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Simulation of single-phase liquid flow in Progressing Cavity Pump

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ABSTRACT

Progressing Cavity Pump (PCP), also known as Moineau pump, is an artificial lift method often used for pumping high viscosity and high solids content fluids from producing wells. Although, PCP has been effectively adopted in oil industry for decades, there is a lack of understanding the effect of its design parameters and operating conditions on the pump performance. The objectives of this study are to develop a model for predicting an actual multi-lobe PCP performance, and to investigate pump performance through simulating single-phase liquid flow behavior. The proposed model is a combination of two existing models in the literature, namely an analytical model to predict the theoretical pump performance, and a slippage model. The proposed model can be used not only to predict the actual multi-lobe PCP performance, but also to optimize pump design under given operating conditions. To validate the modeling results, an experimental study was carried out using a commercial PCP. The experiments were conducted with liquid viscosities ranging from 0 to 450 cp, rotational speeds ranging from 0 to 300 RPM, and pump differential pressures ranging from 0 to 300 psi. The validation study revealed satisfactory results and reasonable match between the model predictions and experimental results. Using the developed model, an extensive sensitivity analysis was performed, which suggested that higher viscosity, in most of cases, minimizes pump slippage. In addition, if the pump clearance is smaller than a specific value, then the effects of differential pressure and liquid viscosity on the pump performance are minimal. Similarly, if the pump clearance is less than a specific value, then a pump with higher stator lobe number will deliver higher actual pump rate. The results of this study are not only important for manufacturers to optimize PCP design, but also for operators to improve PCP operational pump performance and pump efficiency.

1. Introduction

Artificial lift methods are usually applied at latter time of a reservoir life to maximize production rate and increase reservoir recovery. There are several artificial lift methods, for example gas lift, pump assisted lift (ESP, PCP, etc.), and plunger lift. Each method has its own advantages and limitations. The selection of an artificial lift method is mainly based on reservoir and fluid properties, available infrastructure, well conditions, and project economics. Among those artificial lift methods, PCP stands out to be a good candidate for heavy oil production including all the recovery methods used in heavy oil developments, such as Cold Heavy Oil Production with and without Sand (CHOPS, CHOP), Cyclic Steam Stimulation (CSS), and steam flooding.

A PCP is a positive displacement pump, which moves fluids by displacing a fixed amount of fluid in each cavity created between rotor and stator. A conventional 1:2-lobe PCP consists of a single helical rotor, and a double threaded helical elastomer, which is always in contact with a single helical rotor (Fig. 1). As the rotor rotates eccentrically inside the stator, fluid is moved helically along the pump from the intake to the discharge. Therefore, PCP has several advantages compared to other pumping methods, such as significant flexibility of fluid viscosity (from gas to very pasty fluid), low pulsation offering more accurate fluid metering, no valve inside the pump which prevents gas lock, low suction pressure requirement, high tolerance for produced abrasive solids, and more suitable for shear sensitive liquid.

Although single-lobe PCP design and operation is relatively understood, multi-lobe PCP has more complex geometry and fluid flow behavior, in addition to elastomer behavior under high pressure and temperature conditions. Determination of the theoretical pump rate is a first step in predicting PCP performance, which requires estimating liquid slippage to predict the actual

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Nomenclature

b	Length of the equivalent channel (L)
d	Diameter of the semicircle (L)
e	Eccentricity of the pump (L)
K	Stator lobe number
L	Depth of the equivalent channel (L)
N	Pump rotational speed, revolution per minute (RPM)
P	Pitch length of the pump rotor and the pump stator, (L); pressure
Q	Pump capacity, L^3/t
r	Radius of the generator circle (L)
S	Slippage
x_n, y_n, z_n	Three components of each point on the modified hypocycloid
w	Clearance between the rotor and the stator, (L); width of the equivalent channel, (L)

Subscripts

a	Actual
H	Hydraulic
L	Longitudinal
n	New
p	Pump
r	Rotor
T	Transversal
Total	Total slippage
th	Theoretical
s	Stator

