Analysis of Siphon String Application to Optimize Gas Lift Injection and Minimize Slugging Flow Condition

(Simulasi Pengaruh Daerah Pengurasan Terhadap Kinerja Sumur Dan Reservoir)

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Abstract
B-X well is an oil producing well at Bravo field in Natuna offshore area, which is completed at IBS zone using 5-1/2 inch tubing size. However, after several years of production period, the production rate decreased due to reservoir depletion and experienced gas lift injection performance impairment, also it observed unstable flowing condition (slugging flow). In year 2020, Siphon String installation is applied to B-X well as a pilot project in order to give deeper point of gas lift injection and better well’s production. The additional advantage by having smaller tubing size (insert tubing) was intended to reduce the slugging flow condition. The objective of this analysis, is to evaluate the effectiveness of siphon string technology application to B-X well, in regard with its production performance and flow patterns in the tubing. Technically, a Well Model simulator is used in evaluating several sensitivity cases, i.e.: (1) Deeper gas lift injection point, (2) Siphon string’s length, (3) Gas lift injection rate, and (4) Well’s productivity (PI). The sensitivity cases calculation results by the Well Model simulation indicates that the depth of the current siphon string has been providing optimum production rate improvement, while in term of the slugging flow condition will still be occurred at any given cases due to very low well’s productivity, even though in a full length of siphon string case, shows reduction in slug flow severity, by having better liquid hold up fraction, but the installation cost will be challenging. Therefore, well’s productivity improvement program is recommended to be evaluated for the better B-X well production performance.

Keywords: Gas Lift Optimization; Siphon String; Flow Regime

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Sumur B-X adalah sumur produksi minyak di lapangan Bravo di area lepas pantai Natuna dengan completion pada lapisan IBS menggunakan tubing ukuran 5-1/2 inch. Namun berjalannya waktu, sumur mengalami penurunan produksi karena reservoir performance yang sudah turun, dan juga terdapat masalah dari performance produksi sumur yang tidak optimum, serta kondisi aliran yang tidak stabil (slugging). Pada tahun 2020, Siphon String installation diterapkan pada sumur B-X sebagai pilot program dengan maksud memberikan titik injeksi gas lift yang lebih dalam untuk meningkatkan gas lift performance, serta secara parsial memberikan ukuran tubing yang lebih kecil pada kedalaman dan panjang tertentu, agar dapat mengurangi kondisi aliran yang tidak stabil (slugging) tersebut. Tujuan dari analisis ini, adalah untuk mengevaluasi efektivitas penerapan teknologi siphon string pada sumur B-X, ditinjau dari kinerja produksi dan pola alirannya di dalam tubing. Secara teknis, simulator Model Sumur digunakan dalam mengevaluasi beberapa kasus sensitivitas, yaitu: (1) Titik injeksi gas lift yang lebih dalam, (2) Panjang siphon string, (3) Laju injeksi gas lift, dan (4) Produktivitas sumur (PI). Hasil perhitungan kasus sensitivitas dengan simulasi Model Sumur menunjukkan bahwa kedalaman siphon string saat ini telah memberikan peningkatan tingkat produksi yang optimal, sedangkan dalam hal kondisi aliran slugging masih akan terjadi pada kasus tertentu karena produktivitas sumur yang sangat rendah, meskipun dalam asumsi kasus panjang siphon string maksimum, menunjukkan pengurangan masalah aliran slugging karena memiliki fraksi liquid hold up yang lebih baik, namun biaya instalasi akan menjadi lebih besar. Oleh karena itu, program untuk meningkatkan produktivitas sumur perlu di evaluasi untuk sumur B-X di masa yang akan datang.

Kata-kata kunci: Optimasi Gas Lift; Siphon String; Rejim Aliran

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I. INTRODUCTION
The radial model in single-well simulation aims to predict changes in reservoir fluid flow from the reservoir to well within a certain time which is influenced by the characteristics of the fluid and reservoir rock itself. Changes can be seen from the parameters of flow rate, pressure, and cumulative production as well as the value of GOR in the well after being produced at a certain time. The pressure change that occurs in the reservoir when production is carried out is part of the transient phase. Transient flow that occurs in a well is influenced by the
properties of rocks and fluid with a pressure decline effect. In this study, changes in the value of the well radius were carried out, then observed performance changes in the well.

Application of gas lift system in Bravo field in offshore area of Natuna sea, has been implemented since the initial of field development in 1992. B-X well as one of the oil well which is using gas lift as its artificial lifting method, in 2007 was conducted a workaround program for a zone shifting, from the high production rate zone (due to watered out) to the lower production rate zone without change its 5-1/2 inch tubing size.

