CLOSING CHAMBER WELL TEST

INCLUDING

FRICTIONAL EFFECTS

A REPORT

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ABSTRACT

Frictional effects were included in the closed chamber well test model in order to develop a more general solution for the closed chamber well test. Superposition of the cumulative influx, constant pressure solution of the radial diffusivity equation is used to overcome the limitations and difficulties resulting from solving the diffusivity equation in the presence of changing wellbore storage and frictional effects.

A sensitivity study was performed to analyze the influence of different tool and reservoir parameters on the closed chamber well test in the presence of frictional effects. Frictional effects significantly affect the early time pressure response of the closed chamber well test.

The superposition model was also improved by using variable time steps, hence, increasing the computation efficiency of the model.
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1. INTRODUCTION

The closed chamber well test is a suitable method to identify and sample formation fluids, as well as to determine oil reservoir parameters required for estimating productivity.

Closed chamber well testing is used in the petroleum industry in the form of backsurge perforation cleaning (Simmons (1985), Simmons (1986)). As shown in Figure 1, the equipment used for backsurge operations includes: a work string composed of two remote controlled valves, a temporary packer, and a pressure recorder. The assembly is run into the wellbore with an enclosed chamber formed between the upper and the lower surge valves. The increase in the hydrostatic pressure is recorded as the assembly is run into the well. When the packer is set the completion fluid overbalance is relieved, and the bottom hole pressure becomes equal to the static initial reservoir pressure. When the lower valve is opened the drawdown is obtained, as the formation sandface is exposed to a minimum pressure, and fluids are produced. Then, the fluid level rises and the bottom hole pressure increases until it reaches the static reservoir pressure. Finally, the upper valve is opened, the packer released and the bottom hole pressure returns to an overbalance.

The closed chamber well test is similar to a conventional drillstem test; moreover, it is a generalized form of the drillstem test known as slug test. The closed chamber well test involves liquid level changes in the wellbore as a result of the instantaneous removal of a specific amount of liquid from the wellbore. The main difference between the closed chamber test and the slug test is wellbore storage. The slug test wellbore storage is constant, related either to fluid level rise or to fluid compression in a fixed volume. The closed chamber test wellbore storage varies from being controlled by fluid level rise, to fluid compression in a changing volume. In a closed chamber test, the initial wellbore storage is high and reduces during the test, as the chamber gas compresses above the liquid column.

The variable wellbore storage and the presence of frictional and momentum effects throughout the test, make the closed chamber well test problem non-linear and difficult to solve.
analytically. Hence, numerical techniques are required to overcome the limitations and difficulties resulting from these non-linearities.

This study was performed in order to develop a more general solution for the closed chamber well test by including frictional effects in the closed chamber well test model developed by Simmons (1985) as well as improving the efficiency of the model by using variable time steps.
Figure 1: Schematic Representation of the Closed Chamber Equipment (after Simmons (1985), Simmons (1986))
2. LITERATURE SURVEY

The first application of slug test analysis was presented by Ferris and Knowles (1954), who proposed the instantaneous slug test method for determining the transmissivity of an aquifer. They analyzed late time data considering the instantaneous line source response, but neglected the effects of wellbore storage and skin.

Cooper, Bredehoeft, and Papadopulos (1967), presented a solution for the variation in the liquid level when a slug test is performed. They considered wellbore storage in the analysis, and proposed using type curves for determining reservoir transmissivity.

After that, Ramey and Aganval (1972) presented the slug test solution including the effects of wellbore storage and skin, but momentum, friction, phase change and wellbore fluid compressibility effects were neglected. Ramey, Agarwal, and Martin (1975), presented type curves for the slug test. Three kinds of curves were developed: a) log-log early time, b) semi-log intermediate time, and c) log-log late time. These curves combine skin effect as well as wellbore storage into a correlating parameter that may be determined from a type curve match.

A theory for analyzing closed chamber well tests was presented by Alexander (1977) and Marshall (1978). They suggested using the results obtained by performing a closed chamber test to monitor the initial flow period of the drillstem test, as well as to identify and measure formation properties.

As an extension of the general slug test solution, Shinohara (1980), presented a mathematical solution to analyze data from closed chamber tests. The solution he proposed can be applied for the closed chamber test problem except when the volume of the closed chamber is very small, or there is a considerable difference between the initial pressure of the closed chamber and the atmospheric pressure. The solution was obtained based on a wellbore momentum balance. Some of the assumptions adopted in the analysis were that the wellbore friction, the compressibility of the liquid in the wellbore, and mass transfer between liquid and gas were negligible. Also, ideal chamber gas behavior was assumed.
After that, Saldana (1983) proposed a mathematical solution to describe the flow phenomena occurring during a slug test, a drillstem test, or a closed chamber test. The solution was obtained by applying a momentum balance equation to the liquid in the wellbore including gravitational, inertial, and frictional effects on the fluid column. Saldana also assumed ideal gas behavior in the analysis.

Simmons (1985) developed a closed chamber test model, obtained by the superposition of the constant pressure cumulative influx solution to the radial diffusivity equation. In his approach he considered real gas compressibility effects, but the effects of friction and momentum were not included. In addition, no mass exchange and incompressible wellbore liquids were assumed.

Based on the results of Simmons’s approach, Simmons and Sageev (1985) presented a method for analyzing backsurge pressure data to determine the reservoir transmissivity and the Hurst skin effect. In a paper to be presented in 1986, Simmons presents a new method for analyzing closed chamber tests. In this method, the recorded chamber pressures are differentiated, yielding the instantaneous sandface rate. Then, the superposition model of constant rates is invoked allowing the determination of formation transmissivity, and the variation of wellbore skin with time. However, we still lack a method for reproducing the bottom hole pressure including the frictional and momentum effects.
3. CLOSED CHAMBER PRESSURE RESPONSE ANALYSIS

3.1. Fluid Flow in Pipes

The pressure drop for a fluid flowing between two points, (1 and 2), in a pipe is expressed by:

\[ \frac{p_1 v_1 + \int PdV - p_2 v_2}{v_1} = \frac{g_c}{g_c} (z_2 - z_1) + \alpha \frac{(V_2^2 - V_1^2)}{2g_c} + h_f \frac{g}{g_c} \]

where:

- \( p \) = pressure
- \( v \) = specific volume \( (v = 1/\rho_f) \)
- \( z \) = elevation
- \( V \) = average fluid velocity
- \( h_f \) = frictional head loss
- \( \alpha \) = kinetic energy correction term
- \( g \) = acceleration of gravity
- \( g_c \) = conversion factor

For liquids, assuming that the density remains constant, equation (1) becomes the generalized Bernoulli equation for flowing liquids in a pipe:

\[ \frac{144}{\rho_f} \frac{p_1 - p_2}{\rho_f} = \frac{g_c}{g_c} (z_2 - z_1) + \alpha \frac{(V_2^2 - V_1^2)}{2g_c} + h_f \frac{g}{g_c} \]

where:

- \( \rho_f \) = fluid density
Equation (2) can be expressed as

\[- \frac{144}{\rho_f} \frac{\Delta p}{\rho_f} = \frac{g_c}{g} \Delta z + \frac{\alpha}{2g_c} \Delta (V^2) + \frac{g_c}{g} h_f\]  

(3)

where:

\[\Delta p = \text{pressure change}\]
\[\Delta (V^2) = \text{change in velocity terms}\]
\[\Delta z = \text{change in elevation}\]

The kinetic energy correction factor, \(a\), is usually set equal to unity (Benedict, 1980). Then, when the pipe diameter is constant, the total pressure drop can be calculated from equation (3) as

\[-(\Delta p)_{\text{total}} = \frac{1}{144} \frac{g_c}{g} \Delta z + \frac{1}{144} \frac{g_c}{g} h_f\]  

(4)

Equation (4) is of the general form:

\[-(\Delta p)_{\text{total}} = (\Delta p)_{\text{elevation}} + (\Delta p)_{\text{friction}}\]  

(5)
3.2. Frictional Head Loss

The head loss due to friction in a pipe is defined by the Darcy-Weisbach equation as

\[ h_f = f \frac{L}{D} \frac{V^2}{2g} \]  

(6)

where:

- \( f \) = friction factor
- \( L \) = length
- \( D \) = inside pipe diameter

The frictional pressure drop in Equation (5) is then given by

\[ (\Delta p)_{\text{friction}} = \frac{1}{144} \rho \frac{g}{g_c} \cdot h_f = \frac{1}{144} \rho f \frac{L}{D} \frac{V^2}{2g_c} \]  

(7)

Expressing (6) as a function of the flowrate, \( q \), we have

\[ h_f = 8 f \frac{L}{\pi^2 D^5 g} \frac{q^2}{g} \]  

(8)

Substituting Equation (8) in Equation (7), yields the frictional pressure drop expressed as a function of the flowrate

\[ (\Delta p)_{\text{friction}} = \frac{8}{144} \rho f \frac{L q^2}{\pi^2 D^5 g_c} \]  

(9)

The friction factor, \( f \), as presented by Moody (1944) is a function of two dimensionless parameters:

- the relative roughness, \( e/D \), where \( e \) is a dimensional quantity that represents the absolute roughness, and
- 9 -

- the Reynolds number,

\[ Re = \frac{\rho V D}{\mu} \]  \hspace{1cm} (10)

where \( \mu \) is the viscosity of the fluid in \text{lbm/ft–sec}.

