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Short Communication Article

Economic Equation and Optimization of Artificial Gas Lift with Coil Tubing Based on Dynamic Simulation in one of Iranian Offshore Fields

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ABSTRACT

One of the most controversial usages of coiled tubing in stimulation operation is the calculation of the optimum pumping rate and coiled tubing depth. Considering the investigations conducted in one of the Iranian offshore oilfields, the simulation and optimization of coiled tubing operation can be accomplished by two phase flow simulator (OLGA) and MATLAB curve fitting Simmons model to obtain the optimum rate and the depth of operation with regard to the limitations imposed by the amount of nitrogen and the operation time. Simulation and field results are compared with good agreement. The simulation and optimization comprise of both theoretical and experimental aspects on the basis of multiphase considerations. The result of simulation and comparisons are done on the basis of the nitrogen amount limitation. In this paper, it is attempted to state the necessity of coiled tubing dominant variable optimization by representing an economic equation, based on simulation results of a real operation with perception of two-phase flow realities.

Keywords: coiled tubing, economic optimization, artificial gas lift, dynamic simulation, operation simulation

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Introduction

During the recent years, coiled tubing has played a significant role to further the objectives of well intervention and stimulation. New applications of CT in recent years had significant growth. Well unloading & Nitrogen lifting are still the two major operations [1]. The service has so far undergone a great progress and greatly reduces the monetary costs and is significantly time-saving with its applications, include wellbore solids cleanout, well unloading, hydraulic fracturing, coiled tubing drilling (CTD), acidizing, cement squeeze and plugs, clean up, sand control, fishing, logging and perforating, and other applications. A number of reasons may lead to pressure drop in wells that necessitates the use of stimulation (acidizing) operation. For reducing hydrostatic pressure of the well-column, nitrogen lifting operation is performed [2]. In such condition by reduction of hydrostatic pressure, bottom hole pressure increases dynamically with respect to unloading rate. The income depletion of main client companies in recent years leads them obligatory to optimize their coiled tubing operations for better incomes.

Literature review

The two-phase fluid model takes into account the fact that the two phases can have different velocities [3]. High volume of gas bubbles in the presence of liquid phase in a vertical or inclined pipe starts to lift the well to surface direction with a continues increase in gas velocity (Vg) [4]. Average density of two-phase flow after to the technical optimum point leads to an even faster rise in the frictional pressure than hydrostatic pressure reduction by the gas phase within the well column [5]. Increase in N_2 rate above this optimum gas rate would increase the friction pressure loss in annulus [6]. Gas bubbles start to separate from bubble regime to sludge, By increasing the pumping rate [7]. Many efforts studied pressure drop and unified model prediction in deviated conduits with accurate results of real operation by PVT dates [8]. pulse of pressure in bottom hole to phase distribution during the time has a delay and the reason is not a quick response [9]. Others show the significant role of stability and behavior of a two-phase flow regime [10]. Nitrogen lifting continues until well fluid samples match the weight of reservoir 's oil weight (API). At the same time, the pressure and temperature of well increases to a stable point with the mentioned phenomena. The process continues until the pressure increases to a stable point with a uniform and steady state flow regime and production rate. The unique feature of CT unloading, as compared to conventional gas lift, is that the gas injection depth can be changed continuously [16]. The main reason behind both is to reduce the hydrostatic pressure of the bottom hole. Despite the variable depths of coiled tubing and optional pumping rates, further instantaneous changes in two phase regimes render discrimination is necessary. R. Zhang et al surveyed about the effect of rate, depth, coiled tubing size and well deviation by a numerical static - classical model on the basis of a static model. M.E. Ozbayoglu and C. Omulro (2005) concluded that, Viscosity has more effective value than density for controlling the flow regime in coiled tubing operation, as effective as conduit geometry. Zheng gang Xu and Jaimar Maurera (2010) simulated a failed operation which was mainly due to limited nitrogen rate and an inappropriate operation procedure. For a proper understanding of flow regimes and their effect on operation and engaged phenomena, OLGA and other related software can help the simulation in many related cases. A transient multiphase flow software model to a field case study of an unsuccessful well unloading operation using nitrogen through CT has been applied. P. Salim and J. Li (2009), mentioned that transient delays and their effect on pressure responses on CT operations are crucial to design a job. They stated that for knowing an accurate steady state flow, simulations should be done in a transient software and developing a code. Salim (2010) developed the code as a software after a year with some modifications [16]. Transient model of a two-phase flow phenomena of an operation helps optimizing the process with equipment selection, pump rates, fluid type and CT tripping procedures [17]. Gu and Walton (1994) [16], Gu. H (1995) considered mass transport for transient flow for simulation of CT but H. Gu (1995) derived equations to consider the negative effects of transient regimes [16]. Discrimination between steady or unsteady state, static or dynamic simulation choices are categorized in many related surveys. Conventional method based on static simulation suggests deeper possible allocation of gas lift, though the method ignored the compressor power limitations and pressure reduction that cause high consumption and more costs. Guerrero-Sarabia, Y.V. Fairuzov (2013) Stated that Optimizations based on Steady state gas lift may lead to 25% reduction in real production rate. their results leaded the authors of this paper to use a dynamic simulator software to have more accurate results [20-4]. Dynamic and steady state simulations show a different result for a gas lift system according to injected gas composition [21]. A transient simulation of mud cleanup operation is modeled by Krogh, E et al. in North Sea [16]. Tang et al (1999) derived a comprehensive transient model based on mathematical model and concluded that the simulation based on static model ignores the instability of fluid transportation within the conduit [16].

