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FLUID FLOW HYDRODYNAMIC MODELING IN THE PASSAGE OF AN OIL ARTIFICIAL LIFT PUMPING UNIT

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ABSTRACT

The study of the two-phase flow through the standing and traveling valves used in an oil artificial-lift pumping unit is presented. The investigation aimed to determine the effects the gaseous phase may cause on the pump volumetric efficiency. Data obtained on a specially designed test facility is presented and analyzed as a first step before developing a semi-empirical model to predict the performance of the pump under two-phase flow conditions. Preliminary results, based on one-phase and two-phase runs, demonstrate important features introduced on the pump performance once the gas-phase is included in the process.

INTRODUCTION

Petroleum in its natural condition is associated with gas and water. If the well is subjected to a method of artificial-lift pumping, this gas could be suctioned by the pump causing a decay in the volumetric efficiency. This effect could reach to the point in that the lifting method does not fulfill its objective and stop to be economically profitable.

The interference of gas in the mechanical pumping process not only diminishes the efficiency of the pump, but it also complicates its prediction. This research seeks to study the behavior of the subsurface pump managing mixtures of crude oil and gas, and its effects on the volumetric efficiency.

THEORETICAL FRAMEVIEW

There are many studies about the volumetric efficiency of mechanical pumping units managing mixtures of petroleum and gas. Most of these works are of qualitative character and few of them introduce equations that describe the process. Next paragraphs give a concise description of those considered the most relevant to this research.

Connally, Sandberg and Stein (1953), described in a qualitative way, the result from a great number of experiments related to volumetric efficiency. They concluded that main cause of the drop of volumetric efficiency is due to the presence of free gas in the pumped liquid.

Haddenhorst and Horn (1962) developed equations to calculate the rate of theoretical pumping when mixtures of petroleum and gas are used.

$$VE = \frac{1}{1-s}\left(\frac{1}{m+1} - \frac{s}{m\,n\sqrt{P1/P2}+1}\right) \qquad (1)$$

where:

VE =pump volumetric efficiency
s = pump clearance
m = ratio of free gas volume to oil volume in the pump barrel at suction pressure
P1 = suction pressure
P2 = discharge pressure
n = ratio of specific heats of the gas, Cp/Cv

This model is found to over-predict the volumetric efficiency.

Ionel (1983) studied the influence of gas in deep wells using mechanical pumping, taking into account the solubility of the gas and the separation for gravity of the gas and the petroleum, being his equation:

$$VE = \frac{1}{1-s}\left(\frac{1}{z}\frac{nR+z}{nR+1} - s\right)\left(f + \frac{z}{nR+z}\right) \qquad (2)$$

where:

$z = k\sqrt{P2/P1}$
k= the adiabatic coefficient of the compressed gas
R= gas-oil relationship in the pump barrel

Inconvenience of the model is the assumption that all measurement errors and uncertainties reported in the pilot tests were reflected in the correlation of f and n.

Schmidt and Doty (1986) developed an analysis system for mechanical pumping, becoming one of those more used and well-known. They described the problem of volumetric efficiency of the pump, delimiting that major influence on the decrease of the volumetric efficiency is the presence of gas in the pumped fluid.

$$VE = \frac{Qo + Qw}{QoBo + QwBw + \frac{RQoBg}{5.614}} \qquad (3)$$

where:

Qo = oil volumetric flow rate at the surface
Qw = water volumetric flow rate
Bo = oil formation volume factor
Bg = gas formation volume factor
Bw = water formation volume factor

Cox and Williams (1989) similarly affirmed that gas handled by pump is the one that affects, by large, its volumetric efficiency.

Tebourski (1993) tried to precisely predict the volumetric efficiency and the work of an subsurface mechanical pump that handles mixtures of gas and liquid. His study was based on the analysis of gas behavior inside the barrel of pump, classifying it according to the following characteristics: gas compressibility, separation due to the gas-liquid gravity and gas solubility in the oil.

Taking into account these factors, the author developed a new equation for the volumetric efficiency of an subsurface pump. This equation generally predicts smaller volumetric efficiency than that neglecting gas behavior, being the simplified equation:

$$VE = \frac{1}{1 - si}\left(\frac{1}{1 + GLRi} - si\right) \qquad (4)$$

where:

GLRi = the pump inlet gas-liquid ratio.

$$si = \frac{\text{volume of the pump clearance}}{\text{total volume of the pump barrel}}$$

Therefore, this equation represented an easy and very precise formula to calculate the volumetric efficiency in mechanical pumping handling mixtures of gas and liquid.

