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Conventional Plunger Lift Designusing Excel®

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ABSTRACT: *Plunger Lift is a low cost, high efficiency, artificial oil raising method for the oil industry and it is primarily used in wells with a high gas-liquid ratio. There are 3 types of plunger lift: conventional, with packer, intermittent gas lift with a Plunger. In conventional plunger lift, the control of the lifting cycles occurs through the opening and closing of the production line, with an accumulation of gas coming from the reservoir in the annular space. The present article details the procedure of the calculations for the design of conventional plunger lift by the method of Foss and Gaul (1965). The research resulted in the elaboration of an Excel® spreadsheet that, applying the equations contained in the literature, quickly and easily calculates the required variables. The worksheet could be validated through a comparison of a case study found in the literature.*

Keywords*:Plunger Lift, Artificial elevation, Oil, Design*

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I. INTRODUCTION

When studying the engineering of oil production, consideration is given to ways for the extraction of oil from the reservoir. This case can be seen and realized through two methods: natural elevation or artificial elevation. In this way, the present research intends to elaborate, to apply and to compare with data predicted in the literature an Excel® spreadsheet for design the artificial elevation method known as conventional Plunger Lift using the method of Foss and Gaul (1965) [1].

At the start of production, the natural lifting process usually takes place. In this method, the fluid can naturally overcome the load losses (friction, hydrostatic tubing weight and acceleration) in the production system. This happens due to the significant difference in pressure between the formation and the wellhead; thus reaching the surface without much need of installation of many artificial equipment and mechanisms. However, when this pressure difference is no longer sufficient to cause the fluid to overcome the load losses and get to the surface, or the flow rates present are no longer economically viable, it is necessary to resort to artificial methods [2,3].

1.1 Artificial Elevation

This mode of elevation is understood as the set of equipment and techniques used for production to occur with economic viability. Artificial elevation is applied when the well can not produce by upwelling or when larger and more economically viable flows can be obtained [4]. There are different methods of artificial elevation: Sucker Rod Pumping, Gas Lift, Electrical Submersible Pump, Hydraulic Piston Pumping, Progressive Cavity Pumping, and Hydraulic Jet Pumping [2].

The conventional method is low cost compared to other methods, as it uses the gas itself from the reservoir to assist in the lifting energy. This happens through the modifications of the pressures in the annulus between the outside of the tubing and the inside of the casing. It has high efficiency because it is applied in oil and gas wells and it is indicated when the greatest interest is in the gas. Conventional Plunger Lift is equipped with a Plunger that acts as an interface between the liquid and the gas that will be produced, which helps to reduce fallback [5].

This method is applied in wells with high gas-liquid ratio (RGL) and it is already used in many countries around the world. Applications include wells with depths of 1,000 to 16,000 ft, producing bottom pressures of 50 to 1,500 psia and liquid flow rates of 1 to 100 bbl/day [6].

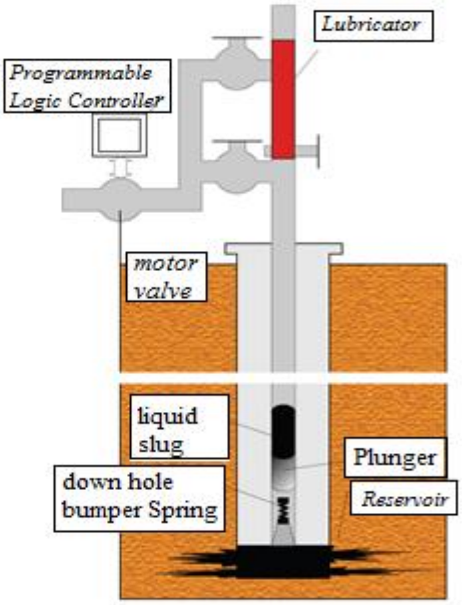

Fig. 1: Conventional Plunger Lift well

Source: GURGEL, 2009

In the conventional system of Plunger Lift is possible to find the Down Hole Bumper Spring. It is responsible for cushioning the Plunger in the descent from the surface to the bottom of the well [7]. The Plunger, responsible for ensuring that the liquid above it can reach the surface and it is produced, as well as avoiding fallback (return of liquid); motor valve, in charge of closing and opening the production line together with the Programmable Logic Controller (CLP) [2].
In Fig. 2 the steps of the Conventional Plunger Lift can be observed and analyzed.

