ANALYZING PRESSURE AND TEMPERATURE DATA FROM SMART PLUNGERS TO OPTIMIZE LIFT CYCLES

A Thesis

by

GOPI KRISHNA CHAVA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Petroleum Engineering

ANALYZING PRESSURE AND TEMPERATURE DATA FROM SMART PLUNGERS TO OPTIMIZE LIFT CYCLES

A Thesis

by

GOPI KRISHNA CHAVA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Gioia Falcone
Committee Members,	Catalin Teodoriu
	Maria Barrufet
Head of Department,	Stephen A. Holditch

December 2008

Major Subject: Petroleum Engineering

ABSTRACT

Analyzing Pressure and Temperature Data from Smart Plungers to Optimize Lift Cycles.

(December 2008)

Gopi Krishna Chava, B.E. (Hons.), Birla Institute of Technology & Science - Pilani

Chair of Advisory Committee: Dr. Gioia Falcone

The problem of liquid loading is common for all gas producing wells and should be identified and solved for efficient gas production. Production engineers and operators need to choose the best solution possible, one that is cost effective and also efficient in doing the job. The plunger lift operation is a cost-effective solution to this liquid loading problem and also is efficient in increasing the gas production. However, the current understanding of plunger lift operation has used field experience and some previous models that have restrictive assumptions which might not be applicable for all plunger lift installations. This research proposes a new plunger lift model that overcomes some of the limiting assumptions of earlier models by using additional data available in the form of pressure and temperature from new technology like smart plunger. The model is based on fundamental principles of mass conservation and pressure balance, and uses the smart plunger data as input. The implementation of the model is carried out in user-friendly and easily accessible software like Excel VBA (Visual Basic Applications). The model predicts the plunger velocity, plunger position and annulus liquid level during an upward travel of the plunger in an onshore gas well in East Texas. The results of model implementation in VBA show the importance of fluid properties for the model, apart from indicating that the model is optimized for the given set of input data. The model developed in this research considers only pressure drop due to gravitational effects, and thus provides a scope for improvement in modeling the plunger lift dynamics by adding frictional and acceleration components. This research also provides recommendations for future work that can be carried out on plunger lift modeling using smart plungers.

DEDICATION

This thesis is dedicated to my parents, who are my source of inspiration for all the major achievements in my life. I also dedicate this work to my sister and all my friends for their encouragement and support during the course of this work. They have endured my absence and always supported me at difficult crossroads.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Gioia Falcone and Dr. Catalin Teodoriu for their guidance and support throughout the course of my research. I would like to thank Crisman Institute for Petroleum Research at Texas A&M University for sponsoring the project.

I would also like to thank Rosemary Hornbrook, Bryan Dotson and Gordon Gates for their support during the project and my advisory committee for their help and support in completing this project.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. Finally, thanks to my family for their encouragement and love.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
DEDICATION	v
ACKNOWLEDGEMENTS	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	ix
LIST OF FIGURES	x
CHAPTER	
I INTRODUCTION	1
1.1 Overview	1
1.1.1 Liquid Loading	1
1.1.2 Plunger Lift	1
1.1.3. Smart Plungers	3
1.2 Research Objectives	6
II CRITICAL REVIEW OF EARLIER PLUNGER LIFT MODELS	8
2.1 Static Plunger Lift Models	8
2.2 Dynamic Plunger Lift Models	10
2.3 Possible Improvements in Modeling	14
III DESCRIPTION OF NEW PROPOSED PLUNGER LIFT MODEL	16
3.1 Possible Interactions between Flow Regions during Plunger Upstroke	16
3.2 Flow Regions of the System	21
3.3 Assumptions Used in the Model	23
3.4 Model Equations Using Gravitational Terms	24
IV INPUT DATA FOR MODEL IMPLEMENTATION	32
4.1 Field Data	32
4.2 Estimated Data	35
4.3 Critical Analysis of Available Field Data	36

CHAPTER Page

V RESULTS OF MODEL IMPLEMENTATION 40

5.1 Procedure for Implementation of Model.. 40
5.2 Validation of Model 44
5.3 Results of Base Case Implementation.. 45
5.4 Sensitivity Analysis of Model... 51
5.5 Summary 58

VI CONCLUSIONS AND RECOMMENDATIONS 59

6.1 Conclusions... 59
6.2 Recommendations... 60

NOMENCLATURE 63

REFERENCES 65

APPENDIX A 67

APPENDIX B 72

VITA 74

LIST OF TABLES

TABLE		Page
5.1	Variable Values for Base Case	46
5.2	Variable Ranges/Variations Considered for Sensitivity Analysis	54
5.3	Variable Values/Variations for the Case with Largest Deviation of Results	54

LIST OF FIGURES

FIGURE Page

1.1 Chart Showing Use of Smart Plunger Data................................ 5

3.1 Interactions between Flow Regions for Option1 for Case1.................... 17

3.2 Interactions between Flow Regions for Option2 for Case1.................... 18

3.3 Interactions between Flow Regions for Option3 for Case1.................... 18

3.4 Interactions between Flow Regions for Option1 for Case2.................... 19

3.5 Interactions between Flow Regions for Option2 for Case2.................... 20

3.6 Flow Regions of the System Identified for Modeling Purpose............... 21

3.7 Various Pressure and Flow Rate Components in the System................. 24

4.1 Field Data for the Five Available Plunger Cycles 37

4.2 The Fourth Upward Cycle of the Plunger, Followed by Natural Gas Flow 38

5.1 Average Plunger Velocity during Plunger Upstroke 47

5.2 Profile Showing Change in Heights of Regions inside Tubing with Time 48

5.3 Annulus Liquid Level Profile during Plunger Upstroke.......................... 49

5.4 Comparison of Annulus Liquid Levels for Three Different Guesses of Gas Specific Gravities... 50

5.5 Comparison Chart for Average Plunger Velocities of the Two Cases 55

5.6 Comparison Chart Showing Heights of Region1 and Region2 56

5.7 Comparison Chart for Annulus Liquid Level 57

CHAPTER I

INTRODUCTION

1.1. Overview

This section provides a brief overview of the phenomenon of liquid loading followed by an overview of plunger lift which is an artificial lift method to solve liquid loading.

1.1.1. Liquid Loading

Liquid loading is a common problem encountered in gas wells and is even more detrimental in cases of mature gas fields. Liquid loading occurs when the gas produced from a reservoir loses the ability to lift the coproduced liquids into the tubing. These coproduced liquids get accumulated at the bottom of wellbore tubing which results in increased backpressure on the formation and causes an increase in the bottomhole pressure. This increase in the flowing bottomhole pressure in turn causes a reduction in the reservoir production rate and, under extreme loading conditions, may kill the well. The problem of liquid loading is tackled using a variety of artificial lift methods, which are applied depending on certain operating conditions and economics.

1.1.2. Plunger Lift

Plunger lift is one of the artificial lift methods used for solving liquid loading problem. Plunger lift operation involves the cyclic travel of a piston (plunger) up and down in the

---

This thesis follows the form and style of the *SPE Journal.*

tubing string, between the bumper spring and the wellhead, in order to remove the liquid that has accumulated in the wellbore. Plunger lift uses the energy from the reservoir and reservoir gas stored in the annulus to lift the accumulated liquid and prevent liquid loading.

The plunger acts as a solid interface separating the liquids accumulated above the plunger from the gas providing the energy for lifting the liquids. This solid interface prevents the production of intermittent slug production from wellbore and also reduces the fallback of the accumulated liquids. Reduction in the volume of liquid slug originally accumulated is achieved with the help of such solid interface.

A typical plunger lift cycle in a packerless completion consists of a shut-in period followed by production of fluids from the wellbore. During the shut-in stage, the flowline valve at the surface is closed, preventing the flow of fluids to the surface, and the plunger is dropped to the bottom of wellbore. However, there will be fluid production from the reservoir into the tubing and annulus during this stage, which causes liquids to be accumulated in the tubing with some gas above the liquid slug. This shut-in stage continues for a certain period of time which not only allows the plunger to reach the bottom of wellbore and sit on the bumper spring, but also allows the casing pressure at wellhead to reach an adequate value that can support the production of liquid slug. At the end of shut-in period, the flowline at the surface is opened for fluid production. During this production period, gas above the liquid slug inside tubing expands into the flow line, and the plunger lifts the liquids accumulated above it with the support of energy stored in annular gas and reservoir. The wellbore produces the liquid slug as the plunger approaches wellhead. The period starting from the rise of plunger from bumper spring until the point when it is caught in the lubricator at the wellhead is considered the "plunger upstroke" period. The plunger upstroke period will be followed by an afterflow production period during which the gas below the plunger is produced. At the end of this afterflow period, the flowline valve at the wellhead is closed and the shut-in period of next cycle starts at this point in time.

Plunger lift is a proven successful method of liquid unloading under a wide variety of operating conditions. It has major advantages over other artificial lift methods when applicable, because of the relatively small investment costs and reasonable operating costs required for plunger lift operation.

Though plunger lift has been used as a successful method of artificial lift for several decades, very few attempts have been made on the modeling of plunger lift cycles and using these models to optimize the lift cycles. The lack of plunger lift models provides a serious drawback for plunger lift operation which then requires very experienced professionals to operate the plunger lift wells. This research attempts to improve the understanding of plunger lift operation by utilizing information from a new technology like smart plunger.

1.1.3. Smart Plungers

The PCS (Production Control Services Inc.) smart plunger consists of a pressure measuring gauge equipped near the bottom of the plunger. This smart plunger has the added functionality of measuring the pressure and temperature and storing the data in an internal microprocessor. The operation of the smart plunger is similar to that of a normal plunger where the smart plunger returns to the surface after each cycle without the use of wireline or crew.

At the surface, the time vs. pressure and temperature data is downloaded from the smart plunger into a computer by plugging a cable in to the measuring sensor. This flowing gradient data can be used by the well operator for further processing.

According to the PCS (Production Control Services Inc.) brochure (2005), the sensor/ logger inside the smart plunger can record pressure data up to 15000 psia with 0.024% accuracy and temperature data up to 150 'C with accuracy of 0.15%. Some other features of this sensor include:

- Data printouts
- Gradient reports
- Gradient plots
- Multi-run data storage capability
- Up to 10 months of sampling
- User friendly windows software
- Single lithium cell in gauge
- 350 'F operation

The data recorded by a smart plunger can provide useful information about the various events occurring during a plunger cycle. Such data along with other measured well data can be used for surveillance and optimization of a plunger lifted well. **Fig.1.1** shows example data from a smart plunger along with measured values of pressures at wellhead, casing and bottomhole, and meter differential pressure (DP) at the surface.

Fig. 1.1 shows the various events during a plunger cycle that are indicated by a comparison of the profiles of smart plunger pressure and wellhead tubing pressure. By observing the trends of wellhead pressure and smart plunger pressure, we can identify various events like the time the plunger hits the liquid at the bottom of well, the time it reaches the surface with the slug for production, and the time it is caught in the lubricator at the surface. For example, at the time when the plunger hits the liquid during its travel from the surface to the bottom of wellbore is indicated by a change in the gradient of the pressure profile recorded by smart plunger.

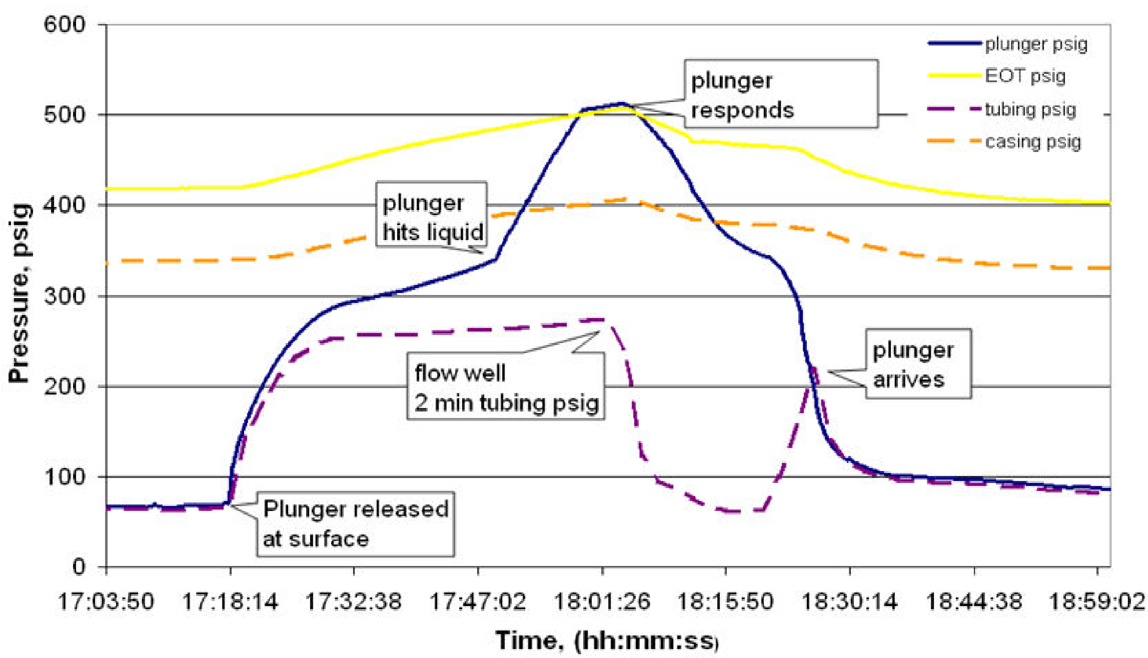

Figure 1.1 – Chart Showing Use of Smart Plunger Data (Chava, 2008)

This information can be very useful for surveillance engineers when monitoring the performance of plunger lifted well. It can also be used as a tool for optimizing the production of a plunger lifted well and increasing the efficiency of plunger lift. Tubing holes can be detected easily by observing the presence of sharp changes in the gradients of pressure and temperature during the plunger cycle.

Smart plunger data has more advantages than simply being used as a surveillance tool. This data provides additional information for modeling plunger lift cycles that allow closure of conservation of mass and pressure balance equations applied to different regions of a plunger lift system. The lack of such information for earlier plunger lift models required those models to invoke restrictive assumptions that limit their applicability. The proposed model tries to take advantage of this additional information to improve the modeling accuracy of plunger lift cycle for increases gas production during liquid unloading phase.

1.2. Research Objectives

The main objective of current research is to develop a model that can simulate the plunger lift operation more realistically. By focusing on the fundamental equations governing the fluid flow during the plunger cycle (conservation of mass and pressure balance equations), the research can achieve this objective and try to overcome some of the assumptions that limited the applicability of earlier plunger models. This approach requires the use of data available from smart plungers along with other field data as input data to the model.

The approach we take is to develop the model assuming steady-state conditions for all the four regions of system discussed in Chapter III. Although transient conditions prevail in nearly all four regions, the steady-state approach can consider all the regions in the same state and attempt is made to reduce the time steps to a small value like 10 seconds to approximately reach the transient conditions. No completely developed model is currently available that can take an account of the transients in the reservoir, and research in this area is still in progress. To provide uniform conditions for all four regions, our approach is a steady-state approach. In the steady-state model, the fundamental equations are developed in a way that includes the gravitational, frictional, and acceleration terms in a stepwise manner. The current work focuses on the model that uses only gravitation terms in the pressure balance equations developed for the model.

Chapter III describes the new proposed plunger lift model in terms of equations that are derived from fundamental equations applied to different flow regions of the system. Chapter V provides the results of the model's implementation in Excel VBA (Visual Basic Applications) program. It also provides the results and discussions from the sensitivity analysis work which was carried out to analyze the impact of different variables of the system on the model and to provide possible recommendations for a better understanding of the model.

CHAPTER II

CRITICAL REVIEW OF EARLIER PLUNGER LIFT MODELS

Many models of plunger lift operation have been developed over the past few decades, but only few of them are extensively published or used in the industry. The models described in this chapter illustrate the improvements made in later plunger models by building on the understanding and usage of earlier models. The models that had significant improvement over earlier models are critically reviewed with an emphasis on their underlying assumptions and approach for development and deployment of the model. This review explains the models in terms of two categories. Category 1 models that are explained in first section consider a constant average value of plunger rise velocity whereas category 2 models explained in the second section of this chapter consider dynamic analysis with variable plunger velocity during plunger upstroke. The possible improvements in modeling are explained in the third section of this chapter before explaining the model development in next chapter.

