Effects of Free Gas and Downhole Separation Efficiency on the Volumetric Efficiency of Sucker Rod Pumps and Progressing Cavity Pumps.

By Jorge Robles (PDVSA INTEVEP) and Dr. A. L. Podio (UT Austin)

1 Abstract

The prediction of the volumetric efficiency of the pump is one of the most important factors in the analysis of sucker rod and progressing cavity pumping systems. In most cases, the reduction of production due to gas interference in the pump exceeds by far the effect of leakage in the pump components. In this paper, the equations to determine the effect of free gas on the volumetric efficiency of a sucker rod pump and a progressing cavity pump, as a function of the downhole separation efficiency, the pump intake conditions and the fluid properties, are presented. Computer programs were written to simulate the hydrodynamic behavior of a sucker rod pump and of an idealized progressing cavity pump. The sucker rod pump was simulated for harmonic motion and for constant velocity motion. A comparison between the three cases is presented. Curves for sensitivity of the sucker rod pump volumetric efficiency to the compression ratio and clearance ratio are also presented. Finally, a much more simplified model based on constant flow rate is presented for the case of sucker rod pump. The results obtained with this model are in good agreement with those corresponding to the simulation based on harmonic motion.

2 INTRODUCTION

One of the most important variables that affect the performance of downhole pumps is the free gas at the pump intake. In the case of Sucker Rod Pumps (SRP), free gas reduces volumetric efficiency of the pump not only because it occupies a space that can not be filled with liquid but also because it delays the opening of the valves. In this work a simple model is presented that consider single phase flow of fluid inside the pump, considering an homogeneous compressible mixture that allows to compute the local flow rate.

3 DEFINITIONS

3.a Separation Efficiency

Separation efficiency is defined as the ratio of the separated gas rate Q_{GS} to the total free gas rate Q_{GT},

$$E_S = \frac{Q_{GS}}{Q_{GT}} \qquad (1.)$$

Q_{GS} and Q_{GT} must be measured or computed at the same conditions, which indicates that although the separation is expressed as a relation of volumes, it also corresponds to a relation between masses. Since the separation starts at the separator intake, the most logical conditions are the separator[1] intake pressure and temperature.

3.b Volumetric Efficiency of the pump

The volumetric efficiency of the pump is often expressed as a ratio of volumes, however, for this discussion it is more convenient to define the volumetric efficiency of the pump in terms of flow rates:

$$E_V = \frac{Q_{LP}}{Q_P} \tag{2.}$$

Q_{LP} is the actual flow rate of liquid pumped and Q_P is the total theoretical flow rate pumped (swept volume), based on the pump's geometric and operational parameters: plunger diameter, downhole stroke length and frequency in the case of sucker rod pumps and diameter, eccentricity, pitch length and angular velocity in the case of progressing cavity pumps.

This definition of volumetric efficiency includes not only the effect of the free gas but also the effect of the leakage of fluid through the components of the pump. Since this study is concerned solely with the effect of the free gas, it was separated from the leakage effect by mean of the following definition

$$E_V = E_{VG} E_{VL} \tag{3.}$$

where E_{VG} is the volumetric efficiency of the pump considering only the effect of the free gas and E_{VL} is the volumetric efficiency of the pump considering only the effect of the leakage. E_{VL} can be expressed as

$$E_{VL} = \frac{Q_{PCL}}{Q_P} = \frac{Q_P - Q_{Leak}}{Q_P} \tag{4.}$$

where Q_{PCL} is the flow rate capacity of the pump corrected for leakage. The effect of the free gas on the volumetric efficiency E_{VG}, can be expressed as

$$E_{VG} = \frac{(Q_L)_P}{Q_{PCL}} = \left(\frac{Q_L}{Q_{IN}}\right)_P \left[\frac{(Q_{IN})_P}{Q_{PCL}}\right] \tag{5.}$$

where Q_L is the liquid flow rate (oil and water), Q_{IN} is the fluid flow rate (liquid and gas) entering the pump and the subscript P outside the brackets stands for *pump conditions* at the moment when the standing valve closes[2], in the case of sucker rod pumps (SRP's), or the pressure of the first cavity in the case of progressing cavity pumps (PCP's). The two terms in Equation 5 represent the two ways free gas affects the volumetric efficiency. The first parenthesis accounts for the fact that the fluid entering the pump contains a fraction of gas. The second bracket represents basically the reduction in pump efficiency due to the expansion of the fluid contained in the *clearance volume*[3] from the moment the traveling valve closes until the standing valve opens. In the most general case, the closing of the standing valve does not correspond to the end of the upstroke, as it will be shown later. Therefore, the volume

---

[1] In this paper, the use of to the term *separator* is reserved for the downhole separator.

[2] It will be shown later that this pressure is equal to the pressure when the standing valve opens, P_{PS}..

[3] The volume enclosed between the two valves when the plunger is at its lowest position.

enclosed between the standing and the traveling valves at this moment is less than the sum of the pump capacity and the clearance volume. This effect is also part of the second bracket in Equation 5. The second bracket is equal to one in the case of a PCP but can have an important effect in the SRP efficiency. Each term is explained in detail and equations for determining them are presented in the following sections.

4 Variables Affecting the Separator Efficiency

Based on the literature review and on the analysis of the phenomenon of separation, the following parameters were selected for characterization of the performance of the separators:

4.a Viscosity of the Oil

The effect of this parameter is related to three aspects. The first one is the drag force that a gas bubble or slug experiments during rising; the higher the viscosity the lower the rising velocity for a given bubble size, therefore, a more inefficient separation should be expected. The second affects the flow regime and pattern; in general, a higher viscosity reduces the level of turbulence and, therefore, prevents the breaking of large bubbles into small bubbles, in such a way that the average bubble size is increased. Later it will be discussed how this increase in the bubble size facilitates the separation process. The last effect is related to the pressure losses through the components of the separator that cause the liberation of gas. This last aspect will not be evaluated experimentally because of the difficulties in saturating the fluids with gas. However, theoretical relations can be used to account for the extra gas released by the pressure loss through the dip tube.

4.b Temperature

The importance of the temperature is related to its effect on other parameters such as viscosity and density of the gas and liquid, and therefore in the computation of the actual gas flow rate.

4.c Pressure

It affects the actual gas flow rate through its effect on the gas density and also affects the average bubble size.

4.d Liquid and Gas Surface Velocities

These parameters have been shown to be essential in the characterization of two-phase gas-liquid flowing systems. They are not obtained from direct measurements but calculated from volumetric or mass-flow rates in conjunction with pressure and temperature data.