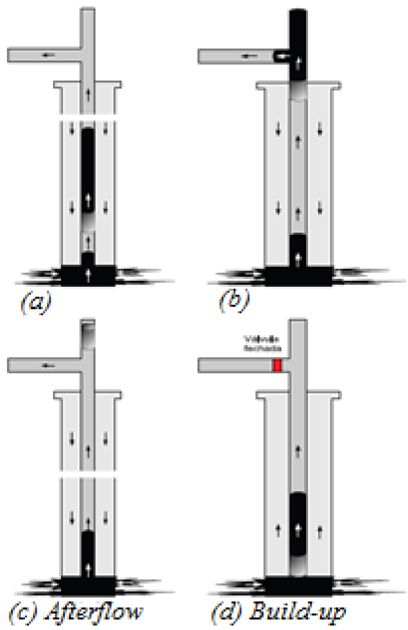

Fig. 2: the steps of the conventional Plunger Lift.

Source: GURGEL, 2009

The conventional method can be divided into stages: piston rise, piston descent and pressure increase [8]. As can be seen in Fig.2, in (a) the first step is the rise of the liquid that will be produced. This step is characterized by the rise of the fluid through the force that provides the displacement of the piston. This is due to the opening of the motor valve, as the pressure in the wellhead decreases and the bottom fluid is raised by the expansion of the accumulated gas in the annulus between the outside of the tubing and the inside of the casing.

With step (b) it can be noted that the piston reaches the wellhead and the oil located above it is produced. The piston, in this case, also helps to prevent fallback (the returning liquid). While the oil is being produced at the wellhead with the help of the piston, more fluid accumulates at the bottom of the well. This oil, which accumulates at the bottom of the well, comes from the reservoir that, due to pressure difference, moves [9]. By analyzing step (c) we can see the Afterflow, that is, the gas production after the Plunger reaches the surface and all the oil that was moved towards the surface with the aid of the Plunger was produced. In this step, the valve is closed and as there was also gas production, by gravity, the Plunger descends rapidly. When reaching the bottom of the well the piston meets the spring, which serves as a shock absorber, as well as with the newly accumulated oil, coming from the reservoir that moved by pressure difference.

At this point, the motor valve is closed so that the internal pressure is increased due to the injection of gas into the annulus between the outside of the tubing and the inside of the casing and, when opened, this new accumulated fluid is raised and produced again, step (d) Build-up [10] . The creation of this spreadsheet is totally beneficial and advantageous for the academy and the petroleum area, since it shows, in an agile, simple and easy way, the conventional Plunger Lift by the method of Foss and Gaul (1965)[1] using the software Excel® .

II. MATERIALS AND METHODS

For the design of the conventional Plunger Lift, an Excel® simulator was developed. The equations of the Foss and Gaul (1965) method were implemented in a spreadsheet and data from a well were taken from the work of Guo, Lyons, Ghalambor (2007) for validation of the simulator.The equations of the Foss and Gaul method (1965) are presented below.

II.1Conventional Plunger Lift Design Equations

For the design of the Plunger Lift was necessary to find the minimum required gas-liquid ratio (RGLmin) and the required minimum casing pressure(Pmin), as well as the maximum liquid production rate (qLmax).

II.1.1 Calculation of the minimum gas-liquid ratio (RGLmin):

Equation (1) was used to calculate RGLmin in 10^3ft^3 / bbl

$$\mathrm{RGLmín} = \frac{V_g}{V_{slug}} \qquad (10^3 ft^3/bbl) \tag{1}$$

Where:

Vg: volume of required gas per cycle, 10^3ft^3;

Vslug: slug volume, bbl.

To calculate the RGLmin it is necessary to determine the value of Vg and Vslug.

II.1.2 Determination of the volume ofrequired gas per cycle (Vg)

The volume of gas required per cycle is given by Equation (2).

$$V_g = \frac{37{,}14\, F_{gs}\, P_{Cavg}\, V_t}{Z\,(T_{avg} + 460)} \qquad (10^3 ft^3) \tag{2}$$

Where:

Fgs: slip factor;

PCavg: average casing pressure, psi;

Vt: gas volume in tubing, 10^3ft^3;

Z: gas compressibility factor in average tubing condition;

Tavg: average temperature in tubing, ° F.

