An experimental study of the applicability of flooding phenomena to the dynamic lubrication method of well control

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AN EXPERIMENTAL STUDY OF THE APPLICABILITY OF FLOODING PHENOMENA TO THE DYNAMIC LUBRICATION METHOD OF WELL CONTROL

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
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In Petroleum Engineering

in

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by
Rishi R. Ramtahal
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NOMENCLATURE

\( \mu \) viscosity (kg/m-s)

\( \rho_g \) gas density (Kg/m\(^3\))

\( \rho_l \) liquid density (Kg/m\(^3\))

\( \mu_w \) water viscosity, 0.001 Kg/m-s

\( C_A \) annulus capacity factor (bbl/ft)

\( C_w \) wall friction factor

\( D \) diameter of the tube cross section (m)

\( d_1/d_2 \) casing diameters (in)

\( Fr \) Froud number

\( g \) acceleration due to gravity (m/s\(^2\))

\( K_{uG} \) Kutatladze number (gas)

\( K_{uL} \) Kutatladze number (liquid)

\( n \) number of moles of gas

\( N_B' \) Bond number

\( Q_l \) liquid Flow rate

\( S \) ratio of gap size to average circumference

\( T \) temperature in degrees R

\( V_{*G}/j_{*G} \) gas dimensionless superficial velocity

\( V_{*L}/j_{*L} \) liquid dimensionless superficial velocity

\( V_{bled} \) volume of gas bled from well (cu.ft)

\( V_{G/USG}/j_l \) superficial gas velocity (m/s)

\( V_{gi} \) initial volume of gas in well (cu.ft)
\[ V_{li} \quad \text{volume of liquid pumped into well (cu.ft)} \]
\[ V_L/U_{SL}/jg \quad \text{superficial liquid velocity (m/s)} \]
\[ \Delta P_h \quad \text{change in hydrostatic pressure (PSI)} \]
\[ \rho_m \quad \text{mud weight (ppg)} \]
\[ \sigma \quad \text{surface tension (N/m)} \]
ABSTRACT

This research investigates the feasibility of the dynamic lubrication method of well control as an alternative to conventional stepwise lubrication. The applicability of flooding phenomena to dynamic lubrication and its use in an optimization method to maximize pumping rates was also investigated. An experimental approach was taken in which experiments were conducted in a 13’ long laboratory apparatus designed to emulate the geometry in a wellhead and also in a full-scale research well. The laboratory experiments were conducted to visually investigate the mechanism of flooding and derive a flooding correlation applicable to this type of system. The full-scale experiments were done to evaluate the dynamic lubrication method, compare it to conventional lubrication, attempt dynamic lubrication at high pumping rates, assess the applicability of flooding as the rate determining phenomenon, and identify any complications encountered during this process.

The laboratory tests produced a correlation that was applicable over a range of 3 annular sizes. The equation resembled correlations from previous studies by Richter (1981) and Dempster(1984) and used dimensionless volumetric fluxes as the non-dimensional parameter.

The full-scale tests showed that dynamic lubrication was more efficient in removing gas trapped at the wellhead, and reduced the severity of pressure fluctuations inherent in conventional stepwise lubrication. Pumping at constant high rates had an adverse effect on the process. This high pumping rate reduced the rate of accumulation of liquid in the well by 50% when compared to the more conservative pumping rates. The boundary between efficient and inefficient pump rates corresponded well to the
correlation from laboratory tests if the relevant dimensions were assumed to be dependent on wellhead geometry.

For this wellhead, the casing-casing annulus has a smaller cross sectional area and therefore higher velocities, which logically should control flooding. However, using the casing annulus geometry in the flooding correlation results in incorrect prediction of the onset of flooding unless revised coefficients are used. These revised coefficients were adopted for a proposed preliminary optimization method.
CHAPTER 1

INTRODUCTION

During conventional drilling operations it is always necessary to maintain the hydrostatic pressure in the well greater than the formation pressure. In some cases this may momentarily cease to occur and the result is a kick with formation fluid entering the well. There are several industry accepted procedures for controlling such situations but a requirement is that the drill pipe be at or near to the bottom of the well. This is needed to provide a flow conduit for circulation of kill fluid in order to facilitate the removal of the influx. In some cases, the drill pipe may be unable to perform this function due to washout, balling at the bit, or the drillstring being off bottom. When this occurs, volumetric methods of well control are used. This allows for the kick to be brought to the surface while controlling pressure to prevent an additional kick. The drawback is that the volumetric method does not provide for the removal of the influx and its replacement with sufficiently heavy fluid to regain a hydrostatic overbalance.

Following volumetric well control, gas that was not bled off during the volumetric process will be trapped at the surface. Similarly, this situation may also occur when gas migrates upwards in a shut-in producing well and collects at the surface in the tubing, or in a shut-in gas lift well with gas remaining in the upper portions of the annulus. Wells with significant sustained casing pressure may also contain gas trapped in an annulus at the surface.

To remove gas trapped at the surface and replace it with kill weight fluid in these circumstances, Lubrication particularly bleed and lube, is the method can be carried out. This procedure involves pumping mud into the well and waiting for it to lubricate or fall
to the bottom of the gas column. After which, an amount of gas pressure is bled at the
choke equal to the gain in hydrostatic pressure due to the mud introduced. This procedure
is repeated until all of the gas has been replaced by mud. The limitation to this procedure
is that it can be considerably slow due to the waiting time for the mud to sink to the
bottom of the gas column as well as small volumes being pumped to prevent over
pressuring of the well.

An alternative to Lubrication is a procedure called Dynamic Lubrication. As the
name implies, it is a continuous process where mud is pumped into the well and gas bled
simultaneously. The fundamental concept remains the same (as in Lubrication) where
gas pressure is traded for hydrostatic pressure while maintaining bottom hole pressure
within an acceptable range. The procedure requires an accounting system be set up where
the amount of mud entering and remaining in the well is monitored by noting changes in
a calibrated pit which takes returns as well as stores mud for the pumps.

Several authorities on well control (Matthews et al. (1983), Randy Smith Training
School, AMOCO Technology Training(1994,1995,1996)) have outlined this procedure
and produced written guidelines for its execution. An observation made on analyzing
these recommended procedures it that the pumping rate is either specified at a
predetermined rate (say 1 or 2 barrels per minute), or the author states use a desirable
rate. This seemingly random pump rate could lead to either a too slow or too fast
lubrication rate. It may prolong the process or complicate accounting procedures since it
can result in significant returns and cause high pressures at the well head when mud
flows through the choke increasing backpressure.

This project attempts to improve the lubrication technique by providing a way to
predict the most efficient pumping rate where returns through the choke/flow line during
dynamic lubrication is minimized. The analysis has two main goals: to maintain the
bottom hole pressure during the dynamic process and secondly, be able to predict the
appropriate pumping rate for a particular gas rate, casing pressure and well head
game. The first goal can be met by using the principle already outlined in well control
literature where gas pressure is traded for mud hydrostatic pressure. Achieving the
second goal leads to analysis hydrodynamic fluid interactions at the wellhead where mud
is introduced to a gas stream and falls due to gravity. The aim is to have full or complete
counter-current flow of mud and gas. The analysis has led to concepts dealing with
counter-current flow of gas and liquid and the limits of this type of system.

One mechanism for the interaction at the well head is the concept of flooding as
the limit of fully counter-current gas-liquid flow. This idea uses a defining equation with
superficial mud and gas velocities as the variables to predict rates of each phase that will
allow for complete penetration of mud into the gas stream. There are numerous flooding
equations or correlations, however, these correlations are not very general. Parameters of
tube diameter, liquid inlet geometries and fluid properties can cause inaccuracies in
predictions when a correlation is applied to a system for which it was not derived. This
work attempts to calibrate relevant or applicable flooding correlations to well-type
applications through use of empirical data obtained from well experiments. Once the
appropriate equation is assessed, and it has been shown to predict flooding with an
acceptable degree of accuracy, it will be applied to the current knowledge on dynamic
lubrication to allow for improved performance of the method. The end result is expected
to be a simplified approach to dynamic lubrication with predictive tools for optimization
during well control operations of this type.
CHAPTER 2
LITERATURE REVIEW

2.1 LUBRICATION

The Lubricate and Bleed Method for well control is a quasi-constant bottom hole pressure method. It is usually used following volumetric well control to remove gas that has been brought to the surface and is trapped under the BOP. This situation arises when conventional well control methods such as Drillers and Wait and Weight cannot be used due to plugging of the drill string, drill string washout, or limitation on surface equipment pressure rating. When such situations occur, a flow conduit to the bottom of the well is not possible and so circulation techniques are rendered unsuitable for removing gas influx due to kicks taken.

In the lubrication method, liquid is pumped into the well via a kill or flow line and is allowed to fall to the bottom of the gas column. Following this, pressure is bled off equal to the gain in hydrostatic pressure due to the liquid. The procedure of injecting liquid, waiting for it to fall, and bleeding pressure at the surface is repeated until the pressure at the surface is zero and all the gas had been removed from the well. If the well is underbalanced, the weight of the fluid introduced should ideally compensate for the difference in formation pressure and hydrostatic pressure of fluid already in the well. This procedure can take a significant amount of time depending on the well configuration, fluid properties and the pressure of the trapped gas column. Fig. 2.1 illustrates the procedure.

2.2 DYNAMIC LUBRICATION

Dynamic lubrication is similar in principle to the conventional bleed and lubricate procedure for well control. In this method there is no waiting time for the fluid to fall or
Fig. 2.1 Conventional lubrication in a well

‘lubricate’ to the bottom of the gas column, instead fluid is continually pumped into the well’s annulus while gas is bled simultaneously. Since this is a quasi-constant bottomhole pressure method, certain operational parameters should be controlled. The gain in hydrostatic pressure due to falling fluid must be compensated for by bleeding an equivalent amount of casing pressure. Other relevant parameters are gas superficial velocity at the wellhead and liquid pumping rate.

Performing this type of well control requires a schedule of casing pressure versus pit gain to be followed. This schedule relates a change in pit gain to the appropriate casing pressure. The schedule shown in Fig. 2.2 illustrates how it is constructed for a surface BOP application. The lower line is constructed by plotting initial shut-in pressure against initial pit gain as shown at point A. The gradient of the line is given by:
\[
\frac{0.052 \times \rho_m}{C_A}
\]  \hspace{1cm} (2.1)

\(C_A\) - annulus capacity factor (bbl/ft)

\(\rho_m\) - mud weight (ppg)

A safety factor of 150 psi is used in this example to plot the line (B) of maximum shut-in casing pressure versus pit gain. The intercept when extrapolated gives the theoretical shut in drill pipe pressure if drill pipe pressure was available. The well setup is illustrated in Fig 2.3

---

**Fig. 2.2 Casing pressure- pit gain schedule**
Fig. 2.3 Well schematic for dynamic lubrication

Fluid is pumped into the well via the kill line and bled through the choke line and manifold into a calibrated tank. This may be a trip tank and a cementing pump is typically used since low flow rates are required for this process.

2.2.1 Jeffery L. Matthews and Adam T. Bourgoyne Jr. (1983)

2.2.1.1 Constant Bottom Hole Pressure Methods for Dynamic Lubrication

Matthews and Bourgoyne conducted experiments on conventional and non-conventional well control methods. Their tests were done on two 6000’ experimental
wells at Louisiana State University. One well was used to represent operations with a
surface BOP stack and the other for a subsea arrangement. Of particular interest for this
research are the volumetric methods investigated.

- **Static volumetric method**

  The static volumetric method was conducted using nitrogen as the influx fluid.

The plot below Fig 2.4 shows the results of the static volumetric method used to remove
a 10 bbl gas kick.

![Fig. 2.4 Results of static volumetric method (Matthews et al.,1983)](image)

Fig. 2.4 Results of static volumetric method (Matthews et al.,1983)

The plot illustrates that bottom hole pressure was kept overbalanced for the entire
process, however, all the gas was not removed. Secondary well control procedures would
have to be incorporated if the gas is to be completely removed. This method works on the
principle that increases in casing pressure due to upward gas migration is balanced by
systematically bleeding a hydrostatically equivalent amount of mud. An example is using
50 psi increments where casing pressure is allowed to increase by 50psi after which mud
is bled through the choke line. The total amount to bleed is given by:

\[
\Delta V = \Delta P_c C_A / 0.052 \rho \tag{2.2}
\]
for 50 psi = 50 \frac{C_A}{0.052 \rho_m}

= 962 \frac{C_A}{\rho_m}

\Delta V \text{-volume bled, } \Delta P_h \text{-change in hydrostatic pressure.}

After this mud is bled at constant casing pressure, casing pressure is allowed to increase again by 50 psi and the process repeated until the gas kick is brought to the surface at constant bottom hole pressure. Typical assumptions for this process are:

- Kick remains as a continuous slug occupying entire annular cross section.
- Gas density is negligible
- Once gas reaches the surface, no gas is to be produced.