The Reynolds number is dimensionless but may be expressed in oilfield units as

\[ Re = \frac{13033 \, q_o(bbl/D)}{\mu_c(cp) \, D(inches) \, (131.5+API)} \]  \hspace{1cm} (11)

The Moody friction factors are also defined according to the flow regime:

- Laminar zone (0 \(<\) Re \(\leq 2000\))

\[ f' = \frac{64}{Re} \] \hspace{1cm} (12)

- Critical zone (2000 \(<\) Re \(\leq 4000\))

\[ f = 0.5/Re^{0.3} \] \hspace{1cm} (13)

- Transition zone (4000 \(<\) Re \(\leq (200D/e)^{1.16}\))

\[ 1/nf = 1.14 - 2 \log(e/D + 9.34/Re^{0.5}) \] \hspace{1cm} (14)

- Turbulent zone (Re \(> (200D/e)^{1.16}\))

\[ 1/nf = 1.14 - 2 \log(e/D) \] \hspace{1cm} (15)

An iterative calculation is required to evaluate the Moody friction factor in the transition zone (Equation (14)).
33. Closed Chamber Well Test Model

33.1. Without Frictional Effects

Simmons (1985) developed a model for analyzing the pressure response for the closed chamber well test. The model presented by Simmons uses superposition, hence, simplifying the solution of the diffusivity equation in the presence of changing wellbore storage. The net influx at a given time step is calculated by using superposition of the cumulative influx, constant pressure solution of the radial diffusivity equation.

The dimensionless radial diffusivity equation is expressed by

\[
\frac{\partial^2 p_D}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial p_D}{\partial r_D} = \frac{\partial p_D}{\partial t_D}
\]

where the dimensionless time, \(t_D\), and dimensionless radius, \(r_D\), are defined as

\[
t_D = \frac{73.25 \times 10^{-9} \cdot k t}{\phi \mu c r_w^2}
\]

\[
r_D = \frac{r}{r_w}
\]

and the dimensionless pressure, \(p_D\), for a constant pressure inner boundary is given by

\[
p_D = \frac{p_i - p_{wf}}{p_i - p_o}
\]

The assumptions considered in the development of the model were:

a. There is no mass exchange between the produced liquids and the chamber gas.

b. Incompressible wellbore liquids.

c. Negligible momentum and frictional effects.
d. The flowrate during the test period is not impeded by critical flow.

e. Only liquid is produced from the reservoir during the test.

f. The reservoir behaves as an infinite homogeneous radial system of isotropic properties during the test period.

g. Negligible gradients of pressure and temperature with respect to depth in the gas column.

The closed chamber model discretizes the pressure response into constant pressure intervals and assumes that the pressure at the beginning of the time step remains constant during the time step. By using superposition of the cumulative influx, constant pressure solution of the radial diffusivity equation, the net influx after \( N \) time steps is calculated as

\[
N_p = \beta \left( p_i - p_o \right) Q_D(N \Delta t_D) - \beta \sum_{j=1}^{N-1} \left[ \left( p_j - p_{j-1} \right) Q_D( \{(N-j)\Delta t_D\}) \right]
\]

where \( N_p \) is the fluid produced (in bbls) after \( N \) time steps, \( \Delta t_D \) is the dimensionless time step, evaluated based on the time step \( \Delta t \), and \( \beta \) is a constant of proportionality equal to

\[
\beta = 1.119 \phi h c_i r_w^2
\]

\( Q_D \) is the dimensionless cumulative influx defined as

\[
Q_D = \frac{Q}{1.119 \phi h c_i r_w^2(p_i - p_w)}
\]

and is evaluated by inverting the dimensionless Laplace solution presented by Da Prat (1981)

\[
Q_D = \frac{\sqrt{\delta} K_1(6)}{\delta^2 \left[ K_0(\sqrt{\delta}) + \delta \sqrt{\delta} K_1(\sqrt{\delta}) \right]}
\]

where \( K_0 \) and \( K_1 \) are the zero and first order modified Bessel functions of the second kind.
From the cumulative influx, the fluid level \( X \), shown in Figure 2, is calculated as

\[
X = L_{ci} + \frac{N_f}{A_{ch}}
\]

where:
\( L_{ci} \) = initial fluid level
\( A_{ch} \) = area of the chamber

and by assuming isothermal gas compression the chamber pressure is calculated as

\[
P_{ch} = P_{ch_i} \frac{[L_c - L_{ci}] Z}{[L_c - X] Z_i}
\]

where:
\( P_{ch_i} \) = initial chamber pressure
\( P_{ch} \) = chamber pressure
\( Z_i \) = initial compressibility factor
\( Z \) = compressibility factor

Assuming negligible momentum and frictional effects, the bottom hole pressure is calculated as

\[
p_{wf} = P_{ch} + \frac{1}{144} \rho_f \frac{g}{g_c} X
\]

where:
\( p_{wf} \) = bottom hole flowing pressure
\( P_{ch} \) = chamber pressure

and the second term in the right hand side is the hydrostatic pressure of the liquid column.
Figure 2: Definition of Variables for the Closed Chamber Model (after Simmons (1985), Simmons (1986))
33.2. With Frictional Effects

Starting with the closed chamber well test model presented in the preceding section, and neglecting momentum effects, the frictional effects can be included in the model. The friction head changes with time until the fluid stabilizes at the initial static liquid level. By using Simmons’s model, assuming that the pressure at the beginning of the time step remains constant during the time step, and taking the average rate and the maximum value of $AX$ per time step, the pressure response can be generated for each time step.

The frictional pressure drop is:

$$h_f = 8f \frac{(X+\Delta X)}{\pi^2 D^5} \frac{q^2}{g}$$  \hspace{1cm} (27)

The oil flowrate changes during the test, and is a function of the bottom hole pressure. For the constant pressure solution of the radial diffusivity equation, the fluid influx rate at the end of a period of interest can be calculated by first determining the corresponding fluid influx terms and approximating their time derivative by dividing the difference between each two successive values by the corresponding difference in absolute time (Chatas, 1953).

That means, the average oil flowrate during the time step $j$ is:

$$q_j = \frac{N_{p_j} - N_{p_{j-1}}}{t_j - t_{j-1}}$$  \hspace{1cm} (28)

Then, the bottom hole flowing pressure considering friction is:

$$p_{wf} = p_{ch} + \frac{1}{144} \frac{\rho_f}{\rho_c} \frac{g}{8c} (X+\Delta X) + \frac{8}{144} \frac{\rho_f f}{\pi^2 D^5} \frac{(X+\Delta X)}{g} \frac{q^2}{8c}$$  \hspace{1cm} (29)

Equation (29) expresses the pressure response during the closed chamber well test, taking into account the frictional effects. The calculation of the pressure response by using the model presented in section 3.2., but including the frictional effects, implies that the assumptions esta-
blished in the development of the model also apply in this case.

### 3.3.2.1. Fixed Time Step

The computer program for the closed chamber well test model, including frictional effects, is presented in Appendix 1. Generally, when using constant time steps, an extremely small time step is required to represent accurately the chamber pressure rise and to avoid numerical over shooting above the upper surge valve due to excessive variation of the fluid level. Therefore, to calculate the pressure response over a reasonable interval of time requires a large number of time steps; that implies, unreasonable amount of computer time.

Simmons recommended to improve the superposition model by using variable time steps, such that the amount of numerical computations be decreased. For this study, a new model with variable time steps was developed. This model is described in the next section.

### 3.3.2.2. Variable Time Steps - Interpolator

To increase the efficiency of the superposition model a new program that uses variable time steps was developed. The computer program of the closed chamber model with variable time steps is presented in Appendix 1.