5 Determination of the Volumetric Efficiency of the Pump

When analyzing a pumping system, the efficiency of the separator is a quantity necessary for the computation of the volumetric efficiency of the pump, and therefore for predicting oil and gas flow rates in the tubing string for a given set of conditions. It is important to highlight that the separator intake pressure P_{SI} is different from the pump pressure P_P and this difference affects the volumetric efficiency of the pump. Whether this effect is important or not depends basically on the ratio of the absolute pressures (P_P / P_{SI}).

Figure 1 shows a schematic of a gravity driven separator. Assuming P_{SI} is less than the fluid's bubble point pressure, the fluid at the separator entrance (point A) is a gas-liquid mixture. Once the fluid enters the separator, it moves downward through the annulus between the outer barrel and the dip tube. Since the velocity in this zone is low[4], the frictional pressure drop can be neglected. From the middle of the perforated section of the dip tube (point D) to the entrance of the pump (point F) the friction loss ($(\Delta P_F)_{DF}$) can not be neglected and is important for sizing the dip tube. In addition there is a pressure drop produced by the restriction at the standing valve ($(\Delta P_F)_{Valve}$). Since point G is above point A, and friction losses diminish the pressure of the fluid, the pressure in F is, in general, lower than the pressure in A.

If the acceleration term and the changes in kinetic energy are neglected, the pressure in the pump is given by

$$P_P = P_{SI} + L_{AD}\rho_1 g - (\Delta P_F)_{DF} - L_{DF}\rho_2 g - (\Delta P_F)_{Valve} \quad (6.)$$

Where ρ_1 is the average density of the mixture in the chamber between the dip tube and the outer barrel and ρ_2 is the average density inside the dip tube. L_{AD} is the distance between points AD, and L_{DE} is the distance between points DE. For most cases, ρ_1 and ρ_2 can be replaced by a single average value ρ_M and Equation 6 becomes

$$P_P = P_{SI} + \rho_M g(L_{AD} - L_{DF}) - (\Delta P_F)_{DF} - (\Delta P_F)_{Valve} \quad (7.)$$

A method to account for the effect of the pressure drop through the separator on the pump volumetric efficiency is presented in this section.

5.a Effect of Free Gas Entering the Pump on its Volumetric Efficiency

Using the concepts of formation volume factors[5] (B_O, B_W, B_G), gas-oil ratio (GOR_F), solution gas (R_S), and water cut (C_W), the total formation volume factor is given by

$$B_T = B_O + C_W B_W + GOR_F B_G \div 5.615 \quad (8.)$$

and the following expressions can be written for the numerator and the denominator of the first bracket of Equation 5,

$$Q_L = Q_O(B_O + C_W B_W) \quad (9.)$$

[4] In order to achieve a good performance of the separator, this velocity must be lower than the rising velocity of the bubbles.

[5] These are the standard terms defined by SPE. Complete definition and corresponding units can be found in the *Nomenclature* section.

$$Q_L + Q_G = Q_O B_T \tag{10.}$$

therefore,

$$\left(\frac{Q_L}{Q_{IN}}\right)_P = \left[\frac{(B_O + C_W B_W)}{B_T}\right]_P \tag{11.}$$

where the subscript P indicates that all the properties are evaluated at pump conditions. The term GOR_F represents the free gas per barrel of oil inside the pump (scf/stbl). In general the gas at the separator intake is not entirely associated with the produced oil, therefore it would not be adequate to estimate the amount of gas inside the pump through a correlation from the API gravity and other physical properties of the oil. Instead, the value of the produced GOR should be combined with the available correlations to estimate the amount of free gas. In the case of the GOR_F inside the pump, part of the gas has been separated, and the gas solubility is affected in such a way that the bubble point pressure of the fluid in the pump can be much lower than the bubble point pressure of the fluid coming from the reservoir. A methodology for accounting for these factors is proposed in the following section.

The first step is to obtain the standard GOR from the production reports. Lets define GOR_{GS} as the GOR measured at the gathering station conditions[6]. The total standard GOR_T is given

$$GOR_T = GOR_{GS} + (RS)_{GS} \tag{12.}$$

where $(R_S)_{GS}$ represents the solution gas at the gathering station conditions, and that can be estimated through the following correlation (Trijana, R. and Schmidt, Z., 1991)

$$R_S = 0.05958\gamma_{G100}^{0.7972} P^{1.0014} 10^{13.1405API/(T+460)} \text{ , for } API \le 30 \tag{13.}$$

$$R_S = 0.03150\gamma_{G100}^{0.7587} P^{1.0937} 10^{11.280API/(T+460)} \text{ , for } API > 30 \tag{14.}$$

where γ_{G100} is the specific gravity of the gas at 100 °F and T is the temperature in degrees Fahrenheit. The free gas at the separator intake can be obtained from

$$(GOR_F)_{SI} = GOR_T - (R_S)_{SI} \tag{15.}$$

The free GOR in the pump is given by

$$(GOR_F)_P = (GOR_F)_{SI}(1 - E_S) + \left[(R_S)_{SI} - (R_S)_P\right] \tag{16.}$$

Substituting in Equation 11,

$$\left(\frac{Q_L}{Q_{IN}}\right)_P = \frac{(B_O + C_W B_W)_P}{(B_O + C_W B_W)_P + (GOR_F)_{SI}(1 - E_S) + \left[(R_S)_{SI} - (R_S)_P\right](B_G)_P \div 5.615} \tag{17.}$$

The bubble point pressure of the fluid in the pump (P_{BP}) can be obtained rearranging Equation 13 and 14 and assuming that at the bubble point pressure the total solution gas (R_{SB}) is equal to the sum of the free gas and the solution gas in oil in the pump.

$$R_{SB} = (GOR_F)_{SI}(1 - E_S) + (R_S)_{SI} \tag{18.}$$

---

[6] In this work, the use of to the term *separator* is reserved for the downhole separator. To avoid cofusions, the term *Gathering Station conditions* is used to refer the surface separator conditions.

$$P_{BP} = \left(\frac{R_{SB}}{0.05958\gamma_{G100}^{0.7972}10^{13.1405API/(T+460)}} \right), \text{ for } API \le 30 \tag{19.}$$

$$P_{BP} = \left(\frac{R_{SB}}{0.03150\gamma_{G100}^{0.7587}10^{11.289API/(T+460)}} \right), \text{ for } API > 30 \tag{20.}$$

Determination of the Pump Pressure while the Standing Valve is Open

In order to evaluate the parameters in Equation 18, it is necessary to determine the pressure in the pump using Equation 7. However, the calculation of the frictional and hydrostatic ΔP is not a straight forward problem, due to the fact that the properties of the fluid, such as, density and GOR_F are function of the pressure, which is the unknown quantity.

