Optimization of the Well Start-Up Procedure and Operating Parameters for ESP Gas Well Dewatering

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Abstract: The Electrical Submersible Pump (ESP) systems were deployed in two gas wells for the dewatering of the gas reservoir. However, problems, such as the failure to start up the ESP, and changes in reservoir parameters occurred during the production. For the first problem, the well startup operation records indicate that the ESP’s gas locking happened. To avoid this, an optimization method of the well start-up procedure for the ESP well with a check valve was correspondingly proposed, which can solve the problem without any workovers. Secondly, based on the working characteristics of the ESP and the nodal analysis method, a set of optimization methods for the operating parameters of ESPs were introduced to achieve the inflow and outflow balance. For one well, the original ESP system was planned to be installed after hydraulic fracturing. Traditionally, the ESP operating parameters were designed based on the production rate. However, in this case, the production rate and the ESP operating frequency were designed simultaneously to maximize the pump efficiency.

Keywords: electrical submersible pump; gas well dewatering; optimization of well start-up procedure; optimization of operating parameters; node analysis method

1. Introduction

As one of the most important clean energies, natural gas is playing an important role in the world energy market [1]. To promote the optimization of the energy structure, it is advisable to increase the exploitation of natural gas [2].

The Kelameili gas field, a reserve of $1.03 \times 10^{11}$ m$^3$, is located in the Junggar Basin, Northwest China [3]. After over 20 years of production, the D18 gas reservoir of the Kelameili gas field has entered the late stage of exploitation. Gas wells are facing serious challenges of liquid loading problems. The overall daily gas production of the D18 gas reservoir is $54 \times 10^4$ m$^3$/d, and the daily water production is $120$ m$^3$/d. The application of the dewatering method is key to avoiding water accumulating in the bottom hole and keeping the gas well flowing [4–6]. In this situation, two sets of Electrical Submersible Pump (ESP) systems were hereby deployed for gas reservoir dewatering.

The advantages of ESP include the capability of lifting an extremely wide flow range; small-size surface equipment; that it is simple to operate; that it is easy to install downhole sensors [7] and easy to perform corrosion and scale treatment; its capability of being installed in deep wells; and its highly flexible production parameters if working with a variable speed drive (VSD). The disadvantage of the ESP includes the need for high voltage electric power; that it is expensive to change the equipment and match the declining well capability; that the cable may be deteriorated under dramatic pressure changes; and that the gas and solid production is troublesome [8–13]. ESP has been widely used in gas well dewatering in recent years [14–16]. However, the main material produced by the ESP in the
dewatering gas well has changed from the liquid form to a gas-water mixture. Additionally, the gas reservoir conditions tend to be more complicated, shortening the ESP’s operating life in the gas well [4].

During the production in the D18 gas reservoir, two main problems are the failure to start up the ESP, and changes in reservoir parameters.

For the first problem, the existing well start-up procedures and operation records were analyzed, and the results indicate the reason that a section of the gas column is sealed in the centrifugal pump below the check valve, thus leading to the ESP’s gas locking. The pump cannot provide sufficient head to open the check valve. To solve this problem, conventional solutions are pulling out the system, running a new system without a check valve, adjusting the position of the check valve upward, or just using an automatic reversing valve [15,17,18]. All of these conventional methods require costly workover operations. However, in this case, a novel method was proposed, which could bleed the gas column trapped in the pump by alternately bleeding off the pressure in tubing and TCA (Tubing-Casing-Annulus). This novel method can solve the problem without any workovers, and save the costs, manpower, and time for the operators.

For the second problem, the nodal analysis method was introduced to solve the problem. After months of production, one ESP system was pulled out and hydraulic fracturing was carried out for this well to enhance the production capacity. The original ESP system was planned to be installed for this well. Because the production capacity changed significantly, the operating parameters should be optimized. Traditionally, the ESP operating parameters were designed based on the water production rate. However, in this case, the liquid production rate and the ESP operating frequency were designed simultaneously using the given ESP performance data to maximize the pump efficiency.