However, after a long production period from 2007 to 2019, the well’s production rate decreased from the level of 1,100 BFPD down to about 220 BFPD, which is mainly due to natural reservoir pressure depletion. It also experienced having sub-optimum gas lift performance (lower injection pressure and higher injection rate). Un-stable production rate or slugging flow was also observed. Figure I shows the fluctuation of the flowing tubing head pressure (THP), as well as fluctuation of production rate at the test separator (TS).

Steps to evaluate the well’s problem were conducted, included a Flowing Gradient Survey (FGS) to confirm the suspected problem of downhole multi point gas lift injection. Therefore, in the early of 2020, Siphon String (2.25 inch ID tubing) with a pack off method has been installed (Figure 2) to provide a deeper gas lift injection from previously at 5045 to 5217 ftMD, in conjunction with the Gas Lift Valve Change Out (GLVCO) program to replace the leaking valves (passing unloader and dummy valves above the orifice valve). The extended length of siphon string about 240 ft was intended to provide a partial velocity string impact in attempt to reduce the slugging flow problem.

Post of the siphon string installation, the well’s production improved from 220 BFPD to about 420 BFPD, with 25% water cut. This improvement as a result of the deeper gas lift injection and no more multipoint injection issue. However, the slugging flow condition is still exist, just slightly reduced as observed from the well performance monitoring.

This paper is intended to review the effectiveness of the siphon string by simulate some calculations using a Well Model against several cases, i.e, depth of siphon string as a function of gas lift’s point of injection, length of siphon string as a function to reduce flow regime problem (slugging), gas lift injection rate for production improvement review, and well’s productivity (PI) to see its impact to the flow pattern inside the tubing.

II. LITERATURE STUDY

Problems with the gas lift system are usually associated with three following main areas as described in Figure 3 [1]:

1. Inlet problems are related to gas lift injection pressure and rate.
2. Outlet problems are related to surface facility in regard to back pressure to the well [2].
3. Downhole problems are related to gas lift valves issues, such as passing gas lift valve due to stem mechanical failure or erosional wash out across the valve’s stem/seat [3].

Evaluation to the liquid flow condition that found un-stable (sluggling), Haidan Lu, suggested the following criterias to ensure the stable flow [4]:

- Sufficient formation inflow
- Smaller tubing size/hydraulic flowing cross section to increase the in-situ gas velocity
- Small enough orifice size for the operation valve to increase the pressure drop across the orifice to maintain critical flow
- Sufficient gas injection rate
- Operating valve at the deepest injection point
- Constant supplied gas rate from the surface compressor station

General practices to mitigate the slugging flow condition is to choke back the well to increase the backpressure. But this is not a universal solution to address all the severe slugging issues, as the physics initiating the slugging are different. Also, excessively choking the well could counteract the goal of boosting the production performance. Identifying the root causes for the severe slugging behavior provides guidance on developing appropriate plan to prevent any further disturbance to the production system [4, 5].

Taitel-Dukler developed a flow regime map for the vertical flow up of gas-liquid system (Figure 4), and the flow regime depends on the superficial liquid velocity (Vsl) and superficial gas velocity (Vsg) [6, 7].

Superficial velocity is velocity of the fluid passing through in a pipe, i.e. the volumetric flow rate of fluid, divided by the cross section area of the pipe:

\[ V = \frac{Q}{A} \]  \hspace{1cm} (1)

Where,

\( V \) = volumetric flowrate, m/s

\( Q \) = volumetric flow, m³/s

\( A \) = area of cross section, m²

In regard to the flow regime in multiphase flow, the amount of the pipe occupied by a phase is often different from its proportion of the total volumetric flow rate. This is due to density difference between phases. The density difference causes dense phase to slip down in an upward flow (i.e., the lighter phase moves faster than the denser phase) both in vertical
and inclined pipes. Because of this, the in situ volume fraction of the denser phase will be greater than the input volume fraction of the denser phase (i.e., the denser phase is “hold up” in the pipe relative to the lighter phase). This liquid hold-up ($y_L$), is defined by [6-11]:

$$y_L = \frac{V_L}{V}$$  

(2)

Where,

$V_L$ = Volume of Liquid, $ft^3$

$V$ = Volume of Tubing or Pipe, $ft^3$

III. METHODOLOGY

The method used to perform analysis or calculations related to the optimization of gas lift well production, and analysis of fluid flow patterns in the tubing (flow regime) using a Well Model (Prosper). Figure 5 is the flow chart of the methodology that is carried out.

By utilizing the Well Model (Prosper), several cases are generated to investigate the impact of siphon string depth (gas lift point of injection depth), length of siphon string, gas lift injection rate and well’s productivity, to the well’s production performance and flow regime inside the tubing.