2.1. Static Plunger Lift Models

Foss and Gaul (1965) developed the first static model on plunger lift upstroke based on their experiences in the Ventura Avenue Field. They developed their static model using the data from a number of packerless plunger lifted wells with high gas-liquid ratios. Their model predicted important plunger-lift parameters like average surface casing pressure, tubing pressure, and load size and gas requirements in cycles per day for a wide range of operating conditions. Though the model's predictions agreed reasonably well with the field results, the model was limited in its application as it did not consider the changes in reservoir performance, which is critical in most low pressured reservoirs. It considers that the energy support for the plunger to lift the liquids comes completely from energy stored in annulus gas. This might not be applicable for plunger lifted installations with packers in the annulus. Some of the major assumptions considered in their model are that the model,

- Neglects the pressure effects caused by plunger friction.
- Assumes that there are slight gas-column pressure differences between the tubing and casing/tubing annulus.
- Neglects the pressure changes in the system because of liquid entry beneath plunger.
- Neglects pressure losses caused by casing-tubing gas friction.
- Assumes an average rise velocity of 1,000 ft/min and a fall velocity of 2,000 ft/min for the plunger through the gas. The fall velocity of the plunger through the liquid was assumed to be 172 ft/min.

The improvements that can be made to this model are to consider changes in plunger velocity and to use reservoir inflow performance relationships in the model to account for reservoir responses.

Building on the understanding from the model of Foss and Gaul, Hacksma (1972) developed a model by incorporating an inflow performance relationship (IPR) to account for reservoir performance in his model. Through this model, Hacksma also tried to analyze the performance of plunger lifted wells for situations where the plunger lifts the liquid slug as soon as it falls to the bottom of well.

Abercrombie (1980) developed a static model similar to that of Foss and Gaul model by incorporating a more realistic value of plunger fall velocity during buildup stage, obtained from additional empirical data. In his work, Abercrombie also presented a discussion of plunger lift design and installations based on operations.

2.2. Dynamic Plunger Lift Models

Lea (1982) developed the first dynamic model focusing on the upstroke stage of plunger cycle, which considered the velocity of plunger to be varying during its upward travel, unlike the constant plunger velocity assumed in earlier static models. The assumption of constant plunger velocity used in the classic Foss and Gaul model, results in prediction of higher casing pressure requirements. Lea's model considers the reservoir performance by using the deliverability equations for a stabilized reservoir flow in its calculations and it also assumes that the gas phase above the plunger in the tubing is in steady state. The approach used for this dynamic model was to consider changes in plunger velocity with time and depth, by using a force balance applied to the plunger and liquid slug. The equations developed with this approach are then incorporated into a computer simulation program for analyzing plunger lifted wells. Some of the major assumptions made in this model are

- Average gas production rates are low enough to rely on plunger lift assistance.
- There is no flow of liquid back in to the formation so that the liquid slug size remains unchanged.
- No gas slippage or liquid fallback past the plunger during the plunger's upward travel in the tubing.

Though this model considered varying plunger velocity, it gives scope for improvement by accounting for transient reservoir performance and the possibility of two-phase flow below the plunger during its upstroke. Also further improvements in modeling are possible by considering complete plunger cycle instead of focusing on just the upstroke of plunger lift cycle.

Rosina (1983) developed a dynamic model similar to Lea's model by focusing on plunger lift upstroke, but incorporated liquid fallback into his model by comparing model simulations with experimental results.

Avery (1988) built on Foss and Gaul's model by adding a simple downstroke model for an oil well to the model for plunger rise stage. This model accounted for reservoir performance using the Vogel IPR for oil wells with solution gas drive mechanism. This model also predicted lower casing pressure requirements than those of Foss and Gaul model.

Marcano and Chacin (1994) developed a dynamic model for complete plunger lift cycle based on the conservation equations of mass and momentum. The major advances made by this modeling work are that it accounts for liquid fallback past the plunger during its upward travel and models complete plunger lift cycles.

Baruzzi and Alhanati (1995) developed a simple hydrodynamic model based on experimental results to describe plunger lift operation in oil wells. This model predicted that maximum production is obtained corresponding to minimum build up pressure.

Gasbarri and Wiggins (1997) improved the dynamic modeling of plunger lift operation by considering complete plunger lift cycle for modeling, and also incorporating the effects of separator and flowline. It differed further from Lea's model by considering transient, single phase gas flow in the tubing above the plunger which predicted lower plunger accelerations when compared to Lea's model. The approach followed to develop this model considers the complete plunger lift system which includes the flowline, tubing and annulus volumes, in terms of multiple control volumes adjacent to each other. Momentum balance is applied on the plunger/slug system for each control volume during upstroke. This model also differentiates between the situations when the slug is in tubing and when it reaches wellhead to be produced. The equations developed using momentum balance for different control volumes are implemented in a computer program using FORTRAN. Some of the major assumptions used in the development of this model are

- Single phase gas is present below plunger during upstroke.
- Liquid produced into the tubing is accumulated at the bottom of tubing and is not pushed back into the formation.
- No gas slippage past the plunger during the plunger's upstroke.

Though better than earlier models, this model provides scope for improvement by considering transient reservoir performance as opposed to the stabilized reservoir deliverability and the possibility of two-phase flow below the plunger during its upstroke.

Tang and Schmidt (1997) developed a dynamic model by considering the changes of tubing and casing pressures to qualitatively explain the liquid accumulation mechanism occurring at the bottom of wellbore. This model also considered the characteristics of liquid fallback and resistance force opposing the motion of plunger. This model considered force balance on the plunger during upstroke and down stroke to account for the varying plunger velocity. This model suggested that there exists liquid transfer at the bottomhole from the tubing to annulus during shut-in period, by observing the changes of wellhead tubing and casing pressures.

Maggard et al. (2000) developed a dynamic plunger lift model that can be applied to tight gas wells. Dynamic models developed prior to Maggard's model used stabilized reservoir deliverability equations to account for reservoir performance, but the changes in flowing bottomhole pressure during a plunger cycle can be incorporated only with a transient reservoir model, which is much more significant in the case of tight gas wells. Maggard's model numerically simulates the entire system: gas flow in the reservoir, wellbore/annulus effects, and dynamic plunger lift cycles, with the momentum balance equation being applied to each grid block as the plunger moves up with the slug. Reservoir performance is modeled using a coupled, real gas, reservoir simulation module, which is based on the GASSIM simulator described by Lee and Wattenbarger (1996). Some of the major assumptions used in the development of their model are

- Liquid produced into tubing is prevented from flowing back into the formation by using a standing valve.
- No gas slippage or liquid fallback past the plunger during the upstroke.
- Water is produced from the reservoir in proportion to the gas with a specified water yield (units of STB/MMscf).
- Temperature profile is the same for both annulus and tubing.
- Produced reservoir fluids and annulus fluids flow into tubing only during gas production.
- Reservoir fluids enter the annulus and tubing based on the proportion of their respective areas.

This model, which can be applied to tight gas wells because it considers transient reservoir performance, may be improved by incorporating two-phase flow in the region below the plunger during its upstroke, considering transient gas expansion in the tubing and incorporating liquid fallback past the plunger.

2.3. Possible Improvements in Modeling

The models discussed above are limited in their accuracy because of the underlying assumptions used to develop them. Improvements in modeling can be made by considering situations close to reality. The possible developments that can be included in the new model taking advantage of the data from smart plungers are:

1. *Two-phase flow conditions inside the tubing below the plunger during its upward travel.* The sudden release of high pressure built up during shut-in stage, with the opening of surface production valve, provides the turbulence effect needed for two phase flow during the initial stages of plunger rise. Previous models which assumed single phase gas flow in this region did not account for this possibility.
2. *Accounting for changing wellhead pressure.* Most of the previous models used a constant wellhead pressure, which can be subject to changes governed by the line pressure. This model accommodates for the changes in wellhead pressure.
3. *Two-phase reservoir flow deliverability.* Previous models considered fluid flow from reservoir using the stabilized reservoir deliverability with a constant value of yield for accounting the water production from reservoir. However, water production from reservoir might be more accurately modeled by developing two-phase reservoir deliverability equations.
4. *Transient reservoir response.* Reservoir response becomes crucial when working with low permeability tight gas reservoirs. Earlier models except Maggard's model, cannot

account for such reservoir transients which are very vital for successful modeling of plunger lift cycles in these wells.

5. *Full characterization of all possible annulus responses.* Reservoir energy stored in the annulus gas is critical in many situations for plunger lift rise phase. This energy can also dominate the energy supplied by reservoir in cases for tight gas wells. This suggests the need for identifying and modeling different situations where annulus response varies.
6. *Liquid re-entry into the formation.* During plunger upstroke, there is the possibility of liquid flow from the tubing back into the formation. This is not accounted in the earlier plunger lift models. Transfer of liquid between tubing, reservoir and annulus can affect the pressures and thereby the modeling results.
7. *Liquid fallback past the plunger during its upward travel.* Experimental studies conducted by Mower et al. (1985) show that liquid fallback varies as a linear function of plunger velocity. This suggests the importance of accounting for liquid fallback in the plunger lift models.

Ideally, incorporating all the above developments will result in a plunger lift model with higher accuracy. However, due to lack of sufficient data, only the first two options of improvement are considered in the proposed model. The implementation of these improvements is possible only due to the availability of pressure and temperature data from smart plungers, which allowed the development of a closed set of equations to model plunger upstroke.

CHAPTER III

DESCRIPTION OF NEW PROPOSED PLUNGER LIFT MODEL

This chapter describes the new proposed model of plunger upstroke developed by taking advantage of the additional pressure and temperature information from smart plungers. The possible interactions between different flow regions of a plunger lift system during plunger upstroke are presented in the first section. Next section describes the four different flow regions considered for the model followed by the assumptions used for developing the equations. Finally, the equations for the model, developed using only gravitational terms in the pressure balance equations are presented.

3.1. Possible Interactions between Flow Regions during Plunger Upstroke

During the plunger upward travel towards surface, various possible interactions occur between different regions of a plunger lift system, including reservoir. These interactions are classified based on the relative contributions from casing-tubing annulus and reservoir in providing energy to the plunger to lift the liquid slug. Also, these interactions between different regions are affected by the presence of liquid in the annulus during the plunger upstroke. Considering the presence of liquid in annulus, two different cases can be considered, one case where the liquid level in the annulus is above the tubing seat (Case 1) and another case where the liquid level in the annulus reaches the tubing seat (Case 2). Case 1 can be categorized into three options based on the relative contributions of energy from annulus and reservoir. The system scenarios described in Case 2 occur when the energy from annulus is significant enough to completely drain the annulus liquid into tubing, and further provide support with gas flow from annulus into the tubing.

Case 1 (Annulus liquid level above the tubing seat)

Option 1. Option 1 considers the situation where the energy contributions from both annulus and reservoir are significant and comparable. This means that there will be flow of fluids into tubing from both the annulus and the reservoir. **Fig.3.1** shows the system interactions in terms of energy contributions for option 1 of case 1.

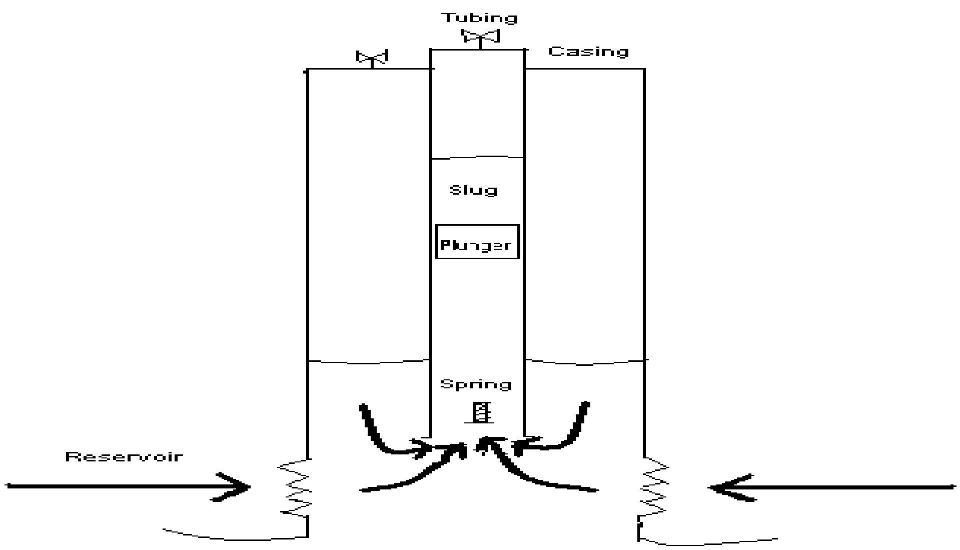

Figure 3.1 – Interactions between Flow Regions for Option 1 of Case 1 (Chava, 2008)

Option 2. Option 2 considers the situation where the energy contribution from reservoir is insignificant compared to that from energy stored in annulus. This situation occurs in tight gas formations with low reservoir pressures. In such situations, the plunger lifts the liquid with support coming completely from the annulus gas energy, and fluid flow in the system is limited to the flow from annulus into tubing. **Fig.3.2** shows the system interactions in terms of energy contributions for Option 1 of Case 1.

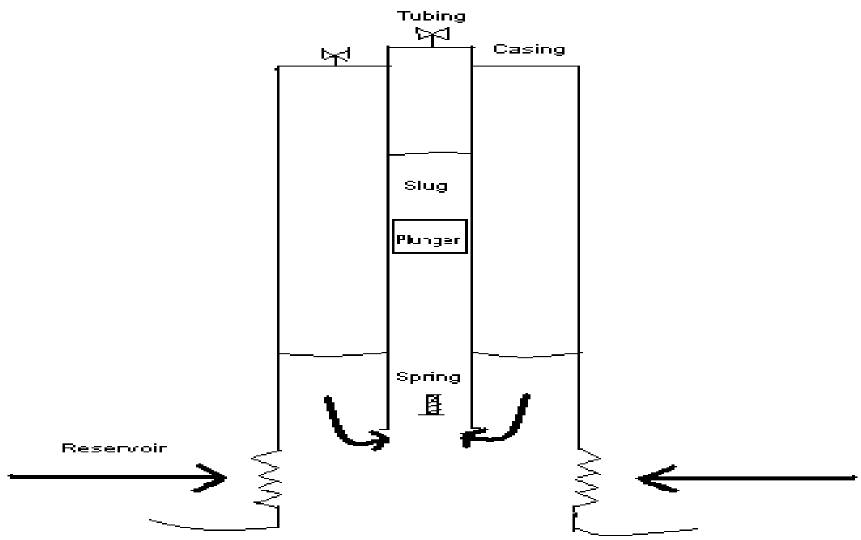

Figure 3.2 – Interactions between Flow Regions for Option 2 of Case 1 (Chava, 2008)

Option 3. Option 3 considers the situations where reservoir energy is significant with flow of reservoir fluids into both the annulus and the tubing. In such a situation, both casing and tubing pressures will be significantly less than the flowing bottomhole pressure. **Fig.3.3** shows the interactions of the regions in system for Option 3 of Case 1.