Problem definition

CT operations are done around the world, though the principle and important questions such as the optimum nitrogen rate and CT depth remained without a specific answer. During operation, rate and depth may not be in optimum mode. In such circumstances, nitrogen reaches the surface earlier than the expected time without achieving the purpose of unloading the well, or else, it might lead to an inappropriate length of time during which a higher amount of nitrogen is required. Job design needs a discrimination of dominant variables. This dominant is grouped in different categories that needs to be mentioned at the same time. main categorized groups are: cost and income (including time and minimum amount of nitrogen), different types of CT nitrogen lift operation, important operational variables (like CT depth and pumping rate), and two-phase flow regime in well as an invisible category, affected by operational variables. Etc.

Operational restrictions, equipment limitations and costs have to be taken into considerations in addition to depth and rate of nitrogen for a real economic optimization. This study is one of the main scopes of this paper. In continue, the methods of CT nitrogen lift with respect to preferred method in Iranian fields is explained, as the most widely used application of CT in stimulation operation for long time producing wells. For Optimization of a gas lift system before considering the amount of nitrogen, depth should be optimized first.

Types of CT nitrogen lift operations

There are 3 types of CT nitrogen lift operations:

1. Continuous lifting with variable increasing depths (nitrogen lifting while running in tubing in hole).

2. Continuous lifting with constant depth: After running the CT according to the client's considered depth, nitrogen lifting starts. The majority of Iranian clients and contractors favor this method as a result of which the simulation and comparisons are done on the basis of the aforementioned method.

3. Intermittent lifting with constant depth

Coiled Tubing Performance Curve (CTPC):

Figure-1 provides information about the trend of unloaded fluids within the well in terms of nitrogen rate. Increase in the rate of nitrogen up to a specific value causes a reduction in average density of multiphase flow and results better unloading. Though the values more than the mentioned point causes reduction in unloading the fluids within the well. This value is called technical optimum point [25]. Technical point demonstrates the maximum value of the lifted fluids without considering the economic optimization of nitrogen rate and the amount of nitrogen needed for the operation [26]. In fact, an increase in nitrogen rate after the technical optimum point is shows a negative effect on the unloading process [27]. High pumping rates lead to an increase in gaseous phase. Further increase in the rate causes an increase in the frictional pressure of the two-phase flow that results reduction in well-head pressure [28]. In many cases choosing the technical optimum point causes the waste of nitrogen despite the same results, so that economic optimum point on should be studied for better optimization.

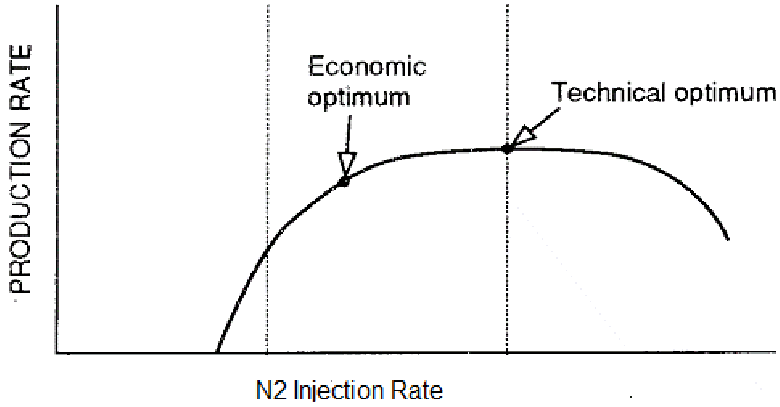

Figure 1: Coiled Tubing Performance Curve (CTPC).