Greek letters

Δ	Differential
θ	Angle between the x-axis and the line connected two center points of the base and generator circle.

performance of the pump. Internal liquid slippage is the difference between the theoretical pump rate and actual pump rate under a particular set of operating conditions. In other words, the internal liquid slippage is a countercurrent flow caused by insufficient displacement between the rotor and stator and it is critical in optimizing PCP design and performance under downhole conditions. In this study, Nguyen et al. (2014) model of theoretical pump rate is combined with a slippage model developed and extended by Vetter and Wirth (1995), Gamboa et al. (2003), Becerra and Mena (2007), Paladino et al. (2008) and Pessoa et al. (2009).

2. Modeling

Nguyen et al. (2014) developed a pure theoretical model based on the three dimensional vector approach to calculate theoretical pump rate for a multi-lobe PCP, given as,

$$Q_{th} = \left[2\pi e^2(K-2)+4de\right]P_s(K-1)N \tag{1}$$

where d (in.), e (in.), K, P_s (in.), N (RPM), and Q_{th} (in^3/min) are the semicircle diameter, pump eccentricity, stator lobe number, stator pitch length, pump rotational speed, and volumetric flowrate, respectively. Eq. (1) shows that the theoretical pump rate is only function of pump geometry and speed, and is independent on pump intake and discharge pressures, fluid temperature, fluid viscosity, and pump clearance between rotor and stator. The actual pump performance depends strongly on these parameters and will be modeled based on the total internal slippage.

As mentioned in the Introduction section, the total internal slippage model for single-lobe PCPs was developed and extended by five different papers in a period from 1995 to 2009. The authors modeled the total internal slippage for a single-lobe PCP by dividing it into two components: longitudinal slip and transversal slip as shown in Fig. 2. According to Gamboa et al. (2003), the transversal slip takes place through the sealing lines formed at straight sections of the stator. The longitudinal slip takes place through the sealing lines at fixed positions of the rotor, where this element is located at semi-circular sections of the stator. The slippage model assumed the geometry of the internal slip flow is equivalent to a flow through a channel at which the cross sectional-area is a rectangle. The two equivalent rectangular shapes in determining the longitudinal slip and transversal slip are defined in Fig. 3.

In Fig. 3, w is the clearance between the pump rotor and stator; b_L and b_T are the surface length of longitudinal and transversal slips, respectively; L_L and L_T are the channel depths of longitudinal and transversal slip, respectively. To define the channel depth, Paladino et al. (2008) and Pessoa et al. (2009) used an iterative computational approach to determine L value, which resulted in $L_L = L_T = 1.65$ mm. These values will be used as inputs in all simulation runs in this study. As defined above, b_L is the perimeter of the semicircle with the diameter of d and, hence, it can be expressed as,

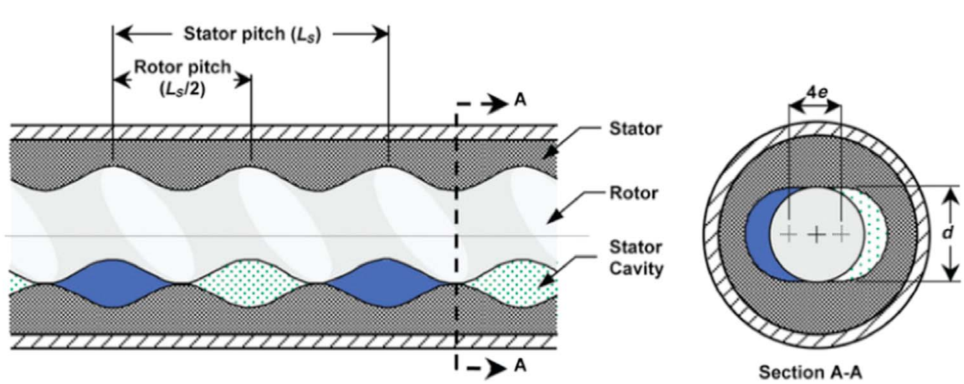

Fig. 1. Schematic of a single-lobe PCP (PetroWiki: Progressing Cavity Pumping System).

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