change in its prediction accuracy, instead the prediction accuracy remained constant at 28.57%.But, for both Li *et al.* and Coleman *et al.* models, decreasing the model coefficient caused their liquid loading prediction accuracy to increase from 28.57% at 20 % model coefficient decrement up to 42.86% at 60% increment. In addition, both Turner *et al.* and Adjusted Turner *et al.* models showed fluctuating prediction accuracies. For Turner *et al.* model specifically, the prediction accuracy initially decreased from 35.71% at 20% model coefficient decrement to 14.29% at 60% model coefficient decrement. But, the prediction accuracy started increasing from there up to 42.86% at 80% decrement. While for Adjusted Turner *et al.*, the prediction accuracy initially decreased from 28.57% at 20% model coefficient decrement to 14.29% at 40% model coefficient decrement. But, the prediction accuracy started increasing from there up to 42.86% at 60% decrement.

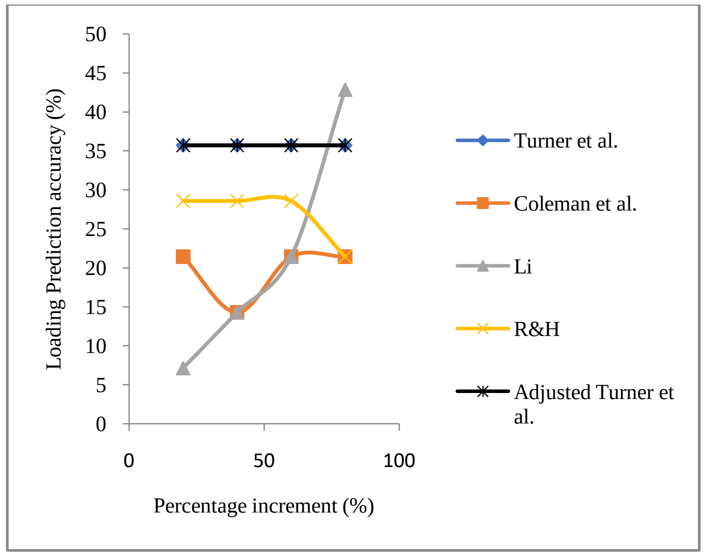

Figure 5: Effects of different percentage increment on model coefficients on various critical velocity models liquid loading prediction accuracy

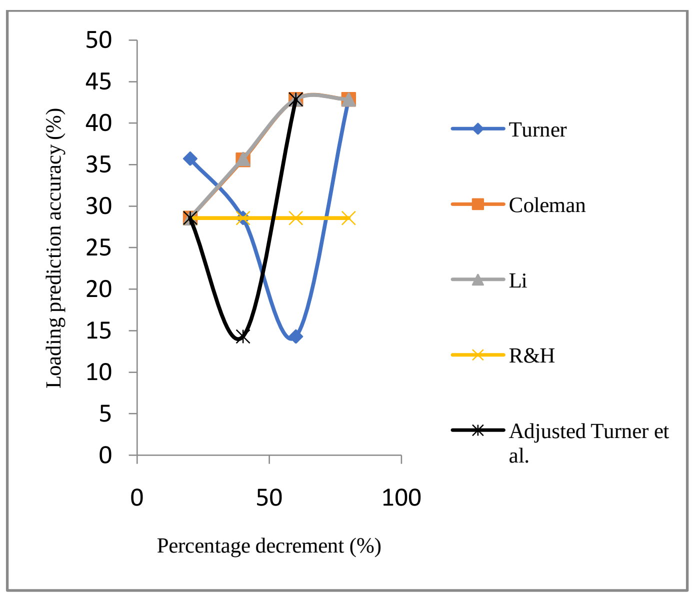

Figure 6: Effects of different percentage decrement on model coefficients on various critical velocity models liquid loading prediction accuracy.

IV. CONCLUSIONS

The following can be deduced from the investigation:

(a) Model coefficient increment improved the liquid loading prediction accuracy of Turner *et al.* model. This was because when Turner *et al.* model coefficient was increased by 20%, the predicted critical gas velocities were closer to actual gas velocities. Also, from the study, it was obvious that for Turner *et al.* and adjusted Turner *et al.* models, increasing model coefficient beyond 20% did not cause any appreciable change in loading prediction accuracy. In addition, both Turner *et al.* and Adjusted Turner *et al.* models showed fluctuating prediction accuracies on decreasing model coefficients.

(b) Coleman *et al.* model showed mixed results on increasing model coefficients. Its prediction accuracy initially decreased up to 40% model coefficient increment and started increasing thereafter, but stabilized again at 21.43%. However, for Coleman *et al.* model, decreasing the model coefficient caused their liquid loading prediction accuracy to increase steadily.

(c) Also, 20% model coefficient increment did not affect the liquid loading prediction accuracy of Li *et al.* model in this study. This was because perhaps, a higher percentage adjustment will be required to have substantial effects on the prediction accuracy Li *et al.* model. Hence, for model coefficient increment beyond 20%, Li *et al.* model experienced a steady increase in prediction accuracy. Interestingly, for Li *et al.*, decreasing the model coefficient equally caused liquid loading prediction accuracy to increase.

(d) For Ruiquing and Huiqun’s model, on increasing model coefficient, the prediction accuracy initially remained constant after which it started reducing. But decreasing the model coefficient for Ruiquing and Huiqun’s model did not cause any change in its prediction accuracy, instead, the prediction accuracy remained constant.

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