Furthermore, the gaseous phase takes precedence over the liquid phase and reaches an early formation of churn and annular regimes without proper unloading and reduction in hold-up This phenomenon is called gas channeling. Although the creation of churn and annular regimes are not avoidable due to a normal increase in Vg specifically in deeper wells while moving toward the surface, minimizing it by reducing the nitrogen pumping rate can highly increase the efficiency of the results. On the other hand, the longer duration and length of bubble to sludge regime phases, moves the technical optimum depth nearby economic optimum depth. both technical and economic points are within the bubble to sludge regime Through the use of OLGA to create a simulation, it has been figured that both technical and economic optimum points are somewhere within the bubble and sludge regimes while a unique regime cannot be considered with certainty due to many reasons such as the fluctuation of pumping rates and the differences between the bottom hole pressure and the completion string of different wells and expansion of gas regarding pressure gradient [4-16].

Methodology

Pre-existing Model

The Simmons method is used for economic optimization of CT operation. According to this method, the economic study of a continues gas lift flow should be done by gas lift performance curve [29]. Gas lift performance curve (here called CTPC performance curve) is given by analyze of liquid unloading (or production) rate in terms of gas injection rate. The heavy line in figure-2 shows CT performance curve. Knowledge of a well's performance curve facilitates the analysis of the economic conditions of gas lifting (coil tubing), because both revenues and lifting costs can readily be determined on the basis of this curve. The following is a discussion on the economic study of coil tubing based on the well's performance curve. Here, it has been assumed that the following parameters are known:(a) The profit made on each barrel of produced oil, (b) The total (capital and operational) cost of nitrogen gas treatment, compression, and transportation for a unit volume of pumped nitrogen gas, (c) The specific cost of water, gas (N_2) and oil treatment by separators on location and burner boom or pit line disposal. If the process begins with a low rate of pumped gas (N_2), the well's response is a relatively low liquid rate. An additional injection of a small gas (N_2) volume, however, results in a relatively high increment of liquid rate. It is a simple task to calculate the increment of revenue and the increment of costs involved, the balance of which is positive in this case. If gas(N_2) injection rates are further increased by the same increment, liquid production rates increase further but the increments will gradually fall which is caused by the performance curve as shown in Figure-2. Eventually, a point will be reached were the increments of revenue and production cost are just equal from which any further increase in gas(N_2) injection rate would result in net economic loss. This condition belongs to this operating point; therefore, the well's optimum production is defined by flow nitrogen lifting.

Model Development

For the economic optimum point, the balance of revenues and costs can be written as follows, where the left-hand side represents the income gained and the right-hand side is the sum of nitrogen gas injection and nitrogen treatment, liquid separation and fuel costs:

$$\Delta q_L f_{Oil} P_{oil} = \Delta q_{N2} C_{N2} + \Delta q_{N2} C_{fuel} + \Delta q_{N2} C_{\mathrm{Dep}} + \Delta q_L (1 - f_{Oil}) C_{sep} \qquad (1)$$

Where: Δq_L = liquid production rate increment, bpd

Δq_{N2} = nitrogen injection rate increment, MMscf/d

P_{oil} = profit on oil, \$/bbl.

f_{Oil} = percent oil in liquid

C_{N2} = nitrogen cost, \$/MMscf

C_{fuel} = Fuel cost per operation, \$/MMscf

C_{Dep} = Prices based on the rate of depreciation, \$/MMscf

C_{sep} =cost of liquid and oil treatment, separation and disposal, \$/bbl.

The equation (1) can be solved for the difference quotient, which is equivalent to the gradient or slope of the nitrogen lift performance curve:

$$\Delta q_L \big/ \Delta q_{N2} = \frac{C_{N2} + C_{fuel} + C_{\mathrm{Dep}}}{f_{Oil} P_{oil} + (1 - f_{Oil}) C_{sep}} \qquad (2)$$

Based on the pervious discussion, this is the slope belonging to the optimum operating point of gas lifting, introduced by Kanu et al., and called the Economic Slope [31]. Figure 2 shows a sample performance curve (heavy line) and its derivative or slope (dashed line). At a N_2 injection rate belonging to the maximum of liquid production rate qL(max), the slope is zero by definition. It must be clear that no profit can be made on the right-hand side because costs are higher than revenues. On the left-hand side, however, profits overcome costs, up to the point belonging to the Economic Slope where, as shown previously, they are equal. Therefore, the liquid production rate belonging to this slop represents the optimum rate qL(opt) that ensures the most favorable economic condition of nitrogen gas lifting for the given well. In conclusion, the determination of the optimum liquid rate for coil tubing is dependent on gaining proper knowledge of the slope of the nitrogen performance curve. The curve itself is usually established with the aid of system analysis computer program packages, and its slope can be derived numerically from the data thus received. A common solution involves curve-fitting of the points of the performance curve and calculating the derivative of the resulting function, usually a polynomial or a spline function Recently with the help of MATLAB software the range of curve fitting results has more accuracy.