Since the gas that can not escape during the separation process at the separator's entrance must be in the form of small bubbles, a non-slip flow condition will be assumed, in other words, the hold-up can be obtained directly from the phase's flow rates ratio. Therefore, the density of the mixture can be expressed as

$$\rho_M = \left(\frac{\dfrac{\rho_{OS}}{B_O} + \dfrac{C_W \rho_{WS}}{B_W}}{B_T} \right)_M \tag{21.}$$

where ρ_{OS} and ρ_{WS} are the densities of the oil and water respectively, at stock tank conditions, and ρ_M is the actual average density of the mixture inside the separator. The mass of the gas has been neglected. The subscript M refers to average conditions between the separator intake and the pump barrel. Since the temperature can be considered constant between these two points, the only property to be averaged is the pressure,

$$P_M = \frac{P_{SI} + P_P}{2} \tag{22.}$$

The value of ρ_M can be used in the hydrostatic term of Equation 7, and for the calculation of the Reynolds's number, in order to determine the flow regime (laminar or turbulent) and to select the corresponding equation for the calculation of the frictional terms of Equation 7. The viscosity used in the equations for the calculation of the frictional pressure losses must be the apparent viscosity of the liquid. The determination of apparent viscosity in a water-oil mixture can be a difficult task if emulsification takes place. This aspect is beyond the scope of this work, therefore, it will be assumed that the apparent viscosity is a known quantity. The following equations can be used for the calculation of the Reynolds's number and the frictional pressure losses:

$$\text{Re} = \frac{\rho V D}{\mu} \tag{23.}$$

for Re<2000, the analytical solution for fully developed laminar flow is:

$$\Delta P_F = \frac{32L\mu V}{D^2} \tag{24.}$$

for Re>2000, there is not an analytical solution for turbulent flow, but a solution can be written as a function of the empirical *friction factor, f*,

$$\Delta P_F = f\,\frac{\rho_M L V^2}{2D} \tag{25.}$$

Due to the implicit nature of the equations, it is necessary to use an iterative method for the calculation of the pump pressure P_P. One way to perform this task is to assume a value for P_P, then use Equation 22 to calculate P_M and then use Equation 23 to calculate the value of ρ_M necessary to compute de hydrostatic and frictional terms. Substituting these terms in Equation 7 will give a calculated value for P_P that must be compared to the assumed value. Iterations must be performed until convergence is achieved.

In the case of SRP, the pulsating nature of the flow leads to a complex dynamic phenomenon, when compared to the constant flow rate performance of PCP. The most relevant aspects to be cosidered when estimating the volumetric efficiency of a SRP system are:

- Fluids flow into the pump only during the upstroke part of the cycle. That implies that the local average flow rate is about twice the flow rate obtained from the production reports.
- Even considering the correction for the average flow rate mentioned above, the instantaneous flow rate, and therefore the instantaneous pump pressure, varies due to the variable-speed motion of the plunger during the upstroke cycle.
- The pulsating motion of the plunger induces a transient dynamic response of the system. Therefore, the amount of mixture entering the pump is no longer equivalent to the displacement of the pump, even if it is corrected for the leakage of the valves and plunger. This effect is amplified by the high compressibility of the gas and the clearance volume, which cause that when the plunger moves upward, any existing gas in the clearance volume of the pump has to be expanded before the pressure falls, producing a delay between the displacement of the plunger and the admission of fluid. When the plunger starts its downward motion, it has to compress the gas up to the value of the discharge pressure, reducing the volumetric efficiency of the pump. This phenomenon is commonly referred in the literature as gas interference.

The last point is closely related to the term $[(Q_{IN})_P / Q_{PCL}]$ in Equation 5. At the beginning of the upstroke motion, the traveling valve has just closed, and the pressure of the fluid in the clearance volume is equal to the discharge pressure. As the plunger moves up, an expansion process takes place and the pressure of the fluid in the chamber decreases to a value low enough to cause the standing valve to open. This opening pressure will be called *static pump pressure*, P_{PS}, and can be calculated from Equation 6 using a flow rate equal to zero[7].

[7] The value of the ΔP required to overcome the weigth of the ball and open the valve should be subtracted from the result of to obtain P_{PS}. , but this parameter is seldom available.

5.b Effect of the Expansion of the Fluid in the Clearance Chamber

Lets define $\mathcal{V}_{CL}$ as the clearance volume and $\Delta\mathcal{V}_{CL}$ as the net change in volume of the fluid in this chamber, from the moment when the traveling valve closes (beginning of the upstroke) until the instant when the standing valve closes and $\Delta\mathcal{V}_P$ is the difference between the maximum swept pump volume and the volume of the chamber between the two valves when the standing valve closes. The expression for the effect of the clearance volume expansion and the delay in the flow due to viscous forces on the volumetric efficiency (second bracket in Equation 5) is

$$\left[\frac{(Q_{IN})_P}{Q_{PCL}}\right] = \frac{Q_{PCL} - spm(\Delta\mathcal{V}_{CL} + \Delta\mathcal{V}_p) \div 6.738}{Q_{PCL}} = 1 - \frac{spm(\Delta\mathcal{V}_{CL} + \Delta\mathcal{V}_p)}{6.738 Q_{PCL}} \tag{26.}$$

where spm is the pumping frequency in strokes per minute and the expression to obtain $\Delta\mathcal{V}_{CL}$ is

$$\Delta\mathcal{V}_{CL} = \mathcal{V}_{CL}\left\{[B_T]_{P_{PE}}^{\mathcal{V}_{VL}} - [B_T]_{P_{PD}}^{\mathcal{V}_{VL}}\right\} \tag{27.}$$

where the superscripts ($\mathcal{V}_{VL}$) outside the brackets mean that the free gas oil ratio GOR_F used in Equation 8 for the evaluation of the formation volume factor B_T, must represent the properties of the fluid left in the chamber at the end of the downstroke motion. This GOR_F can be lower than the average GOR_F of the fluid entering the pump, at the same conditions, if some gas segregation takes place inside the pump. The subscript P_{PE} and P_{PD} outside the brackets in Equation 27, correspond to the pump pressure when the standing valve closes and to the discharge pump pressure, respectively. Later it will explained how P_{PE} is equal to the static pump pressure, P_{PS} and why this value is an important parameter for computing the volumetric efficiency.