It was observed that theoretical estimates, considering the gas as a continuous slug and the gas law, of a final shut in casing pressure of 1350 psi and a pit gain of 15.4 bbl (26.3-10.9) was not observed. Instead, the test showed a 3.5 bbl pit gain and a final casing pressure of 1050 psi. While mud was being bled gas was also observed and vented earlier than expected in test. This resulted in both gas and mud being bled and then gas only. This did not cause drill pipe pressure to fall below it initial shut-in value and well control was maintained during the entire run.

- **Dynamic Volumetric Method**

  The Dynamic method investigated by Mathews and Bourgoyne is based on a similar principle as the static method. This method involves continuously pumping mud into the well through the kill line across the top of the annulus and out the choke while the gas is being brought to the surface and after it has surfaced. The well is essentially used as a mud-gas separator with gas exiting through the choke line and mud entering through the kill line. The pressure control is carried out again by relating a gain in
hydrostatic pressure due to a pit loss to a reduction in casing pressure controlled by choke adjustment.

As shown in Fig 2.5 the desired kill line pressure or choke pressure is a function of pit gain. A 200 psi overbalance was used to compensate for choke adjustment. The graph shows a comparison between desired values for bottom hole pressure and those obtained during the test. It is clear that the procedure was a success since the bottom hole pressure was kept very close the desired value. Also illustrated in Fig 2.5 is the same plot except over time.

Important points to note here are the fact that this demonstrates the validity of dynamic lubrication as a constant bottom hole pressure method and also that the operation was carried out on a real well using typical well control equipment. This is a key concept that will be used in the current work, however optimization will also be attempted here. The dynamic volumetric tests carried out by Matthews and Bourgoyne were done at a constant pumping rate of one barrel per minute. This was done primarily to have all the mud pumped into the well actually fall and not flow through the choke. Taking mud returns through the choke makes following the casing pressure pit gain schedule more difficult because accurate accounting of mud returns must be made, and it served no purpose to pump more kill fluid than the well will accept.

2.2.2 Amoco Technology and Training (1994,1995,1996)

In this training manual, a Dynamic Lubricate and Bleed Procedure is outlined. The procedure is similar to that of Matthews and Bourgoyne where a casing pressure pit gain or lubricated barrels schedule is followed. This well control scenario is the same as that being analyzed in the current work and the difference is optimization. This procedure as outlined pumps kill fluid into the kill line and takes returns of any fluid through the
choke line. Pressure control is done by choke manipulation. The procedure recommends a pump or lubrication rate of one or two barrel per minute. Here again, as in the Matthews and Bourgoyne method, no quantitative reasoning is given for the lubrication rate selected. It can be inferred that this rate was used to ensure that all mud pumped into the well will actually remain and not flow out through the choke line.

![Graph](image1.png)

Fig. 2.5 Results of the dynamic volumetric method (Matthews et al. 1983)

### 2.3 FLOODING

The downward flow of liquid under gravity is limited by the upward flow of gas. This phenomena is referred to as *flooding* where there is a limit on the rate at which liquid can flow counter-current to a gas stream flowing at a particular gas velocity, after which any increase in liquid rate would result in co-current flow of the additional liquid.
introduced into the flow section. Flooding has been studied for decades and even till today a unified theory describing its mechanisms has not been achieved. In many industrial processes counter-current gas liquid flow is seen to occur and flooding is usually an undesirable characteristic. Flooding gained great importance in the nuclear industry where Loss of Coolant Accidents (LOCA) can create a flooding condition in a downcomer. In this situation water is needed to flood the reactor core by flowing counter-current to a hot gas stream, but its flow may be limited or completely prevented by upward moving gas and thus increasing the possibility of meltdown.

![Diagram of Flooding in Downcomer](image)

**Fig. 2.6 Flooding in downcomer (Levy 2000)**

Fig (2.6) shows counter-current annular flow through a small diameter tube. The gas phase flows upward and the liquid flows down under the influence of gravity. At no gas flow, the liquid flows downward in a smooth pattern with very few ripples. However as the gas flow rate is increased the liquid film becomes wavy and droplets are carried over the inlet (flooding) (b). With increase in the gas flow, more liquid is carried over in greater quantities and the flow is now co-current above the liquid inlet and still counter-current below (c)(d). As the gas rate is increased even more, there is complete flow reversal where all the liquid moves co-current with the gas (e). If the gas rate was kept
constant at a rate seen in (b) and the liquid rate was increased, initially at low liquid rates all the liquid would flow counter-current to the gas. By increasing the liquid rate a maximum liquid flow rate is achieved. Beyond that rate liquid flow would move upward co-current to the gas. This therefore implies that there is a maximum liquid rate that can flow counter-current to a particular gas flow rate. This downward liquid rate cannot be increased unless the gas rate is decreased.

There are several proposed mechanisms for predicting flooding. Each model seems to match the experimental data obtained by the investigators but seem to fail at different flow geometries and entry and exit conditions. This has made it difficult for various operating conditions to be grouped and modeled. It should be noted that end conditions used in flooding experiments are often chosen for experimental convenience and do not always have direct industrial relevance (McQuillan 1984).

It is generally believed that flooding occurs when large waves, formed near the liquid outlet, are swept upwards by the gas phase (Jayanti et al. 2000). This wave phenomena on the other hand was not reported by Zabras and Dukler (1988) and Biage (1989). This difference in mechanisms observed can be attributes to inlet and outlet conditions varying among experiments. Jayanti et al. (1996) indicated that tube diameter was determining factor in the way flooding occurred. They deduced that flooding could occur by one of two mechanisms: upward transport of waves near to the outlet or droplets being carried over having broken off from the film in the test section. The reasoning here is that the gas flow rate required to carry a wave upward in a large tube would be larger than that required to cause droplets to be sheared off the film and carried up the tube. Experiments carried out on flooding usually showed the droplet entrainment mechanism in tubes greater then 50 mm in diameter and smaller tubes showed wave like
mechanisms. In the case of wells the large tube criteria (50 mm) would be applicable and the mechanism of droplet entrainment would be a main contending mechanism. Other mechanism worthy of mention is the occurrence of perturbations in the liquid film that increase with increasing gas flow rate. These disturbances in the form of waves may grow in amplitude and cause bridging. This in turn results in the gas stream carrying over liquid.

There are two widely accepted flooding correlations which have emerged from different research. The first is by Wallis (1969) which is based on the wave concept and relates dimensionless gas and liquid velocities at the flooding point:

\[
\left( V_L^* \right)^{1/2} + \left( V_G^* \right)^{1/2} = C \tag{2.3}
\]

\[
V_L^* = \text{liquid dimensionless superficial velocity} \quad V_L^* = \frac{\rho_L^{1/2} v_L}{[gD(\rho_L - \rho_G)]^{1/2}} \tag{2.4}
\]

\[
V_G^* = \text{gas dimensionless superficial velocity} \quad V_G^* = \frac{\rho_G^{1/2} v_G}{[gD(\rho_L - \rho_G)]^{1/2}} \tag{2.5}
\]

D is the diameter of the tube cross section or in the case of annular sections it is the average circumference.

The second flooding correlation (Pushkina and Sorokin (1969)) uses the Kutateladze number. It specifies the point of zero liquid penetration at \( \text{Ku}_G = 3.2 \), where

\[
\text{Ku}_G = \frac{\rho_G^{1/2} j_G}{[g\sigma(\rho_L - \rho_G)]^{1/4}} \tag{2.6}
\]

\[
\text{Ku}_L = \frac{\rho_L^{1/2} j_L}{[g\sigma(\rho_L - \rho_G)]^{1/4}} \tag{2.7}
\]

\( \sigma \) is surface tension, Ku-Kutateladze number
The Kutatladze number has been derived from considerations of the stability of the liquid film and from the gas flow needed to suspend the largest stable drop. The Wallis correlation had proven to predict flooding in pipe sizes up to 0.058 m in diameter and the Kutatladze number for pipe sizes larger than 0.152 m in diameter.

Flooding in annular sections has also been investigated since this is the geometry found in nuclear downcomers. The mechanism is very similar to that of tubes except that the characteristic length of diameter is replaced by the average annular circumference. Equations of the Wallis (1969) type for annular geometries are given by:

\[ V*_{G}^{1/2} + 0.8V*_{L}^{1/2} = 0.9 \text{ - for } 1/30 \text{ scale of a nuclear reactor downcomer} \]

\[ V*_{G}^{1/2} + 0.77V*_{L}^{1/2} = 0.8 \text{ - for } 1/15 \text{ scale of a nuclear reactor downcomer} \]

The mechanisms of flooding are still not fully understood today, and testing and empirical correlations are the primary means for predicting their occurrence and behavior (Levy 1999). In the research under consideration, flooding would be one of the limiting mechanisms considered for lubrication. Neither wellhead geometries nor large scale well-type experiments have been investigated before. For this reason, empirical calibration of current accepted models for flooding and partial liquid penetration would be the chosen method of investigation to improve applicability to wells.

2.3.1 Horst J. Richter (1981)

Richter presented a new correlation for flooding which addresses the conflict between the Wallis (1969) correlation and the study done by Pushkina and Sorokin (1969). This new correlation was found to be applicable for partial penetration of water in pipe sections as well as annuli with the limitation that the liquid must travel down the pipe in the form of a film.
The work done by Pushkina and Sorokin considered the effect of flooding on varying diameter pipe sections with flooding characterized by the point of no liquid penetration. They concluded that critical gas velocity for no liquid penetration was independent of pipe size. Noteworthy here is the fact that their conclusion was valid for pipes sizes over 0.15 m in diameter. The second correlation considered in Richter’s work was that of Wallis. This flooding correlation considered the effect of zero liquid penetration as well as the delivery of liquid as a function of gas flow rate. The experiments done by Wallis were for small diameter pipes. The result was that gas flow rate for zero penetration was proportional to the root of pipe diameter and increased with the pipe size.

Equations are shown below:

\[ j^* G^{1/2} + mj^* L^{1/2} = C \]  (Wallis Type flooding equation with \( j^* G \) / \( j^* L \) used instead of \( V_L^* \) and \( V_G^* \), m and C are constants and m is approximately set to unity for two component systems when there is no mass transfer between the phases. C is dependent upon entrance conditions and ranges usually between C=0.7 and C= 1.0 (Richter (1981))

Here there is a conflict in the applicability of the two correlations over various pipe sizes. Pushkina and Sorokin predict no dependence on pipe geometry for the onset of flooding where as Wallis has a square relation for flooding velocity and pipe diameter. This study by Richter resulted in a correlation that is applicable over the entire test section range of Wallis and Pushkina and Sorokin with applicability to zero penetration as well as partial delivery in both tubes and annular geometries.

The approach can be considered a semi-empirical method which is based on a force balance between the liquid and gas regions of a counter-current in annular flow
regime. The onset of flooding was characterized by the destabilization of waves due to the pressure difference between wave crests and troughs not being balanced by surface tension. This results in droplets being broken off and transported co-current by the gas stream. The resulting equation resembled both the Wallis and Pushkina and Sorokin correlations when considered for different pipe diameters.

When a similar method was applied to annular sections where the characteristic diameter for a pipe was replaced by the average annular circumference the resulting flooding equation was:

\[ C_w N_B^3 J_G^6 S^2 J_L^2 + C_w N_B J_G^4 + 150 C_w J_G^2 / S^* = 1 \]

(2.10)

where: 
- \( C_w \): wall friction factor, 
- \( N_B \): Bond number 
- \( S^* \): ratio of gap size to average circumference

\[ N_B^* = \left[ \frac{D^2 g (\rho_l - \rho_g)}{\sigma} \right] \]

(2.11)

D-tube diameter

Richter directly addresses annular pipe configuration and produced Fig. 2.7 to illustrate his results:

2.3.2 Yehuda Taitel and Dovora Barnea (1983)

Taitel and Barnea worked on a model for flow pattern prediction and transition for vertical counter-current gas-liquid flow as well as associated pressure drop. They presented a model from a mechanistic standpoint and paid particular attention to transition mechanisms. Taitel and Barnea used the model developed by Wallis (1969) as a basis for their no solution line on a flow map or instead the limit of counter-current flow.

