PRODUCTION OF MATURE UNCONVENTIONAL WELLS USING JET PUMPS, RECOMMENDATIONS FOR PRODUCING WELLS WITH LOW PRODUCING BOTTOMHOLE PRESSURES

Osman A. Nunez-Pino
Liberty Lift Solutions, LLC.

ABSTRACT

During the hydraulic fracturing age, hydraulic jet pumps have seen an increase of installation numbers across the most prolific unconventional well fields in the United States of America, as well as in overseas oil and gas fields. Its simplicity, reliability, robustness, and adaptability have made the jet pump one of the known artificial lift systems on the production of unconventional wells, specifically on the early stage of production. During this stage, production rates are high, and solids (proppant) are produced; this can be a challenging combination to deal with. When correctly operated, jet pumps can be a useful and affective solution for this unconventional well production cases.

Jet pumps can and it have been used to continue to produce an unconventional well through its producing life to depletion, until a transition to a different method is needed, mainly because of the minimum required pump intake pressure that a jet pump needs to operate. Jet pumps require a minimum suction pressure to operate with a reasonable energy efficiency, otherwise a phenomenon called “power fluid cavitation” or “low intake pressure cavitation” can occur. When the downhole pressure of an unconventional well that is operated with jet pump declines to lower levels, specific operating and optimization strategies must be implemented, to maintain acceptable production rate levels, and to optimize the usage of the available surface equipment capacity.

During the late stage of production of an unconventional well, a successfully operated jet pump strategy includes several good practices that include well completion configuration, surface equipment selection, suction and discharge piping, production data processing and analysis, nozzle and mixing tube resizing and power fluid pressure schedule. The correct application of the previously mentioned actions increases the possibilities to approach to a trouble-free operation, and to a continuous jet pump system implementation from its installation, from the early production stage to a point where the well flowing pressure is too low that a change of system is required, to a low rate – low pressure production system.

This paper presents a straightforward discussion on the operation of jet pump systems during the late production stage of unconventional wells, recommended practices, and procedures to keep the well producing, even when the pump intake pressures are relatively low.

INTRODUCTION

When an unconventional well is fractured, its reservoir’s energy in the form of pressure, can flow its contained fluids all the way through the well horizontal section, up to the surface and finally to the processing and storage facilities. During this early production stage, it is said that “the well is flowing”, which typically means that no artificial lift system (ALS) is used yet, to produce the well. Overtime the energy in the reservoir declines as well as the flowrate of fluids to the surface, which can be observed on the reduction of total pressure at the wellhead. At some point of the well early production stage, the production of fluids to the surface is going to cease, and it is at this moment that an artificial lift system is installed to restore the production of reservoir fluids.

During the period that the unconventional well is being produced using an artificial lift method, the finite volume of reservoir fluids contained in the drainage radius will exert a pressure that makes fluids to flow from the reservoir porous, through the artificially created passages (cracks), to the perforations, wellbore, horizontal well section and finally, to the artificial lift method intake of fluids. Because the volume contained inside the well radius is limited, the pressure will decline with time; the more reservoir fluids are pumped out of the well reservoir, the lower the producing pressure will be.

Down the road, after the well has been producing for a specific amount of time, the reservoir pressure can be low enough to make the production using artificial lifting a challenge. Depending on the type of method, challenges can certainly be related to pump cavitation, gas interference, low pump fillage, motor high temperature, elastomer degradation due to high temperature and low cooling action, and high horsepower requirements. The just mentioned issues on the well production, can cause a variety of difficulties that include system unplanned stops, pumper repetitive trips to location, unproper operation, system failures, and workover jobs. At the end of the street, these forementioned problems increase the operational expenditures, making the well operation sometimes uneconomical, i.e., the amount of money expended on keeping the well working, surpasses the cash produced by the well sales.

