IOP Conference Series: Earth and Environmental Science

Improved method on hydraulic power calculations for conventional sucker rod pumping system

To cite this article: O E Mwangupili *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **431** 012026

IOP Conf. Series: Earth and Environmental Science **431** (2020) 012026 doi:10.1088/1755-1315/431/1/012026

Improved method on hydraulic power calculations for conventional sucker rod pumping system

O E Mwangupili[1, 2], P Chunsheng[1], C Bululu[1], S L Nyanswi[1] and S M Muya[2]

1 China University of Petroleum (Huadong), Qingdao, China
2 Mbeya University of Science and Technology, Tanzania
E-mail: Osmund94@gmail.com

Abstract. The annual energy consumption of suck rod pumping units in China is more than 10 billion kWh, but the average efficiency is only about 25-31%. Limited information is known, about the efficiency of various components of the pumping unit. The current methods for calculating the hydraulic power neglect the effect of friction and free gas. This research introduces an improved method for calculating hydraulic power which takes into account the effect of friction and free gas. The model was obtained from the product of two parameters which were, predicted pressure increased by the downhole pump and predicted flow rate. The pressure increased by the pump was obtained by the nodal analysis approach in which the concepts of multiphase flow were included. The Computer program was developed and all calculations in this paper were computed by this program developed from python programming language version 3.5. This model was compared with the previous models and showed that, the previous models underestimated the hydraulic power since the influence of gas and friction were not included.

1. Introduction

When there is inadequate pressure in the reservoir to lift the produced fluid to the surface, artificial lift is inevitable to maintain its production life [1], [2]. Sucker rod pumping system is the oldest of all artificial lift systems, covers approximately 71% of all. It is powered by the electric motor which supplies mechanical energy to the motor shaft then utilizes a subsurface pump to lift reservoir fluid from the bottom of the well to the surface [3], [4].

Beam pumping units have been leading the mechanical oil-production equipment regardless its disadvantages including low efficiency and high energy consumption, but there is a certain degree of difference according to various well conditions. The sucker rod pumping system is limited to severe friction in deviated wells, solids, sensitive problems in gassy wells, deep wells due to rod capacity and offshore operations due to its huge size [5], [6].

According to the related statistics, power consumption makes up about one-third of the total costs in oilfield production. Power consumed by beam pumping unit accounts for nearly 80% of the total. At present, there are more than 100,000 beam pumping units in China, and the total installed capacity is more than 3500 MW, consuming more than 10 billion kWh each year. Therefore, there is a huge potential for energy savings of the beam pumping units [5].

1.1. System efficiency

The ratio of the hydraulic power to the net motor input power is defined as the total system efficiency. This value accounts for the losses in the motor, belts, pumping unit gearbox, pumping unit bearings, rod string, liquid, viscous losses, tubing back pressure, stuffing box friction, and other losses.

IOP Conf. Series: Earth and Environmental Science **431** (2020) 012026 doi:10.1088/1755-1315/431/1/012026

Efficiency measurements are useful in identifying high operating cost components of a beam pumping system. For example, a well may have a relatively high lifting cost due to low average motor efficiency, high mechanical losses in the pumping unit, significant rod/tubing friction, high tubing pressure or many other problems that can be identified by analyzing efficiencies.

System efficiency of the sucker rod pumping systems is contributed by surface and subsurface efficiencies. This research focused on the hydraulic power which is essential for calculating a subsurface efficiency.

As for a conventional sucker-rod pump, the main factors that affect its pumping performance in wells are volumetric efficiency, stroke loss, leakage, and high oil formation volume factor [7].

1.2. Subsurface system efficiency

Subsurface system efficiency of the beam pumping unit is the ratio of the hydraulic power to the polished rod power. Hydraulic Power is the power required to lift the fluid from downhole to the surface, usually regarded as a net lift. Net lift is the height to which the work provided by the pump alone lifts the produced fluid, similarly the depth at which the pump is set is referred to as a net lift.