The new model allows the use of different time increments along the closed chamber well test. For instance, a larger time increment is used when the chamber pressure is insignificant compared to the reservoir pressure; then, when the fluid level approaches the upper surge valve the time increment is reduced to avoid over shooting above the upper surge valve; finally, larger time increments are used when the chamber pressure has increased close to its final pressure.

The evaluation of the net influx at a given time by using superposition requires the calculation of the dimensionless cumulative influx (Equation 22) for all combinations of the previous time steps. When variable time steps are used, new dimensionless cumulative influx values
have to be obtained for each pressure change in all the pressure history for every time step. To calculate these dimensionless values by inverting the dimensionless Laplace solution (Equation 23) would be a disadvantage and the computational time will increase instead of decrease. To avoid this problem an interpolator was developed. This interpolator interpolates between two successive values in a given table that contains the dimensionless cumulative influx values for different dimensionless time values. Thus, for a given dimensionless time the interpolator computes the closest lower entry in the table, and interpolates between this and the following entry in the table. The interpolator subroutine is presented in Appendix 1.

To check the new program, the closed chamber well test was analyzed for a specific case with the two models: with a fixed time step and with variable time steps. One of the cases studied in the sensitivity study, that will be presented later in section 5, was chosen. The selected case corresponds to a skin value of 2 and zero initial fluid level.

Figures 3 and 4 show the comparison between the results obtained with the two models. Figure 3 presents the bottom hole flowing pressure response and Figure 4 presents the frictional pressure drop. The dotted Curves in both figures represent the response obtained with a fixed time step, and the continuous curves correspond to the response with variable time steps. According to these figures, the pressure response obtained with both models is identical. Moreover, only 1000 time steps were required with variable time steps, while 10000 time steps were used with a fixed time step (0.01 seconds in this case). That means, that using the new program reduced the number of computations and CPU time by a factor of 10.

The new model including variable time steps is an interactive program, in which the time steps are chosen according to the development of the pressure response. This model could be improved by allowing the computer to select the time step during the well test. Some important facts should be considered in such a model: the oil flowrate continuously decreases during the test, and the rate of change in the bottom hole flowing pressure has to be maintained within a tolerance range avoiding the over shooting above the upper surge valve.
Figure 3: Bottom Hole Pressure Obtained with 2 Different Models

Figure 4: Friction Pressure Drop Obtained with 2 Different Models
4. VERIFICATION OF THE MODEL INCLUDING FRICTION EFFECTS

4.1. Verification of Basecase Results

Since the difference between the model presented in this study and Simmons’s lies in the consideration of frictional effects, the new model can be tested by generating Simmons’s basecase for no friction conditions in the tubing.

The basecase response that will be explained in next section was obtained by using an absolute roughness factor, \( e \), of zero. In other words, it was assumed that the frictional pressure drop during the test is always zero. Figure 5 presents the bottom hole flowing pressure response obtained with the two models. The continuous line represents the pressure response generated with Simmons’s model. The dotted line corresponds to the pressure response calculated with the new model, assuming no frictional effects. According to this figure, both responses are identical. Hence, the new model accurately duplicates Simmons’s results when the frictional pressure drop is neglected in the calculation of the closed chamber pressure response.
Figure 5: Bottom Hole Pressure for Basecase Without Friction
42. Basecase Analysis

In this section we describe the basecase for the parameter investigation that will follow. The basecase described by Simmons consisted of zero skin and 100 feet of initial fluid cushion in the well above the lower valve. Since in this study the momentum effects in the wellbore were not considered, the basecase was changed so that there is no initial fluid level in the wellbore above the lower valve. More than that, for this study the momentum effects of the fluid between the lower valve and the formation were not considered. In other words, the model assumes that the lower valve is positioned opposite the tested zone. All the other parameters such as chamber length, initial chamber pressure, and fluid gravity are the same as were presented by Simmons. Table 1 presents the parameters of the basecase.

Figure 6 presents the closed chamber pressure response for the new basecase, without initial fluid level, and without wellbore frictional effects. There are three curves in Figure 6. The uppermost curve represents the bottom hole pressure response, and is the sum of the two other curves: the hydrostatic fluid pressure drop and the chamber pressure. The hydrostatic pressure drop curve represents the fluid level rise after the lower surge valve is opened. As the chamber gas compresses, an abrupt rise in the bottom hole flowing pressure is observed. The difference between the chamber pressure and the bottom hole flowing pressure is the hydrostatic pressure drop of the fluid column, neglecting momentum and frictional effects.

Figure 7 illustrates the closed chamber pressure response for the basecase, without initial fluid level, but including wellbore frictional effects. In this figure, in addition to the three curves shown in Figure 6, a fourth curve is present that represents the frictional pressure drop in the wellbore. The bottom hole flowing pressure in this case corresponds to the sum of the fictional pressure drop, the hydrostatic fluid pressure drop and the chamber pressure. As in the basecase without friction, the abrupt rise in the bottom hole pressure is due to the rapid compression of the chamber gas. The separation between the bottom hole pressure and the chamber pressure is given in this case by the sum of the hydrostatic pressure drop and the frictional pressure drop. After about 25 seconds, when the friction pressure drop reduces to zero,
the difference is given only by the hydrostatic pressure drop like in the basecase without friction.

Figure 8 shows the bottom hole pressure response for the basecase with and without friction. As can be observed in this figure, during the first 20 seconds of the test the bottom hole pressure with friction is larger than the bottom hole pressure without friction. At this time the two curves overlap. After that, the bottom hole pressure without friction becomes larger than the bottom hole pressure with friction. The reason for this can be explained by observing Figures 9, 10, 11 and 12, which represent respectively: closed chamber pressures for both cases, hydrostatic fluid pressure drops for both cases, frictional pressure drop for the basecase with friction, and oil flowrates for both cases.

According to these figures, during the first 20 seconds of the test, the most important factor in the bottom hole pressure response is given by the elevation pressure as well as the friction pressure, which is proportional to the fluid level. During these 20 seconds both pressure drops are increasing. But, because of the friction effects, the fluid level rise is delayed in the case when friction is considered (Fig. 10). The chamber pressure, when no frictional effects are considered, starts its abrupt rising earlier than in the friction case (Fig. 9). After 20 seconds, the frictional pressure drop starts diminishing rapidly (Fig. 11) due to the decreasing oil flowrate (Fig. 12); the hydrostatic fluid pressure drop is practically constant and equal for both cases; and the chamber pressure is higher in the case without friction than with friction. All effects combined result in frictionless late time bottom hole pressures higher than the late time bottom hole pressures with friction.

Figures 13 and 14 represent the log-log early and late time responses for the basecase with and without friction. The log-log early and late time responses are represented as functions of the dimensionless variables defined in section 3 of this study. The early time response is significantly affected by the presence of wellbore friction, while the late time responses are very similar for both cases as can be observed in Figure 14.
### TABLE 1. BASECASE PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Diameter</td>
<td>2.44 inches</td>
</tr>
<tr>
<td>Roughness</td>
<td>0.00060 inches</td>
</tr>
<tr>
<td>Relative Roughness</td>
<td>0.00025</td>
</tr>
<tr>
<td>Total Chamber Length</td>
<td>1000 feet</td>
</tr>
<tr>
<td>Initial Fluid Height</td>
<td>0 feet</td>
</tr>
<tr>
<td>Initial Chamber Pressure</td>
<td>30 psig</td>
</tr>
<tr>
<td>Chamber Gas Gravity</td>
<td>0.65 (to air)</td>
</tr>
<tr>
<td>Initial Reservoir Pressure</td>
<td>5000 psig</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>175°F</td>
</tr>
<tr>
<td><strong>Produced Fluid Specific Gravity</strong></td>
<td>25 API</td>
</tr>
<tr>
<td>Produced Fluid viscosity</td>
<td>1.25 cp</td>
</tr>
<tr>
<td>Porosity</td>
<td>27 %</td>
</tr>
<tr>
<td>Reservoir Permeability</td>
<td>100 md</td>
</tr>
<tr>
<td>Skin</td>
<td>0</td>
</tr>
<tr>
<td>Well Diameter</td>
<td>10 inches</td>
</tr>
<tr>
<td>Formation Total Compressibility</td>
<td>$10 \times 10^{-6}$ psi$^{-1}$</td>
</tr>
<tr>
<td>Formation Thickness</td>
<td>25 feet</td>
</tr>
<tr>
<td>Total Test Time</td>
<td>100 seconds</td>
</tr>
</tbody>
</table>
Figure 6: Basecase Without Friction

Figure 7: Basecase With Friction
Figure 8: Bottom Hole Pressure for Basecase With and Without Friction

Figure 9: Chamber Pressure for Basecase With and Without Friction
Figure 10: Elevation Pressure for Basecase With and Without Friction

Figure 11: Frictional Pressure Drop for Basecase
Figure 12: Oil Flowrate for Basecase With and Without Friction
Figure 13: Early Time Plot for Basecase With and Without Friction
Figure 14: Late Time Plot for Basecase With and Without Friction
5. SENSITIVITY STUDY

In this section we present a sensitivity study of various tool and reservoir parameters of the closed chamber test, including frictional effects.

