A CASE STUDY OF MULTI-STAGE GAS SEPARATION COMBINED WITH VENTED, FORCED GAS SEPARATION - SETTING A PERFORMANCE BENCHMARK

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INTRODUCTION

It is now well-known throughout the Permian Basin as well as many other basins that typical means of gas separation techniques just do not cut it if you desire exceptional performance. To make matters even worse, what most would now categorize as more aggressive or innovative methods to deal with these troublesome separation conditions are still overall and for the most part, unable to yield desired results at the highest level and certainly not with the consistency everyone wants to see.

After much observation and analysis of how effective our own advanced separation techniques applied are and looking much deeper too at all of what else is currently being done in the gas separation realm, we were prompted to think more freely about a whole new and innovative approach with which to attack this difficult problem and finally yield the desired results we all want with extreme consistency.

Background and the General Solution Proposed

Having no shortage of data with regards to the benefits to gas separation quality achievable by putting specific emphasis on slowing down the fluid intake velocity withing the separation "dead space" to a pace of 2.0 inch/second or less (for reference, outdated and historic design protocol calls for 6.0 inch/second and the more recent industry agreeable minimum for the Permian is ≤4.0 inch/second), we found there to be a diminishing return with drawdown pace being utilized between ~2.0-3.0 inch/second or less in the most common Permian producing horizons.

What that means in the most simple terms is this: if you're wells have not already achieved an exceptional level of separation quality and pump fillage (I would suggest +95% daily avg fillage as a superior benchmark) AND also producing the desired volume of fluids you target when ingesting at a the very slow pace of 2.0-3.0 inch/second or less, then you better start looking for another solution because you'll never get where you want to be without building such a huge capacity separator, if that's even a potential option to expand the capacity (most separators cannot even offer this), and it will quickly then become uneconomic or certainly much less economic depending on how much potential production you are giving up and/or how much the separator may end up costing.

As that fact was becoming more and more evident, it was a huge factor in pushing for a completely new style of attack and, thus, the concept of putting 4 stages of separation, consisting of 3 different types, all in series and achieving greater results from the system as a whole versus the sum of the parts, was born. Also important items to remember: it's packer-less, built to last, completely modular, and easily/inexpensively serviced.

Bottom-hole Assembly Details and Function Described

The three different types of separation applied are the following: 1) poor-boy, labyrinth path separation in the 1st and 3rd segments, 2) a double-stacked spiral inducing "forced gas separation" with a dedicated vent annulus in the 2nd segment, and finally an advanced form of sand/solids separation in the 4th and final segment. See Figure 1 below for visual context regarding the assembly and how the 3 separation types are assembled.

From the outside profile alone, there is nothing that one would consider wildly different in the appearance of this separation unit when compared to what has been run by many others over many decades; the unique components and their functions that make for all the difference in performance are all unsuspectingly hidden inside the rugged and slick 3.5" OD body.

Inside the upper 3.5" OD separation housing is a very typically sized 1.0" nominal (aka 1.315" OD) stainless steel diptube, but there is one very interesting difference a skilled eye will notice when peering through the lower portions of the elongated intake slots of that upper housing and that is the upper and open-ended piece of 1.5" nominal (aka 1.9" OD) stainless steel tubing that encases the OD of the 1.0" inner tube in a concentric fashion. Also note that upper termination point of the 1.9" OD tube is located ABOVE the lowermost potential intake point for gassy fluids to enter the separator which is created by three holes drilled in the upper outer housing body and located several inches below the series of slots located above and that stretch nearly to the top end of the 3.5" upper outer tube body.

This is not typical for any separator and certainly not from a performance or "capacity" perspective in that the upper section with the larger 1.9" OD tube eats up some of the dead-space area in said upper separation housing, further with the termination point being located where it is that also reduces the dead-space length, but it's placement provides an absolutely necessary and vital function: that function is to serve as a dedicated gas ventilation annulus for all the free-gas captured and vented out the top end of the new and exceptionally unique "double-stacked spiral" located immediately below the bottom end of this upper outer separation housing.