The following are the components of the subsurface system efficiency; sucker rods, tubing, downhole pump, pump dynamometer card, polished rod and gas separator. Subsurface losses can be grouped into the following categories; frictional losses in the stuffing box, frictional losses between the rods and tubing, hydraulic losses which include fluid friction and pump leakage. The mechanical energy required to operate the polished rod at the surface is defined as the sum of the useful work performed by the pump and all the downhole energy losses detailed previously, i.e., those occurring in the sucker-rod pump, the rod string, and the fluid column.

Energy efficiency of the downhole components of the pumping system is characterized by the relative amount of energy losses in the well.

$$\eta_{sub} = \frac{P_{hyd}}{PRP} \times 100\% \quad (1)$$

where: η_{sub} –Subsurface efficiency, %; P_{hyd} –hydraulic power, kWh; *PRP*-Polished Rod Power, kWh.

The characteristics of the reservoir used in this research were, the reservoir is old, which means, it is the mature reservoir with the high permeability, high water cut and excellent reservoir deliverability. For cost reduction and performance improvement, the integrated analysis and management of the pumping wells are inevitable [8].

Currently, there is no precisely method of studying an oil well system and estimating the hydraulic power of sucker rod pumping system. The current methods of calculating the hydraulic power neglect the effect of friction and the effect of free gas. Therefore this research introduced the improved method for calculating the useful power developed by the subsurface pump.

2. The improved calculation method for predicting hydraulic power

This model was obtained from the product of two parameters which were; the predicted pressure increase by the downhole pump and the predicted flow rate. Basically this model encompassed the effect of friction and the presence of free gas which were not incorporated in the previous models for calculating hydraulic power. The frictional energy losses comprised of hydraulic frictional losses of the fluid as it flows between rods and tubing.

2.1. Predicted pump discharge pressure and pump intake pressure

Pressure gradient prediction requires determination of individual phase velocities, densities, viscosities, and, surface tension at different pressures and temperatures. In dynamic conditions of multiphase flow in pipes, the pressure and temperature of the fluids change continuously, and mass transfer occurs between the liquid and the gas phases.

As pressure decreases below bubble point in the direction of flow, gas evolves from solution in the oil increasing the gas velocity, the oil density and viscosity. Such flow and fluid properties changes are predicted with either compositional or black-oil models.

In this research black oil model was used to determine fluid physical properties. The assumption made in the black oil model was that, at any fixed temperature, pressure, API gravity of the liquid phase and specific gravity of gas, the liquid phase had a fixed gas solubility and formation volume factor.
Most black oil models that relate fluid physical properties can be determined by using Pressure-Volume-Temperature (PVT) cells. McCain Jr presented the fluid physical properties used in this paper. The calculated fluid physical properties were used to predict the pump discharge pressure and the pump intake pressure [9].
Beggs and Brill correlation was used to predict the flow patterns, pressures drops and finally pump intake pressure and discharge pressure. Beggs and Brill model was chosen for this research because, the model considered the inclination angles, the influence of free gas and the friction of the fluid being pumped when predicting pressure.
The total depth of the oil well was divided into segments, each segment being 100m long. The pressure gradient was determined in each of the segment starting from the top (well head) and then added to each successive segment; hence the pump discharge pressure was determined. On the other hand, the pump intake pressure was obtained starting from the fluid level to the pump intake in the annulus between tubing and casing.
The pressure increased by the pump was determined from the difference between the pump discharge pressure and pump intake pressure as shown in the equation (2).

$$P_u = P_d - PIP \tag{2}$$

2.2. Predicted flow rate
Due to effects of stroke loss, pump fillage, leakage and formation oil volume factor, the actual displacement of pump is generally less than the theoretical displacement. Hence pump efficiency was introduced to obtain the actual pump displacement.
Predicted flow rate was determined from the parameters designed by Dong and the pump efficiency [10]. Pump efficiency was found from the pump discharge coefficient simulation model given by Yao [11].