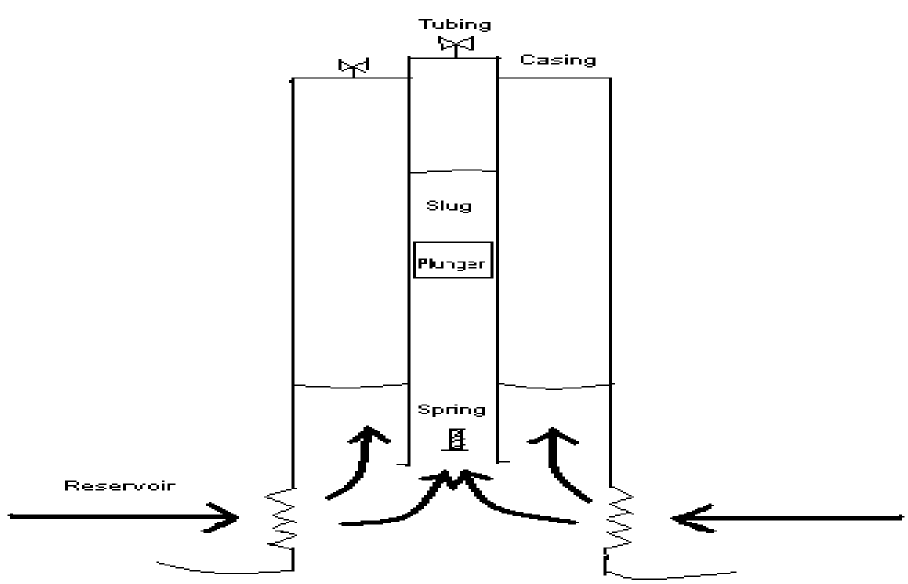

Figure 3.3 – Interactions between Flow Regions for Option 3 of Case 1 (Chava, 2008)

During the plunger upstroke, the energy contribution from the annulus to the plunger rise causes a decrease in the annulus liquid level. This gradual decrease will make the annulus liquid level drop to the tubing seat depth at some point during plunger upstroke, which causes different interactions to occur between the regions discussed in Case 2.

Case 2 (Liquid level in annulus reaches the tubing seat depth)

*Option 1***.** Option 1 considers the situation when the contributions from both the annulus and the reservoir are significant and comparable. This situation arises at some point in time as continuation of Option 1 of Case 1, where the liquid level in the annulus reaches the tubing seat depth due to the energy supplied by gas expansion in the annulus. This scenario causes the flow of annulus gas into the tubing, apart from the reservoir fluids. **Fig.3.4** shows the interactions of the regions in system for option 1 of case 2.

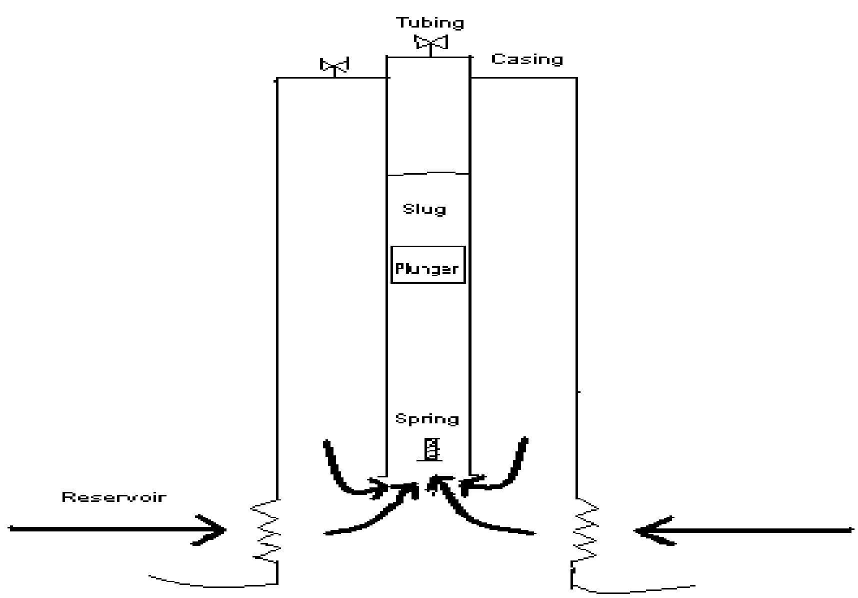

Figure 3.4 – Interactions between Flow Regions for Option 1 of Case 2 (Chava, 2008)

Option 2. Option 2 considers the situations similar to Option 2 of Case 1. In this option, the energy support from reservoir is insignificant in comparison to the energy stored in annulus. This scenario again can occur as a continuation of Option 2 of Case 1, if there was some annulus liquid prior to production. **Fig.3.5** shows the interactions of regions in the system for Option 2 of Case 2.

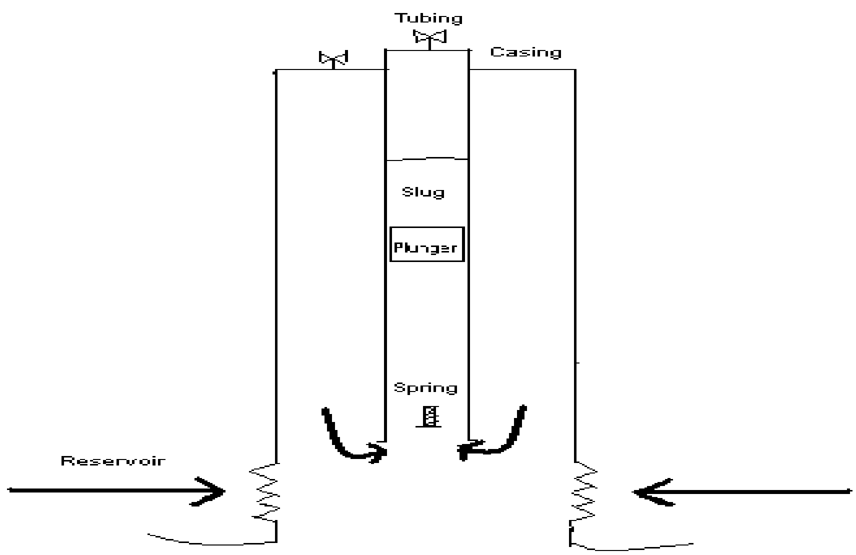

Figure 3.5 – Interactions between Flow Regions for Option 2 of Case 2 (Chava, 2008)

The new proposed plunger lift model described in subsequent sections of this chapter considers the situation corresponding to Option 1 of Case 1 when there is contribution from both annulus and reservoir. It also assumes that annulus liquid remains above tubing seat allowing the flow of annulus liquid into the tubing during plunger upstroke. Though the data available from smart plungers indicate that there is liquid in the annulus and casing pressure is large enough to contribute to plunger rise, there is possibility that other situations can arise in different stages of the plunger's operating life.

3.2. Flow Regions of the System

The model considers a packerless plunger lift installation which is divided into four flow regions considering the upward travel of the plunger. These four regions are related to each other through pressure and flow communications. **Fig.3.6** shows these regions of the system.

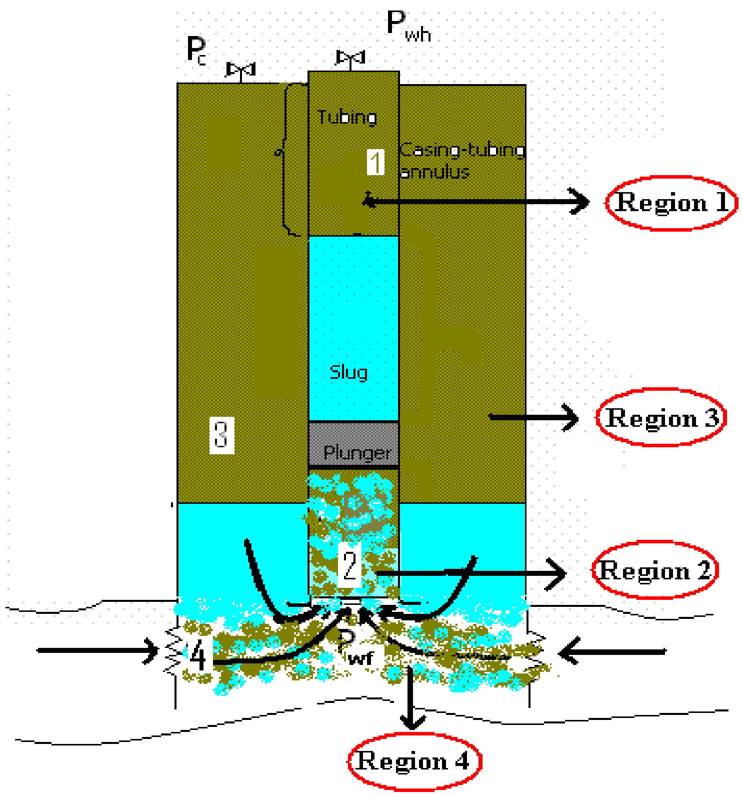

Figure 3.6 – Flow Regions of the System Identified for Modeling Purpose

These flow regions can be described in terms of the fluids present in those regions as the plunger rises to the surface along with accumulated liquid slug.

Region 1. This region contains single phase gas above the plunger/slug system in the tubing. We assume this region to be modeled with steady state gas flow above the liquid slug.

Region 2. This region contains two-phase mixture that is produced below plunger inside the tubing. This region provides the opportunity for implementation of a major improvement from the earlier dynamic models discussed in Chapter II. The flow in the tubing below the plunger as the plunger rises with a high velocity is mixture of gas and liquid flowing at different velocities. This condition implies the necessity to use two-phase correlations in this region to model the fluid flow. Previous models assumed separate and distinct gas and liquid phases to identify the flow in this region. Thus, the new model differs from the earlier models as it incorporates the two-phase flow consideration in the tubing below the plunger.

*Region 3***.** This region considers the gas and liquid present in the casing/tubing annulus as separate and distinct phases with a clear interface. The model considers steady-state gas expansion over the liquid accumulated in the annulus during plunger upstroke.

*Region 4***.** This region represents the fluid flow region in the reservoir near wellbore. This region provides another significant opportunity for improvement over the earlier models. The region involves the flow of fluids from the reservoir into the wellbore. As the reservoir produces both gas and liquid phases, the use of a two-phase Inflow Performance Relationship (IPR) equation to relate the bottomhole pressure to the production rate is more appropriate than using a steady-state single phase IPR equation presented by the backpressure equation. However, for the proposed model, backpressure equation for gas production from reservoir is used along with a constant value of yield for water production, because of the lack of reservoir fluid properties. This can be an area of future study on the model when information about fluid properties is available.

These regions are coupled to each other through pressure and flow communications. Regions 2, 3, and 4 have the flowing bottomhole pressure as a common parameter.

3.3. Assumptions Used in the Model

Though the proposed new plunger lift model tries to eliminate many of the restrictive assumptions used in previous approaches, it still considers a set of fundamental assumptions used in earlier plunger lift models. The assumptions used to develop the current model are as follows.

1. The water production from the reservoir is obtained through the specified value of yield and the gas production rate. This concept accounts for liquid production from the reservoir until the two-phase IPR equations are used for better representation of water production from reservoir.
2. The plunger acts as a complete seal for the liquid slug above it and the two-phase flow below it. It does not allow the fallback of any liquid as it travels upward, carrying the slug.
3. The height of liquid slug accumulated by the start of plunger upstroke is considered constant until it is produced at the surface. This is also a consequence of the assumption that there is no liquid fallback during plunger upstroke.
4. The produced reservoir fluids flow into the tubing along with the liquid that is produced from the annulus.
5. The liquid (water) is incompressible, with a constant density and viscosity.
6. The gas and liquid phases in the annulus are considered as separate phases with a clear interface between them.
7. Liquids produced from both annulus and reservoir flow into the tubing only during plunger upstroke.

The major assumptions which limited the accuracy of earlier models and effectively removed in the proposed new model are the two-phase flow below the plunger during upstroke and variable wellhead pressure. The current model allows high gas-liquid flow rates from the reservoir during initial stages of plunger upstroke, which causes two-phase flow in region below the plunger. The changes in wellhead pressure are automatically accounted in the new model because of the changing tubing pressure data used for the model.

3.4. Model Equations Using Gravitational Terms

The model is developed by assuming steady state conditions in different flow regions for the time steps considered during plunger upstroke. The model also uses only gravitational terms in pressure balance equations. **Fig.3.7** shows the pressures acting at various points along with the flow rates in the system as the plunger moves upwards along with the accumulated liquid slug.

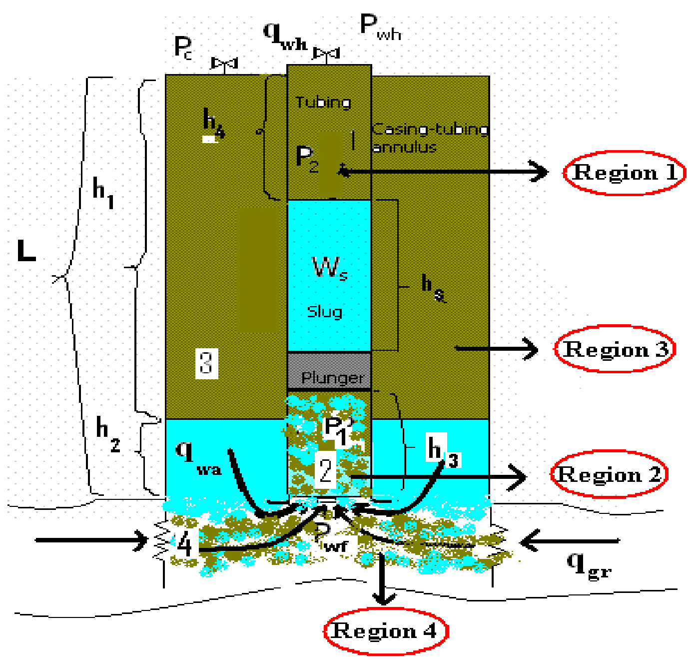

Figure 3.7 – Various Pressure and Flow Rate Components in the System (Chava, 2008)

The scenario shown in the above figure assumes that the plunger has traveled some distance already in the tubing and the liquid level in the tubing is still above the tubing seat, which facilitates only the flow of liquid from annulus into the tubing. Conservation of mass and pressure balance equations are written for all four regions for different time steps to obtain unknowns in terms of known values or inputs. The steady-state approach taken in the model implies that the equations assume discrete time intervals.

The current model considers the initial time (t_1 = 0 seconds) as the time when the plunger is just about to rise from the bumper spring towards the surface. The initial length of Region 3 at this time is zero since the plunger is still sitting on the bumper spring. Liquid slug accumulates over the plunger and is lifted by the plunger to the surface starting at this time. The height of liquid slug (h_s) is calculated by a simple pressure balance equation applied for the region 1 inside the tubing given by **Eq.3.1**.

$$p_1 = p_{wh} + \left(g\overline{\rho_g}\left(L - h_p - h_s\right) + g\rho_w h_s + g\rho_w h_p \right) / 6894.757 \tag{3.1}$$

The gas density used in **Eq.3.1** is a function of pressure and temperature which are the averages of corresponding pressure and temperature values measured at wellhead and smart plunger. Rearranging **Eq.3.1** gives the height of liquid slug (h_s) as

$$h_s = \frac{6894.757 * \left(p_1 - p_w\right) - g\rho_w h_p - g\overline{\rho_g}\left(L - h_p\right)}{g\left(\rho_w - \overline{\rho_g}\right)} \tag{3.2}$$

Consider the first time step ($\Delta t = t_2 - t_1$) as the period at end of which plunger reaches some distance along with the liquid slug starting from the initial static position on the bumper spring. During this time step, the total mass flow rate into the tubing (Δm_T) is equal to the sum of the mass flow rates of fluids from the annulus (Δm_a) and the reservoir (Δm_r) assuming that annulus and reservoir fluids enter only the tubing .

$$\Delta m_T = \Delta m_a + \Delta m_r \tag{3.3}$$

The total mass flow rate coming out of the annulus (Δm_a) during this time step is obtained as a product of volumetric flow rate of annulus liquid during the time step (Δq_{wa}) and its density (ρ_w).

$$\Delta m_a = \Delta q_{wa} \rho_w \tag{3.4}$$

The volumetric flow rate of annulus liquid (Δq_{wa}) can be expressed in terms of the change in annulus liquid level during this period (Δh_2) as

$$\Delta q_{wa} = \left(\frac{\Delta h_2}{\Delta t} A_a \right) \tag{3.5}$$

The total mass flow rate from the reservoir (Δm_r) during this time step is the sum of mass flow rates of gas and liquid produced from reservoir into the tubing, which is obtained from **Eq.3.6.**

$$\Delta m_r = \Delta q_{gr} \left(\overline{\rho}_g + x \rho_w \right) \tag{3.6}$$

In Eq.3.6, "x" represents the ratio of volume of water produced from reservoir (m^3) to the volume of gas produced from the reservoir (m^3). The gas volumetric production rate from the reservoir is obtained using the empirical "backpressure" equation of Rawlins and Schellhardt (1936).

$$q_{gr} = C \left(p_r^{\,2} - p_{wf}^{\,2} \right)^n \tag{3.7}$$

Since **Eq.3.7** is empirical, the units of pressures used for calculation of the gas flow rate (Mcf/D) from this equation are in psig and units for C are Mcf/D/psi^{2n}. Though the implementation of model uses SI units, the backpressure equation is still calculated using field units, and the values calculated from this equation are converted to SI units for further use in the code. The values of C and n used in the above equation are constants reflecting the performance of reservoir. The value of reservoir pressure is also assumed to be constant and obtained from extrapolation of the flowing bottomhole pressures for different plunger cycles which is available in the field data. The value of flowing bottomhole pressure is obtained from the data through the use of bottomhole pressure measuring devices. These bottomhole gauges measure the values of flowing bottomhole pressure (in psig) with time and this data can be retrieved at the surface.

