UNIVERSIDADE ESTADUAL DE CAMPINAS
FACULDADE DE ENGENHARIA MECÂNICA
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NASSER ALAHMED

Experimental Study of the Dynamics and Stability of Intermittent Gas-Lift in a Laboratory Scale Model

Estudo Experimental da Dinâmica e Estabilidade do Gas-Lift Intermitente em Modelo de Escala de Laboratório

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Dissertation presented to the Mechanical Engineering Faculty and Geosciences Institute of the University of Campinas in partial fulfillment of the requirements for the degree of Master in Petroleum Sciences and Engineering in the area of Exploitation.

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Orientador: Prof. Dr. Sérgio Nascimento Bordalo

Este exemplar corresponde à versão final da Dissertação defendida pelo aluno **Nasser Alahmed**, e orientada pelo Prof. Dr. **Sérgio Nascimento Bordalo**.

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A Ata da defesa com as respectivas assinaturas dos membros encontra-se no processo de vida acadêmica do aluno.

Campinas, 17 de fevereiro de 2017

Dedication

This dissertation is dedicated with all my heart to My Parents

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Abstract

Conventional intermittent gas-lift systems (CIGL) are usually employed for petroleum wells in mature fields when the reservoir pressure becomes so low that continuous gas lift is no longer efficient. The purpose of this experimental study is to investigate the dynamics and stability of the cycles for conventional intermittent gas-lift systems (CIGL) for petroleum wells. Presently, this kind of experimental data is rare in the literature, following the advances achieved so far by Carvalho (2004) and Lara (2013) on this subject, further development of a laboratory scale physical simulator was carried out for a CIGL, and a selected set of experiments was conducted. The laboratory apparatus for the CIGL is composed of three operational sets, representing, respectively, the oil reservoir, the well production section and the injection gas system. However, water and air are used, instead of oil and natural gas, as the produced fluid and the lifting gas, respectively. A microcontroller board is used for data acquisition of key pressure nodes and also for the actuation system of a gas-lift valve proxy in addition to a variable flow valve provides a range of productivity index for the mock up reservoir and three vertical pipes of different diameters as production tubings are used. A series of experiments were done to analyze the influence of main parameters on the productivity of the CIGL system and to identify the stability conditions for the CIGL cycles. For this reason, the fallback for various operational parameters and concurrent stages was determined, the repeatability of the cycles was verified. The results from this study will help to develop a mathematical simulator for the CIGL. Such simulator may be extended for mature oilfield wells and be applied to design the CIGL cycles and the injection gas volume per cycle to achieve optimum production rates.

Key words: Petroleum wells, Petroleum mature fields, Intermittent gas-lift,
Experimental methods

Resumo

Os sistemas convencionais de *gas-lift* intermitente (GLIC) são normalmente empregados para poços de petróleo em campos maduros quando a pressão do reservatório fica tão baixa que o *gas-lift* contínuo não é mais eficiente. O objetivo deste estudo experimental é investigar a dinâmica e a estabilidade dos ciclos para sistemas convencionais de *gas-lift* intermitente (GLIC) usados em poços de petróleo. Atualmente, este tipo de dados experimentais ainda está faltando na literatura. Seguindo os avanços alcançados até agora por Carvalho (2004) e Lara (2013) sobre o assunto, um simulador físico em escala de laboratório para um GLIC foi aprimorado e um conjunto selecionado de experimentos foi conduzido. O aparato de laboratório do GLIC é composto por três conjuntos operacionais, representando, respectivamente, o reservatório de óleo, o poço produtor e seus controles e o sistema de injeção de gás. No entanto, água e ar são usados, ao invés de óleo e gás natural, como o fluido produzido e o gás de elevação, respectivamente. Uma placa de microcontrolador é usada para aquisição de dados de pontos chaves de pressão e também para o sistema de atuação de uma válvula *proxy* de *gas-lift*. Além disso, uma válvula de fluxo de entrada variável fornece uma gama de índices de produtividade para o reservatório modelo. Três tubos verticais de diâmetros diferentes são usados como colunas de produção. Uma série de experimentos foi realizados para analisar a influência dos principais parâmetros na produtividade do sistema de GLIC e para identificar as condições de estabilidade dos ciclos do GLIC. Para esse fim, o *fallback* foi determinado para várias condições dos parâmetros operacionais e a repetibilidade dos ciclos foi verificada. Os resultados deste estudo ajudarão no desenvolvimento de um simulador matemático para o GLIC. Tal simulador pode ser estendido para poços de campos petrolíferos maduros e ser aplicado no projeto de ciclos de GLIC para atingir vazões de produção otimizadas.