To calculate the value of Vg by the formula quoted above, it is necessary to calculate the Fgs, Pcavg, Vt and Tavg.

II.1.3 Calculation of slip fator (Fgs).

The slip factor was obtained by Equation (3).

$$F_{gs} = 1 + 0{,}02\left(\frac{D}{1.000}\right) \tag{3}$$

Where:

D: depth to plunger, ft.

II.1.4 Calculation of the average gas pressure in the annular space (PCavg).
Equation (4) was used to determine the average gas pressure in the annulus between the outside of the tubing and the inside of the casing.

$$P_{Cavg} = Pmín\,(1 + \frac{A_t}{2A_a})\ (psi) \quad (4)$$

Where:
Pmin: minimum required gas pressure, psi;
At: tubing inner cross-sectional area, in^2
Aa: annulus cross-sectional area, in^2.

II.1.5 Calculation of the annulus cross-sectional area.
The annulus cross-sectional area was obtained by Equation (5).

$$A_a = \frac{(\pi Dic^2)}{4} - \frac{(\pi Dec^2)}{4}\ (in^2) \quad (5)$$

Where:
Dic: inner diameter of the casing, in;
Dec: outside diameter of the production tubing, in.

II.1.6 Determination of the gas volume in tubing, 10^3ft^3.
The gas volume in tubing was calculated by Equation(6).

$$V_t = A_t(D - V_{slug}\ L)\ (10^3ft^3) \quad (6)$$

Where:
At: tubing inner cross-sectional area, ft^2;
D: depth to plunger, ft;
Vslug: slug volume, bbl;
L: tubing inner capacity, ft/bbl.

II.1.7 Calculation of the tubing inner capacity.
Equation (7) makes it possible to calculate the tubing inner capacity.

$$L = \frac{5{,}615}{\frac{A_t}{144}}\ (ft/bbl) \quad (7)$$

Where:
At: tubing inner cross-sectional area, in^2.

II.1.8 Determination of the average temperature in tubing, °F.
To calculate the average temperature in tubing was used the Equation (8).

$$T_{avg} = \frac{T_{wf} + T_{hf}}{2}\ (°F) \quad (8)$$

Where:
Twf: temperature at the bottom of the well, °F;
Thf: temperature at the wellhead, ° F.

II.1.9 Calculation of the required minimum casing pressure, psia
Equation (9) was used to calculate the required minimum casing pressure.

$$Pmín = [P_P + 14{,}7 + P_t + (P_{lh} + P_{lf})V_{slug}].\left(1 + \frac{D}{K}\right)(psi) \quad (9)$$

Where:
Pp: Plunger pressure, psi;
Pt: tubing head pressure, psia
Plh: hydrostatic liquid gradient, psi/bbl;
Plf: flowing liquid gradient, psi/bbl;
Vslug: slug volume, bbl;
D: depth to plunger,ft;
K: characteristic length for gas flow in tubing, ft.

According to Foss and Gaul [1] there is an approximation where Kand Plh+Plf are constant for a given tubing size and aplunger velocity of 1,000 ft/min as can be seen in Table 1 [2].

Table 1: characteristic length for gas flow in tubing (K) and (Plh+Plf)
Author: Adapted by Guo, Lyons e Ghalambor (2007, p. 219)

Dec (in)	K (ft)	(Plh+Plf) (psi/bbl)
2 3/8	33500	165
2 7/8	45000	102
3 1/2	57000	63

II.1.10 Determination of the Plunger pressure, psi.
The Plunger pressure was determinated by Equation (10).

$$P_p = \frac{W_p}{A_t} \text{ (psi)} \qquad (10)$$

Where:
Wp: plunger weight,lbf;
At: tubing inner cross-sectional area, in².
Having calculated all the above information it is possible to determine the minimum gas-liquid ratio (RGLmin).

II.1.11 Calculation of the maximum liquid production rate, bbl/dia
It was obtained by Equation(11).

$$q_{Lmax} = N_{Cmax}\, V_{slug} \text{ (bbl/day)} \qquad (11)$$

Where:
Ncmax: maximum number of cycles per day, cycles/day;
Vslug: slug volume, bbl.