With the introduction and development of hydraulic fracturing for unconventional well production, a handful of challenges were introduced to the artificial lifting operation, as higher flow rates, production of higher solids percentages, high deviations, and dogleg severities. The selected artificial method to produce and unconventional well, is required to handle as much as possible of these conditions, as effective as possible. One of the most difficult tasks to be handled by the artificial lift that is designed to produce the well all the way from early production stage through late production stage, is the flow rate difference, higher at the beginning and considerably lower at the end of the well production life.

The jet pump utilization has become increasingly important since the beginning of unconventional well hydraulic fracturing. It working principle enables the jet pump to be manufactured in small sizes as 1'' jet pump, which can be installed to produce in an API 2-3/8'' string as casing, and on large sizes as the 5-1/2'' jet pump that can be installed in 9-5/8'' casing. Because their short length, jet pumps can be installed and circulated literally through any well deviation and dogleg severity. The ability to be manufactured from resistant alloys and compounds, gives the jet the desirable features to be resistant against erosion, liquid wash, and chemical attack. The most important characteristic of the jet pump is that it can be circulated in and out of the well, by the reversing of the power fluid injection; no workover is required to get the pump to the surface, one jet pump service technician can repair or resize and get the jet reinstalled and producing. The entire jet pump retrieval, repair/resize, circulate back down to the BHA, and system restart, can take from two to five hours, depending on the pump installation depth and surface configuration. Please see figure # 1, this is a generic jet pump diagram.

WELL COMPLETION CONSIDERATIONS AND RECOMMENDATIONS – THE JET PUMP CASE

There are several good practices that should be applied on any jet pump installation, that will help on the overall system performance and to keep the workover rig away, some of which are:

Tubing Size Selection: A proper tubing size is of remarkable importance for a well-designed jet pump system, it will determine the size of the jet pump and its capacity to handle the production rate, as well as the friction losses of the power fluid and commingled fluids flow through the well tubulars. A 2-3/8'' tubing string will need to be installed into a 4-1/2'' casing at least, a 2-7/8'' tubing string will need at least a 5-1/2'' casing, and a 3-1/2'' jet pump BHA requires a 7'' casing. Jet pump sizes are typically referred as their nominal diameter, i.e., a jet pump assembly for 2-3/8'' tubing is named 2'' jet pump, for 2-7/8'' tubing string is a 2.5'' jet pump, and 3'' jet pump for the 3-1/2'' tubing.

Packer Installation Depth: Whenever it is feasible, the annular production packer shall be installed as close as possible from the top of the perforations. The reason behind this good practice is that the closer the jet pump suction is from the perforations, the higher will the pump intake pressure be, consequentially the potential production rate will also be higher. A jet pump close to the perforations can keep the well producing for longer, specially down the road when the bottomhole pressure has declined.

A jet pump can work at any installation deviation angle, from vertical to horizontal, this is not an issue for a jet. However, there are some peripherical limitations that need to be considered when deciding at what depth the jet pump (packed) will be landed. First and foremost, the annular production packer to be used shall offer the required characteristics to be effectively installed at the desired depth and to hold the differential pressure and temperatures at which it will be subjected. The other important point to consider, is the maximum well inclination at the point where that jet pump standing valve will be located. Standing valves are retrieved using standard slickline procedures, on which a retrieving tool is run with the slickline down the hole, the retrieving tool latches at the standing valve fishing neck and an equalization device (typically a knock-out plug) is activated. Based on field experiences, the maximum inclination angle that an average slickline equipment can get its tool string, when retrieving a standing valve, is around 65 degrees. That said, no matter that a jet pump can satisfactorily work at any well inclination angle, the maximum depth at which it is recommended to land the jet pump is where its standing valve depth corresponds to the inclination angle is 65 degrees (from the vertical).

Jet Pump Assembly Configuration: The two most common jet pump modalities that are used on unconventional well production are standard flow and reverse flow. By far, the most typical configuration used in unconventional well in the United States is standard flow jet pump, in which power fluid is pumped down the tubing, and returns are brought back to the surface through the casing-tubing annular conduit. There are several other configurations that can be used to deploy jet pumps, but these two previously mentioned are the most common.