Substituting **Eq.3.4**, **Eq.3.5.** and **Eq.3.6** in **Eq.3.3**, we can get the value of the total mass flow rate into the tubing (Δm_T) for the given time step using **Eq.3.8.**

$$\Delta m_T = \left(\frac{\Delta h_2}{\Delta t} A_a \right) \rho_w + \Delta q_{gr} \left(\overline{\rho}_g + x \rho_w \right) \tag{3.8}$$

In Eq.3.8, values of different parameters are available from the field data except the value of change in annulus liquid level. A simple pressure balance equation for the region inside the casing – tubing annulus is required to obtain the value of annulus liquid level at any instant of time.

$$p_{wf} = p_c + \left(g \left(\overline{\rho}_{ga} h_1 + \rho_w h_2 \right) / 6894.757 \right) \tag{3.9}$$

$$h_1 + h_2 = L \tag{3.10}$$

Solving **Eq.3.9** and **Eq.3.10** gives annulus liquid level at any instance of time.

$$h_2 = \frac{6894.757 * \left(p_c - p_{wf} \right) + g \overline{\rho}_{ga} L}{g \left(\overline{\rho}_{ga} - \rho_w \right)} \tag{3.11}$$

The change in annulus liquid level during a given time step is the difference of the heights of annulus liquid levels at beginning and end of the time step given by

$$\Delta h_2 = h_2 \left(t_2 \right) - h_2 \left(t_1 \right) \tag{3.12}$$

Considering the conservation of mass inside the tubing during the time step, the total mass flow rate just below the plunger (Δm_1) is the same as the total mass flow rate into the tubing from reservoir and annulus (Δm_T).

$$\Delta m_1 = \Delta m_T \tag{3.13}$$

Eq.3.13 is obtained assuming a homogeneous mixture. This equation is particularly valid only in the situation where the liquid level in the annulus is still above the tubing seat (Case 1). This situation requires that all the fluids coming out from the annulus and the reservoir enter the tubing, making **Eq.3.13** valid. For the case when the liquid level in the annulus reached the tubing seat, flow of fluids into the tubing from reservoir and annulus will change. In such situations, the reservoir fluids can enter both annulus and tubing, and the total mass flow rate from annulus and reservoir must be distributed between the tubing and annulus.

The mass flow rate below the plunger is the product of the volumetric flow rate and the density of the two-phase mixture (ρ_m) below the plunger during the time step.

$$\Delta m_1 = \overline{v}_p A_{tub} \overline{\rho}_m \tag{3.14}$$

The density of two-phase mixture changes with time not only because it depends on the relative amounts of gas and liquids, but also because the density of gas below plunger changes as a function of average pressure and temperature in Region 2 that change with time. The value of average plunger velocity is obtained from mass balance equations in the Region 1.

Considering the conservation of mass in region 1 during the time step, the total mass flow rate at the point just above liquid slug (Δm_2) is equal to the total mass flow rate of gas at the wellhead (Δm_{wh}).

$$\Delta m_2 = \Delta m_{wh} \tag{3.15}$$

The total mass flow rate above liquid slug (Δm_2) is the product of volumetric flow rate of gas and the average density of gas in the region just above liquid slug (ρ_{g2}) during the time step.

$$\Delta m_2 = \overline{v}_p A_{tub} \overline{\rho}_{g2} \tag{3.16}$$

Similarly, the total mass flow rate at the wellhead (Δm_{wh}) is given by the product of volumetric flow rate of gas and the density of gas at the wellhead (ρ_{gwh}) during the time step.

$$\Delta m_{wh} = \overline{q}_{gwh} \overline{\rho}_{gwh} \tag{3.17}$$

Substituting **Eq.3.16** and **Eq.3.17** in **Eq.3.15** gives the value of average velocity ($\overline{v_p}$) of plunger during the given time step.

$$\overline{v}_p = \frac{\overline{q}_{gwh} \overline{\rho}_{gwh}}{A_{tub} \overline{\rho}_{g2}} \tag{3.18}$$

Using the value of average plunger velocity obtained from above equation in conjunction with **Eq.3. 12**, **Eq.3.13** and **Eq.3.14**, we obtain the value of average two-phase mixture density for a given time step (ρ_m) as given in **Eq.3.19**.

$$\overline{\rho}_m = \frac{\Delta m_r + \Delta m_a}{\overline{v}_p A_{tub}} \tag{3.19}$$

The value of two-phase mixture density obtained from **Eq.3.19** can be used to calculate the liquid mass fraction present in region 1 during the time step using **Eq.3.20**.

$$x_w = \frac{\left(\overline{\rho}_m - \overline{\rho}_g\right)}{\left(\rho_w - \overline{\rho}_g\right)} \tag{3.20}$$

The liquid mass fraction provides the value of total mass of liquid flowing into the tubing, Δm_{Tw} during a given time step as per the following equation.

$$\Delta m_{Tw} = x_w * \Delta m_T \quad (3.21)$$

The mass of reservoir liquid (water) coming into the tubing (Δm_{wres}) can be obtained from the difference of total mass flow of liquid into the tubing (Δm_{Tw}) and total liquid mass from annulus (Δm_w).

$$\Delta m_{wres} = \Delta m_{Tw} - \Delta m_w \quad (3.22)$$

The ratio of the mass flow rate of liquid from the reservoir calculated from **Eq.3.22** and total mass flow rate from reservoir calculated from **Eq.3.6** is the value of water yield from the reservoir (x). This value can be used to check with the initial guess of water yield that is used in the calculation of total mass flow from reservoir from **Eq.3.6.**

Finally, the position of plunger at the end of each time step can be obtained by calculating the distance covered by plunger during the time step. In the model, as the plunger rises during each time step, the length of Region 2 increases and length of Region 1 decreases. Thus, the position of plunger can be obtained in terms of heights of Region 1 and Region 2 using **Eq.3.23** through **Eq.3.25**.

$$\Delta h_3 = \bar{v}_P \Delta t = -\Delta h_4 \quad (3.23)$$

$$h_3(t_2) = h_3(t_1) + \bar{v}_P \Delta t \quad (3.24)$$

$$h_4(t_2) = h_4(t_1) - \bar{v}_P \Delta t \quad (3.25)$$

The heights of Region 1 and Region 2 for subsequent time steps are calculated by adding the difference in heights of corresponding regions obtained during the time step from

Eq.3.23 to the total height of the regions at the end of previous time step obtained from **Eq.3.24** and **Eq.3.25**.

The equations developed in this chapter provide the values of unknowns by using the data from smart plungers along with the fluid and reservoir properties and operating conditions.

CHAPTER IV

INPUT DATA FOR MODEL IMPLEMENTATION

This chapter describes the data that is estimated or available from the field, and required as input to the model during implementation. The field data set is provided by BP for an onshore field in East Texas.

4.1. Field Data

The field data available from smart plungers and other measuring devices that can be used as input to the code are:

Surface measurements

The parameters like tubing pressure, casing pressure and gas flow rate are measured at the surface for every 2 minutes. This data is collected from plunger cycles run on the 22nd of February, 2007.

1. *Tubing pressure*. Pressure measured at the wellhead (p_{wh}), provided in units of psig. These units are to be converted to pascals for the current model so that all the equations are implemented in SI system.
2. *Casing pressure*. Pressure near the casing measured at the surface (p_c) is also provided in psig units. These values are also converted to pascals like all other pressure values.
3. *Gas flow rate*. The gas flow rate at the surface (q_{wh}) is measured with the help of an orifice-meter located in the flowline before the separator. This value represents flow rate measured at standard conditions near the separator.

Other information provided in the 2 minute surface recordings (not required as inputs to the equations) is presented as follows.

1. *Static pressure*. The pressure at the header measured in psig. This value is influenced by the high flow rates from the well.
2. *Meter DP*. The orifice pressure differential measured in psig.
3. *Volume*. It represents the total gas volume in Mcf accrued during each cycle which is set to zero at the beginning of each cycle.

Smart plunger and Tailpipe measurements

The pressure and temperature data of plunger and bottomhole are provided from the smart plunger and Tailpipe gauge measurements respectively. This data is collected at a frequency of 5 seconds for three days from February 21- 23, 2007.

1. *Plunger pressure*. Pressure (p_1) measured by the sensor present inside the smart plunger. This data is provided every 5 seconds during the plunger cycles in psig unit, which is converted to pascals.
2. *Plunger temperature*. Temperature (T_1) measured by smart plunger sensor, measured in degrees F. Though these temperature values are not directly used in the equations, they are required for the calculation of gas densities for different conditions of pressure and temperature as the plunger rises to the surface.
3. *Tailpipe (TP) pressure*. Pressure (p_{wf}) recorded by the bottomhole gauge representing the bottomhole pressure conditions, provided in psig units, and converted to pascals during the implementation of model.
4. *Tailpipe (TP) temperature*. Temperature (T_{wf}) recorded by bottomhole gauge measured in degrees F.

Constant Inputs

The remaining data available from field includes the following constant parameters required for the code.

1. *Length of tubing*. The total length of tubing (L) is provided as 10500 ft (3200.4 m).
2. *Tubing diameter*. The tubing is considered to be of 2 3/8 inch diameter. This value is used in the calculation of tubing flow area, A_{tub}, used in the code in m^2.
3. *Casing diameter*. The casing is considered to be of 5 ½ inch diameter. This diameter is required for the calculation of the area of annulus, A_a, in m^2.

These values available from field are used as input to the equations developed for the model.

The measurements from smart plunger and tailpipe are recorded continuously and retrieved after few plunger cycles. Thus, there is a need to sort this data along with the surface data to obtain a complete set of combined data for one upward travel of the plunger. For this purpose, we chose the plunger upward travel of fourth cycle from the five complete plunger lift cycles available from field data. Since the data from the surface measurements is available at a frequency of 2 minutes, a sorted data set is obtained by collecting corresponding pressure and temperature measurements from smart plunger and tailpipe for every 2 minutes. Thus, the sorted data set consists of data from smart plunger, tail pipe gauge and surface measurements at an interval of 2 minutes for the plunger upward travel. However, the data frequency of 2 minutes doesn't allow the possibility of the model simulating transient condition because of the very large time steps involved. To solve this problem, the sorted data set is interpolated to obtain a final data set for the plunger upward travel with a frequency of 10 seconds. This dataset which is used as input to the model is presented in Appendix A along with other data.

4.2. Estimated Data

The data required for implementation of the model, but not available from the field data, is estimated based on generic values taken by the parameters. The parameters of the model which are estimated are as follows.

1. *Plunger height*. The height of plunger (h_p) is a constant value required in the equations of the model. This value for the smart plunger used in the well considered for this model is not provided in the field data. However, an approximate value of the length of smart plunger is obtained from the brochure PCS smart plungers as 1.48 ft (0.451 m).
2. *Yield from reservoir*. The value of yield from the reservoir, x, which represents the ratio of the amount of water produced in equivalent scf to the amount of gas produced from the reservoir. This value is assumed to be 0.7.
3. *Backpressure equation constants*. The values of constants for backpressure equation, C and n, are unavailable from field data. A value of 0.85 is used for n, which is in the range of typical values of n provided in the literature. The value of performance coefficient, C, is also estimated from the typical range of values provided in the literature, and a value of 0.005 Mcf/D/psi^{2n} is used for the implementation of current version of model.
4. *Reservoir pressure*. The reservoir pressure, p_r, required for the calculation of gas production rate from the reservoir is also unavailable from the field data. This value is obtained by extrapolating the buildup of pressures recorded by tailpipe gauge during shut-in periods for the five plunger cycles. An approximate value of 515 psia for the reservoir pressure is obtained using this procedure.
5. *Fluid properties*. The densities of gas at different conditions of pressure and temperature are calculated by assuming a gas specific gravity of 0.60 and using the

natural gas property correlations from Guo and Ghalambor (2005). The equations used for these calculations are presented in Appendix B.

4.2. Critical Analysis of Available Field Data

Fig.4.1 shows all 5 available complete plunger cycles which span a total duration of about 670 minutes. Each cycle begins with the shut-in period, followed by the plunger upstroke, afterflow (the production time with the plunger in the lubricator), and finally the cycle repeats with shut-in period of the next cycle. The key parameters reported in the field data are bottomhole pressure, wellhead pressure, casing pressure, smart plunger pressure and gas flow rate. The profile of the parameters considered in the plot look similar for all the five plunger cycles. However, it can be observed that the afterflow production period was very small for first cycle and maximum for the second plunger cycle. This afterflow can be identified by comparing the profiles of pressure recorded by smart plunger and wellhead pressure. These pressure profiles come closer as the plunger reaches wellhead and remain almost same for the length of time during which plunger is caught is lubricator with afterflow gas production. Also, the sudden spike in wellhead pressure before plunger gets caught in the lubricator indicates the start of liquid slug production at the wellhead.

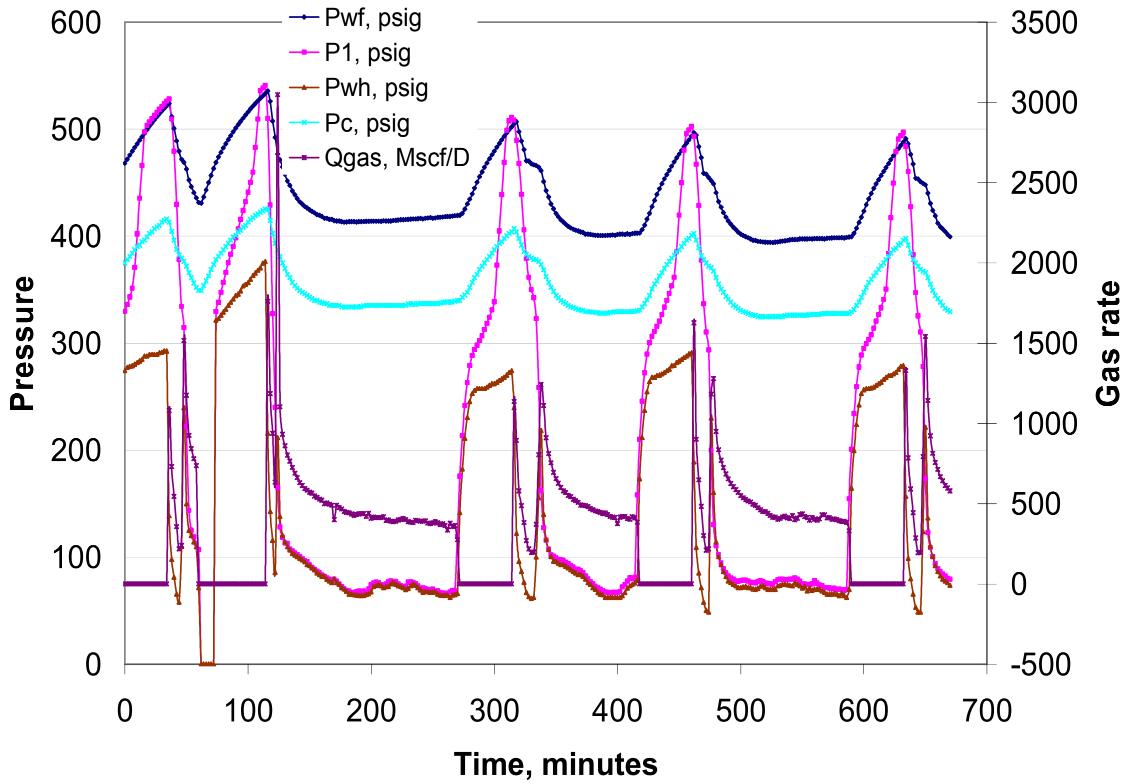

Figure 4.1 – Field Data for the Five Available Plunger Cycles (Chava, 2008)

Fig.4.2 reports a more detailed extract from the above figure, namely the fourth plunger upstroke (with the time starting at zero when the plunger starts to rise to the surface), followed by the natural flow period. The red dotted lines indicate two events of the plunger upstroke period, the point where the liquid slug hits the surface and that point where the plunger enters the lubricator, in line with the trends previously reported in Fig.4.1. Also, it can be noted for the plunger upward travel period under consideration, the difference between wellhead pressure and smart plunger remains almost constant indicating that the liquid slug height is virtually constant.