5.1. Effect of Wellbore Skin

Skin effect values of 0, 2 and 5 were considered in the sensitivity study. Figure 15 presents the bottom hole pressure response, including Friction effects, for the skin values considered in the analysis. Since the presence of wellbore skin reduces the sandface flowrate into the wellbore, the rapid pressure rise during chamber compression is delayed. Yet, the final fluid level and the late time responses are similar. The frictional pressure drops for these skin values are illustrated in Figure 16. According to this figure, the frictional pressure drop is smaller but lasts longer as the skin value increases. The reason for this is explained in Figure 17, that represents the oil flowrate for the skins studied. For higher skins the oil flowrate is smaller and decreases slower than for lower skins. In other words, because the cross sectional area of the pipe remains constant, and the initial fluid conditions are identical the fluid rises to the same level in all cases.

Log-log early and late time plots are presented in Figures 18 and 19. Like in the cases studied by Simmons, the late time format gives the largest resolution to skin effect. The early time response in the presence of wellbore skin differs significantly from the early time response without wellbore skin as shown by Sageev (1986). In the early time log-log format the slope of the pressure response without wellbore skin is $1/2$, denoting transient linear flow. The early time response with wellbore skin has a unit slope, representing constant flow rate.

The bottom hole pressure responses, with and without friction, for skin values of 0, 2 and 5, are presented in Figures 8, 20 and 21 respectively. Because the frictional pressure drop decreases as the skin value increases, the difference between both curves becomes less significant for larger skins.
By observing the dimensionless plots of the pressure response, with and without friction, for the different skins analyzed (Figs. 13, 14, 22, 23, 24 and 25), we conclude that the late time plot matches better both responses. Moreover, for larger skins the difference between the curves is insignificant.
Figure 15: Bottom Hole Pressure for Different Skins

Figure 16: Frictional Pressure Drop for Different Skins
Figure 17: Oil Flowrate for Different Skins
Figure 18: Early Time Plot for Different Skins
Figure 19: Late Time Plot for Different Skins
Figure 20: Bottom Hole Pressure for Skin=2 With and Without Friction

Figure 21: Bottom Hole Pressure for Skin=5 With and Without Friction
Figure 22: Early Time Plot for Skin-2 With and Without Friction
Figure 23: Early Time Plot for Skin-5 With and Without Friction
Figure 24: Late Time Plot for Skin=2 With and Without Friction

Figure 25: Late Time Plot for Skin=5 With and Without Friction
5.2. Effect of Initial Reservoir Pressure

The values for initial reservoir pressure considered in the analysis were 3000 and 5000 psig, where the last one corresponds to the basecase.

Figure 26 shows the influence of the initial reservoir pressure on the bottom hole pressure when considering wellbore frictional effects. As expected, the bottom hole pressure response tends to the initial static reservoir pressure. Like in the cases presented by Simmons, the period of rapid pressure rise due to gas compression occurs earlier for higher pressure formations.

As can be observed in Figure 27, the frictional pressure drop is smaller and lasts longer as the initial reservoir pressure decreases. The reason for this is that the oil flowrate for higher pressure formations is larger because the greater initial pressure differential at the sandface (Figure 28). However, since the final volume of oil produced is about the same, (chamber gas is compressed to different pressures), the areas under the flowrate curves (Figure 28) are about the same.

Log-log early and late time plots for different initial reservoir pressures are presented in Figures 29 and 30. Again, since skin is not present, the early time response is similar to the slug test response with a slope of $1/2$. The late time log-log pressure response approaches the unit slope of the line source slug test response presented by Ferris and Knowles (1954).

Figure 31 illustrates the bottom hole pressure response, with and without friction, for the case when the initial reservoir pressure is 3000 psig. Comparing this figure to the figure corresponding to the basecase (Figure 8), it can be inferred that the relative effect of friction in lower initial reservoir pressure formations is smaller than in higher pressure formations.

Figures 32 and 33 present the early and late time plots for an initial reservoir pressure of 3000 psig, with and without friction and without wellbore skin. For smaller initial reservoir pressures the late time portion collapses better because the frictional effects in these cases are smaller.
Figure 26: Bottom Hole Pressure for Different Initial Reservoir Pressures

Figure 27: Frictional Pressure Drop for Different Initial Reservoir Pressures
Figure 28: Oil Flowrate for Different Initial Reservoir Pressures
Figure 29: Early Time Plot for Different Initial Reservoir Pressures
Figure 30: Late Time Plot for Different Initial Reservoir Pressures

Figure 31: Bottom Hole Pressure for $p_i=3000$ psig with and without friction
Figure 32: Early Time Plot for $p_f=3000$ psig with and without friction
Figure 33: Late Time Plot for $p=3000$ psig with and without friction
Effect of Chamber Diameter

The closed chamber pressure response was studied for two chamber diameters, 2.441 and 4.0 inches. The closed chamber pressure response when considering frictional effects in the wellbore is closely related to the chamber diameter because the frictional head loss is inversely proportional to $D^5$.

Figure 34 presents the bottom hole pressure for the two cases studied. As the tubing diameter increases, the rapid chamber compression is delayed. The frictional pressure drops for these cases are represented in Figure 35. As the chamber diameter is increased the friction pressure losses become less important in the behavior of the total pressure response. For example, according to Figure 36, for a chamber diameter of 4.0 inches, the friction pressure loss is practically negligible though it lasts longer, and both pressure responses, with friction and without it, are practically identical.

The oil flowrate for both cases of Figure 34 are shown in Figure 37. As expected, the area beneath the curve for a chamber diameter of 4.0 inches is larger than the area beneath the curve corresponding to a chamber diameter of 2.441 inches, since wellbore volume is larger. Like in the no-friction cases presented by Simmons, there is a dimensionless time shift to the right on the early and late time log-log pressure responses due to larger chamber diameters (Figures 38 and 39).

Early and late time plots for the case corresponding to a chamber diameter of 4.0 inches can be observed in Figures 40 and 41. Again, for a larger chamber diameter, because the frictional pressure drop is smaller, the late time log-log responses are practically identical. The early time log-log responses are slightly different during the "slug test" response. However, during the rapid pressure rise and thereafter the responses are practically identical.
Figure 34: Bottom Hole Pressure for Different Chamber Diameters

Figure 35: Frictional Pressure Drop for Different Chamber Diameters
Figure 36: Bottom Hole Pressure for $D_{ch}=4.00$ inches With and Without Friction

Figure 37: Oil Flowrate for Different Chamber Diameters
Figure 38: Early Time Plot for Different Chamber Diameters
Figure 39: Late Time Plot for Different Chamber Diameters

- $D_{ch} = 2.441$
- $D_{ch} = 4.000$
Figure 40: Early Time Plot for $D_{eh}=4.00$ inches With and Without Friction
Figure 41: Late Time Plot for \(D_{\alpha}=4.00\) inches With and Without Friction
54. Effect of Roughness

Because the Moody friction factor is a function of the relative roughness, \( \varepsilon/D \), we analyzed the influence of this parameter on the closed chamber pressure response. Two different values of the absolute roughness, \( \varepsilon \), were used in the sensitivity study.

A typical absolute roughness value selected for the basecase was 0.0006 inches. The corresponding relative roughness, for a chamber diameter of 2.441 inches, is 0.00025. To perform the analysis the another value considered for the absolute roughness was 0.00015 inches, that gives a relative roughness of 0.00006 for the same chamber diameter. It is important to notice that a skin value of 2 was used to generate the pressure response for the different relative roughness values.