Standard Flow Jet Pump: Also called "conventional flow" or "direct flow", is by far the most popular type of installation. When a jet pump is installed this way, the jet pump can be circulated in and out of the well by just inverting the power fluid injection at the Christmas tree. This is the most relevant advantage of the jet pump system, and it makes the task of repair / optimize the jet pump an activity can easily be accomplished by one qualified person in a time frame of 3 to 5 hours, depending on the installation depth.

Reverse Flow Jet Pump: This type of installation is the second most common. It is reserved for mainly three specific challenges: Production of corrosive fluids, large solids production rate and drill stem test (DST) completions. A reverse circulation jet pump needs to be secured in the ported nipple (BHA or SSD); a lock mandrel is normally used for this purpose, and slickline procedures are implemented when this jet pump style is installed and retrieved from the well.

Other type of installations are: Concentric jet completion, parallel free and casing fixed pump installations, but these are not the subject of this paper.

MATURE WELL PRODUCTION USING HYDRAULIC JET PUMPS:

Depending on what area the well is located, and from the jet pump system standpoint, an unconventional well can reach its maturity when its 85% of its absolute open flow production has reached a production rate of approximately 400 bfpd. This production rate magnitude has been adopted for several oil and gas producers that use jet pumps, because this rate might also be produced by conventional rod pumping units, using less horsepower that the jet pump system requires. Now, horsepower reduction when converting to rod pump is not the only consideration to take, it is also important to consider, the following aspects: Cost of conversion, potential rod pump failures associated to well deviation and sand production, inability to produce high rates if the well is re-fractured or its drainage radius is affected by a nearby fracturing job.

When a jet pump well is considered a "mature" system, author recommends this production strategy: "**To produce the well at its maximum flowrate, by optimizing the surface equipment usage, and operating at a jet pump producing pressure right above the low intake pressure cavitation on-set pressure".**

The strategy that the author has developed and applied to produce mature wells using jet pump systems can be expanded in several steps, which are explained below:

- Recording of production and operating data: The daily registry of production and operating information is the root of this process, without consistent, accurate and frequent data it is not possible to create a strong foundation for the rest of the optimization process. The author recommends basing this jet pump analysis on an average of at least 5 days of consistent operation. The specific information that are required to make a jet pump optimization analysis are:
    - Formation (net) oil production rate.
    - Formation water production rate.
    - Formation gas production rate.
    - Power fluid pressure at wellhead.
    - Returns stream pressure at wellhead.
    - Current nozzle and throat sizes.
    - Power fluid injection rate.
- Create a graph using the collected data, with time on the horizontal axis and the magnitude of each parameter on the vertical axis. A graph is often useful to realize about trends that can help on troubleshooting the system, and get a solution mapped out.
- From the collected data source, select the most recent five days of consistent and fully operating days (24 full hours of operation per day). Calculate an average (arithmetic mean) of each of the parameters.
- Use the averaged values as inputs for the jet pump analysis. Jet pump calculations can be completed faster using existing jet pump analysis software. Currently there are a handful of computer programs to analyze jet pump performance.
- Calculate the jet pump intake pressure, which is the producing pressure at the pump installation depth. This pressure is the “suction” pressure at the point where the jet pump receives the formation fluids.
- Use the program’s calculated power fluid injection rate as the verification variable. To expand on this topic, the program calculates the power fluid flowrate by an iteration process based on the data input. If this iterated value of injection rate differs within 5% from the measured injection rate value (at the flowmeter), then the calculated jet pump intake pressure and the other calculated resultant values should be accurate enough.
- The available jet pump programs can also calculate the numerical value of the production rate where the production cavitation will happen, at the studied pump intake pressure and at the same gas to liquid ratio. Make sure that the current production rate is at a safe point away from the production cavitation onset rate. The author of this paper often uses the following criteria for production cavitation rate vs current rate: Production cavitation rate should equal to around 1.5 times the current production rate.
- Some of the jet pump programs might also have an algorithm to calculate the pump intake pressure below which low pump intake pressure cavitation (LPIP Cavitation), also known as “power fluid cavitation”, can happen. Compare the calculated current jet pump intake pressure with the LPIP cavitation onset pressure to know what the possibility is for this type of cavitation to be happening. If the available jet pump program does not have the code to calculate the LPIP cavitation onset pressure, then the equation and process that is described further in this paper on the “low pump intake pressure cavitation” section, can be used. The author of this paper recommends operating jet pumps at an intake pressure that is at least 100psi higher than the calculated LPIP cavitation pressure.
- Once the jet pump intake pressure is calculated, and the current operating point is being confirmed to be at a safe spot from both cavitation limits, it is time to make a nozzle / throat combinations comparison analysis. On this analysis, the jet pump/well system is studied with different nozzle/throat combinations, at a specific producing pressure. The combination that enables the jet pump best performance, is the combination that should be selected to equip the jet pump and provide the most appropriate rate and lifting capacities (vertical lift performance),