IV. RESULTS AND DISCUSSION

4.1. Before Siphon String Installation

The sub-optimum gas lift problem of B-X well before siphon string installation, was associated with lower gas lift injection pressure and higher injection rate than it should be as per design, which was suspected due to having a downhole multi point gas lift injection. This condition was confirmed by the Flowing Gradient Survey (FGS) for both downhole pressure and temperature. Multi point injection was detected came from the installed dummy and unloader valves, as can be seen by cooling effect from the temperature gradient survey at the gas lift valves depth above the point of injection. Figure 6 depicts this multi pointing of gas lift injection.

Therefore in the B-X well case, siphon string installation was intended to change out the leaking GL valves, provide deeper injection, and install partial insert string installation (siphon string, 2.25 inch ID), to optimize the well’s production, and also reducing slugging flow condition.

In actual, flow regime analysis was not conducted before the siphon string installation, but here using Well Model calculation, clearly the slug flow was identified at the whole tubing section from the bottom up to the wellhead. Note that the actual production rate was very low (220 BFPD) compare to the installed 5-1/2 inch tubing. Table-1 shows the calculated liquid hold up and flow regime indicates severe liquid hold-up (very low liquid fraction) at the lower tubing depth section 1751 ftMD. Figure 7 shows the plot of liquid hold-up against the installed tubing depth.

4.2. After Siphon String Installation

After the siphon string installation as depicted in Figure 2, the gas lift point of injection (POI) is deepened 172 ft, from 5045 ftMD to 5217 ftMD. The well’s performance was then improved almost double from 220 BFPD to about 420-440 BFPD. Figure 8 is the IPR vs VLP after siphon string installation.

4.2.1. IPR-VLP Matching

Prior well performance analysis, after a siphon string installed, it was required to match the actual production performance with the Well Model (Prosper) as depicted in Figure 8. VLP correlation will be the first parameter to be matched or closely matched prior to do further analysis with the model. Figure 9, shows that the closest match is using correlation provided by Prosper Well Model, i.e., Petex-2 correlation.

4.2.2. Hold-Up Analysis

After the siphon string has been installed and the POI of gas lift is deepened, the slugging flow still exists although it is less severity, as can be observed from the fluctuation of production rate at the test separator. Therefore, from the Well Model, liquid hold up calculation along the production tubing is derived as shown in Figure 10 and Table 2. The model’s calculation shows the fraction of liquid hold up is better (higher) than the condition before siphon string installation.

In the Table 2, the liquid hold up fractions at the siphon string section are improved but getting worst again as it flows through the bigger tubing size (5-1/2 inch OD or 4.89 inch ID).

4.2.3. Case-1: Sensitivity to POI Depth

Sensitivity cases to the deeper gas lift POI (point of injection) is sentized to the deeper point that can be achieved by siphon string with the existing tubing installation profiles. The smallest ID of the installed 5-1/2” tubing is at a landing nipple profile (4.313 inch) at depth of 5419 ft MD, where the pack off equipment will not be able to pass through. So, based on the Traverse Gradient calculation with the Well Model, deepening POI from 5217’ MD (current siphon string depth) to 5419’ MD (additional 202 ft MD or 115 ft TVD deeper) generates liquid hold up calculations as listed in Table 3, whereas the fraction of liquid hold up at the wellhead improved from 0.0676 become 0.2247 (after siphon string), meaning less severity of slugging flow.

The plot of the liquid hold up can be seen in the Figure 11, which has higher liquid hold-up value if it is compared to the existing siphon string depth But
in term of production rate, this deeper POI and siphon string depth, will not give production rate improvement, as depicted in Figure 12.

4.2.4. Case-2: Sensitivity to the Length of Siphon String

This case is designed to see the impact on the siphon string length from the existing POI depth at 5217 ftMD to the highest depth possible at just below the SCSSV depth, i.e., 581 ftMD. The result of the Well Model’s calculation demonstrates better liquid hold up or higher hold up fraction numbers along the tubing pipe, but no reduction with the production rate. Table 4 and Figure 13 depicted these case calculations.

4.2.5. Case-3: Sensitivity to GL Injection Rate

Sensitivity to the gas lift injection rate is also carried out to see whether with the current POI depth, (at 5217 ftMD), is still possible to optimize the production of B-X well. The sensitivity is starting from the actual condition of 1.3 MMSCFD, then 1.8, 2.3 and 2.8 MMSCFD.

From this case-3 simulation, did not give a significant change in production, namely only 2 BFPD (from 419 BFPD to 421 BFPD). Figure 14 is IPR-VLP plots of this case.

4.2.6. Case-4: Sensitivity to the Well’s Productivity

Evaluation of the well production rate which is influenced by the well’s PI (productivity index) is carried out to find out whether the assumption of an increase in PI, namely with higher production rate, can provide better flow pattern. This is also related to the previous literature review, where inflow performance as a representation of PI can affect the stability of the flow pattern in gas lift wells. Or is it necessary to improve the inflow performance of B-X well.