The "double-stacked spiral" or "DVS" (aka double-vaned spiral) is encased within a very precisely machined housing to ultimately create a near gas-tight fit around the OD of the DVS which will help maximize efficiency in getting all the captured gas vented up and out of the system and without allowing the gas to be reintroduced to the fluid intake flowpath. See Figure 2 below for a visual example of the DVS section and the flowpaths generated there within (and can be fully reviewed in the US patent which has been allowed, but at this time has not been issues a formal Patent number):

The DVS is designed such that ingested fluids are pulled into the larger vane gap between the stacked-spirals and are spun centrifugally at a pace that generates enough outward spinning force to create a preferential accumulation of gas surrounding the OD of axial shaft yet is also focused towards the ID of the downward flowpath they are traveling around and down. The effort to "force" the entrained gases to separate from the gassy fluid mixture we have dubbed as "forced gas separation" since we are making the gas separate against it natural desire and will. The result is a newly accumulated slug of gas that ejects out the bottom of the DVS and into the top end of the lower 3.5" OD outer housing.

Upon the downstroke of the pumping unit, when fluid ingestion ceases, the gas slug has the opportunity to rise quickly upward, BUT instead of migrating upward against and through the entire and long gassy fluid column that likely exists in the dead-space of the upper separation housing, the slug of gas rises until it hits the underside of the top spiral in the spiral stack and rides along it's underside until it make a couple revolutions upward and is then "caught" between the gap created between the underside of the top DVS stacked-spiral and the top side of the bottom DVS stacked-spiral. The gas captured can then rise up freely and at whatever pace, slow or fast, that it desires until it flows upwards and out of the top discharge head of the DVS and into the gas vent annulus created between the inside of the 1.9" ID and the 1.315" OD. That gas vents upwards in it's own dedicated path, uninhibited by any downward flowing gassy fluid mix which would be the norm, and is then allowed to vent itself out the very top and termination point of the 1.9" tube which, again as noted previously, is placed well above the lowermost fluid intake point of the 3.5" slotted outer tube.

These unique functions are in stark comparison to all other forms of separation that have ever been constructed before and have clearly proven to provide exceptional and very measurably improved levels of separation performance attainable when compared to other separation techniques being applied today.

As previously noted, the fourth and final separation technique applied in series within this singular assembly is a true centrifugal, phase-separating sand & solids separator which incorporates an expendable "Erosion Tube (ET)," wrapping itself neatly around the OD of the sand spiral vanes.

This sand spiral design w/ the intertwined ET is very unique in that it provides the following functions (and can be fully reviewed in US patent #11,603,748): 1) the flatter and more continuous and lengthy spiral flowpath generated allows longer residence time throughout the unit to allow solids to be aggressively slung outward and more fully segregated from the likely solids laden fluid mixture that is passing through, 2) a "tighter" flowpath is applied with a smaller flowing cross-section such that a higher spinning force is applied to all the solids passing through beyond what is desirable for other more commonly used desander tools and this is totally allowable in this design because the spiral-wrapping ET constructed from hard and thick metal protects the desander mandrel from being damaged and possibly cut through, which could otherwise lead to dropping the tailpipe assembly in the hole, but also cold destroy the desander tool itself so the entirety would have to be replaced upon servicing. The ET is designed to be a sacrificial element and allows us to spin the fluids harder and get more effective solids mitigation with no risk increase, and finally 3) the use and placement of flow-restrictive sized fluid entry hole aligned with the bottom-most terminating point of the sand spiral blade allows a strategically proportioned amount of the total flowing fluid volume, yet not all of it, to be easily and smoothly ingested into the intake hole allowing the quickly sweeping solids to continue flowing in the circular and low-siding flow pattern while allowing that bit of fluid to depart cleanly from those spinning solids in effort to reduce the amount of total fluid that must then make the u-turn into the downward facing intake hole in the bottom facing end of the spiral. All of these small, but very effective and patented elements yield exceptional sand capturing capabilities leading to long runtimes and less wear on pump components, tubing, and rods.