and according to the well inflow performance relationship. The jet pump is equipped with the chosen combination, and reinstalled.

- To restart the jet pump system operation, the author recommends following a group of best practices which are presented on this paper, further below.
- These production optimization process should be reapplied at least once a month (once every week is preferred), to assure that the well/jet pump system is working at its best performance, according to the criteria that its operating company has lineout for its production operation.

POWER FLUID CAVITATION

The term “power fluid cavitation” was adopted by the jet pump industry from long time ago, however it might cause confusion because power fluid does not cavitate. The author prefers to name this type of cavitation “low intake pressure cavitation”, this is because this hydrodynamic phenomenon takes place when the bottomhole producing pressure is relatively low, compared to the minimum required levels that a jet pump working at specific conditions needs.

Low Intake Pressure Cavitation typically happens when a jet pump is operated to produce relatively low flow rates at a very low intake (“suction”) pressure. In unconventional oilwell production, this scenario might take place during the late production stage, where the well deliverability is being depleted, and the production operating point is pushed down the IPR curve to achieve a flow rate that is close to the AOF (absolute open flow), where the correspondent production pressure is usually below the pressure limit that a jet pump needs to don’t fall into low intake pressure cavitation.

When a low inflow well is produced with a jet pump, the magnitude of energy that needs to be provided to the jet pump, by means of the power fluid, is usually high. In more practical words, to produce a deep well with low intake pressures, the injection pressure and rate to power the jet pump are considerably high. That said, when the large potential energy supplied to the nozzle entrance, and the energy transformation takes place from potential to kinetic energy, that results on a jet core which mean flow velocity is substantially greater than the mean flow velocity of the produced fluids entering the suction area between throat and nozzle. As previously indicated, the molecules of produced fluids are “dragged” into the throat by the power fluid jet core molecules. When high injection pressures are required for the jet pump to lift depleted wells, where both production rates and pump intake pressure are low, the difference of velocities between jet core and produced flow can be very large. Along the mixing layer, where high velocity molecules (jet core driving molecules) collide with low velocity molecules (dragged molecules), a sort of vortices or “mini-tornados” are formed. The center portion of these vortices present a total pressure, low enough to initiate the inception of bubbles. As in the production cavitation, the recently formed bubbles grow, shrink, collapse, and if located around the throat inner surface vicinities, impact and cause damaged to the throat.

Low Intake Pressure Cavitation – Predictive Analysis.

This type of jet pump cavitation hasn’t been studied as much as production cavitation has. According to this author, the most relevant literature related to low intake pressure cavitation is a paper titled: “Obtaining Low Bottomhole Pressures in Deep Wells with Hydraulic Jet Pumps”, by F.C. Christ and H.L Petrie. Christ and Petrie derived a theoretical equation to estimate the minimum required submergence that a jet pump needed to operate without low intake pressure cavitation, the expression is:

$$S = \frac{1}{1 + \left[\frac{N}{(1+N)}\right] * \left\{\left[\frac{[0.831] * \left(\frac{1-R}{R}\right)}{M}\right]\right\}^2}$$

Equation # 1

Where:

S: Minimum Required Submergence (S = Pump Intake Pressure / Pump Discharge Pressure).