5.c Calculation of Pump Volumetric Efficiency from the Integration of the Rate of Liquid Entering the Pump, Based on Plunger's Harmonic Motion

Equation 26 and Equation 27 are useful for understanding the phenomenon but are not convenient for calculating the volumetric efficiency of the pump due to the necessity of determining the pump volume between the two valves when the standing valve closes. The approach presented so far is convenient for PCP's, because the second bracket in Equation 5. is equal to one, and the volumetric efficiency is given directly by Equation 17. For the SRP case it is more convenient to apply the definition of volumetric efficiency based on volumes,

$$E_V = \frac{\mathcal{V}_L}{\mathcal{V}_{PCL}} \tag{28.}$$

where $\mathcal{V}_{PCL}$ is the volumetric capacity of the pump corrected for slippage. The total net volume of liquid entering the pump during one cycle can be obtained integrating the instantaneous mass flow rate and multiplying the result by the formation volume factor of the liquid computed at the conditions prevailing when the standing valve closes:

$$V_L = (B_W + C_W B_W)_{P_{END}} \int_{t_{OSV}}^{t_{CSV}} \frac{Q_{IN}}{(B_T)_{P_P}} dt \qquad (29.)$$

where t_{OSV} is the time corresponding to the opening of the standing valve and t_{CSV} is the time corresponding to the closing of the standing valve. Equation 29 involves the evaluation of the instantaneous values of pressure, volumetric formation factors and other parameters. In order to evaluate the dynamic effects on the volumetric efficiency of the pump, a computer program was developed, for the case of harmonic motion of the plunger. Small time steps were taken so that the changing conditions could be simulated as a succession of steady states.

Computer Simulation of the Hydrodynamic Behavior of a Sucker Rod Pump

- From the motion of the plunger, the plunger displacement volume and flow rate were calculated.
- P_{PS} was calculated and the total formation volume factor was used to determine the volume occupied by the fluid in the clearance chamber in the instant when the standing valve opens and the corresponding time.
- Until the opening of the standing valve the mass of fluid inside the pump is constant, and the pressure is calculated based on the change of the total volume of the mixture due to the motion of the plunger and considering the change in the free gas and the total formation volumetric factor.
- Since the correlations for free *GOR* and volumetric formation factors can not be rearranged explicitly for P_{PS}, it was necessary the use of an iterative technique.
- An iterative method was also used after the opening of the standing valve to determine, for each time step, the instantaneous pump pressure that satisfied the equations for the change in volume of the fluid present in the chamber at the moment, and the equations of fluids flow for the mixture entering at instantaneous flow rate.

Results of the Simulation for the Base Case

Figure 2a shows the curves for the pump pressure, and for the instantaneous flow rate displaced by the plunger (Q_{SWEPT}), and the instantaneous flow rates of liquid (Q_{LIQUID}) and mixture ($Q_{LIQ+GAS}$) entering the pump. Figure 2b shows the cumulative volumes corresponding to the pump displacement (V_{SWEPT}) and to the liquid (V_{LIQUID}) and mixture ($V_{LIQ+GAS}$) entering the pump. The volumes presented are corrected by the instantaneous pressure in the pump, in other words, the values plotted correspond to actual volumes occupied by the mass of liquid and gas that have entered the pump during the cycle studied, at the instantaneous pressure. The clearance volume has been subtracted from all the values.

Point "O" in Figure 2 (a and b), corresponds to the instant when the standing valve opens. Up to this point, the pump pressure decreases as the pump displacement is absorbed by the expansion of the fluid in the clearance volume. The volume indicated as • VCLopen is the increment in volume of the fluid in the clearance space. Fluid starts entering the pump when the pump pressure reaches a value equal to the static pump pressure (PPS). The delay of the opening of the standing valve with respect to the beginning of the upstroke is driven by the clearance volume and the compressibility of the fluid enclosed in the clearance space.

After the traveling valve opens, frictional losses cause the pressure to keep decreasing. This decrease in pressure expands the volume of the fluid inside the pump and creates a delay between the curves of swept and entering mixture flow rates. When the viscosity is high, this delay is evident in the way the maximum flow rate of mixture entering occurs later than the maximum pump swept flow rate. Note also how at the end of the upstroke, when the plunger velocity is zero, there is still flow entering the pump, and how the pressure is lower than the initial pressure, therefore the standing valve remains open and fluid continues to enter the pump while the plunger moves downward, until the pump pressure reaches a value equal to P_{SP} (Point "C").

Note how the incremental volume at the end of the stroke, represented as $\Delta\mathcal{V}_{CLend}$ is equal to $\Delta\mathcal{V}_{CLopen}$, because the pressure at the end of the stroke is equal to the pressure when the standing valve opens, P_{PS}. Therefore, the value of P_{PS} is important not only to determine the time when the standing valve opens, but also to calculate the volumetric efficiency of the pump.

The distances indicated at the right of Figure 2b can be used to visualize the two factors affecting the volumetric efficiency. The ratio C/A represents the effect of the expansion of the clearance volume and the delay of the closing of the standing valve, in other words, it corresponds to the second bracket in Equation 5. The ratio E/C represents the effect of the volume of free gas that comes with the fluid entering the pump, which corresponds to the first bracket in Equation 5. The volumetric efficiency is represented by the ratio E/A.

Sensitivity to the Clearance Ratio and Compression Ratio

Figure 3 shows the effect of the *clearance ratio* on the performance of the pump. The *clearance ratio* (R_{CL}) is defined as the ratio of the clearance volume to the theoretical displacement of the pump and the *compression ratio* (R_{CO}) is defined as the ratio of the absolute discharge pressure to the absolute suction pressure. Curves in Figure 3 were obtained for a fixed compression ratio of 10 and for clearance ratios of 0, 0.2 and 0.4.

Figure 4 exhibits the effect of the compression ratio on the volumetric performance of the pump at a fixed clearance ratio of 0.2 and compression ratios of 2, 5 and 10. Note in figure 3.5b, how the curves for R_{CO} equal to 5 and 10 are superimposed and that the corresponding efficiencies (shown in the lower part of the figure), are also identical. The explanation for this is that the discharge pressure for the case of R_{CO} equal to 5 is above the bubble point pressure of the mixture, therefore, the only additional change in volume of the clearance fluid for the case of R_{CO} equal to 10, is due to the compressibility of the liquid, which is very low. This explains why sometimes in the field increasing the tubing head pressure reduces the volumetric efficiency but sometimes it does not affect, or even enhances the performance of the pump.

5.d Simulation of Non Conventional Pumping Systems

The program used for the simulation of the hydrodynamic performance of a pump with harmonic plunger motion was modified in order to see the effect of other types of internal flowing conditions on the volumetric efficiency of the pump.