The equation is of the form:
\[
\left[ \frac{U_G \rho_G^{1/2}}{\sqrt{gD(\rho_L - \rho_G)}} \right]^{1/2} + \left[ \frac{U_L \rho_L^{1/2}}{\sqrt{gD(\rho_L - \rho_G)}} \right]^{1/2} = C
\]  

(2.12)

Where \( U_{SG} \) and \( U_{SL} \) are superficial velocities of gas and liquid respectively and \( \rho_G \) and \( \rho_L \) are gas and liquid densities, \( g \) is the acceleration due to gravity, \( C \) is a constant approximately equal to unity, and \( D \) is the pipe diameter. The liquid was in the form of a falling film for a range of gas flow rates up to the flooding point above which the down coming liquid is carried co-current to the gas steam. The gas velocity for no liquid penetration is found by letting the liquid term equal to zero and solving for the gas velocity. The flow pattern map for vertical counter-current flow is shown in Fig 2.8. The line a is dependent on entry conditions and tube geometry. Important to note as is illustrated in the map is that annular is the most natural flow pattern present in counter-current flow. It was the only pattern observed for an open exit tube.
Taitel and Barnea state that there is no acceptable theory for prediction of the flooding process and even today this statement stands. Prediction techniques rely heavily on empirical correlations. This method of empirical calibration of established models for flooding and partial penetration of liquid in counter-current vertical gas-liquid flow will be employed in this current work.

2.3.3 K.W McQuillan and P.B Whaley (1984)

McQuillan and Whalley performed a comparison among flooding correlations and experimental flooding data for gas-liquid flow in vertical pipes. Their study used a data bank of 2762 experimental flooding data points and 22 flooding correlations. The data bank contained flooding information for various fluid properties and flow conditions and so offered a way of testing the span of precision and accuracy of the various correlations.

The data bank was biased as far as fluid properties were concerned. It mainly had water-air experimental data (68%) and small diameter tubes (78% less than 50mm). For the current research, this was also considered as a limiting factor since well annuli are in the great majority of instances found in the ‘large tube’ (greater then 50.0mm) range and seldom are the fluids water and air. However there is value in testing correlations which

![Fig 2.8Flow pattern map for vertical countercurrent pipe 5 cm in dia., air-water at 25°C, 0.1MPa. A-annular, S-slug, B-bubble (Titel 1983)](image-url)
are so widely scattered in fundamental mechanisms as well as span of results. The results offered some insight into how empirical versus theoretical equations compare and also on the non-generic nature of flooding correlations.

The results of the comparison between the correlations and the experimental data were compiled and measured differences computed. The deviation was used as a measure of how well an equation performed. The key conclusions drawn were:

- empirical correlations performed better than theoretical correlations.
- correlations which used dimensionless superficial velocities were distinctively less accurate than other empirical correlations especially when applied to high liquid rates and non air-water systems.
- The best theoretical correlation was one presented by Bharathan (1978). This equation was good over a range of liquid viscosities and surface tensions but over predicted flooding gas velocity for large diameter tubes.
- The best empirical equation was that of Askeev (1972). This equation performed well over a range of tube diameters and liquid surface tensions, but it over predicted flooding gas rates for high viscosities. The over prediction was corrected by McQuillan and an improved equation of the form:

\[ K_g = 0.286 \, \text{Bo}^{0.26} \, \text{Fr}^{-0.22} \left\{1 + \frac{\mu}{\mu_w}\right\}^{-0.18} \tag{2.13} \]

\( K_g \) - gas Kutateladze number, \( \text{Bo} \) - Bond number, \( \text{Fr} \) - Froud number, \( \mu \) - dynamic viscosity.

\[ \text{Fr} = \sqrt[4]{\frac{g(\rho_l - \rho_g)^3}{\sigma^3}} \tag{2.14} \]

This modified equation gave the most accurate results of all the correlations. The author advises that the comparison was carried out for vertical circular tubes and care should be taken if the correlations are used in other geometries, such as annular.
2.3.4 C.E Lacey and A.E Dukler (1993)

Lacey and Dukler were concerned about the entry region effects on flooding. They contended that the reason for the large disparities among flooding correlations was that previous research was not based on the physical mechanism that causes flooding. They conducted experiments in 50.0mm tubes and investigated the flow of liquid above and below the feed region. Their conclusion was that flooding occurred due to the changes in the velocity profile of the film going from counter-current to co-current. That is, not by the previous mechanisms of upward wave propagation which result in liquid carryover or liquid bridging in the tube (Imura et al., 1976) resulting in gas forcing liquid ejection and hence flooding. This hypothesis is one that contradicts long standing accepted mechanisms of flooding. It is important to note that this is yet another example of experimental work done in single tube geometry for a specific fluid and so care must be taken when accepting this conclusion as a generic concept of flooding.

2.3.5 M. Vijayan, A.R Balakrishnan (2000)

This paper was one of the more recent works published on flooding. It investigates the effect of tube diameter on flooding in annular flow as well as tube length effects. Vijayan and Balakrishnan’s experiments were conducted using clear acrylic tubes with diameters of 25, 67 and 99mm and height 4 m with varying distances between the water inlet and outlet. Air and water were used as test fluids. Visualization was carried out by the naked eye as well as still photography and videography. The aim was to observe the appearance of waves, interface structures and entrained droplets as indications of flooding mechanisms. The water flow rate was established and air injection incrementally increased to and above the flooding point.
The conclusion of their observations was that there are three identifiable mechanisms by which flooding occur. They are: (1) formation of large waves, (2) creation of droplets, and (3) the formation of ring type waves. In the 25 mm tube (1), (2), and (3) were the dominant mechanisms. In the larger tubes, 67 and 99mm, only (1) was observed. These phenomena provided three possible explanations of flooding: upward transport by waves, carryover of liquid due to droplet entrainment in the gas core, and by carryover of liquid due to churn like motion. The flooding velocities recorded were well correlated by equations using tube diameter as a significant parameter (Hewitt and Wallis, 1963 and Alekseev et al., 1972). Another important observation was that for the larger tubes the best correlations were for Kutatladze-type correlations which are independent of tube diameter.

The effect of test section length was also investigated. The conclusion drawn here was that a higher air flow rate was required for flooding in shorter test sections. This is an important point to note since wells may vary significantly in depth, and for well control the length of the gas column when a gas kick is taken would vary depending on kick volume and annular capacity.
CHAPTER 3

THE PROPOSED METHOD

3.1 PREVIOUS WORK

The proposed method is similar in principle to the conventional bleed and lubricate procedure for well control. In this method there is no waiting time for the fluid to fall or ‘lubricate’ to the bottom of the gas column, instead, fluid is continually pumped into the well’s annulus while gas is bled simultaneously. Since this is a quasi-constant bottomhole pressure method, certain operational parameters should be controlled. The gain in hydrostatic pressure due to falling fluid must be compensated for by bleeding an equivalent amount of casing pressure. Other relevant parameters are gas superficial velocity at the wellhead and liquid pumping rate. These parameters influence the stability of the desired counter-current flow pattern at the well head.

In dynamic lubrication, fluid is pumped into the well via the kill line and bled through the choke line and manifold into a calibrated tank. This may be a trip tank, and a cementing pump is typically used since low flow rates and sometimes high pressures are required for this process. This procedure was done by Matthews et al.(1983) using a similar equipment setup as shown in Fig 2.5. The experiments were done on a 6000ft. experimental well at Louisiana State University. The method produced good results in keeping bottomhole pressure at or above the required value as well as a pit volume loss indicating mud was lubricated into the well. Matthews reported no difficulties in using this dynamic method during kick migration and kick removal.

This investigation attempted to use this proven concept of dynamic lubrication to develop an optimized, industry-useable dynamic lubrication process by the application of
multi-phase flooding phenomena as well as experimental testing of the procedure being developed to identify complications that may arise during execution.

In the work done by Matthews et al. (1983) the pumping rate was specified as 1 barrel per minute. This was done to prevent too much kill fluid from being returned through the choke line and allowing for the fluid to efficiently displace an equivalent volume of gas and not compress gas as the fluid is pumped into the well. In order to optimize the process, a maximum pumping rate should be specified and not an arbitrary conservative lubrication rate used.

3.2 OPTIMIZATION

To achieve optimization, an analysis of hydrodynamic effects resulting in counter-current flow of gas and liquid at the wellhead was carried out. Investigation into various types of counter-current gas-liquid flow identified the concept of flooding as being the most applicable mechanism for modeling the fluid interactions at the well head. As noted in the literature review, a practical application of flooding is usually in the nuclear industry where counter-current flow of high velocity steam and water in a reactor downcomer is predicted by flooding correlations. The geometry of a downcomer and that of a well are very similar; both are annular sections of cylinders, however, entry and exit conditions vary for gas and liquid. Also, the counter-current flow of gas and liquid is desired in both wells and downcomers. This leads to the possible use of flooding concepts already proven to be effective in Lost of Coolant Accidents (LOCA) in nuclear reactors.

The proposed method for optimizing pumping rates during lubrication applies flooding concepts that can be used to predict the onset of co-current flow. Co-current
flow is undesirable during lubrication since it is inefficient (a minimum amount of fluid should be returned during lubrication) and can cause complications in tracking the amount of fluid remaining in the well. There is however, need for refinement of the established flooding correlations to improve applicability to wells since these correlations were derived for different inlet flow geometries and tube diameter sizes. As prescribed by Titel(1983) and Levy(2000), empirical analysis is the preferred method for producing applicable, system-specific flooding correlations. This will be the method used for the flooding analysis in the current work.

3.3 THE METHOD OF INVESTIGATION

In order to apply flooding concepts to wells it is necessary to have a correlation that can predict the onset of co-current flow in a well-type geometry. Two stages of testing were done. In the first stage, a series of experiments were carried out that allowed for a visual inspection of the flooding phenomena as well as measurement of the flow parameters at the flooding point under different conditions. The visual inspection was done to validate models for flooding proposed in previous studies and select one that is most applicable for a well. The measurement of flow parameters, liquid and gas velocities and pressures, was done to empirically and graphically form a correlation based on the results of tests and then compare the result to the established flooding correlations. Once an acceptable correlation was realized it was then applied the previously established dynamic lubrication procedure in order to predict maximum allowable pump rates. The second stage of testing involved a full-scale test that was done at Louisiana State University’s Petroleum Engineering Research and Technology Transfer Laboratory (PERTTL). These tests were performed to evaluate dynamic
lubrication as a feasible alternative to conventional lubrication. This full-scale test also provided good insight into the possible complications encountered during lubrication since actual field equipment was used. The research well was an excellent tool in investigating the dynamic lubrication procedure since it was instrumented to measure surface pressures, bottom hole pressure, gas rates out of the well and pump rates. The instrumentation was connected to a data logging system that allowed for easy analysis of the data obtained during testing.
CHAPTER 4

EXPERIMENTS IN 13FT. TRANSPARENT TUBE LABORATORY APPARATUS

As the first stage of testing, a laboratory apparatus was constructed at Louisiana State University’s Petroleum Engineering Research and Technology Transfer Laboratory (PERTTL). This apparatus provided an excellent way to investigate the mechanisms of counter-current gas-liquid flow and also make measurements of the flow parameters as the flow changes from fully counter-current to partially co-current. The flow parameters measured were used to generate flooding curves to be compared to previous work done in this area and also to be used in further full scale testing.

4.1 EXPERIMENTAL SETUP

The first stage of experiments involved the visual inspection of flooding in a well-type geometry and the measurement of flow parameters at flooding points. To do this an apparatus was designed and constructed at Louisiana State University’s Petroleum Engineering Research and Technology Transfer Laboratory (PERTTL). The apparatus consists of a clear, schedule 80, 6” PVC tube which was operated at atmospheric pressure to avoid the hazard of failure. It simulated the well casing. A schedule 80, 6” flow cross was used to simulate the wellhead. Schedule 40, 4” or 2” tubing was placed inside the 6” clear pipe in order to investigate annular effects. A 2” water injection line or kill line, 2” water collection line or choke line, 3/4” air injection line, metering devices for air and water rates into the system, and pressure sensors. Fig. 4.1 illustrates the completed apparatus. The onset of flooding was identified when water was carried over co-current with the air stream and was being discharged through the air-water outlet.
The shape of the apparatus was designed to resemble the entry region on a wellhead where a casing-casing, casing-tubing or casing-drillpipe annulus forms a sharp edge entry region. The entry region plays a significant role in flooding according to Dukler(1983), and so, it was necessary to design an entry region that simulates the entry region on a wellhead. The entry region of an actual wellhead is illustrated in the cutout shown in Fig. 4.2. It can be seen that the entry region is sharp edged and cylindrical and the use of a large cross connection at the top of the clear tube matched this geometry reasonably well. It also facilitated the insertion of different diameter inner tubing strings to change the annular clearance.