II.1.12 : Determination of the maximum number of cycles per day.
The maximum number of cycles per day was determinated by Equation (12).

$$N_{Cmax} = \frac{1440}{\frac{D}{V_r} + \frac{D - V_{slug}\, L}{V_{fg}} + \frac{V_{slug}\, L}{V_{fl}}} \text{ (cycle/day)} \qquad (12)$$

Where:
D: depth to plunger, ft;
Vslug: slug volume, bbl;
L: tubing inner capacity, ft/bbl;
Vr: plunger rising velocity, ft/min;
Vfg: plunger falling velocity in gas, ft/min;
Vfl: plunger falling velocity in liquid, ft/min.

Having the information and formulas described above, it is possible to calculate the qLmax in bbl/day.

To scale the Conventional Plunger Lift a spreadsheet was created in Excel® 2013 using Equations (1) to (12). The elaboration of this worksheet collaborated in the design of the conventional Plunger Lift, because it was able to make the calculation quicker and easier. The spreadsheet users only need to enter the input variables to get the output variables.

- Input variables:

D	depth to plunger, ft
Dec	outside diameter of the production tubing, in
Dic	inner diameter of the casing, in
Dip	inner diameter of the production tubing, in
K	characteristic length for gas flow in tubing, ft
Plh + Plf	sum of pressures per barrel of liquid, psi/bbl
Pt	tubing head pressure, psia
Tavg	average temperature, °F
Vfg	plunger falling velocity in gas, ft/min
Vfl	plunger falling velocity in liquid, ft/min
Vr	plunger rising velocity, ft/min
Vslug	slug volume, bbl
Wp	plunger weight, lbf
Z	gas compressibility factor in average tubing condition

-Output variables:

Aa	annulus cross-sectional area, in^2.
At	tubing inner cross-sectional area, in^2.
At	tubing inner cross-sectional area, ft^2
Fgs	slip factor
L	tubing inner capacity, ft/bbl
Ncmax	maximum number of cycles per day, cycles/day
Pcavg	average casing pressure, psi
Pmin	minimum required gas pressure, psi
Pp	Plunger pressure, psi
qlmax	maximum liquid production rate, bbl/day
RGLmin	minimum gas-liquid ratio, 10^3ft^3/bbl
Vg	volume of required gas per cycle, 10^3ft^3
Vt	gas volume in tubing, 10^3ft^3
Vt	gas volume in tubing, ft^3

II.2 Example Problem:Conventional Plunger Lift

In order to validate the elaborated worksheet, a case study was selected from the book by Guo, Lyons and Ghalambor (2007) (Table 2).

Table 2: Example Problem

Source: Guo, Lyons e Ghalambor (2007, p. 220)

Variable	Value	Unit
Gas rate	200	10^3ft^3/day
Liquid rate	10	bbl/day
Liquid gradient	0,45	psi/ft
Inner diameter of the production tubing(Dip)	1,995	in
Outside diameter of the production tubing(Dec)	2,375	in
Inner diameter of the casing(Dic);	4,56	in
depth to plunger (D)	7.000	ft
tubing head pressure (Pt)	100	psi
Available pressure	800	psi
Pressure in Reservoir	1.200	psi
Gas compressibility factor in average tubing condition (Z)	0,99	-----
Average temperatura (Tavg)	140	°F
Plunger weight (Wp)	10	lbf
Plunger falling velocity in gas (Vfg)	750	ft/min
Plunger falling velocity in liquid (Vfl)	150	ft/min
Plunger rising velocity (Vr)	1000	ft/min
Slug volume(Vslug)	1	bbl

With the data provided from the well, the Conventional Plunger Lift was designed. The results were compared with those determined by Guo, Lyons and Ghalambor (2007).

III. RESULTS AND DISCUSSIONS

Applying the equations from (1) to (12) it was possible to elaborate a simulator that provides in a practical and simple way the design of the Conventional Plunger Lift. The spreadsheet is easy to understand. The user needs to enter the input variables to get the output variables.

In Fig. 3 it is possible to observe the developed simulator, more specifically the supply area of the input variables.