N: Jet Pump Pressure Ratio = (Discharge Pressure – Intake Pressure) / (Injection Pressure – Discharge Pressure).

R: Area Ratio = An/At.

M: Flow ratio = Qproduction / Qpowerfluid.

The calculated actual submergence (Scalc) can be estimated using the following equation:

$$Scalc = \frac{Pps}{(gs \times D + Pwh)}$$

Equation # 2

With gs = go(1-Wc) + (gw*Wc) – Note that this is a simplified equation to calculate suction gradient.

Where:

D: Well depth [ft].

gs: Gradient of suction fluid [psi/ft].

Pps: Jet pump suction (intake) pressure [psi].

Pwh: Wellhead flowline pressure [psi].

Wc: Water Cut [fraction].

So, in order to determine the minimum required Bottomhole pressure to avoid cavitation, before the jet pump continues its operation, equation # 1 will give us a good idea of this pump intake pressure lower limit. On the side, if we need to estimate the current submergence of the jet pump, it is recommended to use the equation 2 and compare it with the minimum required submergence calculated with equation 1.

The pump intake pressure at equation # 2 (Pps), can be calculated using a jet pump program, or measured using a memory gauge or a real time gauge (wired to surface).

<u>Actions to be taken when a jet pump is working on Low Intake Pressure Cavitation</u>

When low intake pressure cavitation on a jet pump application has been verified, there are three options that the user can apply to mitigate this issue:

- If the same nozzle/throat combination is going to be used, low intake pressure cavitation can be avoided by shifting the production operating point to an upper zone on the PI-IPR curve. The problem with operating at a higher pump intake pressure, is that the correspondent production rate is going to be lower. Resolving the cavitation issue by letting the intake pressure to be higher (above the minimum required submergence S), some production rate is sacrificed, but the throat run life will be longer.
- In a scenario where the jet pump is working under low intake pressure cavitation, we can temporarily get back to a partial percentage of the nominal performance of the jet pump, by

increasing power fluid injection pressure. When injection pressure is increased, the jet core mean velocity is also increased; and as consequence, the cavitation vapor bubbles might be driven to a section of the throat located beyond the area that is being already damaged by the bubble's implosion. When this action is implemented, larger energy is supplied to the secondary stream and the negative effect created by the cavitated damaged surface, is up to some extent, offset by the increased hydraulic momentum supplied. Again, this mitigating action is temporary, and a new throat needs to be installed, as soon as possible.

- The last potential, and more permanent solution for the mitigation of low intake pressure cavitation, is to increase the suction area between nozzle and throat. By providing a larger annular passage between the throat's surface and the jet core, there will be a larger space available for the bubbles to travel further into the throat and diffuser. A bigger number of bubbles will have the chance to implode within the mixing stream, causing no damage, and fewer bubbles will implode and strike the throat's inner surface.

Physical Location of the Damage caused by Low Intake Pressure Cavitation

The process of bubbles formation when low intake pressure cavitation appears to require a longer time compared to production cavitation, mainly due to the longer process that low intake pressure cavitation needs to produce the vortices that give place to the inception of bubbles. In this scenario, bubbles are formed later, already into the throat's straight section, and they typically implode within this the straight section or at some point at the pre-diffuser or diffuser. The implosion of bubbles is most caused by the progressive collapse due to the increasingly higher-pressure environment in the throat, and due to the contact of the imploding bubble with the throat's surface. Long history short, low intake pressure cavitation damage is typically located across the throat straight section, pre-diffuser or in the diffuser. One fact to keep in mind, the closer the low intake pressure cavitation damage is from the throat entrance, the worse the cavitation problem, and the more difficult to mitigate. Please look at figure # 2.