2. Materials and Methods—Situation of Gas Reservoir, Wells, and ESP Systems

D18, located between 3200–3800 m, is a condensate gas reservoir containing bottom and side water. The geological structure of the gas reservoir and the relationship between gas and water are rather complex, and the fractures are well-developed in the reservoir. With the exploitation of the gas reservoir, the formation pressure continues to drop, with the edge and bottom water invading significantly, thereby leading to a gradual increase in the water production of the gas wells.

As the water rate increases in a gas well, the gas rate will be too low to take all water production to the surface, so that a point will be reached where water begins to accumulate in the bottom hole. This will eventually stop the production of the gas well [5].

Considering the high water production in the gas reservoir, the operators decided to use the ESP system for dewatering the gas reservoir. Two ESP systems were installed on two wells, i.e., D4 and D8, which were located in the water-flooded zones of the D18 reservoir. The location of these two wells is shown in Figure 1, and the well performance data summary is shown in Table 1.

The ESP systems used in D4 and D8 are the same, and the basic and performance data of the ESP system are shown in Table 2, while the performance curves of this ESP system are shown in Figure 2. According to the API recommendation, a check valve was installed with two tubing strings above the pump discharge [19].
Figure 1. D18 gas reservoir and location of Wells D4 and D8.

Table 1. Well Performance Summary.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Well D4</th>
<th>Well D8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PVT</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Gravity (Kg/m³)</td>
<td>1020</td>
<td>1014</td>
</tr>
<tr>
<td>Gas Specific Gravity</td>
<td>0.603</td>
<td>0.655</td>
</tr>
<tr>
<td>BHT (Deg C)</td>
<td>107.6</td>
<td>113.3</td>
</tr>
<tr>
<td>GLR (sm³/m³)</td>
<td>82.1</td>
<td>85.9</td>
</tr>
<tr>
<td><strong>Inflow Characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir Pressure (MPa)</td>
<td>31.1</td>
<td>31.5</td>
</tr>
<tr>
<td>PI (sm³/d/MPa)</td>
<td>0.87</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Well Structure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubing ID (mm)</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Tubing OD (mm)</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>Casing ID (mm)</td>
<td>121.36</td>
<td>121.36</td>
</tr>
<tr>
<td>ESP Intake Depth (m TVD)</td>
<td>3102</td>
<td>3098</td>
</tr>
<tr>
<td>Reservoir Depth (m TVD)</td>
<td>3562–3644</td>
<td>3577–3621</td>
</tr>
</tbody>
</table>

Table 2. ESP System Performance Data Used for D4 and D8.

<table>
<thead>
<tr>
<th>Model</th>
<th>Nameplate Frequency</th>
<th>Nameplate Voltage</th>
<th>Nameplate Current</th>
<th>Nameplate Rate</th>
<th>Nameplate Head</th>
</tr>
</thead>
<tbody>
<tr>
<td>QYDB116-30/3200C</td>
<td>50 Hz</td>
<td>1420 V</td>
<td>38.2 A</td>
<td>30 m³/d</td>
<td>3200 m</td>
</tr>
</tbody>
</table>
3. Results and Discussion


3.1.1. Challenge Overview—Fail to Start the ESP

The gas well shut-ins lead to pressure build-up in the wellbore [20]. Before starting up the pump, the high-pressure gas in the well has to be bled off at the wellhead, and the pressure bleed-off operation follows the procedure below. Firstly, the pressure in TCA was bled for 1 h. To protect the ESP downhole cable from decompression [21,22], the pressure bleed-off speed needs to be controlled at 3–4 MPa/h. Secondly, the well was shut in for 20 min. These two steps were repeated until the casing pressure dropped to the target value. During the above processes, the tubing was kept shut off to prevent the gas from entering the pump. After that, the tubing choke was opened to bleed the tubing pressure. Changes in the wellhead tubing pressure and casing pressure during the whole procedure are shown in Figure 3.

![Figure 2. The performance curve of QYDB116-30/3200.](image)

Afterwards, the pump could be started. However, no liquid production could often be observed at the surface when the ESP was started. In this case, the well could not be normally put into production. To start the ESP system smoothly and put the gas well into production, it is necessarily important to analyze the reasons for this phenomenon.