Simulation of a Pump with Constant Velocity Plunger Motion

Some manufacturers offer hydraulic (Hydrowell®) or mechanical (Rotaflex®) surface equipment that allow to maintain an almost constant-velocity during the up and down strokes. In order to evaluate the effect of this type of motion, an ideal case of constant plunger velocity was simulated, and the results are shown in Figure 5. If we compare this case to the harmonic motion case (Figure 2), we can see how for the same average flow rate, the minimum pressure is higher (and the maximum flow rate is lower) than for the harmonic case. Since all the conditions are the same as for the conventional unit case, the opening (and closing) pressure, P_{PS}, and the change in volume of the fluid in the clearance space ($\Delta \mathcal{V}_{CLopen}$) are the similar to the values obtained for the harmonic motion. For this particular case, a slightly lower fill of the pump and efficiency was obtained with this system compared to the obtained with the harmonic motion.

Although the opening of the valve occurs earlier in the constant velocity case, it corresponds to the same volume (and displacement) than for the harmonic case. In both cases the effect of the clearance volume on the volumetric efficiency is a function of compressibility of the fluid in this space and the size of the clearance space.

Simulation of a Progressing Cavity Pump

The case of PCP is completely different. Since there is not a clearance volume, the second bracket in Equation 5 is equal to one. The constant angular velocity of the PCP induces a constant flow rate, and since the area exposed at the pump intake is also constant, a constant average flow total velocity is maintained. In this case, the pressure at the pump intake remains constant, and this value substitutes the value of the pump pressure in the equations presented in this section. Since the PCP is continuously admitting fluid, the instantaneous flow rate is the same as the average flow rate. As it was mentioned earlier, in the case of reciprocating systems, the pump only admits fluid during part of the cycle (about half of the total cycle), therefore the average flow rate during the flowing part of the cycle is about twice the overall average flow rate.

Figure 6 shows the result of the simulation of the PCP performance. Since there is no clearance volume, the curves of swept flow rate and fluid flow rate are superimposed, and there is no difference in the cumulative swept volume and the cumulative volume of fluids coming into the pump. In the right end of Figure 6 this fact is indicated as B=C=A, which means that the second bracket in 5 is equal to one.

Comparison of the Harmonic Motion Sucker Rod System, the Constant Velocity Sucker Rod System and the Progressing Cavity Pump System

Figure 7 shows comparisons of the curves for the three cases studied. The following parameters were compared: a) pump displacement flow rate, b) pump pressure, c) flow rate of fluids entering the pump, and d) volume occupied by liquid into the pump. The highest volumetric efficiency was obtained for the PCP case (E_V = 55.0 %), basically because there is no intake valve and there is no clearance volume effect. The standing valve of the constant velocity pump opens before and closes before the standing valve of the conventional unit. The net effect is that the constant velocity pump's standing valve remains open longer than the valve of the harmonic motion pump. However, the flow rate of fluids entering the harmonic pump (figure c) is high enough to overcome this apparent disadvantage and at the end of cycle, there is more liquid accumulated in the harmonic motion pump (E_V = 47.2 %), than for the constant velocity case (E_V = 44.0 %). This result of higher efficiency for the harmonic case than for the constant velocity case must not be generalized, because it depends on the flow dynamics of the system.

The dynamics of the rod and tubing strings system was not included in this study. The constant velocity unit provides in general a longer stroke (amplitude), which allows lower pumping frequency for a fixed flow rate. The dynamic response of the rod-tubing string system to these parameters (frequency and amplitude) have probably a stronger effect on the volumetric efficiency than those observed in the simulation of the hydrodynamic behavior of the pump.

6 Conclusions

1. The pressure drop in the standing valve reduces the fraction of liquid of the fluid entering the pump in two ways: a) Increasing the volume of the free gas, b) allowing more gas to come out from solution.
2. The volumetric efficiency of a sucker rod pump can be considerably less than the fraction of liquid of the mixture entering the pump barrel, and this is true even for a pump with no leakage through the valves or through the plunger-barrel fit. The reason is that there is a delay between the closing of the traveling valve and the opening of the standing valve, due to the expansion of the fluid in the clearance volume. This delay is proportional to the clearance volume and to the compressibility of the mixture in the clearance chamber.
3. If the pump discharge pressure is above the bubble point pressure of the fluid in the clearance chamber, the reduction in the volumetric efficiency of the pump due to the expansion of the fluid in the clearance volume is not longer a function of the pump compression ratio, but it is a function of the ratio between the bubble point pressure and the barrel pressure when the standing valve opens.
4. The properties of the fluid trapped in the clearance chamber are not the average properties of the produced fluid. Since some segregation takes place inside the pump barrel, the bubble point pressure and the liquid fraction of the fluid in the clearance chamber should be lower than the average values. This lessens the negative effect of the expansion of fluid in the clearance volume and, therefore, increases the pump volumetric efficiency.
5. Reducing clearance between standing and traveling valves is a very effective and easy way to increase the volumetric efficiency of the pump in those wells with gas interference.
6. Since progressing cavity pumps have no valves, there is no clearance volume effect in the pump volumetric performance.
7. In SRP, the maximum instantaneous flow rate is much higher than the average flow rate; first, because the fluid goes into the pump only during a portion of the pumping cycle and second, because of the non constant velocity of the plunger.

References

Cambell, J. H. and Brimhall, R M.: "An Engineering Approach to Gas Anchor Design," SPE 18826, Presented at te SPE Production Operations Symposium held in Oklahoma City, Oklahoma, March 13-14, 1989, pp. 71-80.

Clegg, J. D. (1963a): "Understanding and Combating Gas Interference in Pumping Wells," API Drilling and Production Practices (1963), pp 149-165.

Clegg, J. D. (1963b): "Get Rid of Gas Problems in Those Pumping Wells," Oil and Gas Journal, April 29, 1963, pp. 106-111.

Clegg, J. D.: " Reducing Gas Interference in Rod Pumped Wells," World Oil, June 1979, pp. 125-129.

Clegg, J. D.: "Another Look at Gas Anchors," Southwestern Petroleum Short Course, 1989, pp. 293-307.

Connally, C. A., Sandberg, C.R. and Stein, N.: "Volumetric Efficiency of Sucker Rod Pumps When Pumping Gas Oil Mixtures," Petroleum Transaction, AIME, Vol 198, 1953, pp. 265-270.

Dottore, E. J.: "How to Prevent Gas Lock in Sucker Rod Pumps," SPE 27010, presented at the III Latin American/Caribean Petroleum Engineering Conference, Buenos Aires, Argentina, April 27-29, 1994, pp.869-881.

Kartoatmodjo, R. S. T. and Schmidt, Z.,: "New Correlations for Crude Oil Properties," SPE 23556 (Unsolicited), SPE Technical Publications, 1991.

Robles, J. "Characterization of Static Downhole Gas Separators"., MSc Thesis. University of Texas at Austin. December 1996.

Schmidt, Z. and Doty, D. R.,: "System Analysis for Sucker Rod Pumping," SPE 15426, presented at the 61st Annual Technical Conference and Exhibition of the SPE, 1986.