Figures 42, 43 and 44 present the results obtained. According to these figures, although the frictional pressure drop is lower for the smallest relative roughness, the bottom hole pressure response is not significantly altered. Also, the decreasing of the flowrate behaves in the same way for the two cases studied. The reason for this is that the flow regime in both cases lies in the transition zone where Moody friction factors do not vary much for different values of \( \varepsilon/D \).
Figure 42: Bottom Hole Pressure for Different Roughness

Figure 43: Frictional Pressure Drop for Different Roughness
Figure 44: Oil Flowrate for Different Roughness
55. Effect of Initial Chamber Pressure

Two values of initial chamber pressure were considered: 0 and 30 psig (basecase). Again, the closed chamber pressure responses for these two values were generated for a skin value of 2. Figure 45 illustrates the bottom hole flowing pressure response for the two different values of initial chamber pressure. The frictional pressure drops for these are presented in Figure 46. Like in the no-friction cases studied by Simmons, larger initial chamber pressure values tend to smooth the pressure response. Also, as expected, the frictional pressure drops for these cases are smaller because less fluid rise is required, and the flowrates are smaller.

Early and late time dimensionless plots are presented in Figures 47 and 48. Similar to the no-friction cases there is a shift to the right in the early time plot for lower initial chamber pressures, and the late time response is not significantly affected by the initial chamber pressure.
Figure 45: Bottom Hole Pressure for Different Initial Chamber Pressures

Figure 46: Frictional Pressure Drop for Different Initial Chamber Pressures
Figure 47: Early Time Plot for Different Initial Chamber Pressures
Figure 48: Late Time Plot for Different Initial Chamber Pressures
6. CONCLUSIONS AND RECOMMENDATIONS

In this study, frictional effects were included in the closed chamber well test model developed by Simmons (1985) in order to develop a more general solution for the closed chamber well test.

According to the results obtained in this study, frictional effects significantly affect the early time pressure response, while late time pressure responses are not highly affected. The inclusion of tubing frictional losses in the closed chamber test acts like a choke, and reduces the instantaneous flowrate into the wellbore. However, at early time, when the bottom hole pressure is not affected by the pressure in the chamber, the presence of frictional effects increase the bottom hole pressure in comparison to the frictionless case. The gas compression in the chamber is only a function of the liquid level, (no mass transfer between the liquid column and the chamber gas). Since the flowrate is restricted by the tubing friction, the liquid levels are lower than in the frictionless case, and the rapid compression of the chamber gas is delayed. Hence, the late time bottom hole pressure for the friction case is lower than the bottom hole pressure for the frictionless case.

A sensitivity study was performed to analyze the influence of different tool and reservoir parameters on the closed chamber well test including frictional effects. The frictional pressure drop is closely related to the tool parameters like chamber diameter, absolute roughness and chamber length. Frictional losses could be reduced by controlling these parameters. For instance, for large chamber diameters the friction pressure losses become small enough such that the total pressure response is practically unaffected.

In general, the frictional pressure loss during a closed chamber test increases rapidly, levels off as it goes through a maximum, and finally decreases rapidly as the chamber gas compresses and chokes the well. We observe that as the frictional effects increase, the durations of significant frictional head losses decrease. This reduction in the durations of the frictional effects is observed when we compare closed chamber tests with different diameters, different initial reservoir pressures and different wellbore skins.
As expected, the sensitivity study showed that the early time responses in the presence of wellbore skin differ significantly from early time responses without wellbore skin. In log-log format the early time response without wellbore skin is similar to the slug test response with a slope of 1/2 denoting transient linear flow. On the other hand, the early time log-log response with wellbore skin has a unit slope, representing constant flowrate. The flowrate profile in the presence of high wellbore skin is practically constant, and decreases rapidly like a shut-in. Hence, the late time build-up could be approximated as a simple build-up flowing a constant rate flow period, and analyzed using a Homer technique.

The closed chamber well test model developed by Simmons was also improved by using variable time steps instead of a fixed time step. With variable time steps the computer time is reduced significantly because the number of computations is reduced by an order of magnitude in comparison to the calculations required when using fixed time steps. The program with variable time steps should be improved by including a restarting routine such that the program could be restarted from a given time greater than zero.

Momentum effects of the fluid between the lower valve and the formation, and in the cushion above the lower surge valve, were not considered in the model. Momentum effects are important in the cases where high flowrates occur and the initial fluid column in the wellbore must accelerate rapidly. For this reason it is recommended to include momentum effects on the closed chamber well test.

In developing the model, it is also assumed that wellbore liquids are incompressible. The late time response depends significantly on the high pressure compressibility of the gas. Yet, at these high pressures, the volume of the gas is small. On the other hand, the liquid column compressibility is low, but its volume is large. The wellbore storage is a function of the two fluid columns in the wellbore. Hence, future studies should analyze the influence of the produced liquid compressibility on the closed chamber pressure response.
Summary

1. Frictional effects were included in the superposition model for the closed chamber well test.
2. Frictional effects significantly affect the early time pressure response, whereas the late time pressure response is not highly affected.
3. As the frictional effects increase, the durations of significant frictional head losses decrease.
4. Early time responses in the presence of wellbore skin differ significantly from early time responses without wellbore skin.
5. The flowrate profile in the presence of high wellbore skin is practically constant, and decreases rapidly like a shut-in. Hence, the late time build-up with high wellbore skin could be approximated as a simple build-up flowing a constant rate flow period, and analyzed using a conventional Horner technique.

Recommendations for Future Studies

1. Consider the effect of momentum effects on the closed chamber well test.
2. Analyze the influence of the produced liquid compressibility on the closed chamber pressure response.
3. Improve the superposition model with variable time steps by including a restarting routine.
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{ch}$</td>
<td>Cross sectional area of the chamber (ft$^2$)</td>
</tr>
<tr>
<td>$c_t$</td>
<td>Total formation compressibility (psi$^{-1}$)</td>
</tr>
<tr>
<td>$D$</td>
<td>Inside pipe diameter (ft)</td>
</tr>
<tr>
<td>$D_{ch}$</td>
<td>Chamber diameter (ft)</td>
</tr>
<tr>
<td>$e$</td>
<td>Absolute roughness (in)</td>
</tr>
<tr>
<td>$e/D$</td>
<td>Relative roughness</td>
</tr>
<tr>
<td>$f$</td>
<td>Moody friction factor</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration of gravity constant (32.2 ft/sec$^2$)</td>
</tr>
<tr>
<td>$g_c$</td>
<td>Conversion factor (32.2 lbm-ft/lbf-sec$^2$)</td>
</tr>
<tr>
<td>$h$</td>
<td>Formation thickness (ft)</td>
</tr>
<tr>
<td>$h_f$</td>
<td>Frictional head loss (ft)</td>
</tr>
<tr>
<td>$k$</td>
<td>Reservoir permeability (mD)</td>
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<td>Modified Bessel function of second kind, zero order</td>
</tr>
<tr>
<td>$K_1$</td>
<td>Modified Bessel function of second kind, first order</td>
</tr>
<tr>
<td>$L$</td>
<td>Pipe length (ft)</td>
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<tr>
<td>$L_{ch}$</td>
<td>Total chamber length, as illustrated in Figure 2 (ft)</td>
</tr>
<tr>
<td>$L_{ci}$</td>
<td>Initial fluid level, as illustrated in Figure 2 (ft)</td>
</tr>
<tr>
<td>$N$</td>
<td>Time step index</td>
</tr>
<tr>
<td>$N_p$</td>
<td>Cumulative liquid production (ft$^3$)</td>
</tr>
<tr>
<td>$P_{ch}$</td>
<td>Chamber pressure (psia)</td>
</tr>
<tr>
<td>$P_{ch_i}$</td>
<td>Initial chamber pressure (psia)</td>
</tr>
<tr>
<td>$P_1$</td>
<td>Pressure at point 1, as expressed in Equation (1) (psi)</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Pressure at point 2, as expressed in Equation (1) (psi)</td>
</tr>
<tr>
<td>$P_D$</td>
<td>Dimensionless pressure</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Static initial reservoir pressure (psia)</td>
</tr>
</tbody>
</table>
\( P_o \) = Minimum well bore pressure achieved during the test (psia)

\( P_w \) = Bottom hole flowing pressure (psia)

\( \Delta p \) = Pressure change (psi)

\( q \) = Flowrate (ft\(^3\)/sec)

\( q_o \) = Oil flowrate (bbl/D)

\( Q \) = Cumulative influx (bbl)

\( Q_D \) = Dimensionless cumulative influx

\( \bar{Q}_D \) = Laplace Dimensionless cumulative influx

\( r \) = Radius (ft)

\( r_w \) = Wellbore radius (ft)

\( r_D \) = Dimensionless radius

\( Re \) = Reynolds number

\( s \) = Laplace variable

\( S \) = Dimensionless skin factor

\( t \) = Time (sec)

\( \Delta t \) = Time step (sec)

\( t_D \) = Dimensionless time

\( \Delta t_D \) = Dimensionless time step

\( v \) = Specific volume \( ((lbm/ft^3)^{-1}) \)