For this case-4, the assumption given for the PI is two to three fold the current well’s PI of 1.9 BFPD/psi. So that the input data into the Well Model is to calculate the liquid hold up with the assumption that the PI is 1.9, 2.8 and 5.7 BFPD/psi.

The results of the calculation of the flow pattern against some of these PI assumptions can be seen in Table 5, and the plot in Figure 15. Liquid hold up becomes larger on the assumption that the PI is two and three times larger, but the slugging flow pattern is still detected from the calculation.

Table 6 summarizes the simulations or calculation derived from cases 1-4 as above.

IV. CONCLUSIONS

This analysis of siphon string installation in B-X well, which is based on several sensitivity cases calculations, provides several conclusions:

1. Siphon string installation in B-X well which the reservoir has already depleted can provide more
downhole pressure drawdown through deeper point of gas lift injection (172 ft deeper, from 5045 ftMD to 5217 ftMD), and therefore the wells’ production can be improved.

2. Slugging flow condition still exist because only partial depth of siphon string length is installed, i.e., 240 ft versus the total 5-1/2 inch tubing length of 6262 ftMD (4687 ftVTD), but the slug flow severity is less, as liquid hold-up fraction can be improved.

3. Case simulation to the deeper gas lift’s POI (case-1), provides better liquid hold-up fraction which means less slugging flow is expected. However, not impacted to production rate increase, as very marginal pressure drawdown can be created.

4. Case simulation to the longest siphon string length (case-2), provides much better liquid hold up fraction, and marginal production increase, but this will need further economic feasibility, since significant longer siphon string gives consequences of higher installation cost.

5. Case simulation to gas lift injection rate (case-3), provides almost no production improvement, and therefore the current injection rate is optimum already.

6. Case simulation to the well’s PI demonstrates that the higher production rate will give better liquid hold up fraction or less slugging, and therefore evaluation to improve PI is recommended to be conducted.

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Figure 1. Real Time Plot of Well Performance Monitoring

Figure 2. Siphon String Installation
Figure 3. Gas Lift System Problems Area, Mazin Zein1 (2000)

Figure 4. Flow Pattern Map, Taitel (1987)
Figure 5. Flow Chart of the Methodology

Figure 6. Flowing Gradient - Temperature Survey
Table 1. Traverse Calculation Result – Before Siphon String Installation

| Label     | MD (feet) | TVD (feet) | Pressure (psig) | Liquid Holdup | Flow Regime | VsL (m/sec) | Vsg (m/sec) |
|-----------|-----------|------------|-----------------|---------------|-------------|-------------|-------------|
| Hanger    | 0         | 0          | 148.0           |               | Wellhead    |             |             |
| 5 1/2"    | 95        | 95         | 151.1           | 0.0044        | Churn       | 0.04        | 8.10        |
| 5 1/2"    | 267       | 267        | 156.8           | 0.0045        | Churn       | 0.04        | 8.05        |
| 5 1/2"    | 440       | 440        | 162.5           | 0.0046        | Churn       | 0.04        | 7.93        |
| 5 1/2"    | 612       | 612        | 168.4           | 0.0047        | Churn       | 0.04        | 7.81        |
|           | 612       | 612        | 168.4           |               |             |             |             |
| 5-1/2"    | 631       | 631        | 169.2           | 0.0047        | Churn       | 0.04        | 7.74        |
| 5-1/2"    | 825       | 824        | 176.0           | 0.0048        | Churn       | 0.04        | 7.66        |
| 5-1/2"    | 1000      | 998        | 182.3           | 0.0049        | Churn       | 0.04        | 7.54        |
| 5-1/2"    | 1397      | 1387       | 197.3           | 0.0053        | Churn       | 0.04        | 7.10        |
| 5-1/2"    | 1596      | 1581       | 205.6           | 0.0055        | Churn       | 0.04        | 6.85        |
| 5-1/2"    | 2046      | 1996       | 224.2           | 0.1244        | Slug        | 0.04        | 6.29        |
| 5-1/2"    | 2156      | 2098       | 228.9           | 0.1258        | Slug        | 0.04        | 6.17        |
| 5-1/2"    | 2389      | 2277       | 237.3           | 0.1277        | Slug        | 0.04        | 6.02        |
| 5-1/2"    | 2621      | 2456       | 245.9           | 0.1302        | Slug        | 0.04        | 5.83        |
| 5-1/2"    | 2854      | 2634       | 254.6           | 0.1326        | Slug        | 0.04        | 5.65        |
| 5-1/2"    | 3086      | 2813       | 263.4           | 0.1351        | Slug        | 0.04        | 5.47        |
| 5-1/2"    | 3131      | 2847       | 265.1           | 0.1366        | Slug        | 0.04        | 5.37        |
| 5-1/2"    | 3175      | 2881       | 266.8           | 0.1370        | Slug        | 0.04        | 5.34        |
| 5-1/2"    | 3190      | 2892       | 267.4           | 0.1373        | Slug        | 0.04        | 5.32        |
| 5-1/2"    | 3205      | 2903       | 267.9           | 0.1375        | Slug        | 0.04        | 5.31        |
| 5-1/2"    | 3407      | 3055       | 275.7           | 0.1386        | Slug        | 0.04        | 5.24        |
| 5-1/2"    | 3608      | 3207       | 283.5           | 0.1408        | Slug        | 0.04        | 5.11        |
| 5-1/2"    | 3810      | 3359       | 291.5           | 0.1429        | Slug        | 0.04        | 4.98        |
| 5-1/2"    | 4240      | 3686       | 308.9           | 0.1485        | Slug        | 0.04        | 4.66        |
| 5-1/2"    | 4255      | 3697       | 309.6           | 0.1487        | Slug        | 0.04        | 4.66        |
| 5-1/2"    | 4461      | 3853       | 318.1           | 0.1499        | Slug        | 0.04        | 4.59        |
| 5-1/2"    | 4667      | 4009       | 326.8           | 0.1522        | Slug        | 0.04        | 4.48        |
| 5-1/2"    | 5038      | 4245       | 340.2           | 0.1565        | Slug        | 0.04        | 4.27        |
| POI       | 5046      | 4250       | 340.4           | 0.1563        | Slug        | 0.04        | 4.28        |
Figure 7. Liquid Holdup before Siphon String Installation