$$Q = 1440 \times \frac{\pi}{4} \times d_p^{\ 2} s n \eta \tag{3}$$

where: Q –Production rate, m^3/d; d_p –Plunger diameter, m; s –Stroke length, m; n –Pumping speed, min^{-1}; η –Pump efficiency
The volumetric efficiency of the downhole pump depends principally upon the fillage of the barrel. This in turn is related to the presence of gas, the viscosity of the fluid being pumped and the pumping speed. The pump efficiency was calculated by using equation (4). This parameter was introduced in this research to account for the inefficiencies (losses) of the downhole pump.

$$\eta = \eta_S \eta_F \eta_L \eta_V \tag{4}$$

$$\begin{cases} \eta_S = \dfrac{s_P}{s} \\ \eta_f = \dfrac{1-KR}{1+KR} \\ \eta_L = \dfrac{f_p s \eta_S \eta_F \eta_V - \Delta Q}{f_p s \eta_S \eta_F \eta_V} \\ \eta_L = \dfrac{1}{(1-f_w)B_{ops} + f_w B_{wps}} \end{cases} \tag{5}$$

where: η_s –The effective stroke coefficient of pump, plunger; η_F –The coefficient of fullness; η_L –Pump coefficient of leaking; η_V –The volume ratio of gas dissolution crude oil under bottom pressure; s_p –Pump plunger stroke length, m; R –Pump intake gas fluid ratio, m^3/m^3 ; K –Clearance coefficient; s_o –The clearance length, m ; B_{ops} –The crude oil volume ratio in the pump intake; B_{wps} –The water volume ratio in the pump intake; ΔQ –The fluid leakage between pump plunger and pump barrel in one stroke.

$$K = \frac{s_o}{s} \tag{6}$$

$$R = (1 - f_w)(R_p - \alpha P_s)\frac{P_{st} T_s Z_s}{T_{st} P_s} \tag{7}$$

$$s_p = s - e_t - e_r + e_o \tag{8}$$

where: R_p –Producing gas-oil ratio, m^3/m^3; α –Dissolving coefficient, (m^3/m^3/MPa); P_{st} – Standard pressure, MPa; T_{st} – Standard temperature, K; T_s –Standard temperature, K; Z_s –Gas deviation factor in the pump intake; P_s –Pump intake bottom pressure (absolute), MPa; s_p –Plunger stroke length, m; e_r –rod stretch, m; e_t –tubing stretch, m; e_o -Plunger over travel, m . Predicted hydraulic power was found from equation (2) and (3).

$$P_{hyd} = \frac{Q(P_d - PIP)\times 10^{-3}}{86400} \tag{9}$$

The Subsurface pump of the conventional sucker rod pumping system is powered by the reciprocating rod string, which increases the potential energy of the liquid being pumped. The logic of the model is that, the effective power of the sucker rod pumping system is the power produced by the subsurface pump. When the pressure increased by the downhole pump and the amount of the liquid pumped are given, the hydraulic (effective) power can be determined from the product of these two parameters. In this model the pressure increased by the downhole pump involved the effect of free gas in which the multiphase flow concepts were taken into consideration. The two phases were liquid phase (water and oil) and gas phase. This means the concept of liquid hold up was introduced when the mixture density was calculated. In addition to that, the effect of friction was also included.

3. Computer program

All the calculations used in this research were computed by the computer programming codes. The computer programming language used was python version 3.5. Python is a high-level programming language which was designed for code readability; it uses whitespace indentation to set the limits of code blocks rather than curly brackets. It can express the concept in few lines of codes than C++ or Java.