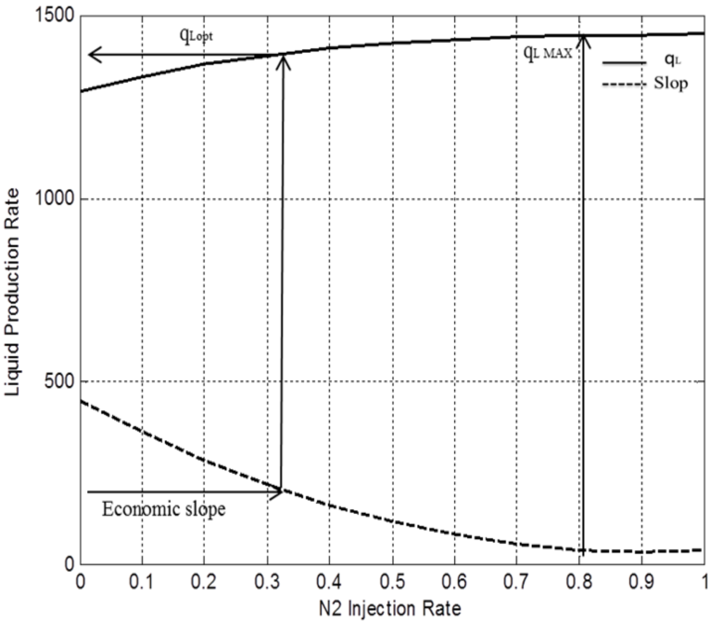

Figure 2: Coiled tubing Economic Optimum Performance Curve.

The economic rate of nitrogen pumping can be derived for any depth inside the well. If the pumping rate is considered to be economic and continuous; then, the multi-phase flow can be controlled to flow with the desired regimes. Under such conditions, the minor possible changes in rate have slight effects on flow regimes and the unloading time. In this manuscript, the operation is simulated and modeled in OLGA to obtain the nitrogen performance curve. The input information of the software includes fluid and reservoir characterizations, well geometry, geothermal specifications, CT nozzle point (nitrogen lifting depth), choke size, and etc.

Regarding the appropriate wellhead pressure, the simulation is performed in variable depths. Furthermore, the amount of the required nitrogen for different rates has been studied in terms of well behavior. Flow chock-size in this field are based on Gilbert equation.

Result and Discussion

As regards different unloading rates, the CT nitrogen lift performance curve is calculated and plotted. With help of writing a code in math lab software, curve fitting of the nitrogen performance curves is performed. At the next step, the economic optimum point of nitrogen lift rates in different depths are obtained as it can be seen in Table-1. The economic slope of each company it is a variable parameter caused by dependency to Oil price and equipment costs. Economic slope illustrates the tendency of a company to participate in a operation project, Thus the well service providers consider this slope as a confidential and private parameter and refuse to represent it. Though the mentioned notes, the authors acquired the slope equivalent to 165 by considering 60 dollars per barrel of oil. Results shows coincidence with Simmons method mostly fitted to third order poly nominal function. Finally, by re simulation of the optimized results are performed in OGLA to calculate the operation time in different depths with optimum pumping rates. The operation time simulation results in terms of wellhead pressure and wellhead temperature as shown in graphs 5 and 6. As stated in the introduction, CT nitrogen lift operation continues to achieve a stable flow in wellhead pressure and wellhead temperature. On the other hand, the operation continues to ensure the flow of the well fluids from the reservoir by collecting oil flow in samples with appropriate temperature that show flow from reservoir.

Table 1: Results of Economical N2 from Curve fitting by Math lab

$q_L = F(q_{N2}) = P_1(q_{N2})^3 + P_2(q_{N2})^2 + P_3(q_{N2}) + P_4$ (bbl./day)	P_1	P_2	P_3	P_4	R^2	Depth (ft)	q_{N2} (MMscf)
1309	27.78	-102.4	126.6	1331	0.991	2500	-0.15
1358	111.1	-297.6	283.4	1306	0.996	3000	0.24
1377	138.9	-361.9	341	1303	0.993	3500	0.3
1365	0	-88.1	183.3	1342	0.999	4000	0.13
1409	166.7	-456	447	1292	0.999	4500	0.4