The air and water delivery system and the metering systems are illustrated in Fig. 4.3. The air handling system consisted of two compressors, a 330 bbl pressure tank (800 psig working pressure), a Daniel senior orifice meter for measuring air flow rates, and two gate valves for regulating flow. The air system could deliver approximately 9.5 Mscfh to the test apparatus which was 150 ft. away from the pressure tank, for a period of 30 minutes.

The water delivery system consisted of a large and small centrifugal pump, 250 bbl and 40bbl water storage tanks, and turbine and paddle wheel meters for measuring liquid flow. The system could deliver up to 100gpm to the apparatus.

A system calibration was conducted prior to, and periodically during testing. For the gas this was done by the use of a positive displacement totalizing air flow meter as shown in Fig. 4.4. The calibration was checked by having a constant air rate run through the primary measuring system for a specified amount of time and checking if the totalizing meter recorded the amount flow that was measured by the rate meters in the time interval. For the liquid system, calibration of the paddle wheel meter was checked
by the local vendor and checks were done daily to ensure the calibration was within an acceptable degree of accuracy. A turbine meter became available at a late stage in the testing and was also used for calibration checks. The turbine meter is illustrated in Fig 4.8. The daily checks were done by simply timing how long it took for a five gallon bucket to be filled and cross referencing that time with the rate indicated by the meter.

![13' CLEAR TUBE](image)

Fig. 4.1 Well-type apparatus
Fig. 4.2 Wellhead cutout
Fig. 4.3 Complete System Setup
Fig. 4.4 Gas positive displacement totalizing meter

Fig. 4.5 13ft. clear tube
Fig. 4.6 Base of apparatus

Fig. 4.7 6” Cross connection
Fig. 4.8 Turbine meter

Fig. 4.9 System in operation with 40 bbl storage tank
4.2 EXPERIMENTAL PROCEDURE

The test matrix range for the experiments was determined by the geometrical setup being used in a particular test. During the preliminary testing of the apparatus, it was observed that apparently apart from flooding, liquid was carried over from the inlet to the outlet due to the momentum of the water being injected into the 6” cross. This carryover point was used as the upper limit of testing since liquid carryover at this point was not due to flooding but another phenomena which prevented determining the flooding point for higher rates.

Initially, for every geometrical setup (6”x 2”, 6”x 4” and 6”(no insert)) water was pumped into the 2” injection line at an increasing rate until carryover was observed. This point was used as the upper limit for testing as described previously. After this point was found, a matrix was determined based on the resolution of the instrumentation. For example if carryover was observed for a pumping rate of 40 gpm, and the resolution of the equipment was 1 gpm, a matrix of 20 points was used increasing in increments of 2 gpm starting at 1 gpm.

Each test was be done by setting a particular water flow rate into the clear tube that was configured with a particular insert (2”, 4” or none) and then allowing air to flow counter-current. The air rate was slowly increased until returns were taken through the air-water outlet. This was the flooding point, and it is here that water and air rates were recorded and used in generating a flooding curve.

4.3 EXPERIMENTAL RESULTS

The results of each test are illustrated in the following plots. The parameters are gas and liquid superficial velocities. Since the system was left open to the atmosphere the pressure remained within 0.5 PSI of atmospheric.
Fig. 4.10 Flooding points for 6” x 2” setup

Fig. 4.11 Flooding points for 6” x 4” setup
4.4 ANALYSIS OF RESULTS

4.4.1 Observations

The goals of the clear tube experiments were to identify and observe the flow behavior at the onset of flooding. Visual inspection was done and documented during experimental runs to compare the observations to the work of previous researchers. The flow pattern leading to the flooding point showed what appeared to be a simple pattern. Comparing the results to previous studies, the following observations were made:

- Unlike the phenomena reported by Wallis (1969), no large kinematic waves were observed at the gas-liquid interface that resulted in droplets breaking off and carried in the gas stream.
- There was no liquid film flow reversal observed as described by Dukler (1980).
- No sudden change in wave motion was observed at the flooding point as described by Imura et al. (1977).
• Limited bridging as described by Imura et al. (1977) and illustrated in Fig. 4.13 was observed except in the small annular clearance (6” x 4”)

During these tests the liquid film appeared to be very stable. The flow cross was not transparent but it appeared that droplets were formed at the injection point due the agitated state of the fluid when it made a 90 degree change in direction upon entering the vertical tube, see Fig. 4.14. These droplets were then evidently carried over by the gas stream and so resulted in flooding. One key observation was that once a droplet passed through the T-section and entered the clear tube, it was not carried over but traveled down the tube in the liquid film. This was in contrast to the observations made by Wallis (1969) which described large kinematic waves forming and resulting in droplet formation at the onset of flooding or the film flow reversal model described by Dukler (1980).

While tests were being carried out another significant observation was made. There was another phenomena observed that resulted in liquid carryover. This was the carryover of liquid from the inlet to the outlet on the opposite side of the flow cross due to the momentum of the fluid entering. This momentum effect is believed to be the controlling phenomena in this instance since no gas was observed exiting the apparatus.

Fig. 4.13 Bridging in an annular section
during this stage of testing. The carryover that was seen at high liquid rates and low gas rates was geometry dependent and will possibly occur in a well since the wellhead has a similar configuration. Fig. 4.15 illustrates this considering a plan cutout view of the cross section.

Fig. 4.14 Schematic of sharp edge entry region of 13” tube

Fig. 4.15 Top view of cross

liquid enters one side of the cross and is deflected by the insert, but, some liquid is carried over to the other side.
Table 4.1 Carryover liquid rates for different geometries

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Flow rate at carryover with no gas injection (gallons per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No inner tube</td>
<td>23</td>
</tr>
<tr>
<td>6” x 2”</td>
<td>33</td>
</tr>
<tr>
<td>6” x 4”</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 4.1 illustrates the difference in the carryover points for different geometries. The largest inner tube, 4”, was able to have the highest liquid rate injected before carryover. This was followed by the 2” and then no insert. Apparently, a relationship exist between the annular clearance and the average annular circumference with the carryover points. It appeared that a larger annular clearance showed carryover at a lower liquid injection rate, and a larger average annular circumference showed carryover at higher injection rates. This can be explained due the inner pipe deflecting the incoming liquid downwards, a larger insert reducing the annular space through which liquid can travel and exit through the opposite side of the cross, as well as a longer average annular circumference requiring the liquid to travel through a longer path to the outlet and hence hindering carryover. This effect can also occur in a wellhead as the geometry is similar.

In order to obtain a flooding correlation for the system under investigation, it was necessary to non-dimensionalize the parameters (gas flow rate, liquid flow rate, pressures and fluid densities) obtained from the small scale experiments. The parameters were grouped into two different types of non-dimensional groups: 1. Kutatladze number (Pushkina and Sorokin(1969) ) and 2. dimensionless volumetric flux Wallis(1969).
The results using the Kutatladze number were grouped as defined by equations 2.6 and 2.7. This is illustrated in Figs. 4.16, 4.17, and 4.18. The results for Wallis type dimensionless volumetric flux were grouped as defined by equations 2.4 and 2.5 to produce the results shown in Figs. 4.19, 4.20, 4.21.

When the flow parameters (gas flow rate, liquid flow rate, pressures, fluid densities and tube diameter) are converted into dimensionless quantities all flooding curves from different geometries should overlap when plotted on the same graph. Reducing quantities to non-dimensional form allows the use of a correlation to any system regardless of the system’s conditions. Fig 4.22 illustrates the results for all geometries tested when the Kutatladez parameter is plotted on one graph. The same was done for the dimensionless volumetric flux with all results for the geometries tested plotted on one graph in Fig 4.23.

\[ y = -0.5921x + 0.8125 \]
\[ R^2 = 0.9752 \]

Fig. 4.16 Dimensionless plot using Kutatladze number for 6” pipe, no insert.
Fig. 4.17 Dimensionless plot using Kutatladze number for 6” x 2” geometry

Fig. 4.18 Dimensionless plot using Kutatladze number for 6” x 4” geometry
Fig. 4.19 Dimensionless plot using volumetric flux for 6” pipe, no inner tube

Fig. 4.20 Dimensionless plot using volumetric flux for 6”x 2” geometry
In looking at the plots (Fig 4.22 and 4.23) is evident that the Kutatladze did not perform as expected. The lines for different geometries when plotted did not have similar gradient’s or intercepts. This is in contrast to the plot of dimensionless volumetric flux which showed a more distinct similarity among the lines. The reason for the disparity can be attributed to the geometrical term in eqns. 2.4 and 2.5 (D-average annular circumference) which takes into account the size of the tube and ‘corrects’ the dimensionless parameter. The differences in the line can be explained by observations made during testing. The geometry of the apparatus at each test had a significant effect on not only flooding but also the mechanism of flooding. Table 4.2 summarizes the observations made during testing.
Fig. 4.22 Kutatlaze number plots for all geometries

Fig. 4.23 Dimensionless volumetric flux plots for all geometries
Table 4.2 Comparison of mechanisms of flooding for different geometries

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Observations at flooding</th>
<th>Comparison to Fig. 4.22</th>
</tr>
</thead>
<tbody>
<tr>
<td>6” (no inner tube)</td>
<td>Early carryover due to momentum of liquid entering tube, some bridging observed, no deflector so gas stream carries liquid over easily</td>
<td>The observations described leads to the 6” (no insert) configuration having flooding initiate at lower gas and liquid rates when compared to the other geometries tested. It appears that flooding is significantly influenced by the presence of an annular section.</td>
</tr>
<tr>
<td>6” x 2”</td>
<td>Fluid carryover due to momentum of liquid hindered by the presence of an insert (deflector). High gas rates required for flooding to initiate and liquid film very stable. Minimal bridging observed.</td>
<td>This configuration appears to be the best for preventing the onset of flooding. Sufficient annular space prevents bridging as well as the insert acts as a deflector to channel liquid downwards and not be swept out and carried over by the gas stream.</td>
</tr>
<tr>
<td>6” x 4”</td>
<td>Frequent bridging due to small annular clearance. The onset of carryover due to liquid momentum significantly hindered due to the large insert deflecting fluid downwards</td>
<td>The small annular clearance caused bridging near to the top of the apparatus which resulted in flooding. The liquid film was stable but the occasional bridge caused agitation in the film. When compared to the 6” x 2” geometry this configuration permits flooding earlier primarily due to bridging since it was the main observable difference.</td>
</tr>
</tbody>
</table>
4.5 CONCLUSIONS BASED ON OBSERVATIONS

1. It appears that for the annular sections under consideration flooding was not independent of tube size.

2. There exist a complex array of factors contributing to the onset of flooding and liquid penetration. The main factors were:
   • Bridging of the tube especially in small annular clearances.
   • Possible agitation of the liquid film at entry causes droplet formation and subsequent flooding.
   • Inner pipes or inserts form a deflector that assists in channeling the liquid downwards and delaying carryover.

4.6 CORRELATION ANALYSIS

One of the goals of the flooding experiments was to compare the experimentally derived to the already established flooding correlations and, if necessary, re-calibrate to form a useable model for flooding in the geometry under consideration. The results showed that the dimensionless volumetric flux approach was better when compared to the Kutatladze grouping.

The points plotted in Fig. 4.23 are from the three geometries tested. They appear to fall on a straight line. A best-fit straight line was plotted through the points as illustrated by Fig. 4.24 The equation of the straight line seen in Fig 4.24 is of the form:

\[ J_g^{1/2} + mJ_L^{1/2} = C \]

where: \( m=0.82 \)  \( C=0.35 \)

This compares well with the work done by Dempster et al. (1994) with coefficient \( m = 0.96 \) and intercept \( C = 0.375 \). This equation was derived from experiments involving an annular geometry.
Fig. 4.24 Dimensionless volumetric flux plot for all geometries

The work done by Richter (1981) for flooding in annuli produced the graph shown in Fig. 2.7, defined by equation 2.10. For the upper part of the penetration curve it appears that the line matches the experimental data well but falls off at lower values. Interesting to note is that a best-fit straight line drawn through the points on Fig 2.7 has an intercept of 0.35 and a gradient of 1.1. This is close to the results obtained in the current work and has significance in the zero penetration point (the zero penetration point is the critical gas velocity at which no liquid can flow counter-current to the gas stream). The critical velocity corresponds to the values of $J_g^{1/2}$ at which $J_l^{1/2} = 0$ in a flooding correlation. Crowley et al. (1976) obtained a value of $J_g^{1/2} = 0.41$ which again is close to that obtained by Dempster et al. (1994) and the current work (0.35).