Setting a Performance Benchmark and Outlining the Process to Prove Performance Achieved Well in Excess of that Benchmark from the Unit Described

Engineers like to ask, "how high of a GLR and/or GOR" can this or that separator handle and those with enough experience know that is a very loaded question and that requires a not so straightforward answer most of the time. You can have a situation where a well produces what I'd consider very low total fluid volume (i.e. 50-100 bfpd) and even in the event that well is producing a reasonable, but respectable 250 mcfd that is anywhere from 2500-5000:1 GLR and, of course, with a normal oil cut of 50% or even 25% that GOR skyrockets.

I find it best to ensure we know the whole situation at hand where total volumes and water or oil cut are clearly defined as well. Further, even a good stab at an average surface system pressure and what is a decent assumption for FBHP are just as important in knowing what you may come to expect from your gas separation selection.

Knowing some good benchmarks for you are helpful to know when things start to "unravel" for most if not all gas separation assemblies, and I'm going to suggest with a high certainty, there is definitely a tipping point most all operators in most all areas have defined as that line in the sand. The gas separator assembly described above in this paper is quite an anomaly, though.

We started with a strong effort being concerted to define just how effective the DVS spiral and it's ability to capture and vent gas really is. Knowing how gas separation design is generally accepted for the Permin Basin to follow the restricted <4.0 inch/sec drop velocity in the separator's dead-space to yield "acceptable" (not exceptional) separation performance, that squarely means you can only ingest ~34 bbls/d/sq.in. of dead-space cross-section and have a decent performing gas separator. This is one of the main reason's I believe many people over the past handful of years have grown prefer packer-type (ANNULAR) gas separators. You can slim down the body of the packer separator and that will yield you the most dead-space cross-section so that should certainly help things out and also that type of separator are rather easy to extend in length as well so you can add some decent residence time to the unit.

The problem for those units and essentially all other separation types is very simply that you will run out of wellbore cross-section at some point if you are shooting for very high volumes and in well conditions that yield very turbulent and foamy conditions where the gas tends to get highly entrained in the fluid mixture. This is the case for all separation types up until now except possibly a well-designed and performing multiple-stage limited-entry (MSLE) gas separator which is NOT prohibited by wellbore cross-section, BUT even that type of unit has limitation when slowing down the fluid intake velocity alone does not solve the separation issues fully and when the cost of a very large unit begins to have notable negative effect. Please recall, much of this was noted earlier in this paper above.

The separator assembly described herein would logically then only be able to perform at a high level or at least as well as other known best-performers in the same intake fluid velocity conditions. That would tend to really raise some suspicion as to the possible volume range that would then be handled by such a unit and still work very well. With the dead-space cross-section this 3.5" OD tool yields, there should only be ~208 bfpd allowed to be pulled into this unit, through it's internals, and ultimately ingested into the pump and maintain a great pump fillage performance – this would be following the same rules and principals most all others do. We can all agree, 208 bfpd is far less capacity than the most-well optimized slim designs of packer-type separators or another large-mouth facing upward and tight OD to casing ID design that is utilized today, are tasked with almost 100% of the time, so as that is the case, at the surface such a design as described here should stand no chance in a heads-up comparison, or so the agreeable capacity calculations would have us believe.

The most simple way to define just how functional the DVS and gas vent capture technology is, is to install this design into wells which pump through the system a fair bit more volume than ought to be capable of being pulled through and still yield even fair separation performance (e.g ~300 bfpd or ~6.0"/sec fluid drop velocity – 50% more than the normally acceptable 4.0"/sec or less) and, so long as the performance is favorable, then continue to take strategic steps in increasing the total fluid throughput volumes in further installations until we are well in excess of what should be theoretically allowable to yield excellent gas separation performance (e.g. 415 bfpd or ~8.0"/sec fluid drop velocity).