Figure 1 demonstrates the procedure for computing hydraulic power by the developed program. The calculations began with the inputting data, and then from the data, the average pressure and temperature at the well surface were obtained. The average pressure was obtained by first estimating pressure drop and the estimated pressure drop was divided by two and added to the surface pressure (downhill). The next step involved making PVT calculations to determine the fluid physical properties, from the relevant correlations at the calculated average pressure and temperature. The fluids were oil, gas and water. The calculated physical properties were; specific gravity, gas compressibility, density, viscosity, gas solubility, solution gas, formation volume factor and surface tension. As soon as fluid physical properties were calculated, the slip density of the pumped fluid (multiphase) was determined.

The slip density was found from the superficial velocities, liquid hold up, Froude number, velocity number and flow patterns.

Reynolds number was then calculated to determine type of the flow (laminar or turbulent), followed by determination of the frictional pressure drop. The correlations used for calculating frictional pressured drop were; Drew, Koo and McAdams and Zigrang and Sylvester. The pressure drop in the segment due to elevation was calculated where the depth was equal to the length of the node, 100m. The pressure drop due to acceleration was set equal to zero. The total pressure drop was obtained by summation of the three pressure drops as shown in equation (10).

$$\left\{\left(\frac{dp}{dL}\right)_T = -\left(\frac{dp}{dL}\right)_f - \left(\frac{dp}{dL}\right)_{el} - \left(\frac{dp}{dL}\right)_{acc}\right. \qquad (10)$$

Beggs and Brill correlation was an iterative process. When the calculated pressure drop was not equal to the estimated pressure drop, the computed pressure became the new estimated pressure drop. The procedures were repeated to achieve the condition where the estimated pressure drop equalled to the calculated pressure drop. The condition was met and the procedures were repeated to calculate the pressure drop of the next segment. When the pressure drops in each node was calculated, the pump intake pressure and pump discharge pressure were calculated. The pump discharge pressure was calculated by summing the surface pressure and all segments (nodes) pressure drops from the well head to the pump depth. On the other hand, the pump intake pressure was obtained starting from the fluid level to the pump intake in the annulus between tubing and casing. Finally, the hydraulic power was obtained by using equation (9).

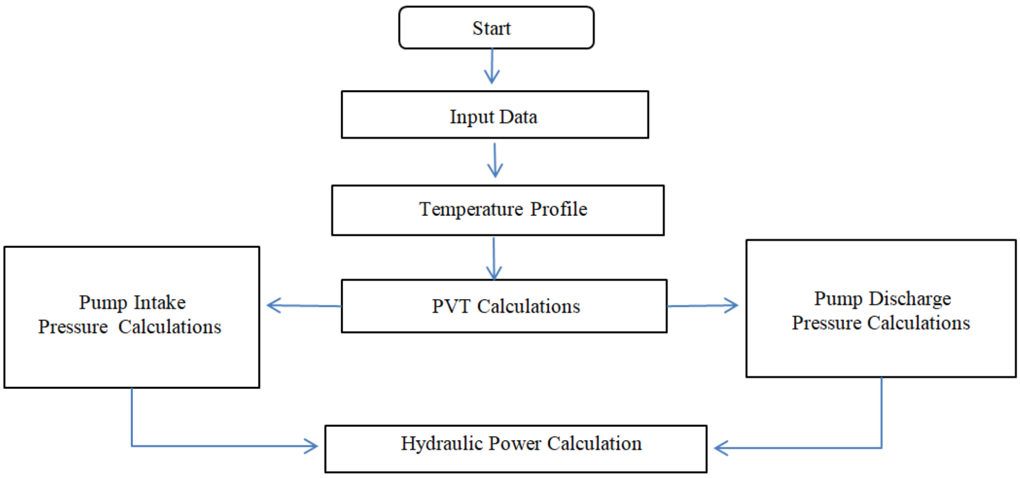

Figure 1. Computer program algorithms for the hydraulic power calculations.

4. Discussion

In this research the improved model considered all concepts that were discussed in the previous models for calculating the subsurface hydraulic power. In addition to that, the improved model included the effect of friction and the free gas. The frictional energy losses were the hydraulic frictional losses of the fluid as it flows between rods and tubing.