![Figure 3. The wellhead tubing and casing pressures during the pressure bleed-off procedure.](image)
3.1.2. Analysis of the Reasons

In the case of the ESP start-up failure, the motor current was recorded to be 21.5–22.5 A (the nameplate current of the motor is 38.2 A, and the no-load amps is 18.7 A). As the motor current changes linearly with motor loading [23,24], this current indicates a low load of the ESP motor. As mentioned above, a check valve was installed above the pump, and the failure is attributed to the fact that gas entered the pump from the intake during the pressure bleed-off process. Besides, the gas column was sealed in the centrifugal pump below the check valve, thus resulting in gas locking. The pump failed to provide enough head to open the check valve and discharge the gas trapped in the pump, as shown in Figure 4. Subsequently, to smoothly start up the well as soon as possible, a well flushing operation was carried out to squeeze out the gas column.

![Figure 4. Schematic diagram of the gas locking during the pump start-up process of Well D8.](image)

3.1.3. Optimization Methods

According to the above analysis, avoiding the gas column trapped in the pump is the key to ensuring the smooth start-up of the well. As mentioned before, conventional methods require costly workover operations. Typically, a workover needs at least six workers, takes one week, and costs about 56,000 USD. To this end, the well start-up procedure was hereby optimized in this study, which was proven effective in the case of avoiding workover operations.

Given that the tubing pressure remains high during the pressure bleed-off process, the pressure above the check valve is always high. In this case, the check valve cannot be opened, and the gas column below it cannot move upwards to the surface, which eventually leads to the gas locking. In order to avoid this gas column in the pump, the hereby-proposed optimization method is to properly control the pressure bleed-off sequence of the tubing and casing, so that the check valve can be opened and the gas column can be bled out from the pump.

3.1.4. Estimation of Tubing Pressure Bleed-Off Speed

(a) Pressure below the check valve

The bottom of the check valve is connected to the intake of the ESP, so the pressure can be directly calculated from the intake pressure \( P_i \) read by the downhole sensor.

\[
P_{vl} = P_i - \Delta P \tag{1}
\]

where, \( P_{vl} \) denotes the pressure below the check valve, MPa; \( P_i \), the pump intake pressure read by the downhole sensor, MPa; and \( \Delta P \), the differential pressure between the sensor and check valve, MPa.

With the water density in the well and the vertical depth difference between the sensor and the check valve, the pressure difference \( \Delta P \) is calculated to be about 0.03 MPa for this case.
(b) Pressure above the check valve

In the case of the check valve being closed, the inside of the tubing is a simple combination of the water column and the gas column. Therefore, the pressure above the check valve can be calculated once the depth of fluid level is given.

When the high-pressure gas in the tubing is bled-off, the gas flow should be connected to a flow meter to calculate the tubing pressure drop speed and gas flow rate within a short period of time. Then, the gas volume in the oil pipe can be calculated using the following equation:

$$V_g = P_t \frac{q_g}{r_p}$$  \hspace{1cm} (2)

where $V_g$ refers to the gas volume in the tubing, m$^3$; $P_t$, wellhead tubing pressure, MPa; $q_g$, the gas flow rate when bleeding pressure through the tubing head, m$^3$/s; and $r_p$, the drop speed of the wellhead tubing pressure, MPa/s.

Then, the depth of fluid level in the tubing can be calculated by the following equation:

$$d_f = \frac{4V_g}{D_t^2}$$  \hspace{1cm} (3)

where $d_f$ is the depth of fluid level in the tubing, m; and $D_t$, the inner diameter of the tubing, mm.

After that, the pressure above the check valve can be calculated using the following equation:

$$P_{vu} = P_t + \rho_w g (d_v - d_f)$$  \hspace{1cm} (4)

where $\rho_w$ denotes the water density, kg/m$^3$; $g$, the gravitational acceleration, N/kg; and $d_v$, the vertical depth of the check valve, m.

(c) Tubing pressure bleed-off rate

The pressure bleed-off speed of the oil pipe can be calculated as follows according to the pressure difference between the top and bottom of the check valve:

$$R_{pt} = \frac{(P_{vu} - P_{vl})}{\Delta t}$$  \hspace{1cm} (5)

where $R_{pt}$ refers to the tubing pressure bleed-off speed, MPa/min; and $\Delta t$, the interval time between two pressure bleed-off for the casing, which shall be 20 min based on the existing procedures.