The process above is precisely the procedure that was followed to help define what upper volume capacity limitation may be for the gas separator described which utilizes the DVS and gas vent technology.

<u>Simple, Add-On BHA Option to Yield Even More Extreme Performance Capability</u>

With immediate and consistent successes being witnessed that were quickly pushing the upper limits of the max trial volume capacities noted above, the multi-stage DVS separator in it's stand-alone form was impressive and doing exactly what it was designed to do. As could be projected, though, while performance beyond expectation is good, even more would be that much better!

I'd previously mentioned the MSLE type of gas separator which controls a limited amount of fluid intake per stage such that the fluid intake velocity potential within each stage is limited by design to keep that drawdown pace at a desirable range for both min and max speed withing each chambers' dead-space. A real benefit of this patented separation type is that is can be easily added in a modular fashion to the top of separators such as the DVS separator to allow a bit of desired production volume to be ingested through even a limited number of stages which then offloads a bit of the fluid throughput otherwise required to all pass through the singular base separation unit made up below in the BHA.

It made very good sense then to apply a 2-stage MSLE stack to the top of the overall separator design applied in conjunction with the multi-stage DVS separator wherein the 2-stage stack was ported such that a controlled 100-200 bfpd maximum, depending on DH conditions, would be ingested through the pair leaving the remaining volume to pass solely through the DVS separator. Now having this extra fluid volume and gas separation capacity then allowed the DVS + MSLE combination to be trialed more confidently in ultra-high volume wells applications where fluid volumes were anticipated to be easily in excess of <u>500 bfpd through the pump</u> and where hopefully as much as 150-250 bfpd would be consistently flowed up the backside. Doing the quick on all that tells us there would be applications targeting 300-400 bfpd produced through the 3.5" OD profile DVS separator itself, 100-200 bfpd through the two MSLE stages located above the DVS separator, and finally 150-250 bfpd flowing off the backside for a total produced fluid range of ~500-700 bfpd that could be attainable with excellent separation performance witnessed.

In a paper I previously authored for the SWPSC I had said, "the most functional way to remedy this shortage of capacity problem generated by the other separators out there is to change the biggest driver of their demise: add separation space (aka separation capacity). The way to alter this is made feasible through adding to the total capacity so we can achieve the desired results."

That was at that time an honest and true statement as far as anyone could verify and was only possible through a couple of very unique and shall I say, not yet widely applied separation techniques, when compared to more widely utilized gas separation designs of that era. Since that time we've more fully come to an understanding of how well decreasing intake fluid velocities can assist in gas separation and, let's note, it certainly can solve separation issues for some high volume application in the Permian. Also too, we've before more fully understanding of the sometimes limiting capabilities of applying only that process to certain well applications within much of the Permian Basin. Not to over genericize this statement, but no singular form of gas separation seemed to meet the high demands of operators, in all areas, and nowhere near all the time.

<u>Successful Installation and Production Gain Details</u>

Applying a truly new approach wherein the best of all forms of separation are applied in unison and allowed to work harmoniously together without creating any impedance on each other, have from the very earliest trials though the most currently refined designs, proven to yield exceptionally special and historically untouchable results. Having so many people and companies working hard for years now to figure out this very difficult problem should, thus, make it come as no surprise to anyone that it appears evident we have to throw everything we've ever learned as an industry at this problem in one well-sorted and highly engineered gas separation package which allows for no compromise in any segment of it's design, maintains reliability in function throughout the ugliest of

DH conditions, and does so in an exceedingly wide range of ever-changing production demands. Also one last ask and that's to ensure it doesn't cost a fortune!

Amazingly all of those items have been delivered through application of the multi-stage DVS gas separator w/ gas ventilation technology + MSLE type separation add-on's and further, the rates attained, maintained, and pumping performance metrics achieved in nearly 100% of every application has be far beyond expectations.