JET PUMP SYSTEM STARTUP BEST PRACTICES

Safety Note: It is of crucial importance the compliance with every QHSE standard stablished by the operator company. A jet pump surface equipment has mechanical, hydraulic and electric components, so exercise extreme caution. Before starting up the unit, these basic safety actions must be performed:

- Absolutely nobody is working in or around the surroundings of the suction piping, power fluid skid, discharge piping, wellhead, or flowline.
- Make sure that all valves, accessories, fittings, gauges, equipment, and sub-equipment are all installed correctly and at the correct working position.
- Make sure that nothing is obstruction or on the way of mechanical moving parts, such as: Motor shaft, shafts coupling, pump shaft, pump cradle, plungers, sheaves, belts.
- Make sure that nobody is working with the power cables or instrument/control cables.
- Make sure that there are no leaks, loose connections, unconnected fittings, or any missing item that could leave an open path for fluids to flow out.

Recommended Steps for a Jet Pump System Start-Up

1. Complete a visual inspection of all suction pipeline valves, they shall all be aligned to the proper position, so the power fluid flow has the required total pressure (NPSHr) and acceleration head that the power fluid pump requires to work correctly.
2. Also make sure that the discharge pipeline has all its valves properly aligned.
3. Christmas tree valves must be opened/closed on the right way, according to where the power fluid needs to be flowed.
4. Verify that Murphy Switch Gauges (if any) are set up properly and that they will allow the system to be restarted.
5. The recommended pump discharge pressure should be around 80% of the final target discharge pressure. For example: If the final target discharge pressure is 3,000psi, then the startup discharge pressure should be 2,400 psi [3,000 x (80/100)] = 2,400psi.

6. When a unit is started for first time or re-started after a system stop, the VFD shall be operated in **Manual Mode (NOT on "PID or AUTO" mode).**
7. With the selector on "Manual" mode, press the start button and turn the motor speed knob clockwise slowly (very slowly), until the desired startup discharge pressure is reached. This process should take 10 minutes, at least, after well tubulars and surface piping are filled.
8. Once the startup discharge pressure has been reached (**using manual mode**), it is a good practice to let the system work for around one (1) hour while it is observed, before leaving location. Letting the system to work on "manual" mode for at least one day is recommended.
9. Set-up Murphy switch gauges shut-down contacts to the right working position.
10. VFD can be changed to "PID" or "AUTO" mode after one entire day (24 hours) of normal operation.
11. Before increasing discharge pressure (next step), please adjust Murphy switch gauges shut-down contacts according to the new discharge pressure.
12. Once the VFD is set to "AUTO" or "PID" mode, the following discharge pressure increments are to be carried on as follow:
    a. Increase discharge pressure set point by 250psi and wait for the system to reach stable parameters (system stabilization). i.e., power fluid injection rate is constant. A practical way to determine that the injection rate has stabilized, is by monitoring motor frequency (Hz); the system has reached hydraulic stabilization when motor frequency does not increase, in a time frame of an hour.
    b. Once the system is hydraulically stable, increase injection pressure by 250psi, and wait for hydraulic stabilization.
    c. Repeat step b until the design pressure (final target discharge pressure) is reached.

ARTIFICIAL LIFT METHOD CONVERSION FROM JET PUMP TO ROD PUMP

At some point down the road at a late production stage of the well, the producing pressure at the jet pump intake will be lower than the minimum required pressure to avoid low intake pressure cavitation. Additionally, there might be problematic and uneconomical for the well owner to continue running a jet pump system on such high horsepower requirements, while the net oil production is considerably marginal. On these cases, it might be wise to consider the possibility of converting the production method from jet pump to rod pump. Below the author presents a process flow chart (condensed version) that he recommends using when the decision of ALS conversions might need to be taken. There are several additional parameters that are considered; however, this diagram should provide an appropriate knowledge base. Please see the proposed flowchart at the illustration section. Please see figure # 3, this is a flowchart that illustrates the recommended process to follow for a potential artificial lift conversion from jet pump to rod pump.