Figure 8. VLP-IPR after Siphon String Installation
Figure 9. VLP Correlation Matching After Siphon String

Figure 10. Liquid Hold Up after Siphon String Installation, POI at 5217 ft MD
Table 2. Gradient Traverse of Liquid Hold Up After Siphon String Installation – POI 5217"

| Label  | MD (feet) | TVD (feet) | Pressure (psig) | Liquid Holdup | Flow Regime | VsL (m/sec) | Vsg (m/sec) |
|--------|-----------|------------|----------------|---------------|-------------|------------|-------------|
| Hanger | 0         | 0          | 148            | WellHead      |             |            |             |
| 5 1/2" | 95        | 95         | 178            | 0.0676        | Slug        | 0.10       | 4.79        |
| 5 1/2" | 334       | 334        | 185            | 0.0666        | Slug        | 0.10       | 4.77        |
| 5 1/2" | 573       | 573        | 192            |              | Slug        | 0.10       | 4.72        |
|         | 573       | 573        | 193            |              | SSSV        | 0.11       | 5.40        |
| 5 1/2" | 612       | 612        | 194            | 0.0658        | Slug        | 0.10       | 4.69        |
| 5 1/2" | 1000      | 998        | 205            | 0.0654        | Slug        | 0.10       | 4.63        |
| 5 1/2" | 1751      | 1724       | 227            | 0.0690        | Slug        | 0.10       | 4.26        |
| 5 1/2" | 1905      | 1866       | 232            | 0.0697        | Slug        | 0.10       | 4.19        |
| 5 1/2" | 2621      | 2456       | 251            | 0.0728        | Slug        | 0.10       | 3.92        |
| 5 1/2" | 2854      | 2634       | 257            | 0.0736        | Slug        | 0.10       | 3.84        |
| 5 1/2" | 3086      | 2813       | 263            | 0.0745        | Slug        | 0.10       | 3.76        |
| 5 1/2" | 3175      | 2881       | 265            | 0.0752        | Slug        | 0.10       | 3.70        |
| 5 1/2" | 3608      | 3207       | 276            | 0.0764        | Slug        | 0.10       | 3.59        |
| 5 1/2" | 3810      | 3359       | 281            | 0.0772        | Slug        | 0.10       | 3.53        |
| 5 1/2" | 3820      | 3367       | 282            | 0.0775        | Slug        | 0.10       | 3.50        |
| 5 1/2" | 3829      | 3374       | 282            | 0.0776        | Slug        | 0.10       | 3.49        |
| 5 1/2" | 4027      | 3524       | 287            | 0.0779        | Slug        | 0.10       | 3.46        |
| 5 1/2" | 4225      | 3674       | 292            | 0.0786        | Slug        | 0.10       | 3.41        |
| 5 1/2" | 4667      | 4009       | 304            | 0.0801        | Slug        | 0.10       | 3.28        |
| 5 1/2" | 4822      | 4108       | 308            | 0.0809        | Slug        | 0.10       | 3.24        |
| insert | 4978      | 4207       | 312            | 0.1838        | Slug        | 0.48       | 15.08       |
| insert | 5004      | 4224       | 314            | 0.1840        | Slug        | 0.48       | 15.04       |
| insert | 5030      | 4240       | 315            | 0.1842        | Slug        | 0.48       | 14.95       |
| insert | 5045      | 4250       | 316            | 0.1841        | Slug        | 0.48       | 14.96       |
| insert | 5060      | 4259       | 317            | 0.1837        | Slug        | 0.48       | 15.05       |
| insert | 5130      | 4304       | 322            | 0.1837        | Slug        | 0.48       | 14.99       |
| insert | 5200      | 4348       | 327            | 0.1842        | Slug        | 0.48       | 14.80       |
| insert | 5209      | 4354       | 328            | 0.1845        | Slug        | 0.48       | 14.69       |
| POI    | 5217      | 4359       | 328            | 0.1845        | Slug        | 0.48       | 14.65       |
Table 3. Gradient Traverse Liquid Hold Up of Case-1 – POI Deeper to 5419 ftMD