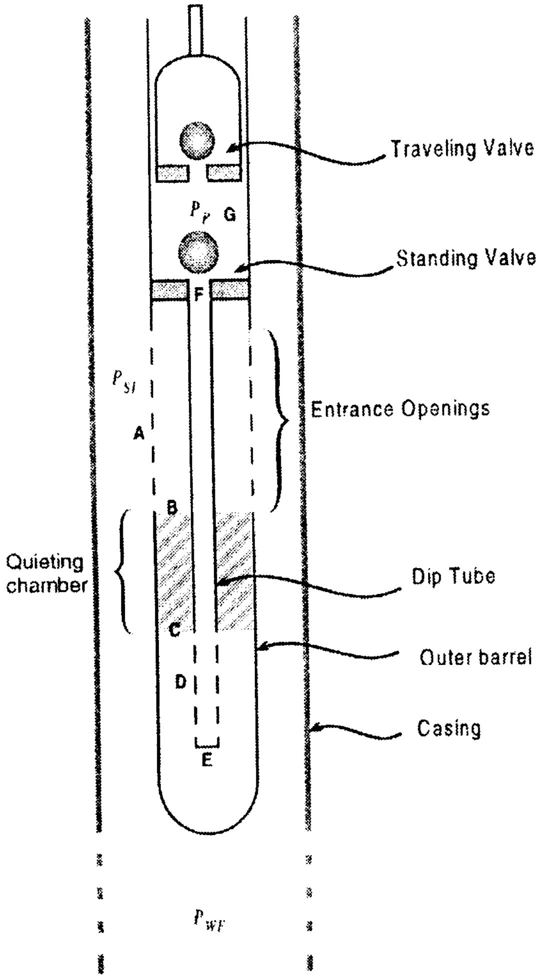
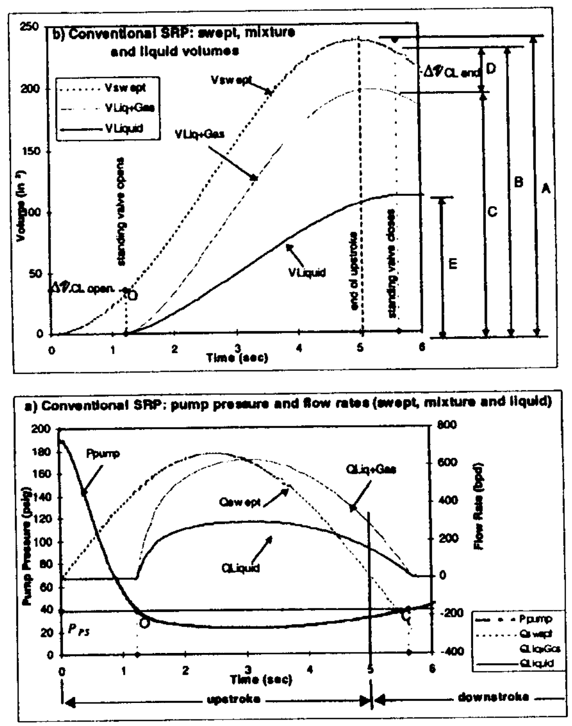
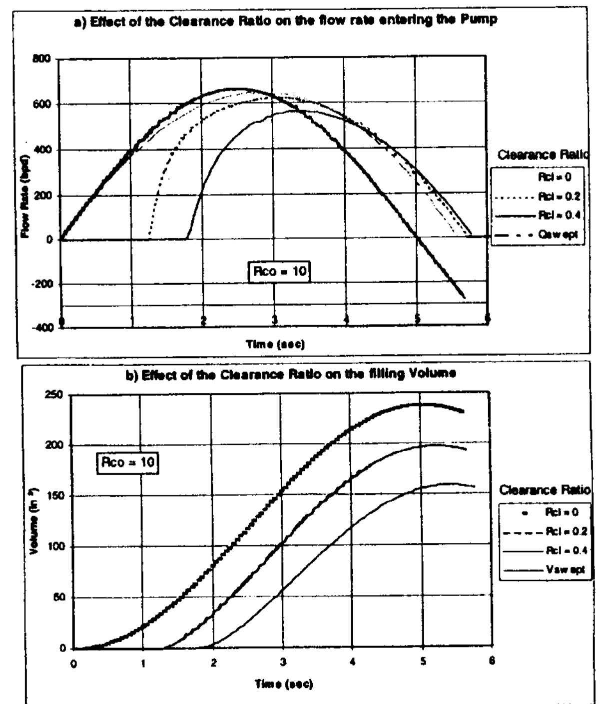


Figure 1 - Gravity Driven Downhole Gas Separator



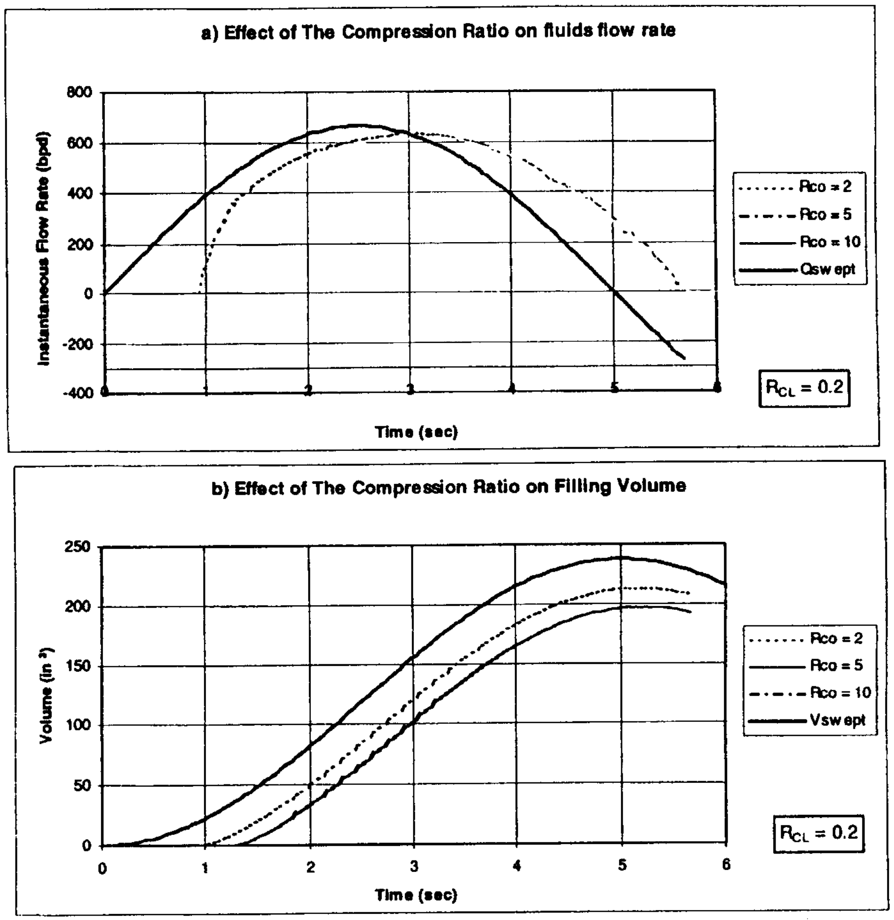
File name:	compara.csv				
vis(cp)=	500	Psi(psig)=	40	Compression R.	10
GOR	250	Pb(psig)=	204,8	EfiS=	0,95
spm=	6	Lstroke(in)=	40	Dplung(in)=	2,75
Di dip tub(in)=	1,75	Do dip(in)=	2	Dimud(in)=	3
Ldip(ft)=	20	Lchamber(ft)=	14	Clearance R.	0,2
EvHarm=	0,4722	Qave(bpd)=	211,6		