The previous hydraulic power models used were; Lea and Minissale, PRC Trade Standard and Takacs model. These models, neglected the effect of friction and the free gas when calculating the useful power developed by the subsurface pump [12], [13], [14]. These models are not suitable for gassy and high friction oil wells. The method for calculating the pressure increased by the pump involved the nodal pressure approach; this means that, the pressures such as pump discharge pressure was calculated starting from the well head to the pump location. Frictions energy losses in all segments were added together, this impacted into higher values of predicted hydraulic power as shown in table 1.

On the other hand, the presence of gas lowers liquid density, which reduces the hydraulic power. In this study the impact of gas was not higher since the data used was from the mature reservoir which had high water cut, less free and dissolved gases.
Table 1 shows the comparisons between the improved model and the previous models. It can be perceived that; the developed model is the advanced model. The model takes into consideration, the factors that were left in the previous models. The model incorporated the actual displacement of the pump instead of using theoretical displacement; in addition to that it also included effect of friction and the effect of gases.
It can be observed that, from figure 2, the Lea and Minassale model predicted values which were almost equal to those of the PRC Trade model. The values were less than those in this proposed model because the latter included the effects of friction and gas. However, they were greater than values in Takacs model, because in Takacs model the well head pressure was excluded in the calculations for the pressure increased by the pump.

Table 1. Hydraulic power (kW) comparison for different models.

Well Name	Hydraulic power calculations model			
	New Predicted	Takács	Lea and Minissale	PRC Trade Standard
A	2.13	1.83	2.02	2.01
B	1.08	0.86	1.03	1.03
C	1.99	1.45	1.72	1.71
D	6.19	5.23	5.99	5.97
E	0.92	0.70	0.83	0.82

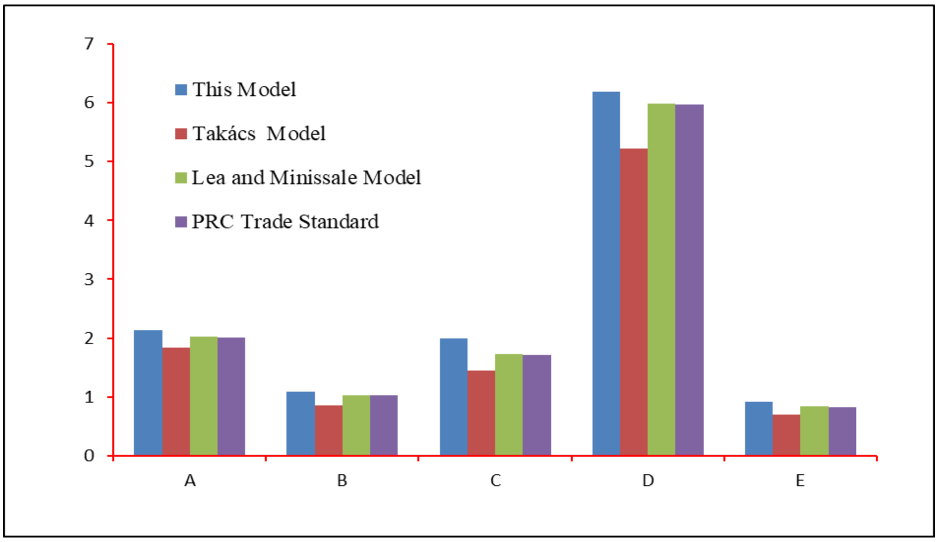

Figure 2. Hydraulic power comparisons between proposed model and previous models.