| Label     | MD (feet) | TVD (feet) | Pressure (psig) | Liquid Holdup | Flow Regime | VsL (m/sec) | Vsg (m/sec) |
|-----------|-----------|------------|----------------|---------------|-------------|-------------|-------------|
| Hanger    | 0         | 0          | 148            |               | WellHead    |             |             |
| 5 1/2"    | 95        | 95         | 152            | 0.2247        | Slug        | 0.09        | 2.28        |
| 5 1/2"    | 334       | 334        | 161            | 0.2264        | Slug        | 0.09        | 2.25        |
| 5 1/2"    | 573       | 573        | 170            | 0.2305        | Slug        | 0.09        | 2.19        |
| 5 1/2"    | 612       | 612        | 171            | 0.2328        | Slug        | 0.09        | 2.15        |
| 5 1/2"    | 1000      | 998        | 186            | 0.2377        | Slug        | 0.09        | 2.09        |
| 5 1/2"    | 1935      | 1894       | 223            | 0.2638        | Slug        | 0.10        | 1.76        |
| 5 1/2"    | 2156      | 2098       | 232            | 0.2682        | Slug        | 0.10        | 1.71        |
| 5 1/2"    | 2389      | 2277       | 240            | 0.2722        | Slug        | 0.10        | 1.66        |
| 5 1/2"    | 2621      | 2456       | 248            | 0.2772        | Slug        | 0.10        | 1.61        |
| 5 1/2"    | 2854      | 2634       | 256            | 0.2823        | Slug        | 0.10        | 1.56        |
| 5 1/2"    | 3205      | 2903       | 268            | 0.2922        | Slug        | 0.10        | 1.48        |
| 5 1/2"    | 3407      | 3055       | 276            | 0.2945        | Slug        | 0.10        | 1.46        |
| 5 1/2"    | 3608      | 3207       | 283            | 0.2989        | Slug        | 0.10        | 1.42        |
| 5 1/2"    | 3810      | 3359       | 290            | 0.3033        | Slug        | 0.10        | 1.38        |
| 5 1/2"    | 4255      | 3697       | 307            | 0.3150        | Slug        | 0.10        | 1.30        |
| 5 1/2"    | 4461      | 3853       | 315            | 0.3174        | Slug        | 0.10        | 1.28        |
| 5 1/2"    | 4822      | 4108       | 328            | 0.3258        | Slug        | 0.10        | 1.22        |
| 5 1/2"    | 4977      | 4206       | 334            | 0.3287        | Slug        | 0.10        | 1.20        |
| insert    | 4978      | 4207       | 334            | 0.1371        | Slug        | 0.46        | 5.65        |
| insert    | 5060      | 4259       | 336            | 0.1354        | Slug        | 0.46        | 5.70        |
| insert    | 5130      | 4304       | 337            | 0.1348        | Slug        | 0.46        | 5.72        |
| insert    | 5224      | 4363       | 340            | 0.1354        | Slug        | 0.46        | 5.68        |
| insert    | 5230      | 4367       | 340            | 0.1355        | Slug        | 0.46        | 5.68        |
| insert    | 5280      | 4399       | 341            | 0.1357        | Slug        | 0.46        | 5.67        |
| insert    | 5330      | 4431       | 342            | 0.1361        | Slug        | 0.46        | 5.65        |
| insert    | 5389      | 4468       | 344            | 0.1366        | Slug        | 0.46        | 5.62        |
| insert    | 5418      | 4486       | 344            | 0.1370        | Slug        | 0.46        | 5.60        |
| POI       | 5419      | 4487       | 344            | 0.1370        | Slug        | 0.46        | 5.60        |
Figure 11. Case-1: Liquid Hold Up with Deeper POI at 5419 ftMD