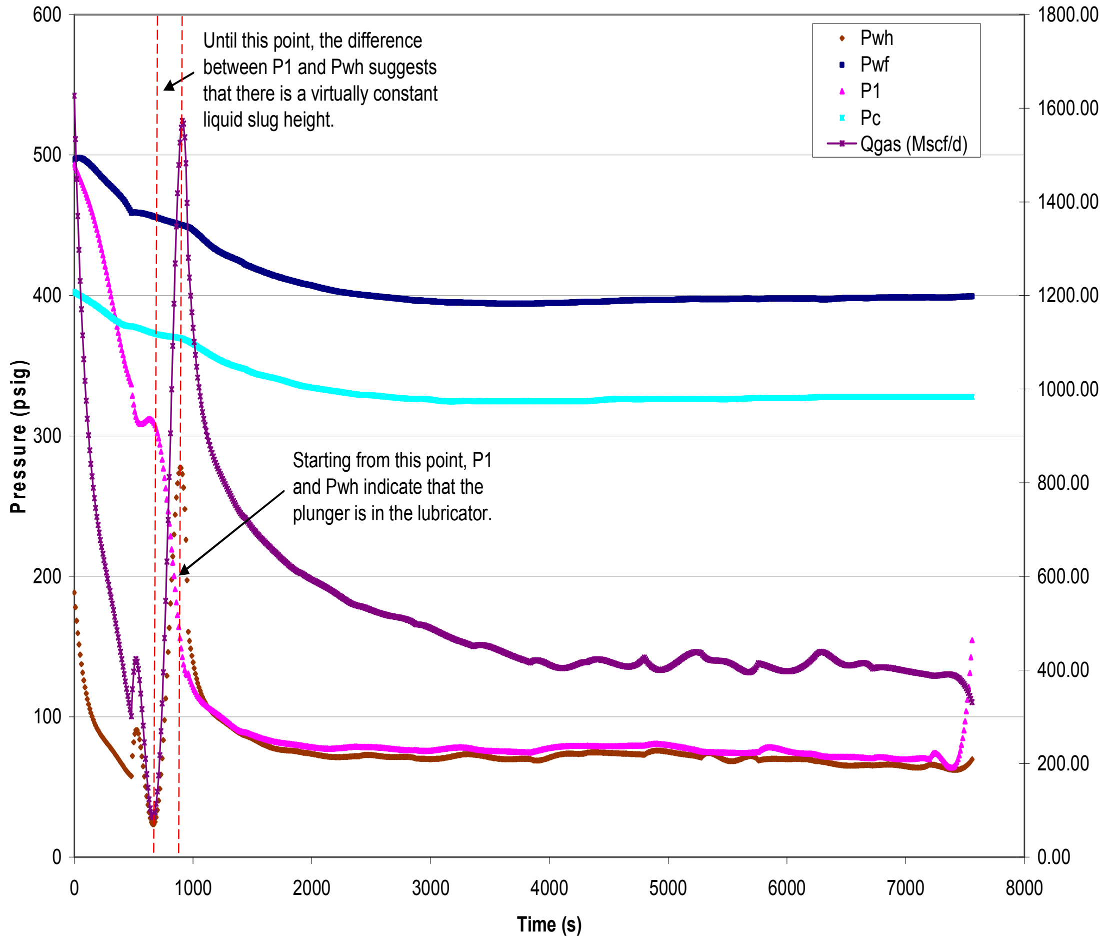

Figure 4.2 – The Fourth Upward Cycle of the Plunger, Followed by Natural Gas Flow (Chava, 2008)

It must be noted that the spike which can be noticed in the data prior to the one between the red lines only appears with the interpolated data (frequency of 10 seconds), but not with the 2-minute field data. However, it is believed that this spike is not just an interpolation feature, as it is also seen in p_1, which is measured every 5 seconds in the field. This spike could be indicating that there is some disturbance in the plunger travel at this point, which might be a small liquid slug being cleared out of the well before the more significant slug captured by the red dotted lines.

It will be seen from **Fig.4.2** that the slug only takes about 780 seconds to reach the surface, and that the liquid slug is cleared out of the well between 780 seconds and 1020 seconds from the time when the plunger starts from bottomhole.

Based on these observations, the model was run with the assumption that the liquid slug height is constant between 0 and 780 seconds. This dataset for the upward travel of plunger as presented in Appendix A is used as input for the implementation of model and the results are presented in Chapter V.

CHAPTER V

RESULTS OF MODEL IMPLEMENTATION

This chapter describes the procedure followed for the implementation of the new proposed plunger model from Chapter III developed in an Excel VBA program. This will be followed by a description of the method for the validation of model, and results for a base case and its comparison with another case from sensitivity analysis. The discussion of results obtained from implementation of model is presented after the results.

5.1. Procedure for Implementation of Model

The new proposed plunger lift model is implemented in Excel VBA program by coding the equations developed for the model in Chapter III. The input data required for solving the equations of the model coded in VBA program is described in Chapter IV. The data set considered for the current version of the code is presented in Appendix A. Only few of the equations developed in Chapter III using only gravitational terms, are slightly modified to be used in the code. **Eq.3.2** is used for the calculation of liquid slug height using the wellhead and flowing bottomhole pressures measured at the start of plunger upward travel ($t = 0$ seconds). However, the value of average gas density which is dependent on the average pressure and temperature in region 1 at time $t = 0$ seconds is required to solve this equation for obtaining liquid slug height. A simple iterative subroutine is used to calculate the average gas density and liquid slug height for solving this problem.

Subroutine for liquid slug height calculation

Step1. Starting value of pressure is the average of wellhead and flowing bottomhole pressures at time t = 0 seconds. The starting temperature considered is the average value of wellhead and flowing bottomhole temperatures.

Step2. Assuming a value of gas specific gravity of 0.6, the average gas density is calculated for the conditions of pressure and temperature of Step 1 using natural gas property correlations from Guo and Ghalambor (2005) as described in Appendix B. This value of average gas density is used to calculate the liquid slug height in the tubing using **Eq.3.2**.

Step3**.** The liquid slug height and average gas density obtained from Step 2 are used to calculate the pressure just above the liquid slug in tubing (p_2) at time t = 0 seconds from the following equation.

$$p_2 = p_1 - \left(\rho_w g \left(h_s + h_p\right) / 6894.757\right) \tag{5.1}$$

The pressures in Eq.5.1 are considered in units of psia while other variables follow the SI system of units.

Step4**.** Average gas density for region 1 is again calculated by using the same temperature but the pressure is the average of wellhead pressure and pressure calculated from Step 3. This is done because the average pressure in region 1 is close to the average of wellhead pressure and pressure just above the liquid slug in the tubing.

Step5. Check to see if the difference between the density values measured from Step 2 and Step 4 is less than the tolerance value of 0.001 kg/m^3. If density difference is greater than 0.001 kg/m^3, then go back to Step 2 and calculate liquid slug height with the value of gas density calculated from Step 4. If density difference is less than 0.001 kg/m^3, then the subroutine reached convergence and the density from Step 4 is the final consistent value of average gas density for time t = 0 seconds.

Step6. Calculate the final value of liquid slug height using the converged value of average gas density from Step 4.

The liquid slug height calculated from the above subroutine is considered as a constant in the current model because we assumed that there is no liquid fallback during plunger upstroke. Also, the equations developed using only gravitational terms from Chapter III assume that there is no liquid fallback during the plunger upward travel and hence do not consider the possibility of changing liquid slug height. However, the above subroutine can be used iteratively for different time steps of plunger upstroke to calculate the values of changing liquid slug height by assuming that the amount of liquid fallback is negligible when compared to the amount of fluids coming into the tubing from the annulus and reservoir. This assumption makes the model equations still valid while considering variable liquid slug height. This chapter presents the results of the model by assuming constant liquid slug height.

Similarly, annulus liquid level is calculated from **Eq.3.11** which is obtained from a simple pressure balance equation applied to the region 3 inside the annulus. Solving this equation for annulus liquid level requires the calculation of the value of annulus gas density which is dependent on the average pressures and temperatures of the gas phase region in the annulus. A subroutine similar to the one developed for calculating liquid slug height is used to solve this problem. However, the equation for calculating the pressure above annulus liquid (p_a) is different from **Eq.5.1** and the following equation is used to calculate the value of pressure above annulus liquid.

$$p_a = p_{wf} - \left(\rho_w g h_2 / 6894.757\right) \tag{5.2}$$

The pressures in Eq.5.2 are considered in units of psia while other variables follow the SI system of units.

Substituting **Eq.5.2** for **Eq.5.1** in the subroutine and using casing and flowing bottomhole pressures for different time steps provides the values of annulus liquid level during each time step of the plunger upstroke.

The value of plunger velocity is calculated for each time step using **Eq.3.18**. The value of average wellhead gas flow rate used in the numerator of this equation is obtained by taking an average of the values of wellhead gas flow rates at the beginning and end of each time step. The average gas density value at wellhead is obtained from the average of gas densities calculated for wellhead pressures at the beginning and end of each time step, and uses an approximate wellhead temperature of 80 degrees F. The average gas density at the point just above liquid slug for each time step is calculated from the average of gas densities calculated from corresponding pressures and average of plunger temperatures at the beginning and end of time step. **Eq.5.3** can be used for the calculation of pressure just above liquid slug at any point during plunger upstroke.

$$p_2 = p_1 - \left(\rho_w g h_s / 6894.757\right) - \left(W_p / 144 * A_{tub}\right) \tag{5.3}$$

The pressures in Eq.5.3 are considered in psia units, weight of plunger is taken in pound force and area of tubing is considered in in^2; while other variables follow the SI system of units.

The value of an average two-phase mixture density ($\overline{\rho}_m$) during a given time step is calculated using **Eq. 3.19**. The total mass flow rate from the reservoir required for solving the above equation can be obtained from **Eq. 3.6**. The average gas density used in Eq.3.6 is obtained from the average of gas densities calculated from flowing bottomhole pressure and temperature conditions at the beginning and end of the time step. **Eq.3.4** and **Eq.3.5** are used to obtain the total mass flow rate from the annulus into the tubing for the given time step.

Finally, the fraction of liquid present in region 2 (x_w) below the plunger inside the tubing is obtained using **Eq.3.19.** The value of average gas density in this region is calculated from the average of gas densities measured in this region at the beginning and end of each time step. The equations discussed above are coded in Excel VBA program and the data presented in Appendix A is used as input for the code to provide values of plunger velocity and plunger position in terms of heights of region 1 and region 2. The model can also provide values of two-phase mixture density and liquid fraction of region 2 below plunger for different time steps during plunger upstroke.

5.2. Validation of Model

The use of available data as input to model's equations developed using only gravitational terms, will provide the values of parameters like heights of different regions, pressure above the liquid slug and the plunger velocity for different points of time during plunger upstroke. After implementing the model in VBA code for the given upward travel of the plunger, the validation of model can be done in the following ways.

1. Plunger velocity, which is calculated from **Eq. 3.18,** depends on the values of wellhead gas flow rates, and densities of gas at wellhead and at the point just above liquid slug for different points of time during plunger upstroke. The densities in the equation are dependent on the pressures and temperatures at those locations for any

given instance of time. Thus, the model could be validated if the profile of plunger velocity predicted by the model could reflect all key events identified by the profiles of wellhead tubing pressure, smart plunger pressure and wellhead gas flow rate for the plunger upstroke period.

2. The heights of regions above and below the plunger and liquid slug inside the tubing are calculated for each time step using **Eq.3.24** and **Eq.3.25.** The values of heights of these regions indicate the position of plunger at different points of plunger upstroke. Since the final time step of model's input data represents the start of liquid slug production as indicated by the smart plunger pressure data, the model can be validated by checking if the plunger reaches the surface along with liquid slug at the end of final time step.

3. The height of annulus liquid (calculated from **Eq.3.11)** depends on the values of casing pressure and flowing bottomhole pressure for different time steps during plunger upstroke. Thus, the profile of annulus liquid level should be consistent with the profiles of casing and flowing bottomhole pressures for the model to be valid.

The model is validated using the above methods for a base case, as described in the next section. The results of the model are obtained from implementation of VBA code and the discussion of these results is also presented.

5.3. Results of Base Case Implementation

The implementation of base case of the model is carried out using input data available from field and assuming other required variables that provide reasonable values of output parameters. Apart from the data available from the field, the values used for other important variables are provided in **Table 5.1.**

Table 5.1 – Variable Values for Base Case

VARIABLE	VALUE
Gas specific gravity, γ_g	0.60
C (Mcf/D/psi^{2n})	0.005
n	0.85
Reservoir pressure, p_r (psig)	515

The value of gas specific gravity is chosen as 0.60 which lies in the typical range of natural gas specific gravities. The values of C and n are estimated from the typical ranges of backpressure constants available for fields with similar gas production rate and flowing bottomhole pressures. The value of reservoir pressure is estimated by extrapolating the flowing bottomhole pressures of the five plunger cycles available from field data. Since the values of these parameters are estimated, they provide an opportunity for sensitivity analysis which is discussed in the next section.

The major parameters evaluated from the calculations in the model are average plunger velocity during each time step (v_p), position of plunger in the tubing at the end of each time step in terms of heights of region 1 (h_4) and region 2 (h_3) and height of annulus liquid level at the end of each time step (h_2).

The profile of average plunger velocity (m/sec) calculated from the model for each time step is shown in **Fig. 5.1**.

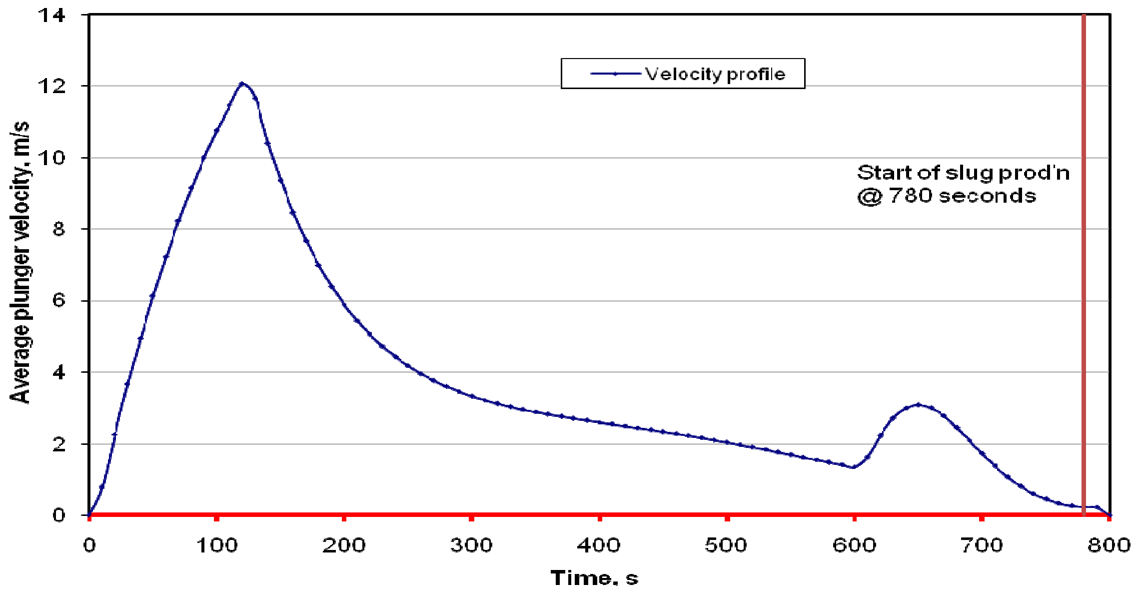

Figure 5.1 – Average Plunger Velocity during Plunger Upstroke

The profile of plunger velocity indicates that the plunger attains a very high velocity in the first few minutes of the plunger upstroke period. The plunger attains a maximum velocity in its travel during the initial few minutes and then the velocity reduces gradually because of either the impact of load or the frictional forces acting on the liquid slug and plunger along the inner diameter of tubing. The velocity profile also reflects the disturbance occurring to the plunger travel after 600 seconds. The velocity of plunger spikes at this point in time, similar to the wellhead gas flowrate and tubing pressure profiles. The model is not valid after the start of liquid slug production which is indicated in the plot with the line at 780 seconds. The average plunger rise velocity calculated from the model is 3.53 m/s or 695.32 ft/min and close to zero (0.221 m/s) at the start of slug production.