\( V \) = Average fluid velocity (ft/sec)

\( \Delta (V^2) \) = Change in velocity terms (ft\(^2\)/sec\(^2\))

\( V_{ch} \) = Chamber gas volume (ft\(^3\))

\( V_{ch_i} \) = Initial chamber gas volume (ft\(^3\))

\( X \) = Dynamic fluid level, as illustrated in Figure 2 (ft)

\( A x \) = Fluid level change per time step (ft)

\( z \) = Elevation (ft)

\( \Delta z \) = Change in elevation (ft)
\[ Z = \text{Real gas compressibility factor of chamber gas} \]
\[ Z_i = \text{Initial real gas compressibility factor of chamber gas} \]
\[ a = \text{Kinetic energy correction term} \]
\[ \beta = \text{Influx constant (bbl/psi)} \]
\[ \mu = \text{Fluid viscosity (cp)} \]
\[ \mu_o = \text{Oil viscosity (cp)} \]
\[ \phi = \text{Formation porosity (fraction)} \]
\[ \rho_f = \text{Fluid density (lbm/ft}^3) \]
REFERENCES


APPENDIX 1

COMPUTER PROGRAM

In this appendix the computer program is presented. Since the program for constant time steps is a subset of the program for variable time steps, only the latter one is presented. Also, the program output for the basecase is presented following the computer code.
This program generates a pressure as a function of time response for a Closed Chamber Test. The method of solution is a wellbore material balance of the fluids produced. Fluid influx is evaluated by superposition of the constant pressure cumulative influx solution. The dimensionless cumulative influx value is calculated by interpolation. The dimensionless cumulative influx values for different dimensionless time values are in a file called 'table'. Run parameters are read from a file called 'bdata'. The output file name is also specified in the data read from this file. The program works interactively, time steps and number of time steps for a given time step are chosen according to the development of the pressure response.

Variable Definitions:

ACH = Closed Chamber Area (ft²)
ALC = Total Chamber Length as shown in figure 2 (ft)
ALI = Initial Fluid Column Length (ft)
API = Produced Liquid Gravity (Degrees API)
B = Influx Constant (ft³/psf)
CDT = Constant for Evaluation of the Dimensionless Time (tdummy)
CFH = Constant for Evaluation of the Frictional Head Loss
CFP = Constant for Evaluation of the Fluid Produced
CP = Constant for Evaluation of Pressure Drops
CQO = Constant for Evaluation of the Oil Flowrate
CRE = Constant for Evaluation of the Reynolds Number
CL = Fluid Column length within chamber (ft)
CT = Total Formation Compressibility (psf²(-1))
D = Internal Chamber Diameter (in) (ft)
DB = Lower Surge Valve Depth (ft)
DES = Logical Variable (y/n)
DF = Mid-Perforation Depth (ft)
DT = Time Step (seconds)
DU = Upper Surge Valve Depth (ft)
DW = Wellbore Diameter (in)
DZ = Change in Z during one iteration
E = Absolute Roughness (in)
ED = Relative Roughness (E/D)
F = Moody Friction Factor
FH = Frictional Head Loss (ft)
FP = Cumulative Liquid Produced (blb)
FPI = Cumulative Liquid Produced for the previous time step (blb)
G = Chamber Gas Gravity (relative to air)
H = Formation Thickness (ft)
IFLAG = Flag Variable for Iterative Z factor Calculation: 0 = Convergence Achieved

KFLAG = Flag Variable for Oil Flowrate Control:

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** Variables: **

- **0**: Total Number of Time Steps
- **1**: Cumulative Number of Time Steps before input
- **N1**: Number of Time Steps for a given time step
- **N2**: Number of Time Steps for a given time step
- **NAME**: Output File Name
- **NCOUNT**: Counter of Time Steps before output
- **NDP**: Number of Output Data Points
- **NLOU**: Closest Lower Entry in the Table
- **NOUT**: Number of Time Steps between output data points
- **P**: Bottom Hole Flowing Pressure Array (psia)
- **PC**: Pseudo Critical Pressure (psia)
- **PCH**: Chamber Gas Pressure (psia)
- **PCHI**: Initial Chamber Gas Pressure (psia)
- **PELEV**: Hydrostatic Pressure Drop (psia)
- **PERM**: Formation Permeability (milli-darcy)
- **PFRIC**: Frictional Pressure Drop (psia)
- **PFRIC1**: Frictional Pressure Drop for the previous time step
- **PHI**: Formation Porosity (fraction)
- **PI**: Initial Reservoir Static Pressure (psia)
- **PR**: Pseudo Reduced Pressure
- **qddummy**: Dimensionless Cumulative Influx Value obtained from interpolation
- **qtab**: Dimensionless Cumulative Influx Values in the "table" for interpolation
- **Q**: Dimensionless Cumulative Fluid Influx Array
- **Q00**: Oil Flowrate for the Previous Time Step (bbl/D)
- **QOTEM**: Oil Flowrate for the Previous Time Step (bbl/D)
- **RE**: Reynolds Number
- **RW**: Wellbore Radius (ft)
- **SGF**: Specific Liquid Gravity (relative to water)
- **SKN**: Hurst Skin Factor
- **tddummy**: Dimensionless Time
- **tdtab**: Dimensionless Time Values in the Table for Interpolation
- **T**: Time Elapsed Array (seconds)
- **TI**: Time in which the Pressure Drop is in Effect Array (seconds)
- **TC**: Pseudo Critical Temperature (R)
- **TEM**: Frictional Pressure Drop for the previous time step
- **TEMP**: Chamber Gas Temperature (F) -> (R)
- **TR**: Pseudo Reduced Temperature
- **TT**: Total Time (seconds)
- **TT1**: Total Time for the previous time step
- **UF**: Produced Liquid Viscosity (sp
- **X**: Fluid Level Measured from Mid-Perforations (ft)
- **Z**: Chamber Real Gas Compressibility Factor
- **Z1**: Initial Chamber Real Gas Compressibility Factor

** NOTE: ** Input variable units are "field units" and converted to absolute units during execution. In the above variable **

** SUBROUTINES: **

- **FM**: Moody Friction Factors Calculation.
- **GPC**: Pseudo Critical Temperature and Pressure Calculation for Hydrocarbon Gas.
- **GZ**: Real Gas Deviation Factor Calculation.
for Hydrocarbon Gas.

INTERP = Interpolator to Calculate Cumulative Influx

Beatriz Salas (After Simmons, 1985)

August, 1986

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IMPLICIT REAL*8(A-H,O-Z)
DIMENSION T(10002), P(10001), Q(10002), Tl(10002)
CHARACTER*1 NAME
CHARACTER*4 DES, DES1, DES2, DES3, DES4
DIMENSION qtab(550), ttab(550)
OPEN(UNIT=2,FILE='basedata*,STATUS='OLD',ACCESS='SEQUENTIAL')
REWIND(UNIT=2)
OPEN(UNIT=3,FILE='table*,STATUS='OLD',ACCESS='SEQUENTIAL')
REWIND(UNIT=3)
OPEN(UNIT=4,FILE='output',STATUS='NEW',ACCESS='SEQUENTIAL')

Read Run Parameters from a file called "basedata"

READ(2,*)NAME
READ(2,*)D
READ(2,*)E
READ(2,*)DB
READ(2,*)DU
READ(2,*)DF
READ(2,*)CL
READ(2,*)PCHI
READ(2,*)GG
READ(2,*)TEMP
READ(2,*)PI
READ(2,*)PHI
READ(2,*)PERM
READ(2,*)SKN
READ(2,*)DW
READ(2,*)H
READ(2,*)CT
READ(2,*)API
READ(2,*)UF

Read dimensionless time and dimensionless cumulative influx values from a file called "table"

DO 5 I=1,550
   READ(3,*)ttab(I), qtab(I)
   CONTINUE

Change units to useable form, calculate initial conditions and constants

ED = E/D
D = D/12.
ALC = DF - DU
ALI = DF - DB + CL
PCHI = PCHI + 14.696
PI = PI + 14.696
TEMP = TEMP + 460
RW = DW/24
SGF = 141.5/(131.5+API)
ACH = (3.1415926)*(D**2)/4
CALL GPC(GG,TC,PC)
TR = TEMP/TC
PR = PCHI/PC
CALL GZ(TR,PR,Z1)