REFERENCES

R.G. Cunningham. "Jet Pump Theory." Pump Handbook, Mac Graw-Hill, third edition 2007.

F.C. Christ, H.L. Petrie. "Obtaining Low Bottomhole Pressures in Deep Wells with Hydraulic Jet Pumps". SPE-15177-PA.

R.G. Cunningham. A.G. Hansen. "Jet Pump Cavitation". J. Basic Eng. 92(3), 482-492. 09/01/1970.

O.A. Nunez-Pino. "Understanding Cavitation in Hydraulic Jet Pumps, a Solid and Easy to Implement Guideline to Avoid and Mitigate Cavitation". 2019 SWPSC.

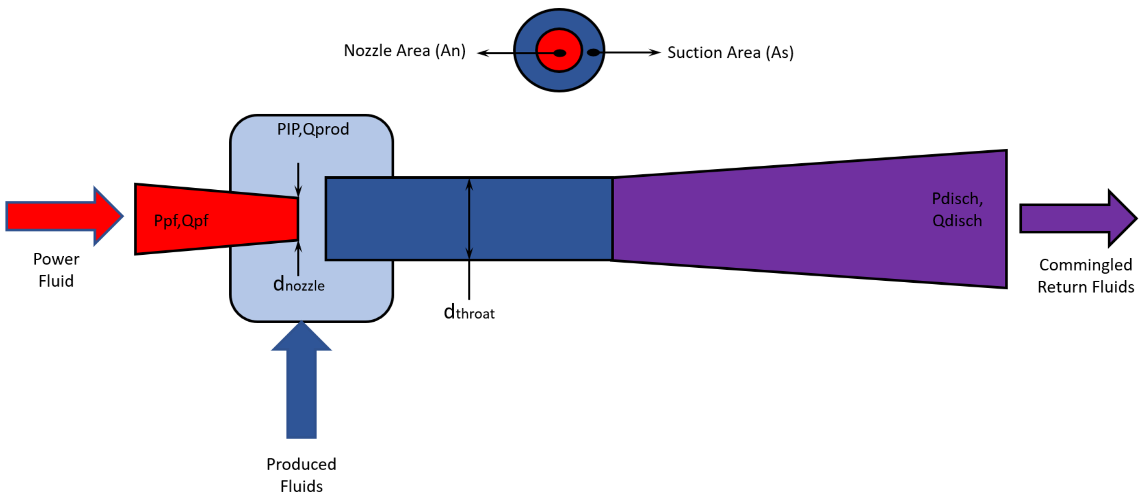

Figure # 1: Jet Pump Diagram

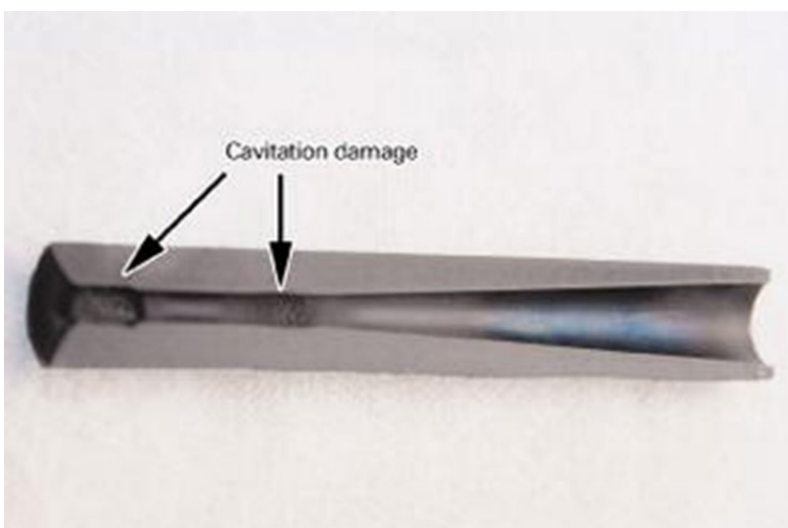

Figure # 2: Throat Damaged by Low Intake Pressure Cavitation

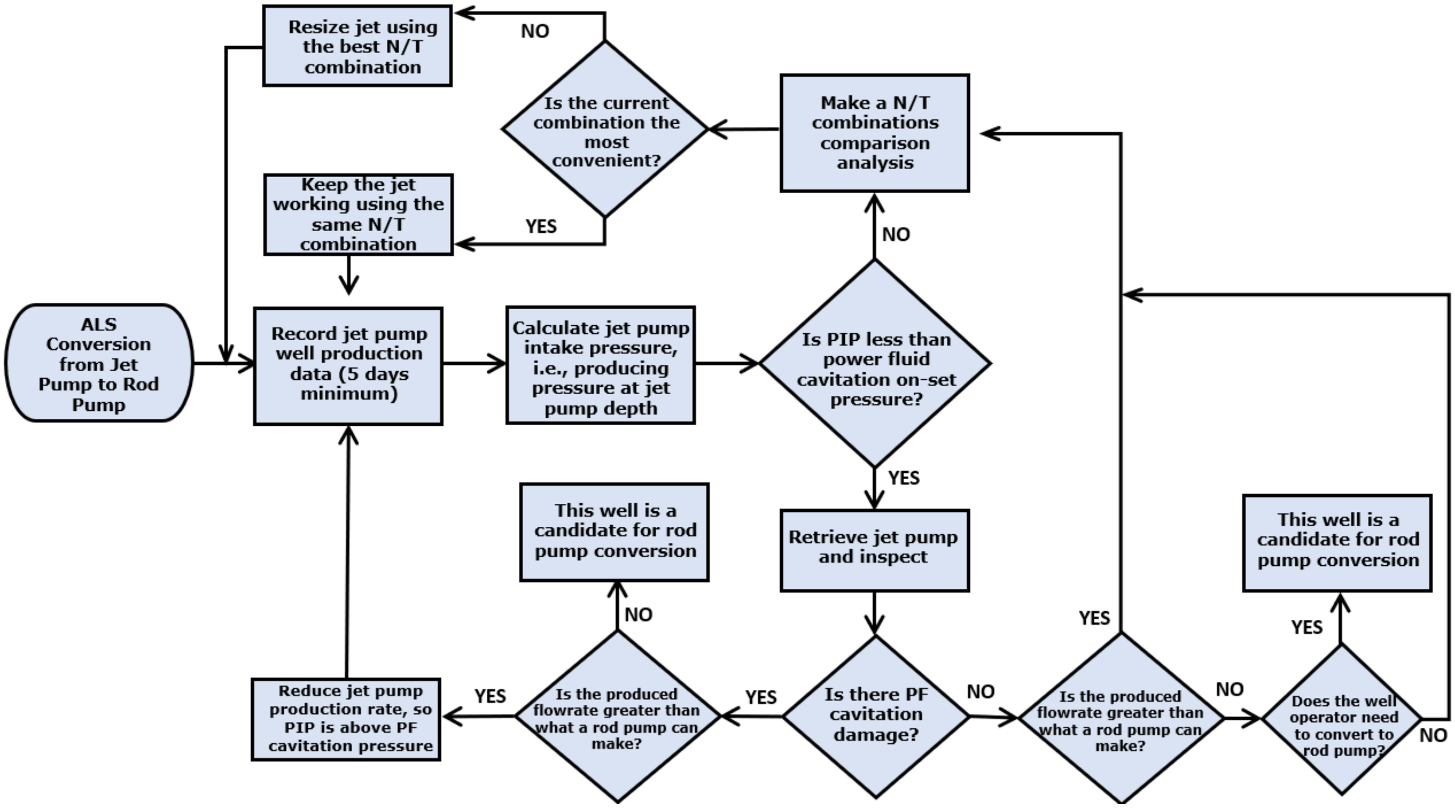

Figure # 3:   Conversion from Jet Pump to Rod Pump – Flow Chart