Robles (1996) developed an algorithm to calculate volumetric efficiency of the subsurface pump in a very practical manner. In the analysis, he took into account the harmonic movement of piston, pump filling, sensibilities in function of the dead space between valves and compression radius, effect of discharge pressure in the production pipe, regarding rod stresses and volumetric efficiency, and effect of gas separation onto the volumetric efficiency.

Antecedents of the facility used in this research

The first experimental study on the operation of subsurface pumps, carried out in the Laboratory of Mechanical Pumping at INTEVEP was made by Busom (1987), followed and improved by Pascual and Rivas (1990), who implemented a position detection system for valves. These works were only limited to one-phase flow (water) without measuring neither pressure nor flow. Coello (1994) re-designed the facility in such a way that the pump lodged inside a casing and simulated conditions of two-phase flow (air-liquid).

Bianchi and Mijares (1995) used the facility for the determination of volumetric efficiency of subsurface pumps, operating under inclined conditions and handling two-phase flow. The study was qualitative and up to now data acquisition has not been obtained along the pump reciprocating process.

PROPOSED APPROACH

The nature of this preliminary report is to gain confidence in the use of the subsurface pump test facility, and obtain a basic understanding of flow behavior, in terms of its pressures at key locations. This included inlet pressure, pressure in the space between valves and pump discharge pressure along the whole cycle of pumping.

Taking into account that pressures inside the pump are directly related to the load the pump handles, part of the results is presented in dynagraph charts. For this reason, it was necessary to modify the facility in such a way to allow the quick, continuous and accurate measurement of pressures, flow, time and position along the whole reciprocating system. Thus, a data acquisition system, three pressure transducers and one flow meter were installed.

The pressure was measured at the following locations:

Pressure 1 (P1): pump inlet (placed exactly at the inlet of the standing valve).

Pressure 2 (P2): discharge (placed after the surface stuffing box).

Pressure 3 (P3): discharge of the standing valve (this pressure together with suction pressure generates the differential of pressure able to register the opening of valve)

Rod position is measured with a position sensor.

Based on the bibliographical review, variables to be included in the study were: gas-liquid ratio, pumping speed, piston stroke, dead space between valves, liquid viscosity and suction and discharge pressures.

Test Facility
(Subsurface Pump Test Facility)

Experiments were performed at PDVSA-Intevep Subsurface Pump Test Facility (see Fig. 1).

The main features of the facility are:

- Transparent pipelines.
- Steel structure.
- 7” Transparent casing.
- Hydraulic system for pump control activation.

Testing pump is SRWB-TS (SIS Pump of two-stage rod with stationary barrel of thin wall with inferior anchorage, size: 2 7/8” x 2”). The pump barrel is made of transparent pipeline, 50 mm in internal diameter, 5 mm thick and 1250 mm long. Rod was constructed from a bar of Plexiglass®, 20 mm in diameter. The piston is 200 mm long. Actual standing and traveling valves were provided, according to casing size.