T(1) = 0.0
P(1) = PCHI + 0.4333*ALI*SGF
Q(0) = 0.0
B = 1.119*PHI*CT*(RW**2)*H
CDTD = 73.25E-9*PERM/(PHI*UF*CT*(RW**2))
CQO = 86400
CPE = 186.88/(UF*D*(131.5+API))
CFH = 4.22E-9*B/((3.1415926**2)*(D**5)*32.174)
CPSI = 0.4333*SGF
CFP = 5.615/ACH
PELEV = CPSI*ALI

*******************************************************************************
* Output the data check *
*******************************************************************************

OPEN(1,FILE=NAME)
WRITE(1,3000)
3000 FORMAT('CLOSED CHAMBER WELL TEST (INCLUDING FRICTIONAL EFFECTS)', &/,'INPUT DATA AS FOLLOWS:','/)
WRITE(1,3005)NAME
3005 FORMAT('OUTPUT FILE NAME = ',T49,Al0,/) 
WRITE(1,3010)D
3010 FORMAT('CHAMBER DIAMETER = ',T47,F6.3,' (FEET)')
WRITE(1,3015)E
3015 FORMAT('ROUGHNESS = ',T46,F7.5)'(INCHES)'
WRITE(1,3016)ED
3016 FORMAT('TOTAL CHAMBER LENGTH FROM PERFORATIONS = ', &T45,F6.2,' (FEET)')
WRITE(1,3020)ALI
3020 FORMAT('INITIAL FLUID COLUMN LENGTH = ',T45,F6.2,' (FEET)')
WRITE(1,3025)PCHI
3025 FORMAT('INITIAL CHAMBER PRESSURE = ',T45,F6.2,' (PSIA)')
WRITE(1,3030)GG
3030 FORMAT('CHAMBER GAS GRAVITY = ',T47,F6.4,' (AIR=1.0)')
WRITE(1,3035)PI
3035 FORMAT('INITIAL RESERVOIR PRESSURE = ',T45,F6.2,' (PSIA)')
WRITE(1,3040)TEMP
3040 FORMAT('RESERVOIR TEMPERATURE = ',T45,F8.2,' (R)')
WRITE(1,3045)SGF
3045 FORMAT('PRODUCED FLUID SPECIFIC GRAVITY = ',T47,F6.4)
WRITE(1,3050)UF
3050 FORMAT('PRODUCED FLUID VISCOSITY = ',T47,F6.3,' (CP)')
WRITE(1,3055)PHI
3055 FORMAT('RESERVOIR POROSITY = ',T47,F6.4)
WRITE(1,3060)PERM
3060 FORMAT('RESERVOIR POROSITY = ',T47,F6.4)
RESERVOIR PERMEABILITY = ,T45,F8.2,* (MD)
WRITE(1,3095)SKN
WRITE(1,3099)DW/DW
FILL DIAMETER = ,T47,F6.4,* (FEET)
WRITE(1,3110)CT
FORMATION TOTAL COMPRESSIBILITY = ,
& T43,E17.4,* (1/PSI)
WRITE(1,3120)H
WELL DIAMETER = ,T47,F6.4,* (FEET)
WRITE(1,3130)DW/12
TOTAL COMPRESSIBILITY = *
WRITE(1,3140)CT
FORMAT('NUMBER OF DATA POINTS = ',T50,'100')
WRITE(1,3150)NDP
TIME DATA:
& TIME,'T17',PWF,'T25','FLD FRD','T37','PELEV',T47,
& PCH,'T55','Z','T63','IFLAG','T72','R0','T81','f','T91','q0',
&(T81,'y'),T3,'(SECONDS)',
&(T55,'psia'),T26,'(BBL/D)',T35,'(PSI)
WRITE(1,3200)0,P(1),0,PELEV,PCHI,ZI,0,0,0

Calculate other initial conditions
Z = Z1
KFLAG=0
PP1 = 0.00
QO1 = 0.00
PFRIC1 = 0.00
T11 = 0.00
N1 = 0
TEM = 100.00
QOTEM = 100.00
PCH1 = PCHI

Input run data

DO YOU WANT TO CHECK EACH TIME STEP? (y/n)
READ(5,*DES2
ENDIF
WRITE(6,5815)
DO YOU WANT TO WRITE THIS SET OF DATA POINTS ?
READ(5,*DES3
ENDIF
WRITE(6,5820)
NUMBER OF DATA POINTS ?
READ(5,*NDP
NOUT = N2/NDP

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Calculate the Pressure Response

*****************************************************
************ Calculate Total Number of Time Steps ************
N = N1 + N2 + 0.1
NCOUNT = 0
*****************************************************

******** Top of Time Step Loop ********
DO 18 I = (N1 + 1), N
NFLAG = NCOUNT + 1
T(I+1) = T(I) + DT
CONTINUE
18

Interpolation to Calculate Dimensionless Cumulative Influx Values

DO 11 L = 1, I
   T(I) = T(I) + DT
   TDDUMY = T(I) * CDTD
   CALL INTERP(TDDUMY, QDDUMY, QTAB, TDTAB)
   Q(L) = QDDUMY
CONTINUE
11

Superposition to Determine Cumulative Influx

FP = B * (PI - PI) * Q(I)
IF(I.EQ.1) GO TO 24
DO 20 J = 2, I
   FP = FP - B * (P(J) - P(J-1)) * Q(J)
   CONTINUE
20

*********** Calculate the Oil Flowrate ***********
IF(KFLAG.EQ.1) GO TO 25
QO = CQO * (FP - FP1) / (T(I+1) - T(I))
FP1 = FP
CONTINUE
25

************ Calculate the Dynamic Fluid Level ************
X = ALI + CFP * FP

Iterative Calculation of PCH and Z

DO 30 L = 1, 30
   PCH = PCHI * (ALC - ALI) * X / ((ALC - X) * ZI)
   PR = PCH / PC
   CALL GZ(TR, PR, ZN)
   DZ = SQRT((ZN - Z)**2)
   Z = ZN
   IF(DZ.LT.1E-04) GO TO 35
CONTINUE
30

IFLAG = 1
The oil flowrate and frictional pressure drop values are checked. If \( Q_0 \) is less or equal to zero or \( F_H \) less than 0.10 ft, the oil flowrate, Reynolds number, Moody friction factor and frictional head loss are set equal to zero.

**Calculate Reynolds Number**

\[ R_E = C_R \cdot Q_0 \]

**Calculate Moody Friction Factor**

CALL FM(RE, ED, F)

**Calculate Frictional Head Loss**

\[ F_H = C_F \cdot F \cdot X \cdot (Q_0 \cdot Z) \]

CONTINUE

Calculate pressure drops and bottom hole pressure (as expressed in Equation (29)).

\[ P_{ELEV} = C_{PSI} \cdot X \]

\[ P_{FRICT} = C_{PSI} \cdot F \cdot X \]

\[ P(I+1) = P_{CH} + P_{ELEV} + P_{FRICT} \]

Print data check

**Print data check**

IF(DES2.EQ."n") GO TO 37
WRITE(6,5025) T(I+1), P(I), P(I+1), Q(I), Q(I+1), PFRIC(I), PFRIC(I+1), PCHR

**Print data check**

5025 FORMAT(1X, "TIME = ", F10.5, 1X, "F10.2", 1X, "F10.2", 1X, "F10.2", 1X, "F10.2", 1X, "F10.2")
Ask to repeat last time step

WRITE(6,5026)

5026 FORMAT('DO YOU WANT TO REPEAT THE LAST TIME STEP? (y/n)')

READ(5,*) DES1

******* Correct counters if the last time step is repeated *******

IF(DES1.EQ.'y') THEN
  N = N1 + NCOUNT - 1
  DO 12 L = 1, I
       Ti(L) = Ti(L) - DT
  CONTINUE
  GO TO 40
ELSE
  DES3 = 'a'
ENDIF

*************** Actualize cumulative data variables **************

37 QQ1 = QQ
    QOTEM = QO
    FP1 = FP
    PFRIC1 = PFRIC
    PCH1 = PCH
    TEH = PFRIC

WRITE(4,3225)T(I+1),P(I+1),FP,ELEV,PCH,Z,IFLAG,RE,F,QQ,PFRIC

Selective Data Output

39 RI = I
    AA = RI/NOUT
    NA = AA
    BB = NA
    IF(AA.NE.BB) GO TO 10
SUBROUTINE FM(RE, ED, F)

IMPLICIT REAL*8(A-H, O-Z)

SL = (200/ED)**1.16

IF (RE.LE.200) THEN
   F = 64/RE
ELSE IF (RE.LE.400) THEN
   F = 0.5/(RE**0.3)
ELSE IF (RE.LE.SL) THEN
   F1 = ED
   DO 40 J = 1, 180
      40 Y = ED*9.34/(RE*DSQRT(F1))
      F = F1
   END DO
   F = Y
ELSE
   F = 0
END IF
\[ F = (1.14 - 2 \cdot \text{DLOG}_1(Y))^{*-2} \]

\[ \text{DIF} = \text{DABS}(F - F1) \]

IF \((\text{DIF} \lt 1 \times 10^{-6})\) GO TO 45

\[ F1 = F \]

CONTINUE

ELSE

\[ F = (1.14 - 2 \cdot \text{DLOG}_1(ED))^{*-2} \]

ENDIF

ENDIF

C

40 RETURN

END

******************************************************************************

SUBROUTINE GPC(GG, TC, PC)

******************************************************************************

THIS ROUTINE CALCULATES THE PSEUDOCRITICAL TEMPERATURE AND PRESSURE FOR CONDENSATE WELL FLUIDS, GIVEN THE GAS GRAVITY. THE EQUATIONS USED ARE THOSE GIVEN BY STANDING.