Flores-Avila (2002) did research that predicted the critical velocity for a case where gas is blowing out of a well. The equation used for the critical velocity
corresponded to the work done by Titel et al. (1983) which gave a dimensionless volumetric flux value \((J_g^{1/2})\) equal to 1.319. This does not correspond to the values obtained in the current work but may be explained by the difference in the geometry of the liquid and gas entry and exit regions. According to Wallis, the value of the constant \((J_g^{1/2})\) at the critical rate is dependent upon the tube end conditions as well as the manner in which gas and liquid is added and extracted to the system.

At this point it was decided that the results of the small scale testing provided results worthy of further investigation. The most general correlation for flooding was derived from Fig.4.23 which is of the form:

\[ J_g^{1/2} + 0.82J_L^{1/2} = 0.35 \]  

(4.1)

This equation bears a close resemblance to that of Dempster(1984):

\((J_g^{1/2} + 0.96J_L^{1/2} = 0.375)\) and Richter (1981): \(J_g^{1/2} + 1.1J_L^{1/2} = 0.35\). These similarities give added evidence that there was validity in the results obtained. The next step was to apply this correlation to dynamic lubrication in a real well scenario with full scale test equipment and elevated pressures simulating what actually occurs in the field. The logic behind the application of the correlation is that once the parameters of gas velocity, pressure, temperature and well geometry are available, a maximum liquid velocity or liquid pumping rate can be determined for a particular flowing condition at the well head.
CHAPTER 5

FULL SCALE TESTING IN 2787 FT. RESEARCH WELL

Full-scale experiments were carried out at Louisiana State University’s Petroleum Engineering Research and Technology Transfer Laboratory (PERTTL) on the LSU #1 well. The full scale testing was done to investigate the advantages of dynamic lubrication over the conventional bleed and lubricate method of well control, identify possible complications that might be encountered during this procedure, and assess the applicability of flooding phenomena as the controlling process in determining maximum lubrication rates.

5.1 EXPERIMENTAL SETUP

The experimental setup consisted of four main components:

1. The LSU #1 well (2787’ TVD)  2. Gas handling system
2. Liquid handling system               3. Data acquisition system

The LSU #1 is a research well located at LSU’s well control research facility. A schematic of the LSU #1 well is shown in Fig. 5.1. The well has 2787’ of 8 5/8”, 36 lb/ft J-55 closed ended casing. A 2746’ string of 5 1/2” 14 lb/ft, K-55 casing is hung inside the 8 5/8” string. The lubrication experiments were conducted between the 5 1/2” and 8 5/8” casings. Fig. 5.2 shows a picture of LSU #1 wellhead.

The gas handling and delivery system at the facility consists of a 600 psi natural gas pipeline that runs to the facility, three high pressure gas storage wells, and a high pressure compressor. The experiments were carried out at pressures up to 800 psi, and so the gas storage wells were used to deliver gas to the LSU #1 well. There is also a flare tower, shown in fig. 5.3., to which gas from the experiments was vented.
(9) Drill pipe pressure monitor line

(8) Tbg/Tbg annulus

(7) Csg/Tbg annulus

(6) Csg/Csg annulus

(5) 1.9", 2.9 #/ft EUE tubing @ 2722' TVD
(6.85 bbl,99 stks) in 1.9 DP

(4) 4", 11 #/ft IJ tubing @ 600' TVD (Note
(9.1 bbl in 4"), include the rest of this ann
volume below by adding (3)=7.2 bbl, 236 ;

(3) 2-7/8", 6.5 #/ft EUE tubing @ 2690' TV
(7.2 bbl, 236 stks up the gas injection
line including (4)

(2) 5-1/2", 14 #/ft casing @ 2746' TVD
(9.8 bbl in 4"annulus+ 25.9 bbl
in 2.875" annulus, Total of 517 strokes)

(1) 8-5/8", 36#/ft casing @ 2787' TVD
Plate welded on bottom of 8-5/8" csg
(82.6 bbl,1196 strokes up the
7.825"O.D.-5.50"ID annulus less pipe
displacement, 134.25 bbl without rathole)
Capacity of entire wellbore = 142 bbl

IF pumping down the 1.9" & up the 5-1/2
the annular capacity from surface to end
of tbg (includes both diam.)is 39.6 bb

The tubing capacity of 1.9" is 6.86 bbl
The gas inj. (gray) annulus is 19.14 bbl

Fig. 5.1 LSU#1 well schematic
Fig. 5.2 LSU #1 well head at the PERTTL
The liquid delivery and handling system consists of a 200 bbl storage tank with pit volume indicators, a centrifugal charge pump, diesel engine driven Halliburton HT-400 Triplex pump, and a mud-gas separator that vents to the flare tower and returns liquid back to the storage tanks. The well is also connected to the mud–gas separator through a 5000 psi choke manifold. A SWACO drilling choke was used to regulate casing pressure during the testing. Fig 5.4 shows the flow path for the system.

The metering and data acquisition system was fully integrated. This meant that no manual data recording was necessary since all instruments were directly connected to the data logging system. However, as a precaution data was recorded by hand during each test at 5 minute intervals. The parameters metered were gas return rate (scfh), liquid injection rate (gpm), liquid return rate (gpm), bottom hole pressure (psi) and casing(choke) pressure(psi).
All instrumentation was already in place at the facility with the exception of the return gas meter. This rate was metered by the use of a Daniel Orifice meter installed between the flare and the mud-gas separator. The meter was set up to measure 8000-100,000 scfh using a 4” meter run and a 2.75” orifice plate. SWACO proprietary software was used to acquire and store the data. The output from the software was stored in an EXCEL™ spread sheet format and was logged on a PC in the facility’s control room.

Prior to experiments being performed all instruments were checked for calibration as much as possible using any redundancy methods available at the facility. Static and differential pressure cells were calibrated using a dead weight tester. The calibration data was then input into a Daniel computer that logged the data to a central personal computer in the facility’s control room. An example of a redundancy check would be to cross

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**Fig 5.4 Flow path diagram for the system**

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reference the liquid flow rate measured by a flow meter with a pump stroke rate or changes in pit level as indicated by the pit level monitors with actual measured change in pit level. Also, the well was pressure tested to 2000 psi after all the instruments were checked and piping was arranged in the desired configuration.

5.2 EXPERIMENTAL PROCEDURE

For every test done, the well was set up in the same manner. The well was initially filled with water. Water was then displaced from the top of the annulus by injecting gas into the 8 5/8” x 5 1/2 annulus until 28 bbls of water, which corresponded to 923’ of water in the 8 5/8” x 5 1/2” annulus, was recovered in the pits. The choke was closed and additional gas was injected until the well was pressured to 600 psi. The hydrostatic pressure of fluid displaced from the annulus was 400 psi. This meant that when all the gas was replaced by the water at the end of the lubrication process the well would still have 200 psi trapped pressure. This was done to allow bottomhole pressure to be monitored by keeping a positive pressure on the 5 1/2” x 1.9” casing-tubing annulus. The well did not have a simulated reservoir. This means that if the bottomhole pressure fell significantly, there would not be any additional influx flowing into the well as would be the case in the field. Fig. 5.5 shows how the well was set up for the lubrication runs.

Once the well was setup as shown in Fig. 5.5, both conventional and dynamic lubrication were carried out. A casing pressure-pit gain schedule was made for the LSU #1 configuration described above and used for all of the lubrication experiments. Fig 5.6 shows that a 100 psi safety margin was planned in the lubrication tests and the well was considered dead when the casing pressure fell to 200 psi. This was the case when lubrication experiments were done with 200 psi trapped pressure in the 5 1/2” x 1.9” casing-tubing annulus.
Fig. 5.5 Simplified schematic of LSU #1 well setup for lubrication

Fig 5.6 Casing pressure-pit gain schedule for the LSU #1 well for tests I, II and IV.
5.3 EXPERIMENTAL RESULTS AND ANALYSIS

There were four tests carried out on the LSU#1 well. The first was a dynamic lubrication procedure where 200 psi was left in the well after lubrication. The second was very similar to the first except that the well was completely killed with no pressure left in the well after lubrication. This was achieved by pressuring the 8 5/8” x 5 ½” annulus to 400 psi before lubrication. The third main test was a conventional lube and bleed procedure for a 600 psi shut-in casing pressure scenario. This test was done to have a comparison between conventional lubrication and the dynamic method for the same well setup (shut in casing pressure, well geometry). The last test was done at high pumping rates to investigate the effects of pumping at a rate higher than the recommended 42 gpm lubrication rate by AMOCO Technology Training (1996).

5.3.1 TEST I- Dynamic Lubrication (600 PSI Casing Pressure)

The results for the first test done are illustrated in Fig. 5.7. This test was considered to be a success since the excess well pressure was removed while maintaining bottomhole pressure relatively constant. Initially the well was pressured to 700 psi by pumping liquid into the well with the choke closed. This was done to give a 100 psi safety margin to work with. It was then observed that even though the Triplex pump was running the well was taking very little liquid. The problem was found to be that the charge pump was not turned on, and so as seen in Fig. 5.7, the liquid in line starts later than the BHP and casing pressure lines. Once the charge pump was turned on the procedure went well for the most part. The liquid pumping rate was kept within a recommended range of 42 gpm. The bottomhole pressure was kept within a 150 psi window except for one spike due to overshoot in choke operation. Casing pressure was
brought steadily down from 700 psi to 200 psi which was, for this test, theoretically zero since the well was considered filled with liquid.

It can be seen in Fig. 5.7 that several spikes in the casing pressure and hence the bottomhole pressure occurred between 11:32 and 11:41. These were caused by poor choke manipulation. The sudden changes in casing pressure did give some insight into possible complications encountered during the procedure. The first decline labeled point A showed high gas rates flowing out of the well and a significant flare at the tower. These sudden, rapid changes in casing pressure cause the gas to expand and produce high gas rates and high wellhead gas velocities. This results in carryover of the liquid being pumped into the well. The series of spikes in the casing pressure between 11:32 and 11:41 could lead to the reason that liquid was seen coming out of the well subsequently after.

Fig. 5.7 Plot of results from Test I- Dynamic Lubrication
It is believed that the early spikes produced high gas velocities and carried over liquid that filled up the separator. However because the separator was not completely full it was not seen as a liquid rate out since the liquid out meter is located downstream of the separator. The last spike (point B), which was a 173 psi drop in pressure over a period of 78 seconds did show a high gas rate out and also a significant flare. This caused the liquid rate out to be seen downstream of the separator as shown in the plot. This gas rate carried over liquid up to the point where liquid in was the same as liquid out. The liquid rate out subsequently dropped again due to the separator needing time to fill up as shown as point C. When the casing pressure reached 200 psi this was the point when the well was considered full of liquid and as seen in the plot, the liquid in again was the same as the liquid out. It is believed that the spike in liquid out at point D resulted as before from the preceding rapid decrease in casing pressure. At that point the pumps were shut down and the well monitored for any pressure changes. No pressure elevation was observed and the well was considered dead after 55 minutes.

5.3.2 Test II-Dynamic Lubrication (300 PSI casing Pressure)

The second test was very similar to the first except that the well was pressured with gas to 350 instead of 600 psi. This setup would result in the casing pressure being zero once all the gas was removed and replaced by liquid. The results of this test are illustrated in Fig5.8

The results show that again the test was a success since the well was killed with the casing pressure brought to 0 psi while the bottomhole pressure was kept well within a 100 psi working window during the entire procedure. The, fluctuations in bottomhole pressures were minimized due to the choke operator becoming more proficient with every test run made.
Again, as in test I, the liquid pumping rate was kept within a recommended range of approximately 42 gpm with two spikes in the liquid rate in (points E,F) The spikes occurred when the flow into the well was dominated by the charge pump and not the Halliburton Triplex pump. Once casing pressure is less than 70 psi, the charge pump is able to force flow through the triplex pump regardless of the stroke rate. Consequently the liquid rate becomes dominated by the charge pump.