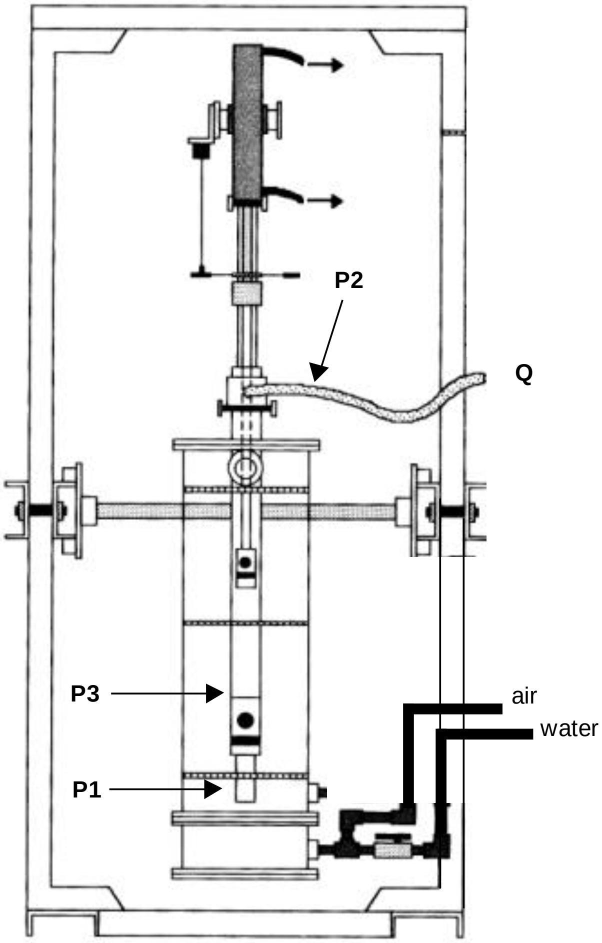

Fig. 1. Schematics of Test Facility

EXPERIMENTAL RESULTS AND ANALYSIS

This section presents results for one-phase flow experiments and two-phase flow experiments including a comparison between both cases.

One-Phase Flow Results

Figures 2, 3 and 4 present plots of P1 and P2 at three different pumping speeds (0.05, 0.10 and 0.15 Hz). It is observed the little influence the speed has on P1, contrasting with the marked changes in P2. In fact, P2 appears as varying cyclically with the same frequency as the rod motion, and reaching a maximum almost at the same time when the rod arrives the top. Just few degrees of shifted-delay is observed in this effect. The largest the frequency, the largest P2. For example, an increase in 3 times of the frequency causes an increase in about 2 times of P2.

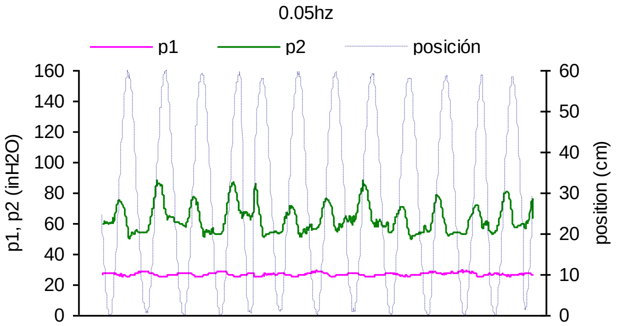

Fig. 2. Position, P1, P2, vs. Time (0.05 Hz, 100% stroke, only water)

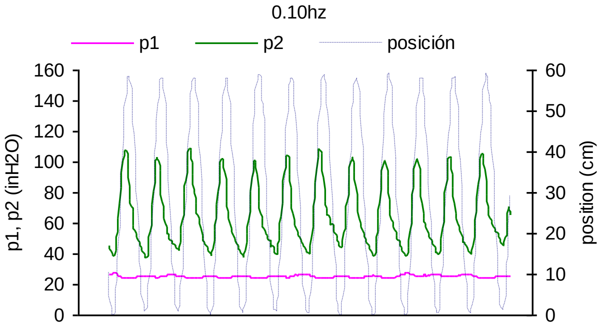

Fig. 3. Position, P1,P2 vs. Time (0.10 Hz, 100% stroke, only water)

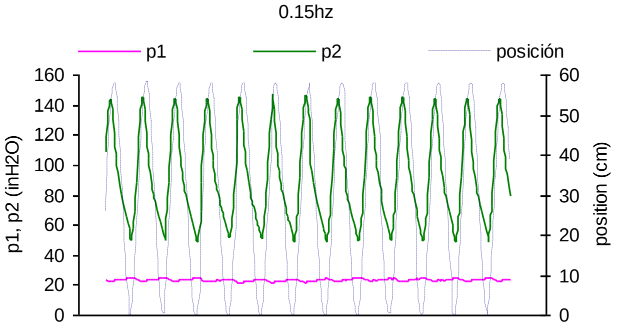

Fig. 4. Position, P1, P2 vs. Time (0.15 Hz, 100% stroke, only water)

Figures 5, 6 and 7, show a dynagraph pressure chart. This plot is built by plotting P3 (discharge of standing valve) as a function of the piston position. Graphs show that when having higher speed, both P3 at down-stroke and at up-stroke tend to lower, approximately maintaining the size of the gap in between. At the same time, it is observed that at larger speed, the plot becomes more ovoid-like in shape, which is explained by the fact that water is the working fluid and the very short piston stroke. Currently, confirmation of this hypothesis is being examined by comparing, at similar Reynolds number, the model and an actual-size unit.