Input variables Conventional Plunger Lift	
Dec (outside diameter of the production tubing, in)	2.375
Plh + Plf (sum of pressures per barrel of liquid, psi/bbl)	165
K (characteristic length for gas flow in tubing, ft)	33500
Dip (inner diameter of the production tubing, in)	1.995
Vslug (slug volume, bbl)	1
Wp (plunger weight, lbf)	10
D (depth to plunger, ft)	7000
Pt (tubing head pressure, psia)	100
Dic (inner diameter of the casing, in)	4.56
Tavg (average temperature, °F)	140
Z (gas compressibility factor in average tubing condition)	0.99
Vr (plunger rising velocity, ft/min)	1000
Vfg (plunger falling velocity in gas, ft/min)	750
Vfl (plunger falling velocity in liquid, ft/min).	150

Fig.3: Input variables

Source: Authors

After the implementation of the input data, the simulator automatically generates all output results as can be seen in Fig. 4.

Output variables	Conventional Plunger Lift Equations	
At (tubing inner cross-sectional area, in²)	Pi.Dip^2/4	3.1259
Pp (Plunger pressure, psi)	Wp/A	3.19907
Pmin (minimum required gas pressure, psi)	[Pp + 14.7 + Pt + (Plh+Plf)*Vslug]*(1 +D/K)	342.012
Aa (annulus cross-sectional area, in²)	Pi/4*(Dic^2-Dec^2)	11.9011
Pcavg (average casing pressure, psi)	Pmin*(1+(At/2Aa))	386.928
Fgs (slip factor)	1+0.02*(D/1000)	1.14
L (tubing inner capacity, ft/bbl)	5.615/(At/144)	258.664
At (tubing inner cross-sectional area, ft²)		0.0217
Vt (gas volume in tubing, ft³)	At ft^2*(D-Vslug*L)	146.287
Vt (gas volume in tubing, 10³ft³)		0.14629
Vg (volume of required gas per cycle, 10³ft³)	(37.14*Fgs*Pcavg*Vt em 10³ft³)/(Z*(Tavg+460))	4.03457
Ncmax (maximum number of cycles per day, ciclos/dia)	1440/((D/Vr)+((D-Vslug*L)/Vfg)+(Vslug*L)/Vfl)	81.2968
RGLmin (minimum gas-liquid ratio, 10³ft³/bbl)	Vg/Vslug	4.03457
qlmax (maximum liquid production rate, bbl/dia)	Ncmax*Vslug	81.2968

Fig. 4: Output variables

Source: Authors

For a better visualization of the created simulator is given Fig. 5.

Conventional Plunger Lift Using Excel®

This spreadsheet aims to scale the artificial elevation method known as Conventional Plunger Lift by the Foss and Gaul method using Excel® software tools.

Author: Juracy Marques de Jesus Junior

Input variables Conventional Plunger Lift	
Dec (outside diameter of the production tubing, in)	2.375
Plh + Plf (sum of pressures per barrel of liquid, psi/bbl)	165
K (characteristic length for gas flow in tubing, ft)	33500
Dip (inner diameter of the production tubing, in)	1.995
Vslug (slug volume, bbl)	1
Wp (plunger weight, lbf)	10
D (depth to plunger, ft)	7000
Pt (tubing head pressure, psia)	100
Dic (inner diameter of the casing, in)	4.56
Tavg (average temperature, °F)	140
Z (gas compressibility factor in average tubing condition)	0.99
Vr (plunger rising velocity, ft/min)	1000
Vfg (plunger falling velocity in gas, ft/min)	750
Vfl (plunger falling velocity in liquid, ft/min).	150

Output variables	Conventional Plunger Lift Equations	
At (tubing inner cross-sectional area, in^2)	Pi.Dip^2/4	3.1259
Pp (Plunger pressure, psi)	Wp/A	3.19907
Pmin (minimum required gas pressure, psi)	[Pp + 14.7 + Pt + (Plh+Plf)*Vslug]*(1+D/K)	342.012
Aa (annulus cross-sectional area, in^2)	Pi/4*(Dic^2-Dec^2)	11.9011
Pcavg (average casing pressure, psi)	Pmin*(1+(At/2Aa))	386.928
Fgs (slip factor)	1+0.02*(D/1000)	1.14
L (tubing inner capacity, ft/bbl)	5.615/(At/144)	258.664
At (tubing inner cross-sectional area, ft^2)		0.0217
Vt (gas volume in tubing, ft^3)	At ft^2*(D-Vslug*L)	146.287
Vt (gas volume in tubing, $10^3 ft^3$)		0.14629
Vg (volume of required gas per cycle, $10^3 ft^3$)	(37.14*Fgs*Pcavg*Vt em $10^3 ft^3$)/(Z*(Tavg+460))	4.03457
Ncmax (maximum number of cycles per day, ciclos/dia	1440/((D/Vr)+((D-Vslug*L)/Vfg)+(Vslug*L)/Vfl)	81.2968
RGLmin (minimum gas-liquid ratio, $10^3 ft^3$/bbl)	Vg/Vslug	4.03457
qlmax (maximum liquid production rate, bbl/dia)	Ncmax*Vslug	81.2968