3.1.5. Optimized Well Start-Up Procedure

Following the existing pressure bleed-off procedure, it is planned to alternately bleed the pressure in the tubing and the casing to open the check valve. Once the check valve opens, the gas sealed in the pump will be squeezed into the tubing and bled through the wellhead tubing choke.

The optimized well start-up procedure can be expressed as follows:

1. Record the parameters such as the wellhead tubing pressure, casing pressure, and intake pressure.
2. Perform the TCA bleed-off process for 1 h at a design rate (3–4 MPa/h).
3. Carry out the tubing bleed-off process, and the bleeding rate should be $R_{pt}$. Pay attention to the reading of $P_i$: significant fluctuation of $P_i$ indicates that the check valve has been opened. Then, shut down the tubing choke.
4. Repeat Steps 1–3 until the casing pressure was bled to the target value.
5. To prevent the gas from entering the pump again, start up the ESP as soon as possible.

Figure 5 depicts the flow chart of the optimized well start-up procedure, while Figures 6 and 7 show the downhole gas-water distribution and wellhead pressure changes during the whole procedure, respectively.
Figure 5. Flow chart of the optimized well start-up procedure.

Figure 6. Schematic diagram of gas–liquid distribution in the wellbore after optimization: (a) initial conditions; (b) pressure bleeding through casing choke; and (c) pressure bleeding through tubing choke.

Figure 7. Changes in wellhead pressures during the pressure bleed-off procedure before and after optimization: (a) before optimization; and (b) after optimization.

3.2. Case 2: Optimization of ESP Operating Parameters
3.2.1. Challenge Overview—Changes in Well Conditions

After the ESP start-up, the bottom hole flowing pressure of Well D4 was about 18.4 MPa, and the water production was about 25 m³/d in the early stage, but decreased
gradually to less than 10 m³/d, failing to meet the overall dewatering requirements of the gas reservoir. Thus, the ESP system was pulled out, and hydraulic fracturing was performed on the well. After that, a production test was carried out on the well using a gas lifting system. An average daily water production of 145 m³/d was obtained, as shown in Figure 8. The average bottom hole flowing pressure was 19.55 MPa, and the production index was 11.9 sm³/(d·MPa). The operators plan to install the original ESP system to the well. However, considering the large change in the water production capacity, the operating parameters need to be further optimized.

**3.2.2. Nodal Analysis Method for ESP**

Based on the nodal analysis method [25,26], the ESP system was selected as the analysis node, and the pump discharge pressure (Vertical Lift Performance, VLP curve) and the pump intake pressure (Inflow Performance Relationship, IPR curve) under various flowrates were calculated, respectively. The difference between the two curves is the head to be provided by the ESP (as shown in Figure 9). \( p_i \) is the pump intake pressure; \( p_d \), the pump discharge pressure; and \( \Delta p \), the difference between \( p_d \) and \( p_i \), which is the head to be provided by the ESP.

**Figure 9. VLP and IPR curves of D4.**

The head curve of the ESP under a given frequency can be obtained by the following affinity laws of the ESP [21]:

\[
Q = Q_r \left( \frac{n}{n_r} \right) \tag{6}
\]

\[
H = H_r \left( \frac{n}{n_r} \right)^2 \tag{7}
\]
where \( n \) and \( n_r \) are ESP operating frequency and nameplate frequency, Hz; \( Q \) and \( Q_r \), the flowrates under \( n \), \( n_r \), \( m^3/d \); and \( H \) and \( H_r \), heads generated by the ESP under \( n \), \( n_r \), \( m \).

The relationship between the heads and the flowrates of the ESP at the nameplate frequency can be fitted into the following polynomial form [27]:

\[
H_r = \sum_{i=0}^{5} c_i Q_r^i
\]

(8)

where \( c_i \) is a constant related to the pump; \( Q_r \), the flowrate under nameplate frequency, \( m^3/d \); and \( H_r \), the head generated by the ESP under nameplate frequency, \( m \).