Fig. 5.8 Plot of results from Test II - Dynamic Lubrication

In the region labeled G high sustained gas rates were observed. This high gas rate flowing through the separator may have caused liquid to be displaced from the separator and the spike and subsequent depression in liquid rate out seen in Fig. 5.8. Once the casing pressure was brought to near zero, the pumps were shut down, and the well shut in and observed for 15 minutes. No pressure elevation was observed and the well was considered dead after 45 minutes. The choke was subsequently opened and again no
liquid unloading or gas venting was observed, which verified that all the gas had been removed and the well successfully killed.

5.3.3 Test III-Bleed and Lubricate (600 PSI Casing Pressure)

Another test was conducted using a conventional bleed and lubricate procedure. The well was prepared as in Test I and shut in at 600 psi casing pressure. The results are shown in Fig 5.9

The bleed and lubricate procedure performed on the LSU #1 well provided a good experimental benchmark for comparison with the dynamic lubrication method. In Fig. 5.9 the yellow (liquid in) spikes correspond to liquid being pumped into the shut in well. As the liquid fell into the well the surface pressure increased. Following this, gas was bled through the choke to reduce casing pressure an amount equivalent to the gain in hydrostatic pressure due to liquid being introduced into the well. The horizontal red dashed lines in Fig. 5.9 show the planned steps in which the casing pressure was reduced.

Fig. 5.9 Plot of results from Test III – Bleed and Lubricate
A common but intermittent complication emerged when a liquid rate out was observed while gas was bled through the choke. The liquid out is shown by the pink dots on base of Fig. 5.9. This resulted in the well being shut for more time to allow the liquid fall. The bottom hole pressure was held in a 200 psi operating window which was larger than that seen in the dynamic process. Seen in Fig. 5.9, the pressure must fluctuate during the pumping and bleeding cycles used in this method. The procedure was very time consuming, and even after 90 minutes, the casing pressure was only reduced by 100 psi. At this point, it was decided that the process was not as time efficient as the dynamic method previously used in Test I on the same well, and the test was stopped. The method appears simple in principle, but requires a significant amount of procedures to be executed. The starting and stopping of the pumps, opening and closing of the choke, and observing whether gas or liquid was being returned from the well all add to a complex array of procedures.

5.3.4 Test IV-High Rate Dynamic Lubrication (600PSI PSI casing Pressure)

This test was done to investigate the effect of pumping at high rates during dynamic lubrication and to identify complications that may arise as a result. The plot in Fig. 5.10 shows the added parameter of “Liquid In Well”. This is the difference between the liquid rate being pumped into the well and the liquid rate returning to the separator. It measures rate at which of liquid accumulates in the well. The test was initiated with a pumping rate of 100 gallons per minute. Almost instantaneously, liquid returns were seen, indicating that complete penetration as observed in previous dynamic lubrication tests was not being achieved. This rate was held for a period of 15 minutes, and the average rate of accumulation was 40 gallons per minute. It appeared that only about 1
barrel per minute was being accepted by the well, and the rest carried over. During this period the gas rate out of the well was slow to moderate with the flare seen at the tower varying in size.

Fig. 5.10 Plot of results from Test IV- High Rate Dynamic Lubrication

The pumping rate was then increased to 135 gallons per minute. This rate had yet another adverse effect, giving an average accumulation of only 16 gallons per minute. Therefore, it is seen that pumping at even higher rates resulted in more fluid being carried over and less liquid accumulation in the well over a given period. Another observation was that the flare seen at the tower was quite small and intermittent apparently due to only small, short slugs of gas emerging. On observing that the pumping rate was rate was too high, it was subsequently reduced to 55 gallons per minute and left for 14 minutes. This reduced rate made no significant difference, resulting in a liquid accumulation rate barely over 16 gallons per minute. Also, noteworthy again was the appearance of
fluctuating gas rates as observed by a flare varying in size from very small to medium. The actual gas rates measured during this period also showed this behavior. However, when rates fell below 8000 scfh, the metering device recorded a zero reading, and exact measurement of the low gas rates was not possible.

It appears that the effect of high pump rates, for this case 100-135 gpm, is compressing the gas and forcing it down in the well, effectively bullheading the gas and not lubricating it. This in turn causes liquid to be intermittently unloaded as shown by the cyclic nature of the “Liquid Out” line in Fig. 5.10. This correlates with the intermittent gas rate and hence flare size observed coming out of the well. The casing pressure was reduced from 600 to 275 psi over a period of 50 minutes where previous dynamic tests were completed in 45 minutes or less. As a result of this, the process appears to be inefficient since excessive pumping rates did not promote a faster reduction in casing pressure and gas replacement by liquid in the well. The bottomhole pressure did however remain within the 100 psi margin observed in previous dynamic lubrication tests. A possible explanation is that the gas is being compressed as a result of high pumping rates, and the gas column acts as a buffer between the wellhead and the bottom of the well masking the bullheading effect that can result from high pump rates. Apparently, once the gas was sufficiently compressed, it may have then unloaded liquid as observed in the Fig. 5.10, and the process repeated where gas is compressed by incoming liquid.

5.4 CONCLUSIONS BASED ON ANALYSIS AND OBSERVATIONS

1. The dynamic lubrication tests were successful in replacing gas trapped at the wellhead with liquid in a timely manner. There were minimal complications encountered in performing this procedure. Several main features of this procedure were: 1. Bottomhole pressure was kept within a 100 to 150 psi window during the
procedure. 2. The procedure was completed in about 45 minutes. 3. No significant
depressurization elevation or liquid unloading was observed after the procedure was
completed indicating it was an efficient means of replacing the gas with liquid. 4. 
Pressure variations were minimal as seen in the casing pressure and bottomhole 
pressure plots, especially after Test I due to gaining some operating experience.

2. The bleed and lubricate procedure was less efficient at removing gas and 
replacing it with liquid at the wellhead than dynamic lubrication. The process was 
very slow. Avoiding bleeding of liquid from the well during the pressure bleeding 
phase was a significant complication. The pressure variations observed during this 
procedure on the bottomhole and casing pressure plots are largely an unavoidable 
characteristic of this method.

3. High pumping rates did not have a positive effect on the rate of liquid 
accumulation in the well. The high rates used, 100-135 gpm, caused liquid 
carryover for the entire process and resultant intermittent unloading of liquid from 
the well due to gas migration. The average rate of liquid accumulation into the 
well for the entire high rate procedure was 25 gallons per minute. The procedure 
was executed for 50 minutes and resulted in casing pressure being reduced from 
600-275 psi.

4. It appears from these tests that recommended rate of 1 barrel per minute produced 
the best results when used in the dynamic lubrication procedure for this well. 
Based on the experimental results given in chapter 4, it is expected that the 
optimum rate is a function of annular geometry.
CHAPTER 6

FLOODING ANALYSIS OF FULL-SCALE TESTING

In chapter 4, the flooding phenomena was investigated in a laboratory apparatus designed to emulate a wellhead’s geometry and the casing-tubing annulus that may exist in a well. The results produced a flooding correlation that was quite similar to that obtained by previous researchers such as Dempster(1984) and Richter(1981) who did flooding experiments in annular sections. This chapter investigates the applicability of the correlation obtained in chapter 4 to a full scale well. The method of analysis involves using the data obtained from the dynamic lubrication testing, converting it into dimensionless volumetric fluxes using the equation described by Wallis(1969), and comparing it to the results from the laboratory tests.

6.1 METHOD OF ANALYSIS

Flooding analysis is done for a process that is initially at steady state. The flooding point is defined at the point where an essentially fully developed annular counter-current gas-liquid flow is converted to a co-current, as well as counter-current flow, with liquid moving upwards co-current to as well as downwards past the gas stream. This phenomena is expected to occur in an annular flow regime. The liquid flow must be gravity driven and not due to hydraulic or pneumatic components “forcing” the liquid to move counter-current to the gas stream. It is believed that the flooding phenomenon occurred in Test IV of the full scale testing with high pumping rates. For at least a portion of the tests, gas was apparently being compressed and pushed down the well as opposed to being replaced by liquid in a volumetric manner. As a result of this, the data was sorted in manner that extracted what appeared to be steady state intervals
where there was continuous, full penetration of liquid in the case of Tests I and II or constant carryover of liquid in Test IV.

6.2 ANALYSIS OF FULL-SCALE DATA

The parameters measured during testing and used in flooding analysis were: gas return rate, liquid return rate, liquid pumping rate, and casing pressure. All were acceptably recorded with the exception of the gas return rate. The metering system could only accurately measure rates above 8000 scfh. This meant that any gas rate below 8000 scfh was seen as a zero or negative value in the data acquisition system. For this analysis, these zero or negative rates were treated as a value of 8000 scfh. The parameters (gas return rate, liquid pumping rate, and casing pressure) were sorted as described above, and using an EXCEL™ spread sheet, non-dimensionalized using equations 2.4 and 2.5. The dimensionless fluxes were then compared to the correlation obtained in chapter 4.

Fig. 6.1 shows the data points for the occurrence of flooding and cases where full liquid penetration was achieved with dimensionless fluxes calculated based on the internal wellhead geometry. The straight line drawn was defined by equation 4.1 which represents what was considered to be the most generic flooding correlation derived from the laboratory testing. It appears that the data from the full-scale tests conforms to the boundary defined by equation 4.1 that separates regions of complete penetration and flooding on the dimensionless plot. Also, the area bounded by the dashed lines can be considered as achieving full penetration counter-current flow. This is because lower liquid rates can be accommodated as the liquid dimensionless flux is reduced while the gas dimensionless flux remains the same. Simply stated, a lower pumping rate for particular flowing conditions will not result in the flow going from counter-current to co-current.
Dimensionless Volumetric Flux for Full-Scale Experiments: (Natural Gas-Water system)

Fig. 6.1 Plot of dimensionless volumetric flux for full scale testing for 9”x 5 1/2” annular geometry.

In computing the dimensionless variables Jl and Jg in Fig 6.1, the same parameters were used as in the laboratory testing (gas rates, liquid rates, pressure and average annular circumference.) The difference is that the average annular circumference used in the full scale testing was the circumference at the outlet of the wellhead and not the casing-casing annulus. This was a 9” x 5 1/2” inch annular space. The reasoning here is that since this phenomena is considered an end effect, the geometry at the liquid inlet should be the one used in computing the dimensionless parameters. Fig 6.2 shows an engineering drawing of the casing spool that was used for the full-scale tests. It shows the 9” diameter where the outlets are located.
Fig. 6.2 Engineering Drawing of the casing spool for 5 1/2” casing in LSU#1 well (Provided by ABB Vetco Gray Inc.)

When the casing dimension instead of the spool’s diameter was used in the full scale data analysis as was done for the laboratory apparatus, the calculated liquid and gas dimensionless fluxes are shifted on the plot due to the computed insitu superficial
velocities increasing and the “D” term decreasing in equations 2.4 and 2.5. Fig 6.3 shows how the plot is affected by using the ID of the 8 5/8” casing.

![Dimensionless Volumetric Fluxes for Full-Scale Experiments: (Natural Gas-Water system)](image)

Fig. 6.3 Plot of dimensionless volumetric flux for full scale testing for 7 7/8”x5 1/2” annular geometry.

The graph shows that the points were shifted upwards and to the right indicating that both gas and liquid fluxes increased. The increase is due to the reduced cross sectional area at the casing-casing annulus that results in a higher superficial velocity for each phase. There is a discrepancy as to which parameter is correct since Figs. 6.1 and 6.3 show different gas and liquid dimensionless fluxes where flooding and full penetration was observed.

One of the underlying concepts in this research is that flooding is an end effect because the gas velocity at the surface or top of the well is expected to be the highest in the well. This implies that once liquid penetrates the high velocity region at the surface, it
will continue to fall in the well. However, this may not happen if there is an enlarged section at the wellhead’s outlet such as the one shown in Fig 6.2. This enlarged section results in lower superficial velocities for the phases when compared to the casing-casing annular section lying just under the wellhead’s outlet. Therefore it is proposed that the casing-casing annular section be used as the parameter in the dimensionless equations because it is the section where the highest superficial velocity will be reached. If the liquid can penetrate this high velocity section it will continue to travel down into the well.

If the casing-casing annulus was used as the dimensional parameter, equation 4.1 no longer defines the line of demarcation between the flooding and fully counter-current flux regions plotted on Fig. 6.3. However, if the value of the intercept (C) was changed in equation 4.1, a new line with the same gradient can be plotted. This is shown by the broken line on Fig 6.3. This method of changing the value of the intercept (C) was proposed by Wallis(1969), who stated that the value of C depended on the way gas and liquid were added to the system and the design of the end of the tubes, in this case the well. This method of empirical calibration of flooding correlations was also prescribed by Levy(1999) who stated that entrance and exit conditions have a significant impact on flooding behavior, and their influence can be established only from tests (preferably full-scale) and empirical correlations.