Figure 12. Production Rate between Existing POI (5217 ftMD) vs Deeper POI (5419 ftMD)
### Table 4. Gradient Traverse Liquid Hold Up of Case-2 – Siphon String up to 581 ftMD

| Label   | MD (feet) | TVD (feet) | Pressure (psig) | Liquid Holdup | Flow Regime | VsL (m/sec) | Vsg (m/sec) |
|---------|-----------|------------|----------------|---------------|-------------|-------------|-------------|
| Hanger  | 0         | 0          | 148            | 0.2666        | Slug        | 0.07        | 1.65        |
| 5 1/2"  | 95        | 95         | 155            | 0.2738        | Slug        | 0.07        | 1.58        |
| 5 1/2"  | 334       | 334        | 172            | 0.2867        | Slug        | 0.07        | 1.47        |
| SSSV    | 573       | 573        | 191            | 0.2867        | Slug        | 0.08        | 1.63        |
| insert  | 581       | 580        | 191            | 0.1134        | Slug        | 0.33        | 6.69        |
| insert  | 650       | 650        | 194            | 0.1135        | Slug        | 0.33        | 6.67        |
| insert  | 825       | 824        | 200            | 0.1136        | Slug        | 0.33        | 6.62        |
| insert  | 1596      | 1581       | 227            | 0.1206        | Slug        | 0.33        | 6.04        |
| insert  | 1935      | 1894       | 239            | 0.1261        | Slug        | 0.33        | 5.68        |
| insert  | 2046      | 1996       | 243            | 0.1269        | Slug        | 0.33        | 5.64        |
| insert  | 2156      | 2098       | 247            | 0.1283        | Slug        | 0.33        | 5.55        |
| insert  | 2854      | 2634       | 269            | 0.1356        | Slug        | 0.34        | 5.15        |
| insert  | 3086      | 2813       | 277            | 0.1382        | Slug        | 0.34        | 5.02        |
| insert  | 3205      | 2903       | 281            | 0.1407        | Slug        | 0.34        | 4.90        |
| insert  | 3407      | 3055       | 287            | 0.1420        | Slug        | 0.34        | 4.84        |
| insert  | 3608      | 3207       | 294            | 0.1443        | Slug        | 0.34        | 4.73        |
| insert  | 3829      | 3374       | 302            | 0.1481        | Slug        | 0.34        | 4.57        |
| insert  | 4027      | 3524       | 308            | 0.1493        | Slug        | 0.34        | 4.52        |
| insert  | 4461      | 3853       | 324            | 0.1543        | Slug        | 0.34        | 4.32        |
| insert  | 4667      | 4009       | 331            | 0.1569        | Slug        | 0.34        | 4.22        |
| insert  | 4849      | 4125       | 337            | 0.1591        | Slug        | 0.34        | 4.14        |
| insert  | 5045      | 4250       | 343            | 0.1612        | Slug        | 0.34        | 4.06        |
| insert  | 5060      | 4259       | 343            | 0.1597        | Slug        | 0.34        | 4.09        |
| insert  | 5130      | 4304       | 345            | 0.1591        | Slug        | 0.34        | 4.10        |
| insert  | 5209      | 4354       | 348            | 0.1598        | Slug        | 0.34        | 4.08        |
| insert  | 5217      | 4359       | 348            | 0.1600        | Slug        | 0.34        | 4.07        |
Figure 13. Case-2: Liquid Hold-Up-Siphon String Depth up to 581 ftMD

Figure 14. Case-3: Sensitivity to GL Injection Rate
Table 5. Gradient Traverse Liquid Hold Up Case-4, Sensitivity to PI