See Figure 3 below for an example of the huge impact experienced by simply pulling out a very widely used slimhole packer-type gas separator that was performing "normally" and as anticipated, then the newly designed multi-stage DVS gas separator w/ gas ventilation + MSLE add-on type separation design was run back in hole and set at the very same setting position as the previous unit, the same pump size and design was rerun, as well as the same rod string and pumping unit.

The top graph is daily oil (bopd), the 2nd is gas (mcfd), the 3rd is water (bwpd), and the 4th or bottom graph is total daily fluid (bfpd). The timeframe covers a total of ~8 full months, wherein time online is split evenly between "before" and "after" at ~3.5 months. The gap in the middle is exactly 1.0 month timeframe waiting on the workover to be completed.

Upon returning the well to production after being offline for ~30 days, the very sharp and distinct ascent to a level of peak production was attained within about 30 days. Many artificial lift and production personnel would have argued that was "all flush production" and nothing to get excited about, but that ascent was further accentuated by the steady and thoughtful SPM increases made regularly to the variable speed drive (VSD).

Once the unit was brought up to full speed, and in this case slightly higher SPM than previously allowable since min and average pump fillage were maintained much higher than before, the well production finally rolled over and proceeded to create a very smooth and predictable decline. The notable thing, though, is that the new decline continues on and on and on for months now – this was not a temporary bump in production for a couple weeks, like so many other separation solutions yield, then the performance of the unit falls flat on it's face. Quite the contrary, actually, and the reservoir engineering team conclusively agrees this decline has now proven beyond any reasonable doubt they could apply a completely new curve to the well's production profile and they could do so with the utmost confidence! Booking this many more reserves to an aging horizontal well on RP is an absolute game changer, and in many cases, a company-maker.

For the record, this example illustrates a now 3 month post-installation <u>maintained</u> NET gains of: +50bopd / +1.7MMcfd / +170bwpd. Note that's a NET revenue yield of ~$350,000 from the increased oil production alone over the timespan (minus lifting costs taking into consideration).

To take this a very encouraging and confidence-building step further, this particular operator has now installed 32 of these separation systems to-date over the last 5 months and the results are highly duplicated and consistently yielding what I like to refer to as "IPR-altering" results just as this example plot would indicate. You can clearly see that is a legitimate assessment as the cut's often change a bit and the GOR/GLR's go absolutely off the charts.

I'll make the suggestion we're seeing the general gasified fluid level above the pump rapidly being pulled down to new low levels near the pump yielding a much lower than ever previously attainable PBHP with any other separator assembly. This assembly's ability to maintain a much higher than "normal" pump fillage throughout the backside drawdown process and also while gas slugging and purging tends to knock other separators in the head, is just a single, but a very critical element of the path to success being created here. Without the ability to delivery in that specific environment, attempts to pump the gassy column down becomes an all too common tail-chasing exercise consisting of slowing the unit SPM down, trying to fight through to no avail, shutting down for some predetermined time, and then start back up and repeat again.

The significant reduction in backpressure on not only the accumulated fluids in the curve, but also on each of the successive troughs dipping up and down along the lateral can now been alleviated to such a high degree that the portions of the lateral near the heal are nearly completely unloaded and thus the pea-traps through a vertical section a bit further out into the lateral and towards the toe can now fully unload themselves towards the heal. With the pump continuing to maintain a very high fillage, this ratcheting effect from further and further out in the later continues for days and weeks until we are seeing more notable and laminar production from the furthest lateral extents, which in many wells may have been fully liquid loaded or near fully loaded for year and since the well was new. As you can imagine those fractured lateral extents have probably produced the least of any amount of contributing perforations since the well was put online after initial completion and are, thus, the reason a whole new and significantly improved production decline and IPR are now made possible.

<u>Conclusions</u>

The on-point early development and rapid industry uptake of the multi-stage DVS type gas separators w/ dedicated gas ventilation + MSLE type separation add-on's has quickly proven the assembly combination to be capable of yielding notably higher average pump fillage performance than other gas separation designs on the market today.