When equation 4.1 is shifted as shown in Fig. 6.3 the equation of the resulting line is given by:

\[ J_g^{1/2} + 0.82J_L^{1/2} = 0.45. \] (6.1)

This plot is shown in Fig 6.4

It is proposed that this equation is the best representation of the applicable flooding correlation for the system being considered. The shift in the correlation can be quantified
by a 29% increase in both gas and liquid fluxes flooding. It is recommended that further testing be done to validate this correlation. This could be done on the LSU#1 well where three different annular sections are available in which testing can be carried out in a similar fashion as described in chapter 5. Performing this type of testing can evaluate the correlation proposed herein and potentially also test the dependence on annular clearance as the relevant parameter to be used in equations 2.4 and 2.5.

**6.3 DEVELOPMENT OF AN ENGINEERING PROCEDURE FOR OPTIMIZED DYNAMIC LUBRICATION**

A goal of this project was to propose a method where the dynamic lubrication procedure may be optimized. Optimization for this case is considered to be a method of
prescribing a maximum liquid pumping rate to be used at a given point in a lubrication procedure. A maximum rate would be one that causes the maximum rate of liquid moving down the well with gas being volumetrically replaced by the liquid without causing compression or downward displacement of the gas that would result in inefficient removal.

To achieve this goal, it is proposed that a flooding correlation be used as a defining equation that governs the stability of a fully counter-current gas-liquid system. In section 6.2, it was seen that the flooding effect may be modeled by a correlation. At this point, the exact correlation is still not known conclusively, but it is believed that the work done does give a good indication of the applicability of this concept and that further testing will allow meaningful evaluation of the proposed correlation described by equation 6.1.

In Appendix A, an analysis is presented showing the gas to liquid volumetric ratio operating during dynamic lubrication if the bottomhole pressure is to be kept constant. The result shows that a 2:1 gas:liquid volumetric rate is required to maintain bottomhole pressure constant in a well during lubrication provided that kill mud weight is used. If kill mud weight is not used the ratio changes and can be found by the method outlined in Appendix A.

To evaluate the derived ratio, the data from the full-scale tests was analyzed with respect to the gas and liquid rates observed during dynamic lubrication tests. Overall, the insitu average gas to liquid ratio for Test I was 2.89 and for Test II was 2.1. The expected ratios were 1.65 for Test I, and 2.0 for Test II. This gives some evidence that the 2:1 ratio for lubrication using kill mud weight has applicability. It should be noted that there were numerous low gas rates that were not recorded due to the limited capability of the gas
meter. If these values were incorporated in the computed ratio for Test I, it is expected that the value would be less than 2.89. A plot of gas:liquid volumetric rate is illustrated in Fig 6.5. In the lubrication tests the liquid rates were held fairly constant. This implies that the fluctuations seen in the gas:liquid volumetric ratio was due to changes in the gas rates. The spikes in gas rates could result from opening and closing the choke too rapidly.

Fig 6.5 Plot of gas:liquid volumetric ratio by rate for full-scale dynamic lubrication tests

In Chapter 2, the dynamic lubrication procedure was outlined, and it was shown that a casing pressure schedule should be followed during the process if bottomhole pressure is to be kept constant. If this casing pressure schedule is followed and the liquid rate used is not excessive so as to cause compression of the gas, the ratio of gas to liquid rate throughout the process should be approximately equal to the computed ratio using the method outlined in Appendix A. This means that a gas rate can be implied from knowing the liquid rate since the volumetric ratio for gas to liquid can be calculated. This ratio would mean that any liquid rate can be used provided that gas rate corresponds to the computed ratio for the system. However, annular counter-current gas-liquid flow can only exist for particular gas and liquid flowing conditions. These conditions or limits are
defined by a flooding correlation as described in section 6.2. The flooding correlations represent the maximum combination of gas and liquid volumetric fluxes, and hence rates, that may exist for counter-current annular flow.

In order to have the gas to liquid ratio required for constant bottomhole pressure dynamic lubrication, as well as satisfy the constraints for liquid and gas rates in counter-current annular flow defined by a flooding correlation, it is necessary to compute flowing conditions that satisfy both these criteria. The problem can be solved by finding a simultaneous solution to the equations describing both the gas and liquid volumetric rates and the volumetric flux limits at the flooding point. However, gas and liquid rates are dimensional, and flooding correlations are plotted using non-dimensional forms of gas and liquid volumetric flux. In order to solve for the flow condition that satisfies all the criteria described previously, it is necessary to non-dimensionalize the gas and liquid rates. This can be done by using equations 2.4 and 2.5 in which the superficial velocities for gas and liquid can be implied by knowing the gas liquid volumetric ratio that should exist. To compute dimensionless volumetric fluxes, pressure and annular geometry is required. The annular geometry is fixed for a given well but pressure varies during dynamic lubrication. If the simultaneous solution is done graphically, the result is a series of lines representing the gas to liquid ratio at different pressures. An example of this type of plot is illustrated in Fig. 6.6. This figure shows the flooding correlation defined by equation 6.1 and plots of the dimensionless gas and liquid volumetric fluxes for different pressures calculated using the gas to liquid volumetric ratio. For this case, the gas to liquid ratio is taken as 2:1. The maximum pressure is 600 psi, the geometry is a 7.875” x 5” annulus and fluids are water and natural gas (specific gravity 0.7) at 75 degrees F.
In Fig. 6.6 the intersection of the flooding correlation and a 2:1 gas:liquid dimensionless flux line, at a specific pressure, represents the maximum liquid dimensionless flux that will permit counter-current annular gas-liquid flow. By knowing the liquid flux, the liquid superficial velocity and hence the liquid flow rate can be calculated. This series of intersections or simultaneous solutions between the flooding correlation and the lines defined by a 2:1 gas-liquid ratio represent the maximum allowable pumping rates to maintain bottomhole pressure and counter-current flow when casing pressure is being reduced, for this case 600 to 15 psi. A step-wise engineering procedure for this optimization method is presented in Appendix B. This engineering procedure recommends a safety factor to be used to compensate for poor choke operation. The safety factor reduces the calculated maximum liquid pumping rate, and so, allows for mistakes to be made when operating the choke without any serious consequences such as
initiating carry over or pumping at a high rate relative to the gas rate such that gas is compressed and not volumetrically replaced by the liquid.
CHAPTER 7
CONCLUSIONS

Data from experiments conducted in a laboratory apparatus and full-scale well have been analyzed to investigate flooding phenomena and its applicability to dynamic lubrication. The experimental observations and data analysis led to the following conclusions:

1. Experiments carried out in the laboratory apparatus produced a flooding correlation using dimensionless volumetric fluxes similar to that obtained in previous research in annular sections. The correlation obtained was:
   \[ J_g^{1/2} + 0.82 J_L^{1/2} = 0.35 \]

2. Flooding in the laboratory apparatus was not independent of annulus size. The flooding points were well correlated using the average annular clearance as the geometric parameter in the Wallis (1969) equations (2.4 and 2.5) for non-dimensional volumetric flux.

3. Counter-current annular flow was observed up to the flooding point. The mechanism of flooding was not obviously the same as that described in previous research. Neither upward wave propagation nor droplet entrainment in the tube was observed. Bridging was observed in some annular configurations, usually in smaller clearances. It is possible that annular flow or droplet entrainment was occurring but was not visible due to the non-transparent flow cross or due to small droplet size.

4. The flooding correlation based on the Kutatladze number did not correlate well
with the observed flooding points in the laboratory apparatus. This was evidently due to the absence of a geometric term in the non-dimensional Kutatladze number equation.

5. The conventional lubricate and bleed method was able to reduce the casing pressure while replacing the gas with liquid in the full-scale tests. This procedure met its functional requirement but was very slow and complications arose when liquid was returned to the storage pits during the gas bleeding stage of the process.

6. In the full scale testing, dynamic lubrication was proven to be more efficient at removing gas trapped in the well than conventional lubrication. The dynamic process was faster and reduced the severity of pressure fluctuations in the well that occur during conventional lubrication.

7. The pumping rate of 42 gallons per minutes recommended by Amoco(1996), was proven to be applicable for the full-scale well’s annulus that contained trapped gas. There were no complications encountered while using this rate. The flow of gas and liquid was fully counter-current when this rate was used in the experiments.

8. The reason that dynamic lubrication was more efficient than conventional bleed and lube is apparently related to flow patterns. Annular flow is the most dominant and natural flow pattern observed for gas-liquid counter-current flow. The continuous flowing gas that exists in dynamic lubrication evidently promotes annular flow. Therefore the dynamic system is more efficient than a static system where gas-liquid separation may occur at a random and slower rate due to the development of other flow patterns that do not maintain separation of the
phases flowing in a counter-current pattern.

9. Pumping at higher rates of 100 to 135 gallons per minute from the beginning of the dynamic lubrication procedure reduced the efficiency of the process. This was evidenced by an overall rate of liquid accumulation for the high rate tests of 24 gallons per minute, about half of that seen at the low pump rate tests. The high rates had an adverse effect causing significant liquid carryover which was observed from the beginning of the test. The high pumping rates also had an intermittent bullheading effect on the gas which resulted in liquid carryover when the gas expanded.

10. Analysis of the full-scale data identified two distinct regions, flooding and complete liquid penetration. Using the average annular circumference in the outlet section of the casing spool, the correlation derived from the laboratory experiments gave a distinct demarcation between these regions. This led to a tentative conclusion that the characteristic geometry controlling flooding in a wellhead is the wellhead geometry opposite the outlet.

11. When the casing-casing average annular circumference was used as the geometric term in computing the dimensionless volumetric fluxes, the correlation from the laboratory experiments no longer demarcated the flooding and complete liquid penetration regions. Empirical calibration of the correlation was done to match the flooding data and a new correlation was proposed by increasing the tolerable fluxes at flooding by 29%.

12. An expected gas to liquid volumetric ratio for dynamic lubrication was computed assuming a goal of maintaining a constant bottomhole pressure. When using a kill
mud weight, the ratio was 2:1. Knowing this ratio made it possible to imply a gas rate out of the well given the liquid pumping rate.

13. The required gas:liquid volumetric ratio for constant bottomhole pressure dynamic lubrication was used to make non-dimensional gas and liquid volumetric flux plots. These plots were overlayed on the proposed correlation. The result was a simultaneous solution to the flow parameters required to achieve both fully counter-current flow and maintain bottomhole pressure at a constant value. This was the basis for a proposed optimization procedure based on the assumed validity of the new proposed correlation. Further testing is required for validation of these concepts.

14. This method of dynamic lubrication may be applied to systems where there is need to replace gas with liquid in a timely manner and where pressure control is important. Application of this method can be in the case of any shut-in well with gas accumulation at the surface. This condition can exist in the annulus of a gas-lift well, an annulus with sustained casing pressure or a gas kick that occurred during drilling operations with the drillstring out of the hole or plugged.
CHAPTER 8

RECOMMENDATIONS FOR FURTHER WORK

Based on the research experiments and analysis carried out in this project, the following recommendations are made to validate the current results and conclusions and develop the practical application of flooding phenomena to improvements in dynamic lubrication and other pertinent well control methods:

1. Additional full-scale testing of flooding at elevated pressures is recommended. This can be done on the LSU #1 well using the same method of testing outlined in chapter 4. The correlations derived from this type of test can be used in further flooding research adding to the current data set obtained from the laboratory tests and give insight into any unforeseen flooding behavior at elevated pressures.

2. Further testing should be carried out to validate the correlation proposed herein. This experiment should be designed to test the applicability of using the casing-casing annular section versus wellhead internal geometry as the characteristic dimension in the Wallis (1969) dimensionless volumetric flux equation. This experiment can be carried out in the LSU #1 well. This well has three annular sections that can form part of a test matrix. Additional testing can be done on different geometries by using LSU wells #3, 4, and 5. It is recommended that flooding experiments be carried out as described in Chapter 4. This type of testing would allow for longer periods of steady state conditions and a wider array of data for validation of the correlation.

3. Additional experiments may be needed if the preceding tests do not yield results indicating that the casing-casing annulus is the applicable region to be used in the
dimensionless volumetric flux equations. There may be need to investigate if the
diameter at the spool’s outlet is the correct dimension to be used in the equations.
This would be difficult to do since it would require that an apparatus be
constructed that varies the diameter at the outlet while keeping the casing-casing
annular clearance constant.