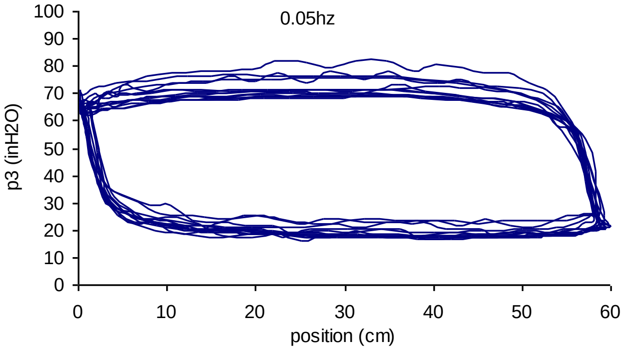

Fig. 5. P3 vs. Position (0.05 Hz, 100% stroke, only water)

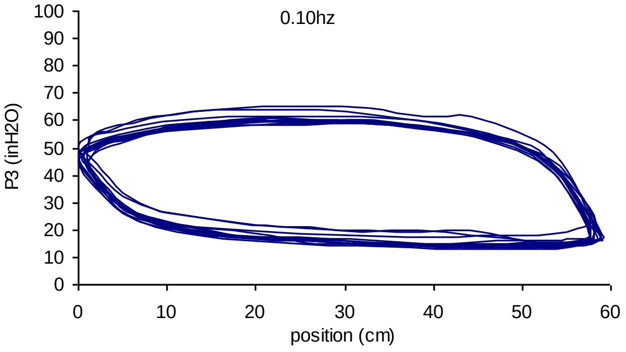

Fig. 6. P3 vs. Position (0.10 Hz, 100% stroke, only water)

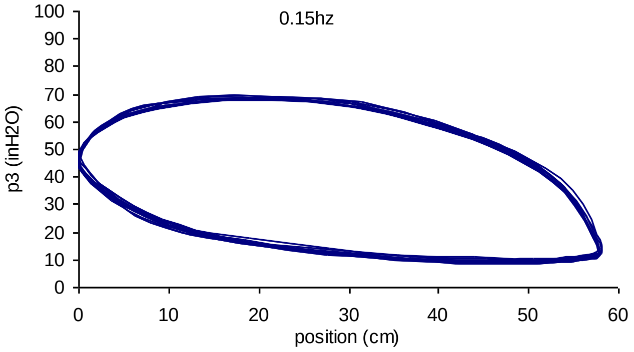

Fig. 7. P3 vs. Position @ 0.15 Hz, 100% stroke, only water

Two-Phase Flow Results

Results for two-phase flow experiments are based on the time-average measurement of the operating cycle after taking a 10-minute run of data acquisition for every case. Thus, all plots are shown for a mean cycle of operation.

Figure 8 depicts P1 as a function of the plunger position. P1 (pressure at the standing valve inlet) behaves as independent on the gas presence. In fact, this behavior mimics the water-alone results in which it was demonstrated that P1 is not dependent on the pumping regime, but on the well (water reservoir) condition.

However, as shown in Figs. 9 and 10, P3 (discharge pressure at standing valve) and P2 (pump discharge pressure) are highly affected by the presence of gas.

Existence of gas causes about a 50% increase of the operating pressure compared to the incompressible one-phase run. In fact, absence of gas phase (one-phase case) lowers dramatically pressures P2 and P3; however, there are no important differences between pressures for water-air cases running at same speed, though carrying different amount of air (10% - 15% of air).

It seems the air-water mixture, in the evaluated proportions, offers an extra resistance to motion which develops a higher pressure at the discharge line (P2)