5. Conclusion

Volumetric efficiency of the pump depends primarily upon the fillage of the barrel. This in turn is related to number of factors such as the presence of gas, the viscosity of the fluid being pumped and the pumping mode. In this model, the effects of stroke loss, pump fillage, leakage and formation oil volume factor, were included for an accurate prediction of the actual pump displacement since, it is generally less than its theoretical displacement.
In this research, the impact of free gas in reducing downhole hydraulic power was considered. However, the presence of gas can contribute to an input energy into the system. Energy is released

during lifting process; the gas expansion power released is the sum of dissolve-gas expansion power and free-gas expansion power. The gas expansion power is the energy that should not be overlooked. The energy plays an important role in the process of lifting, reduces the input power and enhances the system efficiency. In this study the gas expansion power was not considered, nevertheless this parameter is very important, and should not be ignored in the calculation of the total system efficiency. The pump's useful power was obtained as a result of the product of the pressure increase by the downhole pump and production rate. The model used to calculate the pressure increase by the subsurface pump, involved the multiphase flow concepts. This means the concept of liquid hold up was introduced when the mixture density was calculated. In addition to that, the effect of friction was also included in the same model.

Lastly the previous models proved to be less suitable for gassy and high frictions wells since the effect of gas and friction were not included in the models. When this model was compared to the previous models, the proposed model predicted higher values of hydraulic power. Higher values of hydraulic power were because of the effect of frictions.

6. References

[1] Lv H, Liu J, Han J and Jiang A 2016 An energy saving system for a beam pumping unit *Sensors* (Switzerland) vol. **16(5)** 685 http://dx.doi.org/10.3390/s16050685

[2] Goswami, Dr. Tej Singh Chouhan "Artificial Lift to Boost Oil Production", International Journal of Engineering Trends and Technology (IJETT), V26 (1), 1-5 August 2015. ISSN: 2231-5381. www.ijettjournal.org. published by seventh sense research group

[3] Xing, M, and Dong, S 2015 A New Simulation Model for a Beam-Pumping System Applied in Energy Saving and Resource-Consumption Reduction *SPE* doi: 10.2118/173190-PA

[4] Brown K E 1982 Overview of Artificial Lift Systems *SPE* doi: 10.2118/9979-PA

[5] Ziming F, Jindong Z, Huibin G and Yunwei L 2013 Research on Energy-saving Technology of Crank Balanced Pumping Unit *RJASET* 6(**22**): 4152-4157 doi: 10.19026/rjaset.6.3525

[6] Podio A L, McCoy J N and Collier, F 1994 Analysis of Beam Pump System Efficiency from Real-Time Measurement of Motor Power *SPE* doi:10.2118/26969-MS

[7] Wang H, Zheng, S and Yang, D 2015 Designs and Application of Multiphase Sucker-Rod Pumps in Wells with High Gas-Oil Ratios *SPE* doi:10.2118/173963-MS

[8] Podio A L, McCoy J N, Becker D, Rowlan, L and Drake, B 2001 Total Well Management II *SPE* doi:10.2118/67273-MS

[9] McCain Jr, W D 1991 Reservoir-Fluid Property Correlations-State of the Art (includes associated papers 23583 and 23594 *SPE* **6(02)** 266-272 doi:10.2118/18571-PA

[10] Dong, S M 2003 Computer Simulation of Dynamic Parameters of Rod Pumping System Optimization *Petroleum Industry Press*(Beijing) 53–72

[11] Yao, C D 2005 Computer simulation for enhancing system efficiency of rod pumping well ActaPetrol. Sinica, **26(4)**: 106-110.

[12] Lea, J F and Minissale J D 1992 Beam pumps surpass ESP Efficiency *Oil&Gas Journal*

[13] Takacs, G 2015 Sucker-rod pumping handbook: production engineering fundamentals and long-stroke rod pumping Gulf Professional Publishing 247-376 ISBN 9780124172043 https://doi.org/10.1016/B978-0-12-417204-3.00004-2

[14] Zhang X, Wu X, Han G, An Y and Wu D 2013 Research on the Calculation Method of System Efficiency Considering Influence of Free-Gas *RJASET* **5(18)** 4552-4555

Acknowledgments

This research was supported by "Natural Science Foundation of China" (NO.51874339 and N0.51904320).