4. The end section where liquid and gas are added and removed from the system has
an effect on flooding. For this reason, it is recommended that alternative methods
of injecting liquid into the annulus be investigated. This type of investigation may
lead to a further optimization of the process making it more efficient.

5. Once a correlation is confirmed and accepted as being generic over a wide range
of annular sections, it should be applied to the engineering procedure proposed in
Chapter 6. It is recommended that lubrication tests be carried out in a manner
described in Chapter 5, but with the optimization method incorporated into the
procedure.

6. The proposed engineering procedure can be time consuming due to the various
calculations and plots required. A computer program that takes the inputs of well
geometry, fluid properties, pressure, temperature and initial shut in conditions can
be made to automatically execute the routines required to produce the
optimization plot and the maximum pump rates. The method described in
Appendix B can be used as a guide for an algorithm to be used in creating this
program.

7. The effect of fluid properties was not investigated in this project. It is
recommended that further testing be done to investigate the effect of different
properties such as density and viscosity on the flooding phenomena.
8. Another area in well control that is similar to the scenario of gas being trapped in an annulus is sustained casing pressure. Further investigation into the applicability of the concepts proposed in this work to sustained casing pressure remediation is recommended.
REFERENCES


APPENDIX A

ANALYSIS OF GAS-LIQUID VOLUMETRIC RELATIONSHIP FOR CONSTANT BOTTOMHOLE PRESSURE DYNAMIC LUBRICATION

Consider the hydrostatic pressure introduced in a well due to liquid being pumped into the well:

Volume of liquid introduced: \( V_{Li} \) (bbls)

Capacity Factor Of Annulus: \( C_p \) (bbls /ft)

Density of liquid : \( \rho_l \) (ppg)

Increase in hydrostatic pressure= \( 0.052 \times \rho_l \times V_{Li} / C_p \)

this increase in hydrostatic pressure must be balanced by a subsequent reduction in casing pressure by bleeding gas through the choke in order to maintain bottomhole pressure at a constant value. This implies that (assuming gas density to be negligible):

\[
0.052 \times \rho_l \times V_{Li} / C_p = P_{c1} - P_{c2}
\]

\( P_{c1} \) = initial casing pressure (psi)

\( P_{c2} \) = casing pressure after bleeding gas (psi)

\[
P_{c1} = \frac{Z_1 \times R \times T_1 \times n_1}{V_{gi}} \quad P_{c2} = \frac{Z_2 \times R \times T_2 \times n_2}{V_{gi} - V_{li}}
\]

\( Z \) : gas deviation factor \quad \( n \) : number of moles of gas

\( R \) : 10.732 gas constant (psi cu.ft./ lb mol oR) \quad T : \) temperature in deg. R

\( V_{li} \) : initial volume of gas in the well (cu. ft) \quad 1 : initial conditions

2 : conditions after bleeding gas

substituting \( P_{c1} \) and \( P_{c2} \) into equation A.1

\[
0.052 \times \rho_l \times V_{li} / C_p = \frac{Z_1 \times R \times T_1 \times n_1}{V_{gi}} - \frac{Z_2 \times R \times T_2 \times n_2}{V_{gi} - V_{li}}
\]
Assume the incremental change in pressure is small such that:

\[ Z_1 \approx Z_2 \approx Z \quad \text{and} \quad T_1 = T_2 = T \]

\[ \Rightarrow 0.052 \times \rho \times \frac{V_{li}}{V_{gi}}(\text{bbls}) / C_p \times V_{gi} \times (V_{gi} - V_{li}) = (V_{gi} - V_{li}) \times n_1 - V_{gi} \times n_2 \]

\[ \text{ZRT} \]

Consider the scenario for TEST II in Chapter 5:

\[ V_{gi} = 28 \text{ bbls} \]

\[ V_{li} = 1 \text{ bbl} \]

\[ C_p = 0.03086 \text{ bbls/ft} \]

\[ n_1 = P_1 \times \frac{V_{gi}}{(ZRT)} = 11.37 \]

\[ \Rightarrow n_2 = 10.59 \]

\[ n_1 - n_2 = 0.78 \text{ moles (volume of gas bled for 1 bbl of liquid pumped)} \]

In terms of volume: @ P- 400 psig, T- 75 deg. F, Z = 1

\[ V_{bled} = n_1 - n_2 \times Z \times R \times T / P = 10.72 \text{ cu ft} = 1.91 \text{ bbls} \]

This implies that for 1 bbl of liquid pumped, 1.91 bbls of gas (insitu) was bled.

To evaluate this relationship a plot of gas:liquid volumetric ratios was analyzed in Chapter 6 (Fig 6.5). The plot showed that an average gas:liquid ratio of 2:1 was observed for the lubrication tests carried out. Significant variation in gas rates was also observed. This is apparently caused by poor choke operation when the choke is closed or opened too rapidly. Poor choke manipulation can lead to high gas rates when the choke is opened too much. The high gas rates may result in carryover of liquid which was shown in chapter 5 to cause inefficiency in the lubrication process. As a result of this, it is recommended that a safety factor be used to adjust for unintended high gas rates. The safety factor was derived by empirical means using the results from the full-scale dynamic lubrication tests. Fig A.1 is a plot of measured superficial gas and liquid
velocities during Test I and Test II from the full-scale testing. The calculated gas:liquid ratio that should exist if the bottomhole pressure is kept constant is also plotted. For Test I, the ratio was 1.65 and for Test II, was 2.0

![Plot of Steady State Superficial Velocity for Test I & II](image)

**Fig. A.1 Plot of Steady State Superficial Velocity for Test I & II**

The maximum gas:liquid ratio for Test II was at point A = 0.41/0.11 = 3.72 and for Test I was at point B=0.30/0.11= 2.72. The calculated ratio was 1.65 for Test 1, this means that the maximum ratio was over by a factor of = 3/1.65 = 1.64. Likewise for Test II the factor was 3.72/2.0 = 1.86. It appears that for these tests, the observed ratio of gas to liquid superficial velocities was approximately double that of the expected value. This is the basis for the empirical safety factor. It is recommended that the calculated gas:liquid ratio be multiplied by 2 when calculating maximum liquid rates to be used at a given pressure during lubrication.
APPENDIX B

ENGINEERING PROCEDURE FOR DYNAMIC LUBRICATION

This procedure can be used to remove gas trapped at the wellhead following volumetric well control.

1. Arrange piping such that returns from the choke are routed to a mud-gas separator and a small calibrated pit.
2. Arrange pumps to discharge to the kill line of the annulus or tubing to be lubricated.
3. Record Shut in casing pressure (SICP) and kick volume ($V_k$)
4. Calculate kill mud weight if desired:
   
   \[
   \text{kill mud weight (ppg)} = \frac{\text{SICP (psi)}}{(0.052 \times D)}
   \]

   where:

   \[
   D \text{ - depth of gas in well (ft.)} = \frac{1}{C_p} \times V_k \text{(bbls)}
   \]

   \[
   C_p \text{ - capacity factor (bbls/ft)} = \frac{(d_2^2 - d_1^2)}{1029.4}
   \]

   \[
   d_2 \text{ - inner diameter of outer casing in annulus (in.)}
   \]

   \[
   d_1 \text{ - outer diameter if inner casing in annulus (in.)}
   \]

5. Construct a casing pressure- pit gain schedule as shown below in Fig A.1:

   Apply 100 psi safety factor

   \[
   \text{Intercept} = \text{SICP (psi)} + 100 \text{psi (safety factor)}
   \]

   \[
   \text{Gradient (psi/bbl)} = \frac{(1 / C_p) x 0052 x \text{kill mud weight (ppg)}}{}
   \]

Construct a pump rate optimization plot as shown in Fig. B.2

To construct an optimization plot the following parameters must be known:

\[
D = (d_1 + d_2) x 6.2857 \text{ (for an annulus being lubricated) (m)}
\]
Fig. B.1 Casing pressure-Pit Gain Schedule

Graph of Dimensionless Volumetric Flux

\[ J_g^{1/2} = -0.82J_l^{1/2} + 0.45 \]

Fig B.2 Generic Dimensionless Volumetric Flux Plot
D- ID of tubing (for a tubing being lubricated) (m)

$\rho_g$ - estimated using Katz et al. (Kg/m$^3$)

$\rho_l$ - mud density (Kg/m$^3$)

$g$ - 9.81 m/s$^2$

The optimization plot is made by first plotting the black line shown in Fig B.2, defined by:

$$J_{g1/2} = -0.82J_{l1/2} + 0.45 \text{ (equation 6.1)}$$

The intersection lines are plotted for a series of pressure steps beginning with the SICP.

As shown in Fig.B.2 SICP was 600 psi.

Compute gas:liquid lubrication volumetric ratio as shown below:

Using:

$$0.052 x \rho_l x V_{li} / C_p x V_{gi} x (V_{gi} - V_{li}) = (V_{gi} - V_{li}) x n_1 - V_{gi} n_2$$

$$\text{ZRT}$$

$n_1$ - number of moles of gas initially in well

$n_2$ - number of moles of gas after bleeding

$V_{gi}$ - Volume of gas initially in well (cu ft)

$V_{li}$ - Volume of liquid pumped (cu ft) = 5.62 cu ft

Solve for $n_2$ knowing $n_1 = P_1 V_{gi} / (\text{ZRT})$

$P_1$ - SICP (psia)

$Z$ - gas deviation factor

$R$ - universal gas constant 10.732 (psi cu.ft./ lb mol °R)

$T$ - average temp in well temperature in deg. R

Compute $n_1 - n_2$ - number of moles of gas bled for 5.62 cu ft. of liquid introduced.

Convert $n_1 - n_2$ to volume by:

$$V_{bled} (\text{cu ft}) = n_1 - n_2 x Z x R x T / P_1$$

Volumetric ratio (VG:VL) = $V_{bled} (\text{cu ft.}) / V_{li} (\text{cu ft.})$
A safety factor is now applied by multiplying the $V_{bled}$ by 2.

This ratio will be used to plot the lines on Fig B.2 corresponding to the pressure steps for lubrication. Recommended number of pressure steps: SICP/100 psi

The dimensionless fluxes are defined by:

$$J_l = \frac{\rho_{L}^{1/2}v_L}{\left[gD(\rho_{L} - \rho_{G})\right]^{1/2}}$$

$$J_g = \frac{\rho_{G}^{1/2}v_G}{\left[gD(\rho_{L} - \rho_{G})\right]^{1/2}}$$

$V_G$ - superficial gas velocity (m/s)

$V_L$ - superficial liquid velocity (m/s)

The gas:liquid ratio computed above also applies to the superficial velocities in the gas and liquid dimensionless fluxes. $J_g$ and $J_l$ can be plotted knowing the $V_L:V_G$ ratio. It is recommended that one value of $V_l$ be chosen (number between 0 and 1 recommended) and compute the corresponding $V_G$ and hence dimensionless fluxes as defined above.

The plot can then be made since it passes through the origin as seen on Fig B.2. This must be done at each pressure step noting changes in gas density as pressure decreases.

Once the plot is completed as shown in Fig B.2 the optimum pumping rates can be computed. The intersection of the flux lines and equation 6.1 represents the operating point.

Maximum pump rate at pressure step (bbls/min) = $j_1^{1/2} \times \left[\frac{gD(\rho_l - \rho_g)^{1/2}}{\rho_l^{1/2}}\right] \times 377.38$

6. Begin pumping at prescribed rate from optimization plot for SICP. When casing pressure is 100 psi over SICP slowly open the choke.

7. Follow the casing pressure-pit-gain schedule by tracking barrels of liquid
8. Lubricated into the well and adjusting casing pressure as per schedule. During the process as casing pressure is reduced adjust pump rate to calculated values from the optimization plot.

9. When the well is full as indicated by the total barrels lubricated in the well, stop pumping and open the choke. Watch for flow, if flowing begin pumping again with choke open. After no gas is observed coming from the well stop pumps again and watch for flow. Repeat process if needed until all gas has been removed.

While dynamic lubrication is being carried out there may be instances where carryover of liquid is observed. When this occurs it is necessary to either reduce the pump rate or close the choke (not completely) depending on the value of the casing pressure. If carryover is observed and the casing pressure is where it should be as defined by the casing pressure schedule, then slow pumps, if casing pressure is too low, close choke accordingly. If casing pressure is high along with carryover being observed, slow pumps and watch if casing pressure is reduced along with carryover, if necessary open choke until required casing pressure is achieved while also reducing pump rate.
VITA

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