For optimum plunger lift cycles, the shut-in period should be of minimum duration such that it allows the plunger to lift the liquids and just reach the surface with a velocity close to zero. The current model's predictions indicate that this objective is achieved for the plunger upstroke considering that the velocity of plunger is close to zero at the start of slug production.

The profile showing the position of plunger is terms of the heights of region 1 and region 2 at the end of different time steps during plunger upstroke is shown in **Fig.5.2.**

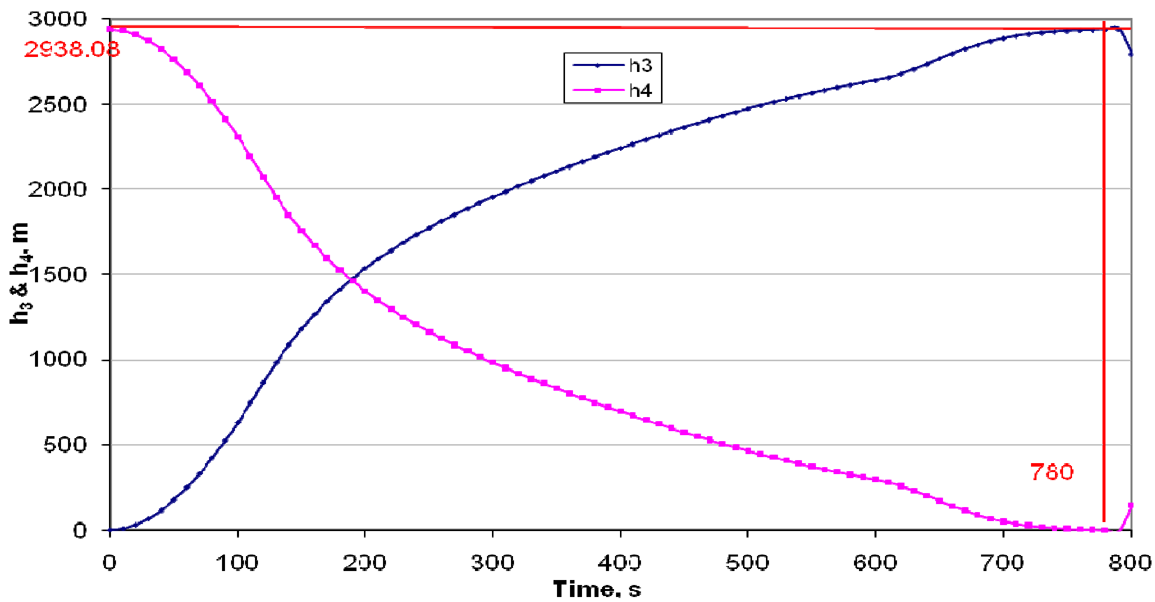

Figure 5.2 – Profile Showing Change in Heights of Regions inside Tubing with Time

The profile indicates that the height of region 1 above the plunger slug system (h_4) starts at a maximum value of 2938.08 m, a value that corresponds to the length of tubing exlcuding the heights of liquid slug and plunger. As the plunger rises towards the surface, the height of region 1 decreases with a corresponding increase in the height of region 2 (starts from zero when the plunger sits on the bumper spring for t = 0 seconds). As the plunger reaches the surface along with the liquid slug, the height of region 2 gets close to the total length of tubing. The fact that the height of region 2 after 780 seconds is nearly equal to 2938.08 m (Initial value of height of region 1) suggests that there is a negligible amount, if any, of liquid fallback ,during the plunger upstroke.

The third parameter evaluated from the model is the height of annulus liquid level at the end of each time step. The value of annulus liquid level is calculated directly from the pressure balance equation in the casing – tubing annulus. Though there is mass flow from annulus, it is not used in the derivation of the value of annulus liquid level. The profile of annulus liquid level calculated from the model is shown in **Fig. 5.3.** The profile shows that the liquid in the annulus is completely drained out in the first 50 seconds as indicated by the zero value for annulus liquid level after 50 seconds. It also indicates that the mass conservations applied to region 3 and region 1 below the plunger might give erraneous results since the model assumes that the annulus liquid level is above the tubing seat during plunger upstroke. This problem can be observed for parameters like two-phase mixture density and liquid mass fraction in region 1 because the values of those parameters are obtained from mass conservation applied between tubing, annulus and reservoir assuming only liquid flows from annulus into the tubing. However, this doesn't affect the values of average plunger velocity since it is obtained from mass conservation above the plunger/slug system which is valid regardless of flow of fluids from the annulus.

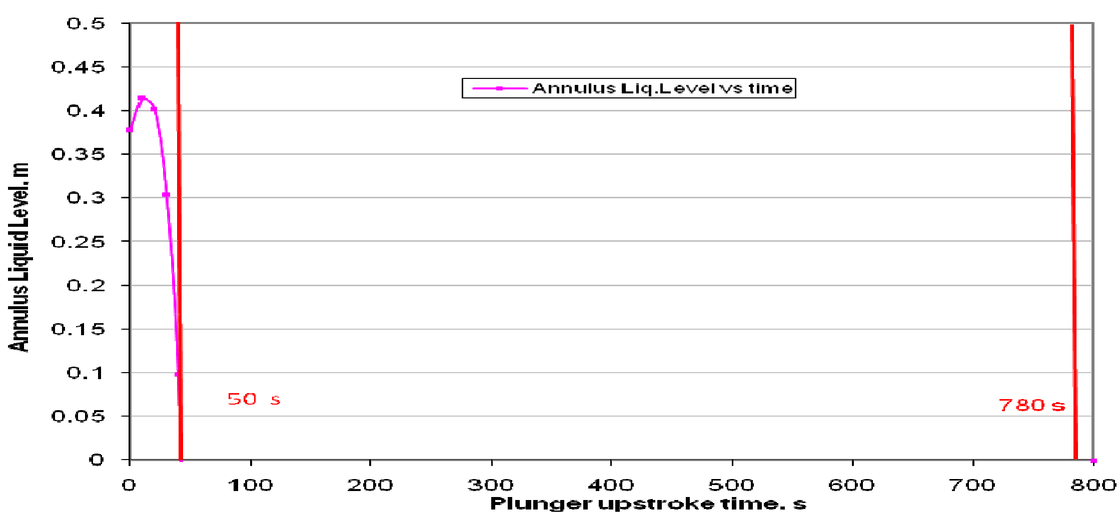

Figure 5.3 – Annulus Liquid Level Profile during Plunger Upstroke

The value of annulus liquid level depends on average annulus gas density which in turn depends on the gas specific gravity used in the model. This value of gas specific gravity is assumed and slight variations in this value can lead to quite different results, perhaps making the applicability of model either completely valid or completely invalid. Three different values of gas specific gravity (0.5, 0.6 and 0.7) are considered at this point to observe the impact of specific gravity on the model results. The value of 0.60 for specific gravity corresponds to the base case considered in the implementation.

Allowing the variable representing the annulus liquid level to take negative values, a comparison of the annulus liquid level profiles for the three different specific gravities is shown in **Fig.5.4.**

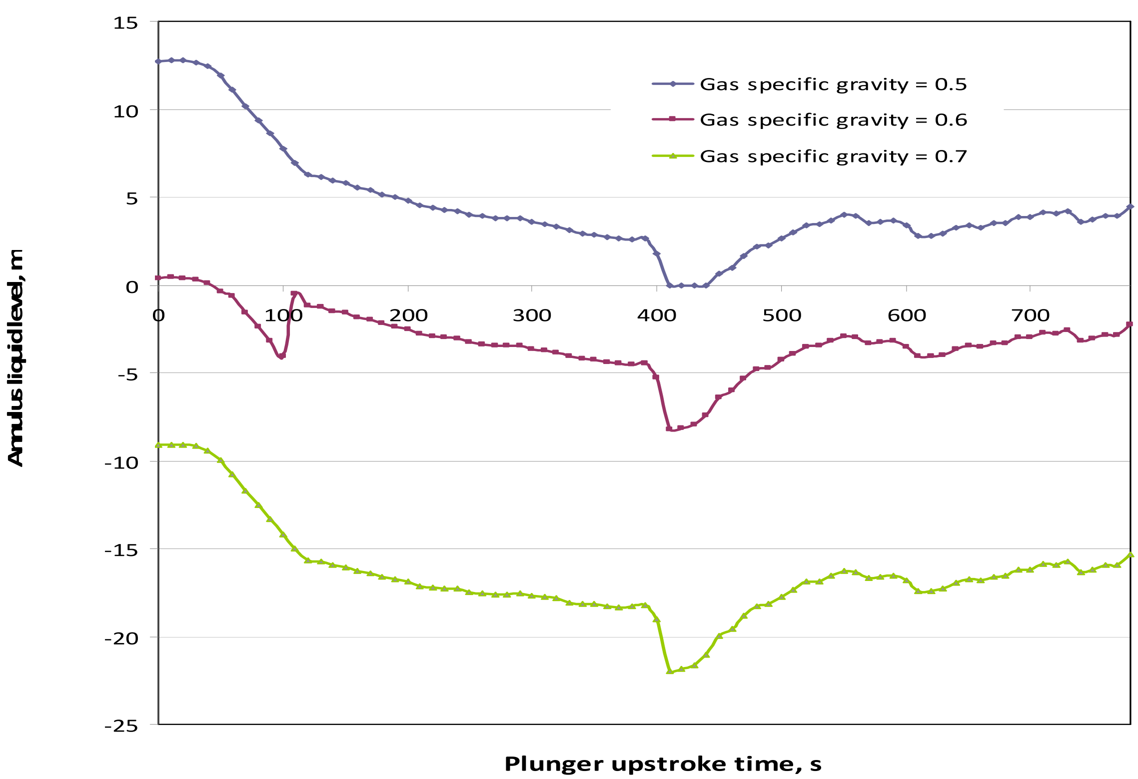

Figure 5.4 – Comparison of Annulus Liquid Levels for Three Different Guesses of Gas Specific Gravities

The comparison of annulus liquid level profiles for the three specific gravities proves that the parameter is strongly dependent on the value of gas specific gravity. Since we don't have any information about the fluid properties, the guessed value for base case might not represent the actual gas specific gravity of the fluids in the well under consideration. Also, it can be observed that the profiles of annulus liquid level move from completely positive values for gas specific gravity of 0.5 to completely negative values for gas specific gravity of 0.7. This observation suggests the importance of having information about the fluid properties which will affect all of the important parameters in the model.

Another observation that can be made with the plots of annulus liquid level profile in conjunction with the plunger velocity profile is that the velocity profile doesn't show any indications of changes occuring in the annulus at the point when the annulus liquid level has completely drained after 50 seconds. This observation means that the flowing bottomhole pressure is the primary driver for plunger lift for the well under consideration regardless of the presence of liquid in the annulus. Positive values of annulus liquid level for the complete plunger upstroke period indicates that there is always liquid in the annulus, where as negative values of annulus liquid level indicate that the annulus liquid drained into the tubing after sometime. In either situation for the current well data, the velocity of plunger is not affected by the changes happening in annulus because of strong reservoir support in the form of flowing bottomhole pressure.

5.4. Sensitivity Analysis of Model

The input data available for implementation of model contains different variables apart from field data whose values are estimated or guessed. A sensitivity analysis work is carried out on these variables to observe the impact of each variable on model results and to obtain reasonable values for results. Sensitivity analysis is done on different variables affecting the key parameters that are evaluated from the model. The variables chosen for sensitivity analysis are

1. Gas specific gravity (γ_g). The value of gas specific gravity is estimated or guessed because of the lack of availability of fluid property data for the particular well under consideration. The value of gas specific gravity directly effects the calculations of gas densities for different time steps, and thereby affects the values of all the parameters considered for evaluation. A wide range of values of gas specific gravity were considered for sensitivity analysis like 0.55, 0.60, 0.65, 0.70, 0.75, 0.80 and 0.85.
2. *C* and *n* (Backpressure equation constants). Though these variables do affect the values of velocity, heights of region 1 and region 2, and annulus liquid level during the plunger cycle, they have significant impact on the values of total mass flow coming in to the tubing from reservoir. This directly affects the values of two-phase mixture densities during each time step. For the purpose of sensitivity analysis, the values {500, 50, 5, 0.5, 0.05, and 0.005} in Mcf/D/psi^{2n} were considered for performance coefficient *C*. For the exponent n, the range of {0.55, 0.65, 0.75, 0.85, and 0.95} was chosen from the typical value range of 0.5 (for fully turbulent flow) to 1 (for fully laminar flow).
3. Reservoir pressure (p_r). Similar to backpressure equation constants, the value of average reservoir pressure used in the calculation of gas flow rate from backpressure equation directly affects only the value of average two-phase mixture density. Since this value is estimated from the flowing bottomhole pressure data for different plunger cycles, the range of this variable chosen for sensitivity analysis doesn't

deviate much from the values predicted from extrapolation. The range chosen for reservoir pressure is {515, 600, 700, 800 and 900} in psig.

4. Wellhead gas flow rate (q_{gwh}). The value of wellhead gas flow rate is considered for sensitivity analysis even though it is directly available from the surface data because of the uncertainty in the error that can be introduced due to the distance of gas flow rate measuring devices from the wellhead. An error in wellhead gas flow rate will directly affect the values of average plunger velocity and, therefore the heights of region 1 and region 2. For current sensitivity analysis, variations of ±5%, ± 10% and ±15% from the measured wellhead gas flow rate are considered.

Other important variables of the model whose data is directly available are p_{wh} and p_1. These variables play an important role in the model because they are used in the calculation of gas density at wellhead and gas density at the point just above liquid slug, and these gas densities are used directly in the calculation of average plunger velocity. However, the values of these variables reported from field data are assumed to be fairly accurate and are not considered for further sensitivity analysis.

A summary of the range of values tried for different variables in the sensitivity analysis is provided in **Table 5.2**.

Table 5.2 – Variable Ranges/Variations Considered for Sensitivity Analysis

VARIABLE	**RANGE OF VALUES/ VARIATIONS**
Gas specific gravity, γ_g	0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85
C (Mcf/D/psi^{2n})	500, 50, 5, 0.5, 0.05, 0.005
n	0.55, 0.65, 0.75, 0.85, 0.95
Reservoir pressure, p_r (psig)	515, 600, 700, 800, 900
Wellhead gas flow rate, q_{gwh}	±5%, ± 10%, ±15%

The results from the base case are compared with the results from the case which provided the largest deviation from expected values of different parameters.

The values of different variables considered for the case that provided the largest deviation of results from expected values are provided in **Table 5.3.** Though the values considered for some of the parameters are not realistic according to industry experiences, they were chosen deliberately to see the largest shift from the results of base case that can be caused by varying the values of these parameters.

Table 5.3 – Variable Values/Variations for Case with Largest Deviation of Results

VARIABLE	**VALUE/VARIATION**
Gas specific gravity, γ_g	0.85
C (Mcf/D/psi^{2n})	500
n	0.95
Reservoir pressure, p_r (psig)	900
Wellhead gas flow rate, q_{gwh}	measured value - 15%

The results of calculations done for the case with largest deviation from base case are presented in the following comparison charts.