1420	138.9	-394	413.5	1307	0.998	5000	0.41
1435	83.3	-275	344.5	1334	0.999	5500	0.41
1433	0	-103.6	238.2	1358	0.999	6000	0.38

After the economic optimization in various depths, the next concerns would be local facilities, equipment or limitations. The choice is between two different criteria of reduced time and reduced value of pumped nitrogen. The selection is subject to restriction of equipment and conditions between contractor of CT operation and client. The results of selection economic pumping rate may be achieved based on the limitations of nitrogen amount on the basis of using ambient or fired nitrogen pump units. From the operational-technical point of view, the highest pumping rate with the deepest depth seems to be more effective while the operation time in such condition increases undesirably and unloading operation fails regarding the Nitrogen channeling and annular regimes. Increasing the operation time may cause the higher overall costs that is not economic. Higher operation time leads to a higher consumption rate of nitrogen. Furthermore, the longer the operation time, the more depreciation occurs in tubing of CT unit. This is considered as unacceptable to the contractor of the operation due to corrosion of CT. For the depth parameter also, there is a same story. Tubing Depreciation of CT is always a challenge for contractors and clients. Operation conducted in lower depths causes more tension that exhausts the tubing. For these reasons, the protection of tubing from corrosion, inevitably leads the contractors to optimizing their operations. All the aforementioned reasons prove the necessity of optimization. The optimization of depth is directly related to the rate of nitrogen lift and well parameters. On account of this, depth is considered as an output function of the optimized pumping rate in different points by taking the maximum length of desirable flow regimes into consideration. As stated in Table1 the depth of 2500 ft. for nitrogen pumping has negative mathematical results. In terms of engineering, the results of the operation are not economically feasible. Table 2 shows the results of re simulation in variable depths with economic optimum rate of nitrogen. As stated in the results of the simulation in the table 2, the operation time starts to decrease by increasing the depth up to the middle depths of the well while increasing the depths after the middle depths to bottom hole shows increase again in time and amount of nitrogen for operation.

Regarding the operational experiences, authors concluded that the operation time and requires more volume of nitrogen for priming the nitrogen unit, loading nitrogen from tank and some wasted nitrogen causes almost a double consumption in time and volume of nitrogen in real operation, so that the simulation time and consumption of nitrogen modified for better results.

Table 2: simulate coil tubing volume and time injection N2 with modified time

Depth (ft)	Rate of N2 (MMscf/d)	Time Coil Tubing job(min)	Volume of N2(Gal)
3000	0.24	274.5	492
3500	0.3	285	638
4000	0.13	399	387
4500	0.4	225	671
5000	0.41	249	762
5500	0.41	360	1101
6000	0.38	337.5	957

Finally, depending on real limitations of the contractor and the client working on oilfields, it has been figured that the optimization based on the amount of nitrogen is more logical than optimization based on operation time due to operation cost. Furthermore, the optimization of nitrogen amount by considering flow regimes by low rates not only leads to acceptable time but also covers the real operation experiences on a scientific basis. Moreover, the results address the limitation of using the ambient pump units that operate with liquid nitrogen regarding the limitations of transportation to well site. Figure 3 illustrates not much difference for operation time; thus the volume of nitrogen is more important for companies in this results. So, the depth is chosen on the basis of lower nitrogen consumption and proper flow regime.