Fig. 5: Simulator with input data and output data.

Source: Authors

III.1 Comparison of simulator results with literature.

The Table 3 shows the comparison between the results obtained by the simulator and the results found in the literature according to Guo, Lyons and Ghalambor (2007).

Variable	Simulator	Literature	Unit
At (tubing inner cross-sectional area)	3,1259	3,1259	in^2
Pp (Plunger pressure)	3,1990	3,1990	psi
Pmin (minimum required gas pressure)	342	342	psi
Aa (annulus cross-sectional area)	11,90	11,90	in^2
Pcavg (average casing pressure)	387	387	psi
Fgs (slip factor)	1,14	1,14	
L (tubing inner capacity)	258,66	258.80	ft/bbl
At (tubing inner cross-sectional area)	0,0217	0,0217	ft^2
Vt (gas volume in tubing)	146,287	146,287	ft^3
Vt (gas volume in tubing)	0,1463	0.1463	$10^3 ft^3$
Vg (volume of required gas per cycle)	4,03	4.20	$10^3 ft^3$
Ncmax (maximum number of cycles per day)	81	81	ciclos/dia
RGLmin (minimum gas-liquid ratio)	4,03	4,20	$10^3 ft^3$/bbl
qlmax (maximum liquid production rate)	81,3	81.3	bbl/dia

Table 3: comparison between the results obtained by the simulator and the results found in the literature according to Guo, Lyons and Ghalambor (2007)

Source: Author

It was observed that the tubing inner cross-sectional area (3,1259in^2), Plunger pressure (3,1990 psi), minimum required gas pressure (342 psi), annulus cross-sectional area (11,90 in^2), average casing pressure (387 psi), slip factor (1,14), tubing inner cross-sectional area (0,0217 ft^2), gas volume in tubing in ft^3 (146,287), gas volume in tubing in $10^3 ft^3$ (0,1463 $10^3 ft^3$), maximum number of cycles per day (81 cycles/day) and the maximum liquid production rate (81,3 bbl/day) presented the same results to the literature of Guo, Lyons and

Ghalambor (2007) when considered with the same decimal places.It is also noted that the tubing inner capacity (258,66ft/bbl) anda theminimum gas-liquid ratio (4,03 10^3ft3/bbl) presented values close to those found by Guo, Lyons and Ghalambor(2007, p. 220). The values available in the literature are equal to:tubing inner capacity (258,80 ft/bbl) and the minimum gas-liquid ratio (4,20 10^3ft^3/bbl).

The values that have suffered a slight difference can be explained by the accuracy and precision of the Excel® program, which program counts all the decimal places. In addition, you do not always get so much accuracy when the same calculations are done manually.As it is observed, the simulator is of easy application and interpretation. It provides answers that are close to or equal to those found in the literature. This validates the simulator developed in Excel®.With this simulator, professionals in the field can save time when they are working with this method. In addition, the spreasheet will stimulate the content and will aim to stimulate the development of other activities that decomplex the teaching learning.

IV. CONCLUSION

The aim of the present work was to develop a spreadsheet in Excel® software that allowed the design of conventional Plunger Lift using the method of Foss and Gaul (1965). It was possible to conclude that: with the comparison, the worksheet was validated, since the values obtained were the same or very close to those found in the literature of Guo, Lyons and Ghalambor (2007).In this way, this work is demonstrated with great importance in the process of teaching learning, because it facilitates this process once it has been validated.

A future suggestion for the continuation of this research is to develop a simulator for the conventional Plunger Lift that can meet different compressibility factors (Z) using, for example, the Beggs and Brill equation.

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