On top of the much higher avg pump fillage attainable, the assembly as described also yields a much "tighter" fillage band (max/min fillage spread) than "normally" expected even throughout the most aggressive gassing-off and slugging phases of wells' unloading cycles.

Solid execution of the first two points above, delivered over and over again, has illustrated the ready capability of the separation assembly to pull historically very difficult, gas-entrained liquid levels down to pump-off or near pump-off conditions unlike that which has ever been experienced in some of the most difficult applications operators have ever witnessed. This then delivers on the goal that everyone desires – it's resulted in significantly more barrels of oil the tanks and more gas down the pipeline. All that while operating much more cleanly, well within safe operating parameters, and at an extremely attractive cost, especially given the next-level results.

The ability of a singular separation solution to consistently create and maintain such huge percentage boosts to production volumes is absolutely unmatched.
All aspects of the separation assembly from the rugged and long-lasting material selections, to the DVS design and extreme separating efficiency, to the advanced desander design have all been very thoughtfully applied within what has proven to be an extremely effective and widely-applicable singular package allowing for the most production possible to be extracted from any well the unit is installed in.

The flexibility and ease of utilizing an MSLE type add-on stack, if desired and deemed necessary, is great insurance to scavenge the last several fillage points to continue seeing expectation-beating results in the highest gas and fluid volume applications.

The multi-stage DVS type gas separators w/ dedicated gas ventilation + MSLE add-on separators are easily torn down, cleaned, redressed, and repurposed as needed. They are designed to be the most flexible separator available with the able to handle any challenge thrown it's way and provide a very long working life.

References

1. Ellithorp, B. and Snyder, D., "Casing Gas Separator – Initial Installation Learnings and Design Progressions," presented at Southwest Petroleum Short Course, Lubbock, TX, April 17-18, 2019

Nomenclature:
AL= Artificial lift
VSD = Variable speed drive
RP = Rod pump
BOPD = Barrels of oil per day
BWPD = Barrels of water per day
BFPD = Barrels of fluid per day
MCFD = 1000 cubic feet of gas per day
ID = Inner diameter
OD = Outer diameter
MA = Mud anchor
BHA = Bottom hole assembly
PBHP = Producing bottom hole pressure

Figure 1 – Schematic of Multi-Stage DVS Type Gas Separator w/ Dedicated Gas Ventilation