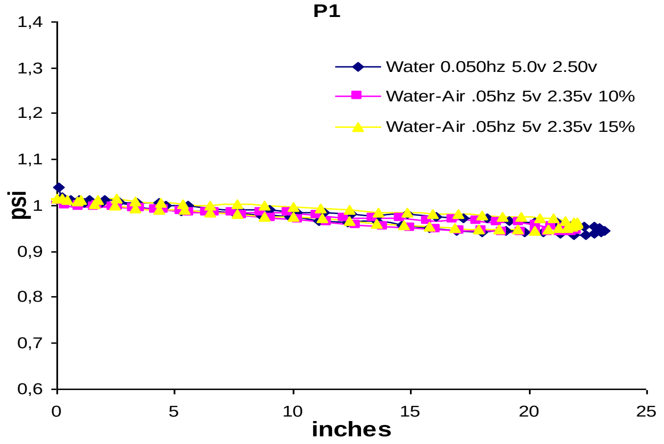

Fig. 8 P1 vs. Position. One-Phase and Two-Phase flow at 0.05 Hz

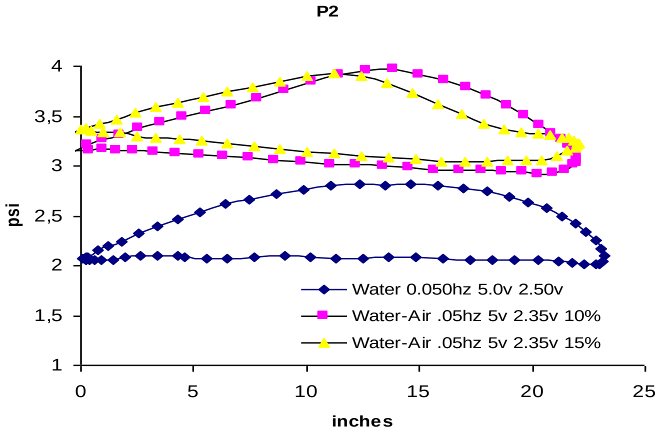

Fig. 9 P2 vs. Position. One-Phase and Two-Phase flow at 0.05 Hz

On the other hand, pressure at standing valve outflow does not vary between the air-water and water-alone cases for the ascending stroke of the sucker rod, while air-water mixture flow presents an almost 40% increase in pressure during the descending stroke of rod, compared to the water-alone case. It is not understood yet whether the speed is a relevant variable in this behavior, but current experiments are aimed to cover a wider spectrum of the variables and to develop correlations between the volumetric efficiency and gas volume in the mixture.

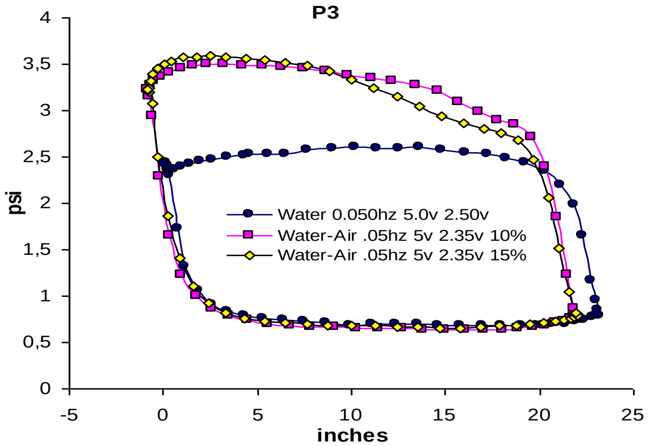

Fig. 10 P3 vs. Position. One-Phase and Two-Phase flow at 0.05 Hz

CONCLUDING REMARKS

Preliminary results from experiments to determine the influence of gas fraction in the volumetric efficiency of subsurface pumps is presented:

It was designed a test facility to monitor changes in pressure, position and fluid flow in several places in the pump, during all the reciprocating operation.

First results show a minimum influence of the gas presence onto the pump inlet pressure (P1). This demonstrates the robustness of the test facility, granting a suction controlled condition for all experiments.

The pressure downstream the standing valve, P3, though independent from the plunger speed (as seen in water-alone experiments), is very sensitive to gas presence. The mixture of gas in the flow causes a significant increase in P3, while the plunger is in the descending stroke, compared to the water-alone flow.

Pressure out of pump, P2, is dramatically affected by both speed (as seen from water-alone experiments) and gas presence. P2 increases significantly for gas-mixtures, compared to water-alone flow at all stages of the plunger stroke, demonstrating an important friction increase caused by the two-phase nature of the flow. However, no evidence of changes related to the amount of gas in the mixture has been detected yet.

Further experiments are currently running to deepen the understanding of the phenomenon by increasing the amount of gas, and by developing semi-empirical correlations amongst all variables.

ACKNOWLEDGMENTS

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