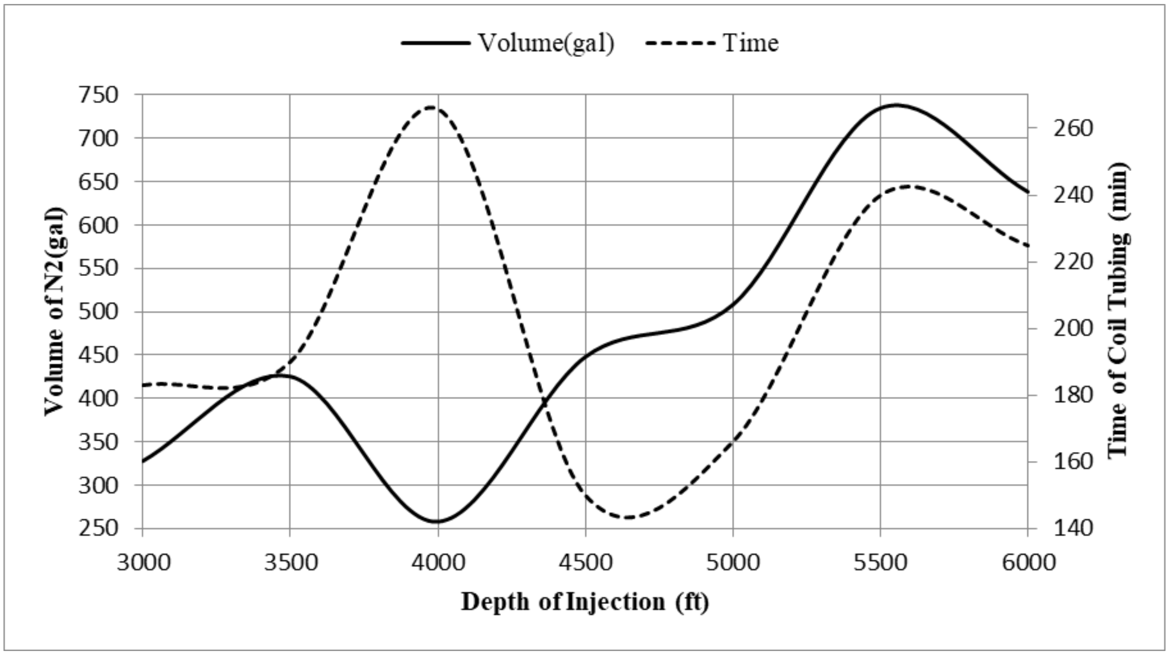

Figure 3: result of simulating coil tubing volume and time injection N_2

Regarding to mentioned reasons rate of 0.13 MM Scf/Day (almost equal with 1 Gallon per minute of liquid nitrogen and 4000ft depth is selected to be the optimum economic rate and depth of CT. The limitations of completion string like Nogo Nipples, Side Sliding Door, Liner Laps and so forth should also be taken into account for real operation. As far as uneconomic results and operational hazards for nitrogen lifting in 6000ft depth are concerned, a volume of acid always remains to be unloaded and lifted by reservoir pressure below the nitrogen pumping point (the nozzle of CT). Increasing the pumping rate may interrupt the quality of unloading the area below the nozzle. High Rates, especially in bottom hole depth, may force the acid toward the direction of the reservoir and cause negative effect on flow regimes. In this section of the well, the optimum rates give bottom hole the opportunity to unload the acid gradually and completely without pushing to well direction.

Conclusions

This paper tried to simulate and optimize the economic, operational and flow regime categories that affects the successful results of CT nitrogen lift real operation. The results are mentioned below:

1- Pumping rate and CT depth has a significant role to reduce the overall costs of operation. Gradual increase in operation time by optimizing the rate reduces the overall costs and has respective improvement effects on well stimulation.

2- The choice of optimizing should be done with respect to Nitrogen limitation and operation time limitation. This choice depends on equipment and their capabilities. Economic equation based on costs and revenues should be considered with appropriate recognition of cost-effective variables and local facilities. The results are fitted with third order polynomial function.

3- Results of real operation and dynamic simulator show the capability of simulating a CT nitrogen lift simulation with good accuracy.

4- simulation results illustrate that the economic optimum point is between bubble and slug section regime of two-phase flow. This shows the important role of flow regimes in economic point. Also, simulation results show a decrease in gas velocity between bubble and slug regime in a specific depth section that shows the boundary between two mentioned regimes in any specified depth. This section illustrates the length of different flow regimes of two-phase flow with dominant effect of them on lifting procedure. On the other hand, the effect of two-phase flow and optimization of depth and rate should be considered simultaneously.

5- The increase in the rate and depth of CT does not necessarily improve the results of nitrogen lifting. the consideration of depth is dependent on rate and flow regime. The depth can be considered as an inner function of rate as a controlling variable.

7- The simulation and optimization are based on low rate and continues nitrogen lifting. Interruption or stop pumping nitrogen during the procedure causes a severe negative effect on operation results. The negative effects are so severe and important for liquid hold-up that it is suggested to continuously pump at the lowest possible rate. Even when the wellhead line shows the signs of gas column without lifting any liquid as an industrial suggestion.

8- CT optimum injection depth as a dependent function of rate. The Functional dependency is due to the combined effect of the hydrostatic and friction pressures in two-phase flow.

9- The reason of difference between simulation temperature and real data's can also be described terms in the energy equation containing the Joule–Thomson coefficient affect sensitively the prediction of temperature, but not the prediction of pressure.