Figure 2 - Results of Simulation for the Base Case of Conventional Sucker Rod Pump (Harmonic Motion)



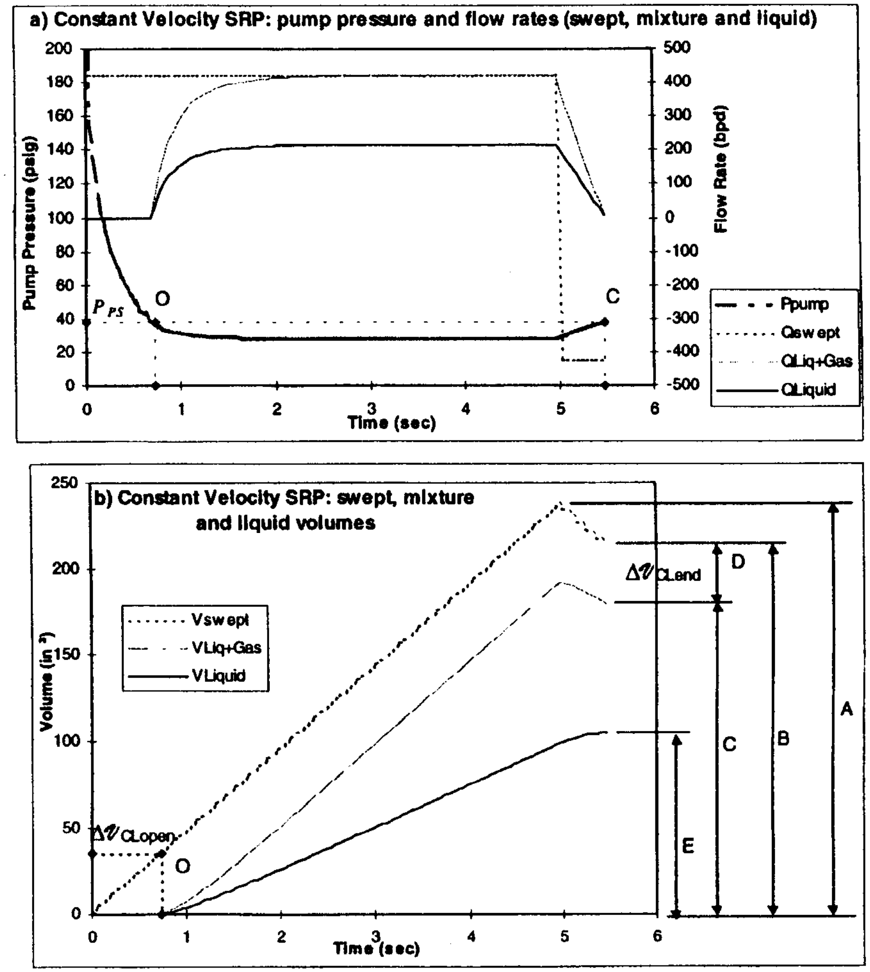
File name:	dyndat.csv			date:			
vis(cp)=	500	Psi(psig)=	40	Compression R.	10		
GOR	250	Pb(psig)=	204,8	EfiS=	0,95		
spm=	6	Lstroke(in)=	40	Dplung(in)=	2,75		
Di dip tub(in)=	1,75	Do dip(in)=	2	Dimud(in)=	3	R_{CL}	Ev
Ldip(ft)=	20	Lchamber(ft)=	14	Clearance R.	-	0	0,564
PumpTemp(F)=	140	Sg_gas(air=1)	0,7	WaterCut=	0	0,2	0,474
EvHarm=	-	Qave(bpd)=	211,6	0	0	0,4	0,383

Figure 3 - Effect of the Clearance Ratio on the Volumetric Performance of a Sucker Rod Pump (Harmonic Motion)



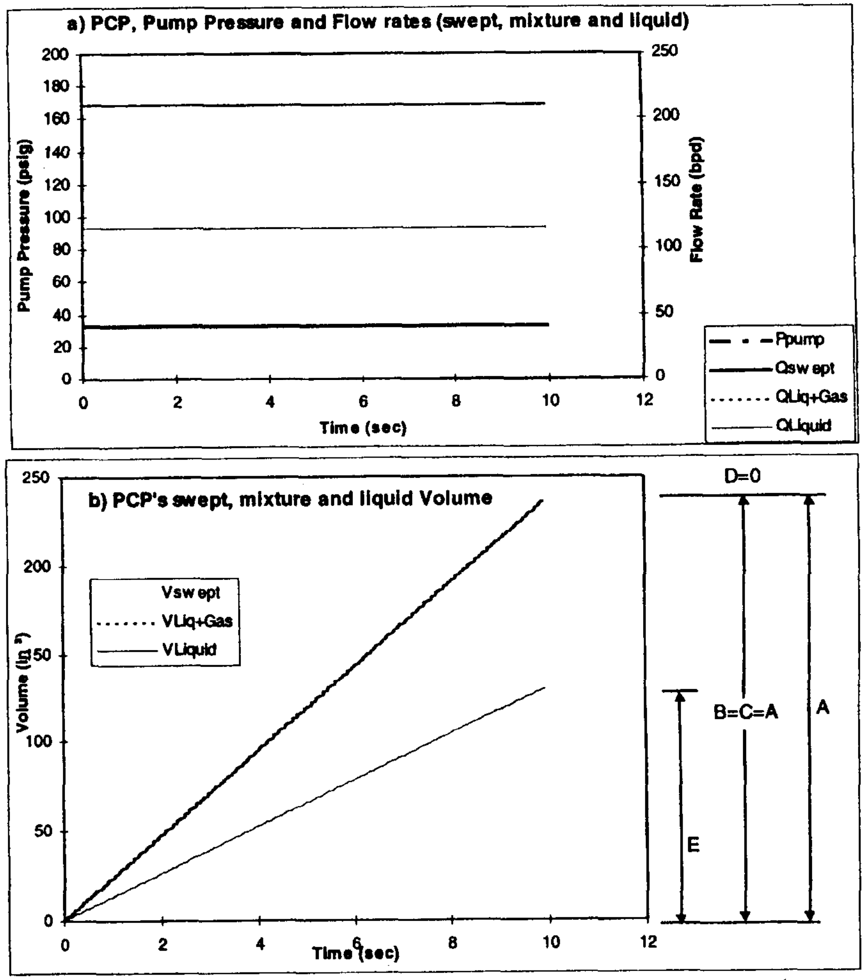
dyndat.csv	:File	08/05/1996	date				
vis(cp)=	500	Psi(psig)=	40	Compression R.	-		
GOR	250	Pb(psig)=	204,8	EfiS=	0,95		
spm=	6	Lstroke(in)=	40	Dplung(in)=	2,75		
Di dip tub(in)=	1,75	Do dip(in)=	2	Dimud(in)=	3	Comp. R.	Ev
Ldip(ft)=	20	Lchamber(ft)=	14	Clearance R.	0,2	2	0,509
PumpTemp(F)=	140	Sg_gas(air=1)	0,7	WaterCut=	0	5	0,474
EvHarm=	0,44412	Qave(bpd)=	211,6			10	0,474