The chart showing a comparison of the plunger velocity profiles for the base case and the largest deviation case is provided in **Fig. 5.5.** The profiles show that the values of plunger velocity for the case with largest deviation from the base case are lower than the plunger velocities calculated from base case. The maximum velocity attainable using base case is 12.06 m/s which is 28.8% greater than the maximum plunger velocity of 8.59 m/s attained using the largest deviation case. However, the plunger velocity profile using both cases has a similar trend that reflects the disturbance caused to the plunger travel after 600 seconds and both profiles attain their lowest values after the start of slug production. The major variable providing such a deviation in plunger velocity profile can be the variation of -15% used with the measured values for the case with largest deviation. The start of slug production is indicated by the solid vertical line in the chart.

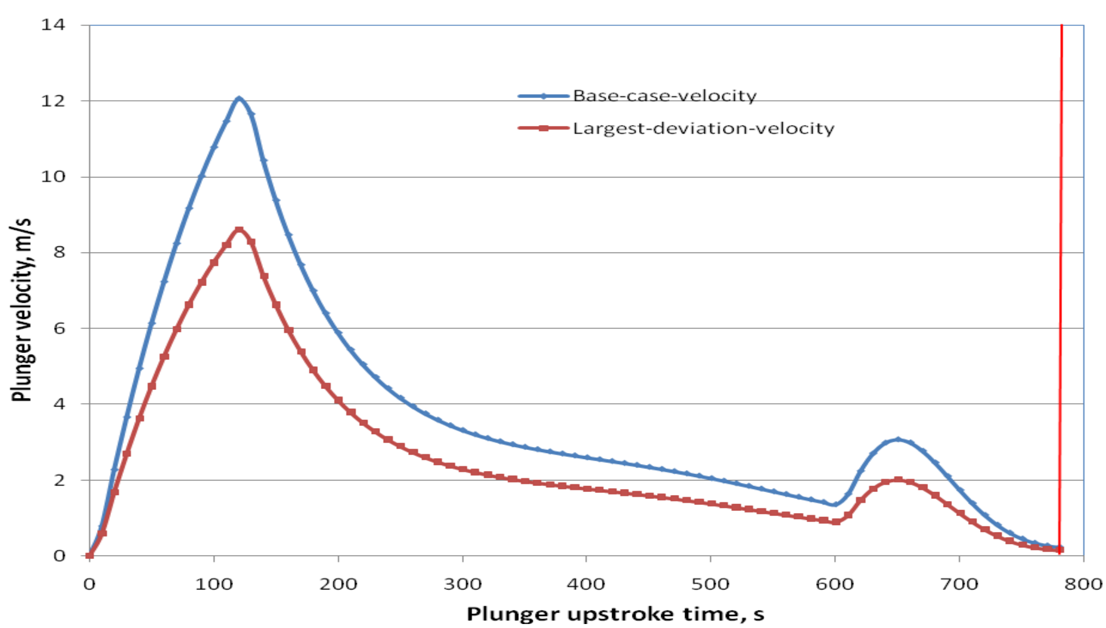

Figure 5.5 – Comparison Chart for Average Plunger Velocities of the Two Cases

The second chart, shown in **Fig.5.6,** provides the comparison of the heights of region 2 (h_3) and region 1 (h_4), calculated from both base case and largest deviation case. The profiles of largest deviation case indicate that the plunger doesn't reach the surface at the start of slug production as shown by the pressure profiles of original field data. However, profiles of the heights of region 1 and region 2 calculated from base case reflect the pressure profiles extremely well by calculating the plunger position to be near the wellhead at the start of slug production. The comparison shows that the distance traveled by plunger as calculated from largest deviation case is 30% less than the corresponding distance calculated using base case.

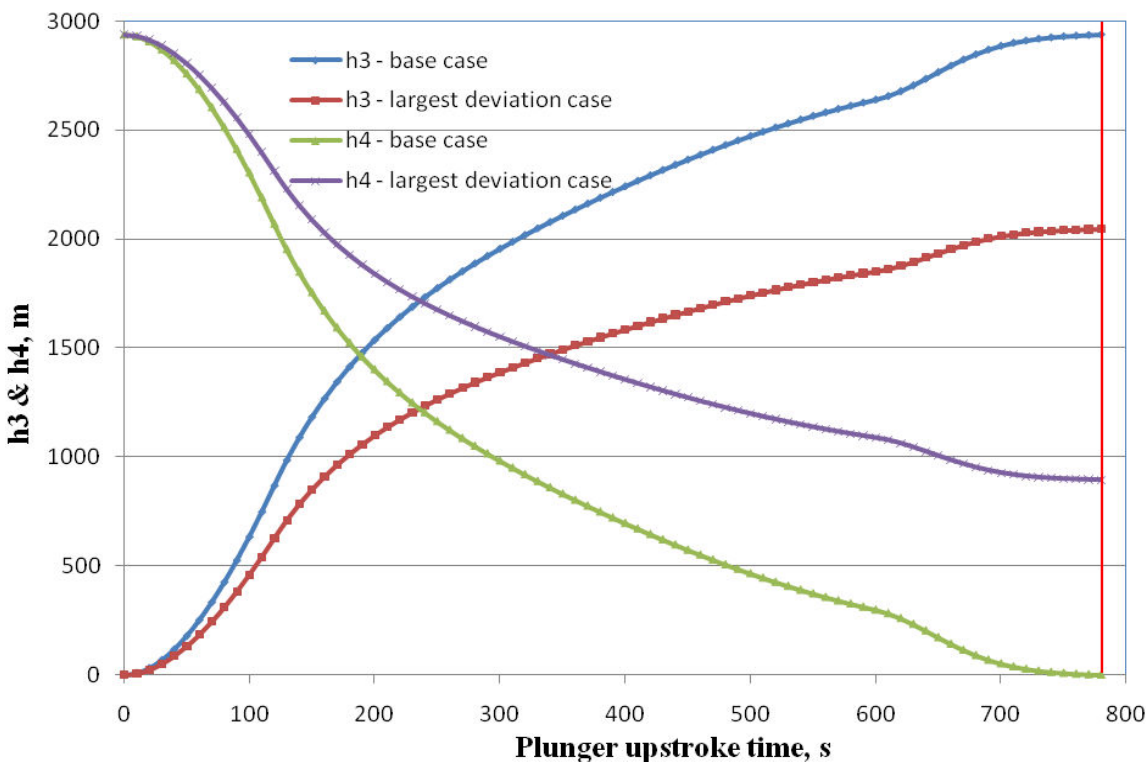

Figure 5.6 – Comparison Chart Showing Heights of Region 1 and Region 2

Finally, the comparison chart showing the profiles of annulus liquid levels calculated from the base case and largest deviation case is provided in **Fig. 5.7.** This chart is obtained by allowing the annulus liquid level to take negative values. Considering practical values of annulus liquid level, both the cases suggest that the annulus liquid level is zero from the beginning of plunger upstroke period. Since the gas specific gravity used in both cases is equal to or higher than 0.60, we obtain negative values for annulus liquid level. Also, the higher value of gas specific gravity used in largest deviation case caused the profile of its annulus liquid level to be much lower than that calculated from base case.

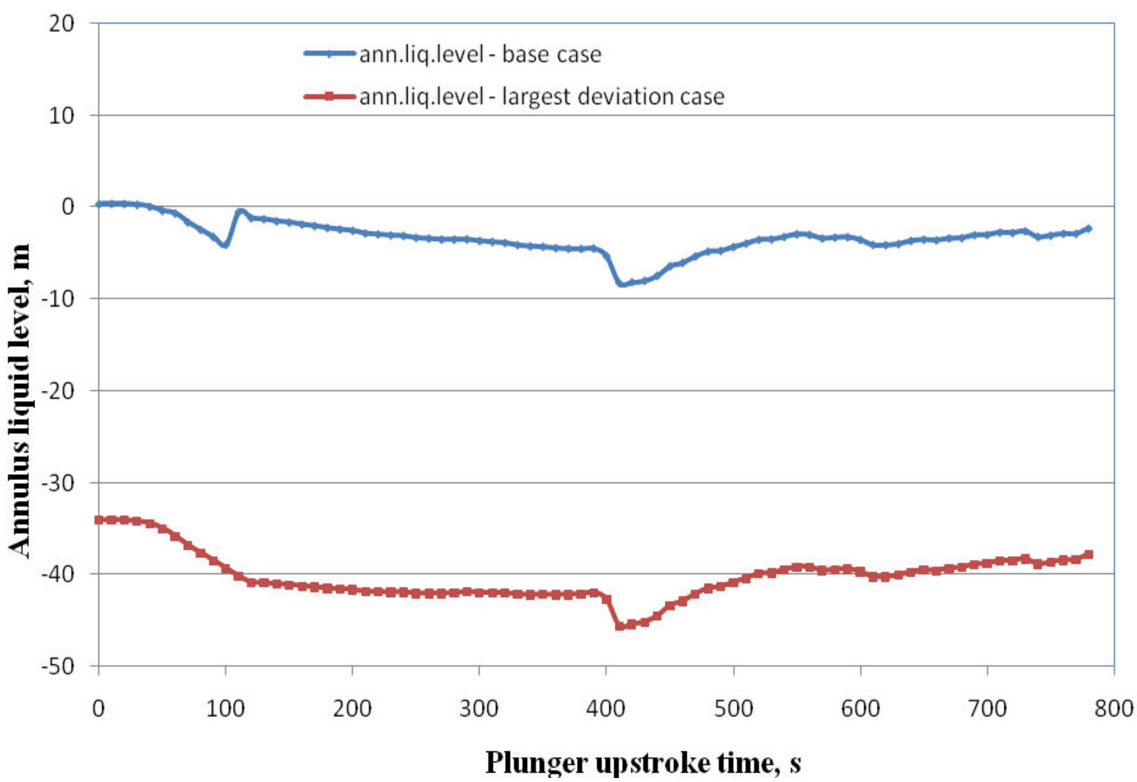

Figure 5.7 – Comparison Chart for Annulus Liquid Level

The results obtained from implementation of base case and sensitivity analysis show the importance of fluid properties in the current model. The results suggest that additional data is required for better modeling particularly while considering the addition of complex friction and acceleration terms to the model. The results also indicate that the model might not be valid in the situation where the annulus liquid is drained into tubing which allows the flow of reservoir fluids into the annulus and tubing. This situation needs to be accounted in the future improvements of the model. Another important observation is that the backpressure equation is not sufficient when applying the models to tight gas formations. This suggests that the near wellbore region of reservoir deserves more focus in modeling tight gas formations.

5.5.Summary

This chapter presented the procedure followed to implement the proposed new plunger lift model in excel VBA program. It provided the results for a base case of the data set that provided reasonable values of calculated parameters. It also compared the results of the base case with another case of data set that has the largest deviation of results from reasonable values. The model could calculate the plunger velocity and position reasonably well, though the sensitivity analysis work suggests the importance of the availability of fluid property data for more accurate results.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This research proposed a new plunger lift model by focusing on the upward travel of the plunger until the start of liquid slug production in a packerless completion. The model eliminates some assumptions that limited the applicability of previous plunger lift models. This was achieved by utilizing additional available data for modeling in the form of pressure and temperature data recorded by smart plungers during the plunger cycles. The model can also consider the possibility of liquid fallback by slight modifications in the equations. The model considered is deliberately simple, focusing more on the fundamental principles that govern fluid flow in the plunger lift system and utilizing the data from smart plungers. The complexities of adding frictional and acceleration terms to the pressure balance equations can be done in steps with the availability of more data.

6.1. Conclusions

The research work provides the following set of conclusions.

1. A new model of plunger upstroke has been proposed with an aim to overcome some of the limiting assumptions of earlier plunger models by utilizing the additional data available from the smart plungers.
2. The simple model developed using only gravitational terms is implemented in VBA program. Excel VBA is chosen because of its accessibility and user friendly features.
3. The new model proves that data available from smart plungers can - not only provide useful information about various events happening during a plunger lift cycle but also be used as a means to improve plunger lift modeling. However, the only drawback of

this technology is that the data cannot be obtained in real time during plunger lift operation.

4. Predictions from the model by using the smart plunger data for plunger upstroke suggest that the plunger lift cycles are optimized with plunger surfacing velocities close to zero. This suggests that the shut-in period prior to the plunger upstroke stage was maintained for minimum duration.
5. The model is deliberately simple, starting with the use of only gravitational terms in pressure balance equations. However, the predictions from the model indicate that it already captures the key physics of plunger lift cycles. The additions of complexities like the use of frictional and acceleration terms in the model's equations can slightly improve the model's predictions.
6. The sensitivity analysis conducted in this work shows the importance of fluid properties for implementing the current model. A slight variation in the assumed value of gas specific gravity can change the applicability of the model.

6.2. Recommendations

The model developed in this work is the first step in the use of additional pressure and temperature data available from a new technology like smart plungers. The derivations of equations used for model are presented in detail along with the assumptions used to facilitate future work on the model improvement. Some recommendations for future work on this model are presented as follows.

1. The model assumes that there is no liquid fallback during the plunger upstroke. However, liquid fallback can be modeled by slightly changing the conservation of mass equations used around the plunger to account for mass flow from the region

above plunger to the region below plunger. To simply account for changing liquid slug height value, an iterative use of the subroutine for calculating liquid slug height during different time steps can be implemented in the current version of model.

2. The slug production period can be modeled by considering the liquid slug height as a changing variable during that period. This modeling can be achieved that liquid slug height decreases from its constant value (calculated for initial time step) at the beginning of slug production to zero by the end of slug production period. This change in height of liquid slug is reflected in the value of plunger velocity because of lower pressures on the plunger.
3. Future work on the model requires more information about fluid properties for obtaining better accuracy from the model. Also, using accelerometers in conjunction with smart plungers can provide useful information about the instantaneous plunger acceleration, which can then be used to solve the force balance on the plunger directly during the cycles. These values of instantaneous plunger accelerations can be used to correlate plunger acceleration to plunger velocity and position.
4. The current model only considers the upward travel of plunger until the start of liquid slug production. For a complete analysis of the plunger lift system and its optimization, the complete plunger cycle should be modeled. The models of shut-in and afterflow periods need to be added to the current model to achieve this objective.
5. Fluid flow from reservoir in case of gas wells with liquid loading is accounted in a better way using two phase IPR (Inflow Performance Relationship) equations.
6. The results of implementation of the model suggest the need for more information about different variables used in the equations. This necessity becomes more significant as further complexities in terms of friction and acceleration are added to the equations.

7. The reservoir transients in the near wellbore region of reservoir become more significant in tight gas formations, and simple backpressure equation is not sufficient to model the performance of reservoir in such formations. It also suggests the need for accounting such reservoir transients by coupling the current model to reservoir simulators that can capture the reservoir transients.