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Appendix

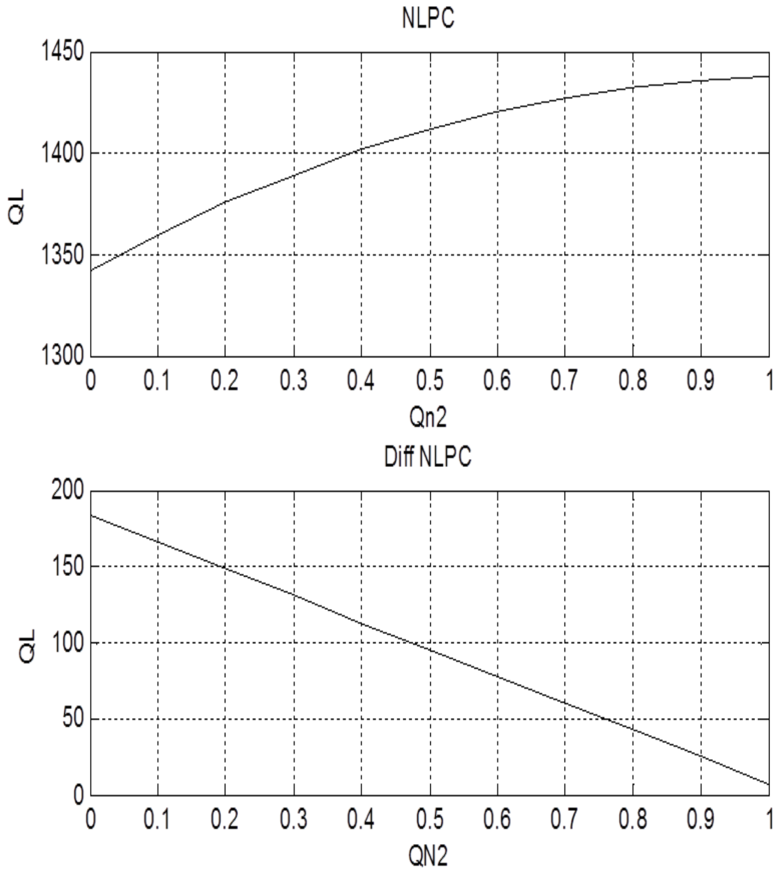

Figure 4: Economic Optimum Nitrogen Rate For 4000 ft. Depth

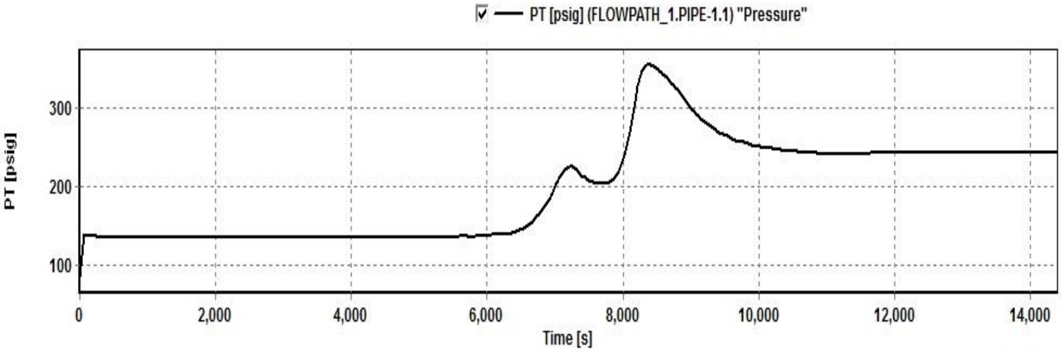

Figure 5: simulation results for wellhead Pressure prediction

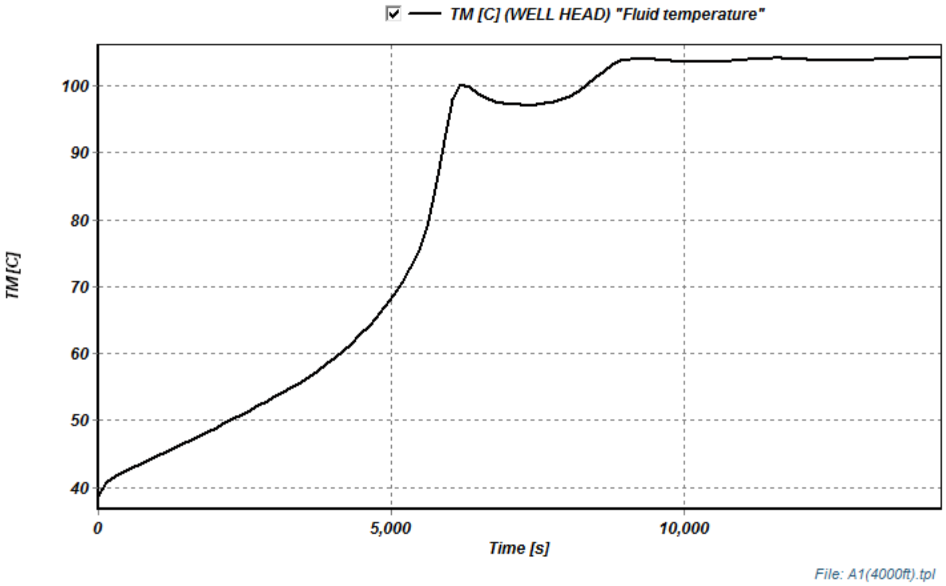

Figure 6: simulation results for wellhead Temperature prediction

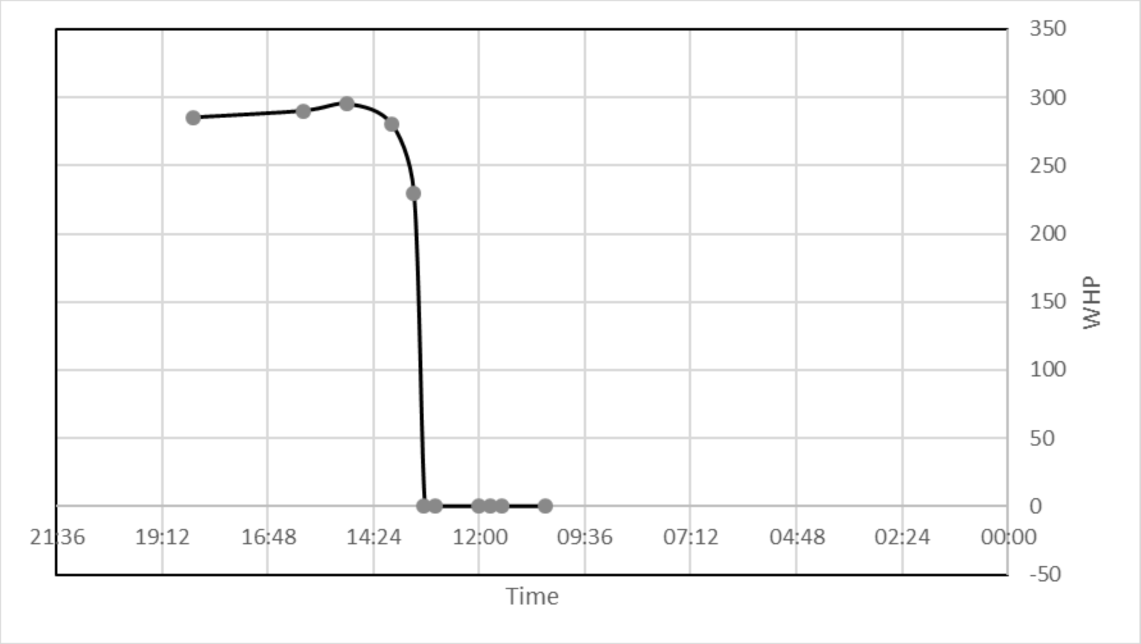

Figure 7: Real time datas for wellhead Pressure prediction

Table 3: Real time datas for Operation

Time (Sec)	Depth(ft)	Pumping Pressure(psig)	Q(Pumping Rate) (gpm)	WHP (psig)	Choke (1/64) in	WHT (F)	%water & Basic sediments	Weight
0	0	0	0	0	64	75	100	66
0	5500	900	6	0	64	75	100	66
900	5500	1500	3.5	0	64	75	100	63
1800	5500	1700	3.5	0	64	75	70	60
5400	5500	1750	4	0	64	75	50	61
6300	5300	1850	4	0	64	75	26	56
7200	5300	1600	4	230	64	115	39	55
9000	5300	1550	3.5	280	64	118	21	53
12600	4000	1250	3.5	295	64	120	8	53
16200	2500	0	0	290	64	120	2	53
23000	0	0	0	285	64	118	0.5	53

Nomenclature

Δq_L = *liquid production rate increment, bpd*

Δq_{N2} = *nitrogen injection rate increment, MMscf/d*

P_{oil} = *profit on oil, $/bbl.*

f_{Oil} = *percent oil in liquid*

C_{N2} = *nitrogen cost, $/MMscf*

C_{fuel} = *Fuel cost per operation, $/MMscf*

C_{Dep} = *Prices based on the rate of depreciation, $/MMscf*

C_{sep} =*cost of liquid and oil treatment, separation and disposal, $/bbl.*

Vg= gas velocity

Vl= liquid velocity

Subscripts

CT = Coil Tubing

L = Liquid

N2 = Nitrogen

Dep = Depreciation

Sep = Separation