Figure 4 - Effect of the Compression Ratio on the Volumetric Performance of a Sucker Rod Pump (Harmonic Motion)



compara.csv					
vis(cp)=	500	Psi(psig)=	40	Compression R.	10
GOR	250	Pb(psig)=	204,8	EfiS=	0,95
spm=	6	Lstroke(in)=	40	Dplung(in)=	2,75
Di dip tub(in)=	1,75	Do dip(in)=	2	Dimud(in)=	3
Ldip(ft)=	20	Lchamber(ft)=	14	Clearance R.	0,2
PumpTemp(F)=	140	Sg_gas(air=1)	0,7	WaterCut=	0
Ev(const. vel)=	0,4397	Qave(bpd)=	211,6		

Figure 5 - Simulation of a Constant Velocity Sucker Rod System (Hydrowell® or Rotaflex®)



pcpdat.csv					
vis(cp)=	500	Psi(psig)=	40	Compression R.	10
GOR	250	Pb(psig)=	204,8	EfiS=	0,95
spm=	6	Lstroke(in)=	40	Dplung(in)=	2,75
Di dip tub(in)=	1,75	Do dip(in)=	2	Dimud(in)=	3
Ldip(ft)=	20	Lchamber(ft)=	14	Clearance R.	0
PumpTemp(F)=	140	Sg_gas(air=1)	0,7	WaterCut=	0
EvPCP=	0,5503	Qave(bpd)=	211,6		

Figure 6 - Simulation of a Progressing Cavity Pump Volumetric Performance

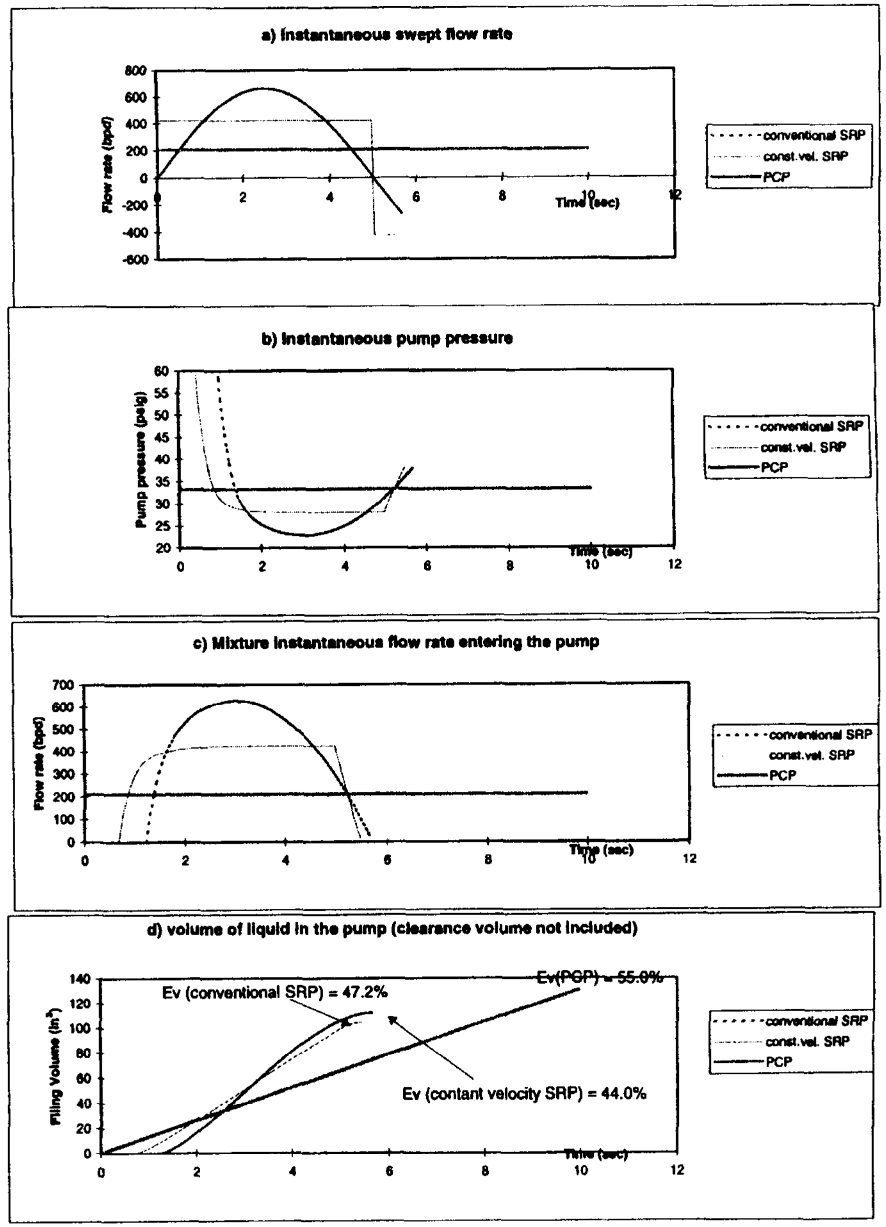


Figure 7 - Comparison of Harmonic Motion SRP, Constant Velocity SRP and PCP