The relationship between the head and flow rate of the ESP at any frequency can be obtained by combining Equations (6)–(8), and the theoretical operating frequency of the ESP can be calculated according to the given production parameters.

### 3.2.3. Optimization of Operating Parameters to Maximize the Pump Efficiency

The water production capacity of Well D4 after fracturing was greatly improved, and the average daily water production during the test pumping period (145 m\(^3\)/d) was much higher than the Recommend Operation Range (ROR) of the original ESP system. To guarantee the smooth operation of the original ESP system in the well, it is necessary to redesign the production parameters [28].

According to well operators, it is the primary goal to improve the pump efficiency while redesigning operating parameters. Based on the working characteristics of ESP, the pump efficiency is only related to the flow rate through the pump when fluid properties are unchanged. The traditional design method calculates the operating parameters such as the pump efficiency according to the given design flow rate. However, when the optimization goal is pump efficiency, the flow rate needs to be designed according to the pump efficiency data. To maximize the pump efficiency, the working point should fall on the best efficiency point (BEP) of the pump. The BEPs under various frequencies can be calculated with the affinity laws of ESP.

In this case, based on the nodal analysis method, the procedure to optimize the operating parameters can be summarized as:

1. Set the pump as the analysis node, calculate the discharge pressure (VLP curve) and intake pressure (IPR curve) under various flow rates, and calculate the difference between the discharge pressure and intake pressure under various flow rates (VLP-IPR curve).
2. Spot the BEP of the ESP under the nameplate frequency and calculate the BEP under different frequencies.
3. Combine the VLP-IPR curve with the BEP curve, and the intersection of the two curves will become the desired working point where the pump efficiency is maximized.

In this case, the wellhead tubing pressure was set to 7 MPa, and the VLP-IPR curve and the BEP curve are shown in Figure 10. The intersection of the two curves corresponds to a flow rate of 56 m\(^3\)/d, and the frequency of the ESP is 40 Hz. Therefore, if the original ESP system is installed into Well D4 after fracturing, the wellhead tubing choke should be adjusted to maintain the tubing pressure at 7 MPa. Besides, the ESP should be set to work at 40 Hz to achieve the inflow and outflow balance. The water production should be 56 m\(^3\)/d, and the pump efficiency is 52% for this point. The pump efficiency was enhanced significantly compared to the previous value of 19.0–39.8%.

After a period of production, the water production capacity of the well may gradually decline. Then, the wellhead tubing pressure can be reduced slightly, and the new IPR and VLP should be correspondingly calculated. Combined with the BEP curve, the maximum pump efficiency operating point can be solved using this very method.
4. Conclusions

- For the ESP system with a check valve, ESP start-up failures often occur in gassy wells. Based on the working record during the well start-up process, the failure was considered the result of some gas entering the pump through the pump intake and being sealed in the pump by the check valve. This gas column caused the gas locking of the centrifugal pump.

- A new well start-up procedure for ESP dewatering gas wells with a check valve was also proposed. The new procedure could bleed the gas column trapped in the centrifugal pump through the check valve by alternating bleeding off the pressure in tubing and TCA. By virtue of this procedure, the ESP start-up failure can be avoided without the need for workover operations, thereby saving time, manpower, and cost for the operators.

- The nodal analysis method was introduced to optimize the operating parameters of an ESP system. Combined with the affinity laws of the ESP system, either the working status can be calculated based on a given frequency, or the optimized working frequency can be calculated in accordance with a working case.

- Based on the nodal analysis method, an optimization method for production rate and ESP working frequency was introduced. Unlike traditional methods, the optimization objective of this method is to maximize the pump efficiency. Additionally, this method can optimize the flow rate based on the pump efficiency data of a given ESP system, and the working frequency of the ESP can be calculated as well.

- The ESP operating parameters optimizing method was applied to a well. The hydraulic fracturing operation was performed on the well to enhance the production capacity and the original ESP system should also be installed into the well. The flow rate and the ESP operating frequency were successfully calculated using this new method. Besides, the calculation results indicate that the best pump efficiency can be reached, and it will be 12.2–33% higher than before.

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