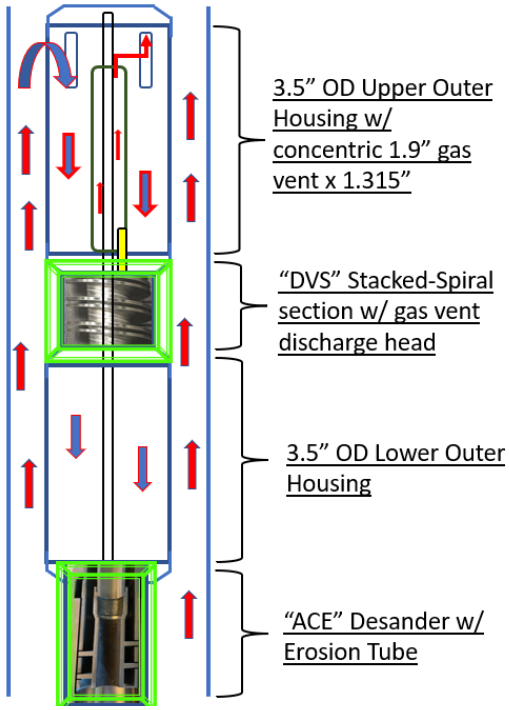
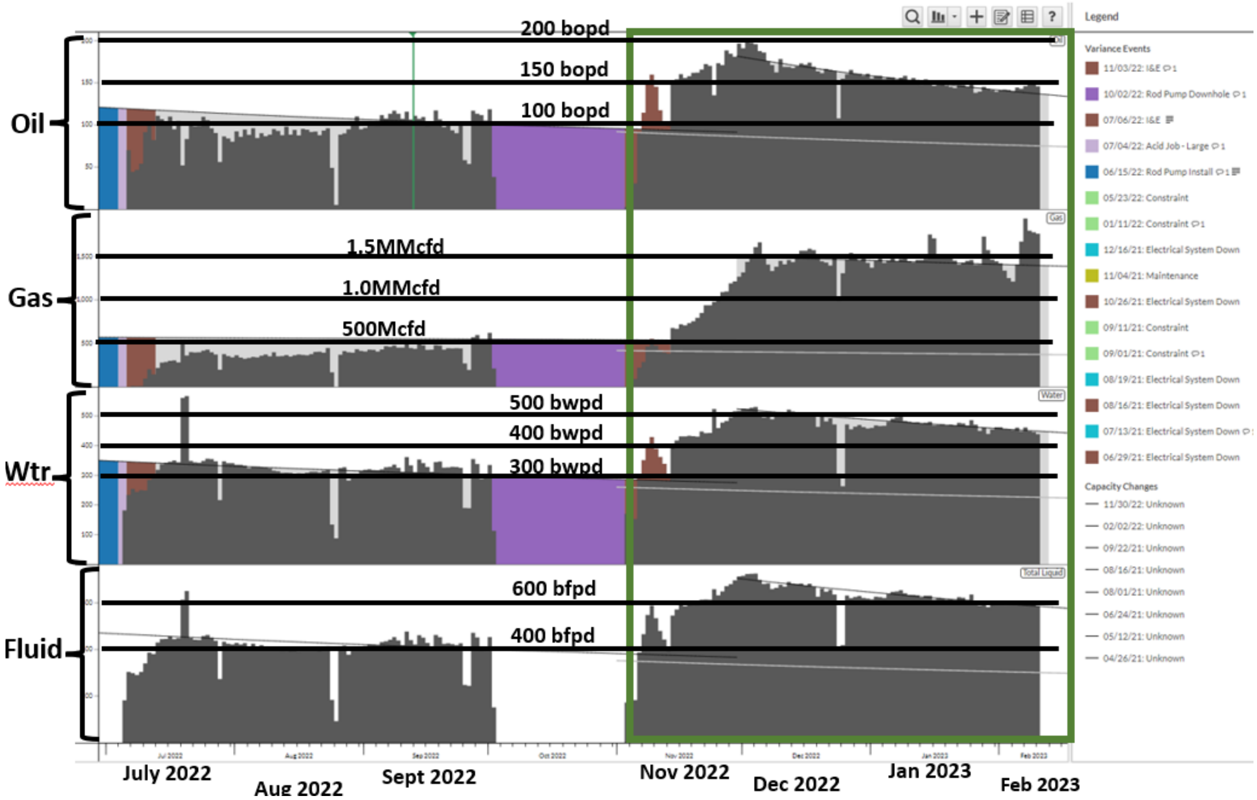


Figure 2 – Dual-Vane Spiral (DVS) Flowpaths

Figure 3 – Production Performance Plot of Multi-Stage DVS Type Gas Separator w/ Dedicated Gas Ventilation + 2-stage MSLE type add-on separation stack



Oil
Gas
Wtr
Fluid
200 bopd
150 bopd
100 bopd
1.5MMcfd
1.0MMcfd
500Mcfd
500 bwpd
400 bwpd
300 bwpd
600 bfpd
400 bfpd
July 2022
Aug 2022
Sept 2022
Nov 2022
Dec 2022
Jan 2023
Feb 2023
Legend
Variance Events
11/03/22: I&E
10/02/22: Rod Pump Downhole
07/06/22: I&E
07/04/22: Acid Job - Large
06/15/22: Rod Pump Install
05/23/22: Constraint
01/11/22: Constraint
12/16/21: Electrical System Down
11/04/21: Maintenance
10/26/21: Electrical System Down
09/11/21: Constraint
09/01/21: Constraint
08/19/21: Electrical System Down
08/16/21: Electrical System Down
07/13/21: Electrical System Down
06/29/21: Electrical System Down
Capacity Changes
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