NOMENCLATURE

A_a	annulus area available for fluids, m^2
A_{tub}	cross sectional area of the tubing, m^2
C	performance coefficient of the backpressure equation, Mcf/D/psi^{2n}
g	acceleration due to gravity, m/ s^2
h_1	height of the gas column in the casing – tubing annulus, m
h_2	height of annulus liquid level, m
h_3	height of the two phase flow region below the plunger, m
h_4	height of gas flow region (region 1) above the plunger, m
h_s	heights of accumulated liquid slug, m
h_p	heights of plunger, m
Δh_2	change in the height of annulus liquid level, m
Δh_3	change in the height of region 2 during a given time step, m
Δh_4	change in the height of region 1 during a given time step, m
L	total wellbore depth, m
Δm_a	mass flow rate coming from the annulus into the tubing, kg/s
Δm_r	mass flow rate coming from the reservoir into the tubing, kg/s
Δm_T	total mass flow rate into the tubing at any instant, kg/s
Δm_{wh}	mass flow rate near the wellhead, kg/s
Δm_1	mass flow rate at the point just below the plunger, kg/s
Δm_2	mass flow rate at the point just above the liquid slug, kg/s
Δm_{wres}	mass flow rate of liquid from reservoir during a given time step, kg/s
Δm_{Tw}	total mass flow rate of liquid into the tubing for a given time step, kg/s
n	backpressure equation exponent

p_c surface casing pressure, psig

p_r reservoir pressure, psig

p_{wh} wellhead pressure, psig

p_{wf} flowing bottomhole pressure, psig

p_1 pressure at the point just below the plunger, psig

p_2 pressure at a point just above the liquid slug, psig

p_a pressure at a point just above the liquid in annulus, psig

q_{gwh} average wellhead gas production rate during a time step, m^3/s

q_{gr} average reservoir gas production rate during a time step, m^3/s

Δq_{gr} differential gas production from reservoir for a given time step, m^3/s

Δq_{wa} liquid volumetric flow rate from the annulus into the tubing, m^3/s

Δq_{wh} volumetric flow rate near the wellhead, m^3/s

$\bar{v}_p$ average velocity of the plunger during a given time step, m/s

$\bar{\rho}_g$ average density of gas during a given time step, kg / m^3

$\bar{\rho}_m$ average two phase mixture density below plunger for a given time step, kg / m^3

ρ_w liquid (water) density, kg / m^3

$\bar{\rho}_{gwh}$ average density of gas near the wellhead for a given time step, kg / m^3

$\bar{\rho}_{g2}$ average density of gas at the point just above the liquid slug, kg / m^3

$\bar{\rho}_{ga}$ average gas density in the annulus for a given time step, kg/m^3

t_1 beginning of the given time step, s

t_2 end of the given time step, s

x water yield from the reservoir

x_w mass fraction of liquid inside the tubing below plunger for a given time step

REFERENCES

Abercrombie, B. 1980. Plunger Lift. In *Technology of Artificial Lift Methods,* ed. K.E. Brown, Vol.**2b**, 483. Tulsa, Oklahoma: PennWell Pub. Co.

Avery, D.J.:1988. Optimization of Plunger Lift Systems for Solution Gas Drive Reservoirs. MS thesis, The University of Oklahoma, Norman, Oklahoma.

Baruzzi, J.O.A, and Alhanati, F.J.S. 1995. Optimum Plunger Lift Operation. Paper SPE 29455 presented at the SPE Production Operations Symposium, Oklahoma City, Oklahoma, 2-4 April.

Chava, G., Falcone, G., and Teodoriu, C. 2008. Development of a New Plunger-Lift Model Using Smart Plunger (*) Data. Paper SPE 115934 presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, 24-26 September.

Foss, D. L., and Gaul, R.B. 1965. Plunger-Lift Performance Criteria with Operating Experience – Ventura Avenue Field. *Drill. & Prod. Prac.*, API, **124-130**.

Gasbarri, S. and Wiggins, M.L. A Dynamic Plunger Lift for Gas Wells. 1997. Paper SPE 37422 presented at the SPE Production Operations Symposium, Oklahoma City, Oklahoma, 9-11 March.

Guo, B., and Ghalambor, A. 2005. Properties of Natural Gas. In *Natural Gas Engineering Handbook.* ed. B. Guo and A. Ghalambor, Chap. 2, 2-26. Houston, Texas: Gulf Publishing Co.

Hacksma, J.D. 1972. Users Guide to Predict Plunger Lift Performance. *Proc.*, 19th Southwest Petroleum Short Course, Lubbock, Texas.

Lea, J.F. 1982. Dynamic Analysis of Plunger Lift Operations. *JPT* **32** (11): 2617-2629. SPE-10253-PA.

Lee, J. and Wattenbarger, R.A. 1996. Gas Reservoir Engineering. Richardson, Texas: Society of Petroleum Engineers.

Maggard, J.B.: 2000. Modeling and Analysis of Plunger Lift for Water Removal from Tight Gas Wells. PhD dissertation, Texas A&M University, College Station.

Marcano, L and Chacin, J. 1994. Mechanistic Design of Conventional Plunger-Lift Installation. *SPE Advanced Technology Series* **2** (1): 15-24.

Mower, L.N., Lea, J.F., Beauregard, E., and Ferguson, B.L. 1985. Defining the Characteristics and Performance of Gas-Lift Plungers. Paper SPE 14344 presented at the SPE Annual Technical Conference and Exhibition, Las Vegas, NV, 22-25 September.

Production Control Services. 2005. *Sales Service Satisfaction*, brochure, Production Control Services Inc., Lupton, Colorado.

Rawlins, E.L. and Schellhardt, M.A. 1936. *Back-Pressure Data on Natural-Gas Wells and Their Application to Production Practices. Monograph Series* **7**, U.S. Bureau of Mines, Oklahoma.

Rosina, L.: 1983. A Study of Plunger Lift Dynamics. MS thesis, The University of Tulsa, Tulsa, Oklahoma.

Tang, Y.L. and Schmidt, Z. 1997. A New Method of Dynamic Analysis and Optimal Design for Plunger Lift Dewatering. Paper SPE 38131 presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 5-8 October.

Supplemental Sources Consulted

Beauregard, E. and Ferguson, B.L. 1981. Introduction to Plunger Lift: Applications, Advantages and Limitations. *Proc.,* 28th Southwestern Petroleum Short Course, Lubbock, Texas.

Economides, M.J., Hill, A.D., and Economides, C.E. 1993. *Petroleum Production Systems,* first edition, Englewood Cliffs, NJ, PTR Prentice Hall.

Ferguson, B.L., and Beauregard, E. 1983. Will Plunger Lift Work in My Well. *Proc.,* 30th Southwestern Petroleum Short Course, Lubbock, Texas.

Lea, J.F, Nickens, H., and Wells, M. 2003. *Gas Well Deliquification,* first edition, St. Louis, Missouri, Gulf Professional Publishing Co.

Turner, R.G., Hubbard, M.G., and Dukler, A.E. 1969. Analysis and Prediction of Minimum Flow Rate for Continuous Removal of Liquids from Gas Wells. *JPT* **19** (11): 1475; *Trans.,* AIME, **246.**

APPENDIX A

The data provided from the field measurements is interpolated to obtain a final dataset with a data frequency of 10 seconds. The final dataset used as input for implementing the model is provided in **Table A-1.**

Table A-1 – Final Dataset for Implementation of Model

t	p_1	T_1	p_{wf}	T_{wf}	p_{wh}	p_c	q_{wh}
(s)	(psig)	(deg F)	(psig)	(deg F)	(psig)	(psig)	(Mcf/D)
0	502.53	265.84	497.72	265.85	291.07	400.91	0.00
10	502.76	265.85	497.93	265.87	282.56	401.04	135.56
20	502.94	265.85	498.07	265.86	274.05	401.16	271.12
30	502.99	265.85	498.10	265.86	265.54	401.29	406.68
40	502.82	265.84	497.98	265.86	257.03	401.42	542.24
50	502.43	265.85	497.40	265.85	248.53	401.55	677.80
60	501.89	265.85	496.43	265.84	240.02	401.67	813.36
70	501.05	265.85	495.25	265.82	231.51	401.80	948.92
80	499.61	265.85	494.28	265.80	223.00	401.93	1084.48
90	498.26	265.85	493.36	265.75	214.49	402.05	1220.04
100	496.65	265.85	492.35	265.71	205.98	402.18	1355.60
110	494.94	265.85	491.37	265.66	197.47	402.31	1491.16
120	493.19	265.85	490.61	265.62	188.97	402.44	1626.72
130	491.12	264.16	489.80	265.89	177.99	401.91	1534.01
140	489.09	263.84	488.83	265.92	168.36	401.39	1448.54
150	487.07	263.51	488.03	265.94	159.55	400.88	1369.86

Table A -1 Continued

t	p_1	T_1	p_{wf}	T_{wf}	p_{wh}	p_c	q_{wh}
(s)	(psig)	(deg F)	(psig)	(deg F)	(psig)	(psig)	(Mcf/D)
160	485.05	263.16	487.09	265.96	151.51	400.38	1297.55
170	483.01	262.80	486.24	265.96	144.18	399.89	1231.19
180	480.94	262.41	485.32	265.95	137.52	399.39	1170.39
190	478.83	262.00	484.47	265.94	131.47	398.89	1114.76
200	476.67	261.57	483.66	265.92	125.99	398.39	1063.92
210	474.44	261.09	482.63	265.90	121.04	397.89	1017.51
220	472.13	260.58	481.85	265.87	116.58	397.38	975.19
230	469.74	260.03	481.05	265.83	112.56	396.87	936.61
240	467.25	259.43	480.31	265.80	108.94	396.34	901.47
250	464.66	258.79	479.35	265.76	105.69	395.81	869.44
260	461.97	258.09	478.56	265.72	102.77	395.26	840.25
270	459.17	257.34	477.72	265.67	100.15	394.71	813.60
280	456.25	256.53	477.01	265.63	97.79	394.14	789.22
290	453.21	255.66	476.32	265.59	95.67	393.56	766.87
300	450.06	254.73	475.33	265.55	93.75	392.98	746.30
310	446.79	253.74	474.45	265.50	92.01	392.38	727.29
320	443.40	252.67	473.53	265.46	90.42	391.76	709.61
330	439.89	251.54	472.42	265.42	88.95	391.14	693.07
340	436.27	250.34	471.45	265.38	87.60	390.51	677.47
350	432.54	249.06	470.58	265.35	86.33	389.87	662.65
360	428.07	247.70	469.58	265.31	85.13	389.23	648.44

Table A -1 Continued

t	p_1	T_1	p_{wf}	T_{wf}	p_{wh}	p_c	q_{wh}
(s)	(psig)	(deg F)	(psig)	(deg F)	(psig)	(psig)	(Mcf/D)
370	424.77	246.28	468.67	265.28	83.97	388.58	634.68
380	420.74	244.77	467.81	265.25	82.86	387.92	621.26
390	416.63	243.18	467.05	265.22	81.76	387.26	608.04
400	412.44	241.52	465.08	265.19	80.67	386.60	594.91
410	408.19	239.77	460.17	265.17	79.58	385.94	581.78
420	403.89	237.94	459.47	265.15	78.48	385.29	568.56
430	399.55	236.03	458.89	265.13	77.37	384.64	555.19
440	395.18	234.04	458.86	265.11	76.23	384.01	541.62
450	390.79	231.96	459.52	265.09	75.08	383.38	527.79
460	386.42	229.80	459.28	265.08	73.89	382.77	513.67
470	382.06	227.56	459.52	265.06	72.68	382.18	499.26
480	377.73	225.23	459.54	265.05	71.45	381.61	484.55
490	373.47	222.82	458.99	265.04	70.19	381.07	469.54
500	369.28	220.33	458.91	265.02	68.92	380.55	454.27
510	365.19	217.76	458.83	265.01	67.64	380.07	438.77
520	361.21	215.11	458.87	264.99	66.36	379.63	423.08
530	357.38	212.38	458.43	264.98	65.10	379.23	407.27
540	353.72	209.57	458.35	264.96	63.85	378.88	391.43
550	350.25	206.69	458.40	264.93	62.64	378.58	375.63
560	347.00	203.73	457.99	264.91	61.49	378.34	359.98
570	343.99	200.69	457.25	264.88	60.40	378.16	344.59

Table A -1 Continued

t	p_1	T_1	p_{wf}	T_{wf}	p_{wh}	p_c	q_{wh}
(s)	(psig)	(deg F)	(psig)	(deg F)	(psig)	(psig)	(Mcf/D)
580	341.25	197.59	457.24	264.84	59.41	378.05	329.60
590	338.82	194.41	457.26	264.80	58.52	378.02	315.15
600	336.73	191.17	456.91	264.75	57.76	378.06	301.39
610	328.73	187.04	455.94	264.69	72.06	377.91	358.73
620	322.37	183.17	455.71	264.63	81.90	377.74	396.43
630	317.47	179.54	455.62	264.57	87.87	377.54	417.17
640	313.84	176.13	455.81	264.53	90.54	377.31	423.45
650	311.29	172.90	455.70	264.48	90.43	377.06	417.63
660	309.66	169.83	455.26	264.44	88.05	376.80	401.96
670	308.77	166.91	455.21	264.41	83.87	376.51	378.56
680	308.48	164.10	454.88	264.38	78.32	376.22	349.40
690	308.64	161.40	454.95	264.36	71.81	375.92	316.34
700	309.11	158.77	454.60	264.34	64.73	375.61	281.11
710	309.76	156.20	454.59	264.32	57.43	375.30	245.31
720	310.49	153.67	454.14	264.30	50.22	375.00	210.39
730	311.17	151.18	454.01	264.29	43.41	374.69	177.70
740	311.71	148.71	452.77	264.28	37.25	374.39	148.44
750	312.02	146.25	452.61	264.27	31.99	374.10	123.69
760	312.02	143.79	452.54	264.26	27.82	373.81	104.41
770	311.63	141.31	452.18	264.26	24.92	373.53	91.41
780	310.79	138.83	452.66	264.25	23.43	373.27	85.38

Apart from the field measurements above which vary during plunger upstroke, there are parameters used in the model that have constant values during the cycles. These parameters and values used for them are presented in **Table A-2.**

Table A-2 – Constant Parameters Used in the Model

Parameter	**Value**
Length of tubing, L (m)	3200.4
Density of Water, ρ_w (kg/m^3)	1000
Yield from reservoir, x	0.7
Area of tubing, A_{tub} (m^2)	0.00286
Area of annulus, A_a (m^2)	0.01247
Plunger height, h_p (m)	0.451
Plunger weight, W_p (lb$_f$)	5

APPENDIX B

The density of gas is dependent on the conditions of pressure and temperature. During the implementation of model, these gas densities are calculated for different pressure and temperature conditions by assuming a value of gas specific gravity. The following natural gas property correlations presented in Guo and Ghalambor (2005) are used for calculation of pressure and temperature dependent gas density.

The pseudo critical pressure and temperature of the gas are calculated using the assumed value of gas specific gravity using **Eq.B-1** and **Eq.B-1**

$$p_{pc} = 709.604 - 58.718\gamma_g \tag{B-1}$$

$$T_{pc} = 170.491 + 307.344\gamma_g \tag{B-2}$$

The pseudo reduced pressure and temperatures required for calculating z – factor are obtained from above pseudo critical properties for given conditions of pressure and temperature using **Eq.B-3** and **Eq.B-4.**

$$p_{pr} = \frac{p}{p_{pc}} \tag{B-3}$$

$$T_{pr} = \frac{T}{T_{pc}} \tag{B-4}$$

The pseudo reduced pressure and temperatures calculated above are used to calculate z-factor using **Eq.B-5** through **Eq.B-11.**

$$A = 1.39\left(T_{pr} - 0.92\right)^{0.5} - 0.36T_{pr} - 0.10 \tag{B-5}$$

$$B = \left(0.62 - 0.23T_{pr}\right)p_{pr} + \left(\frac{0.066}{T_{pr} - 0.86} - 0.37\right)p_{pr}{}^{2} + \frac{0.32\,p_{pr}{}^{6}}{10^{E}} \tag{B-6}$$

$$C = 0.132 - 0.32\log\left(T_{pr}\right) \tag{B-7}$$

$$D = 10^F \tag{B-8}$$

$$E = 9\left(T_{pr} - 1\right) \tag{B-9}$$

$$F = 0.3106 - 0.49T_{pr} + 0.1824T_{pr}^{\ 2} \tag{B-10}$$

$$z = A + \frac{1 - A}{e^B} + Cp_{pr}^{\ D} \tag{B-11}$$

Finally, the gas density for given conditions of pressure and temperature is calculated using the z-factor from **Eq.B-11** substituted into **Eq.B-12** along with the pressure and temperature values at given conditions.

$$\rho_g = \frac{2.7\gamma_g p}{zT} \tag{B-12}$$

Above correlations to calculate the gas density are used in the implementation of model for different conditions of pressure and temperature that prevail in the flow regions during plunger upstroke.

VITA

Name:	Gopi Krishna Chava
Permanent Address:	3116 TAMU, Richardson Building
	Texas A&M University, College Station, Texas, 77843
Education:	B.E. (Hons.). Chemical Engineering
	Birla Institute of Technology & Science – Pilani 2006
	M.S. Petroleum Engineering
	Texas A&M University, College station 2008
Member:	Society of Petroleum Engineers
Email Address:	gopikrishna.chava@gmail.com