******************************************************************************

IMPLICIT REAL*8(A-H, O-Z)

TC = 187 + 330\cdot GG - 71.5\cdot (GG^2)

PC = 706.5 + 1.7\cdot GG - 11.1\cdot (GG^2)

RETURN

END

******************************************************************************

SUBROUTINE GZ(TR, PR, Z)

******************************************************************************

THIS ROUTINE CALCULATES THE GAS DEVIATION FACTOR FOR A NATURAL GAS GIVEN THE REDUCED PSEUDOCRITICAL TEMPERATURE AND PRESSURE. THE EQUATIONS USED ARE CURVE FIT RELATIONS FROM THE STANDING-KAT2 CHART GIVEN BY BRILL AND BEGGS.

******************************************************************************

IMPLICIT REAL*8(A-H, O-Z)

A = 1.39\cdot \text{SQR}(TR - 0.92) - 0.36\cdot TR - 0.101

B = \(0.62 \cdot (0.23\cdot TR)\cdot PR\) + \((0.66/\text{SQR}(TR - 0.86) - 0.837)\cdot (PR^2)\) + \((0.32/(10^{9\cdot (TR - 1)})\)\cdot (PR^6)

C = 0.132 - 0.32\cdot \text{DLOG}_1(\text{TR})
D = 10**(0.3106 + 0.49*TR - 0.1824*(TR**2))
Z = A + (1-A)/(2.718281828**2) + C*(PR**D)

RETURN
END

*******************************************************************************
SUBROUTINE INTERP(tddumy,qdumy,qtab,ttab)
*******************************************************************************

THIS ROUTINE INTERPOLATES BETWEEN TWO SUCCESSIVE VALUES IN A TABLE THAT CONTAINS THE DIMENSIONLESS CUMULATIVE INFLUX VALUES FOR DIFFERENT DIMENSIONLESS TIME VALUES.
FOR A GIVEN DIMENSIONLESS TIME THE INTERPOLATOR SUBROUTINE COMPUTES THE CLOSEST LOWER ENTRY IN A TABLE, AND INTERPOLATES BETWEEN THIS VALUES AND THE FOLLOWING ENTRY IN THE TABLE.

*******************************************************************************
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION tddumy(558),qtab(558)

IF (tddumy(1)) GO TO 18
IF (tddumy(1)) GO TO 28
IF (tddumy(1)) GO TO 38
IF (tddumy(1)) GO TO 48
IF (tddumy(1)) GO TO 58

****** 108-1088 RANGE ******

nlow=468+(tddumy-1088)/108
qdumy=qtab(nlow)+(qtab(nlow+1)-qtab(nlow))*
& (tddumy-tddumy(nlow))/108
GO TO 999

****** 18-188 RANGE ******

nlow=278+(tddumy-188)/18
qdumy=qtab(nlow)+(qtab(nlow+1)-qtab(nlow))*
& (tddumy-tddumy(nlow))/18
GO TO 999

****** 1-18 RANGE ******

nlow=288+(tddumy-18)/18
qdumy=qtab(nlow)+(qtab(nlow+1)-qtab(nlow))*
& (tddumy-tddumy(nlow))/18
GO TO 999

****** 5-1 RANGE ******

nlow=198+(tddumy-1)/18
qdumy=qtab(nlow)+(qtab(nlow+1)-qtab(nlow))*
& (tddumy-tddumy(nlow))/18
GO TO 999

****** 5.1-1 RANGE ******


C
20 nlow=1+8+(tddumy-0.1)*1000
qddumy=qdtab(nlow)+(qdtab(nlow+1)-qdtab(nlow))*
& (tddumy-tdtab(nlow))/0.01
  go to 999
C
C
C
10 nlow=1+(tddumy-0.01)*1000
qddumy=qdtab(nlow)+(qdtab(nlow+1)-qdtab(nlow))*
& (tddumy-tdtab(nlow))/0.001
C
C
999 return
end
APPENDIX 2

NUMERICAL VALUES FOR THE BASECASE
WITH AND WITHOUT FRICTION
CLOSED CHAMBER WELL TEST (INCLUDING FRICTIONAL EFFECTS)

INPUT DATA AS FOLLOWS:

- **OUTPUT FILE NAME** = basecase
- **CHAMBER DIAMETER** = 0.203 (FEET)
- **ROUGHNESS** = 0.0 (INCHES)
- **RELATIVE ROUGHNESS** = 0.0
- **TOTAL CHAMBER LENGTH FROM PERFORATIONS** = 1000.00 (FEET)
- **INITIAL FLUID COLUMN LENGTH** = 0.00 (FEET)
- **INITIAL CHAMBER PRESSURE** = 44.70 (PSIA)
- **CHAMBER GAS GRAVITY** = 0.650 (AIR=1.0)
- **INITIAL RESERVOIR PRESSURE** = 5014.70 (PSIA)
- **RESERVOIR TEMPERATURE** = 635.00 (R)
- **PRODUCED FLUID SPECIFIC GRAVITY** = 0.9042
- **PRODUCED FLUID VISCOSITY** = 1.250 (CP)
- **RESERVOIR POROSITY** = 0.2700
- **RESERVOIR PERMEABILITY** = 100.00 (MD)
- **SKIN** = 0.0
- **WELL DIAMETER** = 0.6333 (FEET)
- **FORMATION TOTAL COMPREHENSIBILITY** = $1.0000e-04$ (1/PSI)
- **FORMATION THICKNESS** = 25.00 (FEET)
- **NUMBER OF DATA POINTS** = 87

PRESSURE VS TIME DATA:

<table>
<thead>
<tr>
<th>TIME (SECONDS)</th>
<th>Pwf (PSIA)</th>
<th>FLN PRD (BBL)</th>
<th>PELEV (PSI)</th>
<th>Pch (PSIA)</th>
<th>Z</th>
<th>Re</th>
<th>f</th>
<th>qo (BBL/D)</th>
<th>Pfri (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000</td>
<td>44.70</td>
<td>87.68</td>
<td>0.9411</td>
<td>121.25</td>
<td>0.9964</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1.00000</td>
<td>117.04</td>
<td>143.87</td>
<td>1.8933</td>
<td>121.25</td>
<td>0.9957</td>
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</tr>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
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<tr>
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<td>147.62</td>
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<tr>
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<td>2.1808</td>
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<td>147.62</td>
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CLOSED CHAMBER WELL TEST [INCLUDING FRICTIONAL EFFECTS]

INPUT DATA AS FOLLOWS:

OUTPUT FILE NAME = skinØ

CHAMBER DIAMETER = 0.203 (FEET)
ROUGHNESS = 0.00060 (INCHES)
RELATIVE ROUGHNESS = 0.0025
TOTAL CHAMBER LENGTH FROM PERFORATIONS = 1000.00 (FEET)
INITIAL FLUID COLUMN LENGTH = 44.70 (FT)
CHAMBER GAS GRAVITY = 0.6500 (AR=1.9)

INITIAL RESERVOIR PRESSURE = 5014.70 (PSI)
RESERVOIR TEMPERATURE = 635.00 (R)
PRODUCED FLUID SPECIFIC GRAVITY = 0.9042
PRODUCED FLUID VISCOSITY = 3.22 (CP)
RESERVOIR POROSITY = 0.2700
RESERVOIR PERMEABILITY = 100.00 (MD)
SKIN Ø = 0.8333
WELL DIAMETER = 0.8333 (FEET)
FORMATION TOTAL COMRESSIBILITY = 0.1000e-04 (1/PSI)
FORMATION THICKNESS = 25.00 (FEET)

NUMBER OF DATA POINTS = 84

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