| Label | MD ft | PI = 1.9 |   | PI = 3.8 |   | PI = 5.7 |
|-------|-------|----------|---|----------|---|----------|
|       |       | Holdup   | Regime | Holdup   | Regime | Holdup   | Regime |
| Hanger | 0     | WellHead | Slug   | 6.85     | Slug   | 8.30     | Slug   |
| 5 1/2” | 47    |          |        |          |        |          |        |
| 5 1/2” | 95    | 4.46     | Slug   | 6.80     | Slug   | 8.25     | Slug   |
| 5 1/2” | 334   | 4.30     | Slug   | 6.71     | Slug   | 8.19     | Slug   |
| SSSV   | 573   | 4.24     | Slug   | 6.69     | Slug   | 8.20     | Slug   |
| 5 1/2” | 612   | 4.20     | Slug   | 6.68     | Slug   | 8.21     | Slug   |
| 5 1/2” | 1000  | 4.13     | Slug   | 6.67     | Slug   | 8.25     | Slug   |
| 5 1/2” | 1751  | 4.36     | Slug   | 7.10     | Slug   | 8.78     | Slug   |
| 5 1/2” | 1905  | 4.41     | Slug   | 7.19     | Slug   | 8.88     | Slug   |
| 5 1/2” | 2046  | 4.45     | Slug   | 7.26     | Slug   | 8.97     | Slug   |
| 5 1/2” | 2156  | 4.48     | Slug   | 7.32     | Slug   | 9.04     | Slug   |
| 5 1/2” | 2389  | 4.55     | Slug   | 7.44     | Slug   | 9.18     | Slug   |
| 5 1/2” | 2621  | 4.61     | Slug   | 7.54     | Slug   | 9.29     | Slug   |
| 5 1/2” | 2854  | 4.67     | Slug   | 7.64     | Slug   | 9.41     | Slug   |
| 5 1/2” | 3086  | 4.73     | Slug   | 7.74     | Slug   | 9.53     | Slug   |
| 5 1/2” | 3131  | 4.77     | Slug   | 7.80     | Slug   | 9.60     | Slug   |
| 5 1/2” | 3190  | 4.78     | Slug   | 7.83     | Slug   | 9.63     | Slug   |
| 5 1/2” | 3205  | 4.78     | Slug   | 7.83     | Slug   | 9.63     | Slug   |
| 5 1/2” | 3829  | 4.94     | Slug   | 8.09     | Slug   | 9.93     | Slug   |
| 5 1/2” | 4027  | 4.97     | Slug   | 8.14     | Slug   | 9.98     | Slug   |
| 5 1/2” | 4225  | 5.01     | Slug   | 8.21     | Slug   | 10.07    | Slug   |
| 5 1/2” | 4667  | 5.12     | Slug   | 8.39     | Slug   | 10.27    | Slug   |
| 5 1/2” | 4822  | 5.18     | Slug   | 8.48     | Slug   | 10.37    | Slug   |
| 5 1/2” | 4977  | 5.21     | Slug   | 8.53     | Slug   | 10.43    | Slug   |
| insert | 4978  | 15.58    | Slug   | 18.73    | Slug   | 20.86    | Slug   |
| insert | 5004  | 15.60    | Slug   | 18.75    | Slug   | 20.88    | Slug   |
| insert | 5030  | 15.62    | Slug   | 18.78    | Slug   | 20.93    | Slug   |
| insert | 5045  | 15.61    | Slug   | 18.77    | Slug   | 20.92    | Slug   |
| insert | 5060  | 15.57    | Slug   | 18.73    | Slug   | 20.87    | Slug   |
| insert | 5130  | 15.57    | Slug   | 18.74    | Slug   | 20.89    | Slug   |
| insert | 5209  | 15.65    | Slug   | 18.83    | Slug   | 21.05    | Slug   |
| insert | 5217  | 15.66    | Slug   | 18.84    | Slug   | 21.07    | Slug   |
Table 5. Cases Summary

| Base and Case | Length of Siphon, ft | Liquid Hold up, % | Flow Regime | BFPD |
|---------------|----------------------|-------------------|-------------|------|
| **Before** Siphon String application: POI at 5046 ft-MD | 0 | 0.44 - 15.5 | Churn - Slug | 220 |
| **After** Siphon String Application (actual current condition): POI at 5217 ft-MD, Length of Siphon String: 4977-5217 ft | 240 | 6.76 - 18.4 | Slug | 419 |
| **Case-1**: POI deepening from 5217 to 5419 ft-MD (+202 ft) | 442 | 13.7 - 32.8 | Slug | 412 |
| **Case-2**: Siphon String Max Length from 518 - 5217 ft-MD. Total Siphon string length = 4699 ft | 4699 | 26.6 - 15.9 | Slug | 459 |
| **Case-3**: Gas Lift injection rate sensitivity. Siphon string length & POI remain as the actual/current condition | 240 | 6.7 - 18.4 (GL=1.3) | Slug | 419 (GL=1.3) |
| | | 1.5 - 3.7 (GL=1.8) | Slug | 421 (GL=1.8) |
| | | 1.3 - 3.1 (GL=2.3) | Churn - Slug | 421 (GL=2.3) |
| | | 0.7 - 1.1 (GL=2.8) | Churn - Slug | 421 (GL=2.8) |
| **Case-4**: Sensitivity to the well’s productivity (PI). Siphon string length & POI remain as the actual/current condition | 240 | 4.5 - 15.7 (PI=1.9) | Slug | 419 (PI=1.9) |
| | | 6.8 - 18.8 (PI=3.8) | Slug | 697 (PI=3.8) |
| | | 8.3 - 21.1 (PI=5.7) | Slug | 912 (PI=5.7) |

Figure 15. Case-4: Sensitivity to Productivity Index – Liquid Hold up Plot