Palavras Chave: Poços de petróleo, Campos maduros de petróleo, lift intermitente, Métodos experimentais.

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NOMENCLATURE

Symbols

Δt	Time variation
ΔP	Pressure drawdown,

a	Empirical factors that vary with the slant angle
Ab	total effective bellows area
Af	Area of the flowline
Ap	valve port area (ball/seat line contact area for sharp-edged seat)
Dt	Tubing inner diameter
fb	Friction factor
Fc	Forces to Close the opearting valve
Fl	Friction factor for the liquid in the tubing
Fo	Forces to open the opearting valve
g	Gravity acceleration
Hb	Bubble length.
Hov	Depth of the operating gas-lift valve
Hsl	Slug length
$Htsl$	Depth of the top of liquid slug.
m	Mass flow rate into the annulus
M	Molecular weight
Pc	Casing Pressure
Pcc	Upstream (Casing) pressure at the moment operating valve closes
Pco	Upstream (Casing) pressure at the moment operating valve opens
Pd	Nitrogen-charged dome pressure
Pwf	Bottom-pipe pressure
Pwh	Pipe-head pressure
$Psbh$	Bottom-pipe static pressure of the well
Pt	Tubing Pressure
Pto	Downstream (Tubing) pressure at the moment operating valve opens
$Ptsl$	Pressure on top of the liquid slug
$Qmax$	Maximum production when bottom-pipe pressure zero
R	Universal gas constant
R	Ratio of the port area to the total effective bellows area of a gas lift valve
$S(t)$	Surface control
T	Absolute temperature
$V(t)$	Control volume

Va	Tubing-casing annulus space volume
Vb	Volume of the gas bubble
Vc	Volumetric capacity of the production conduit
Vf	Velocity of the liquid in the flowline
vpl	Velocity of the liquid slug
vsl	Liquid slug velocity
Z	Compressibility factor
ρa	Gas density in the tubing-casing annulus space
ρb	Average gas density inside the gas bubble
ρbov	Gas density inside the gas bubble and at operating gas-lift valve depth.
ρbsl	Density of the gas inside the bubble just underneath the liquid slug
ρl	Liquid density
$(\bar{Z}\ \bar{T})\mathrm{a}$	The average compressibility factor and temperature of the gas in the tubing- casing annulus space.
$(\bar{Z}\ \bar{T})t$	Average compressibility factor and temperature of the gas in tubing string above the liquid slug;

Subscript

a	Annulus
C	Casing
c	Closing
b	Bubble
b	Bottom
b	Bellow
bsl	Bottom liquid slug
ov	Operating valve
t	Tubing
o	Open
s	Surface
d	Dome
sbh	Static bottom hole.
wf	Well flowing
f	Fallback

Acronyms

CSG	Casing
IPR	Inflow Performance Relationship
MV	Motor valve
OV	Operating Valve
S.V.	Solenoid Valve
TBG	Tubing

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CHAPTER 1

INTRODUCTION

1.1 Overview

Intermittent gas lift is a cyclic production technique to produce the maximum amount of liquids with the minimum injection of gas, where gas is injected into the tubing-casing annulus; the cycle frequency is normally controlled by either an electronic or clock-driven time-cycle controller, or an adjustable or fixed choke at surface allowing for a slug of liquid to build up periodically in the tubing string. When the slug reaches a given length through a predetermined time interval; high-pressure gas loaded in the annulus is injected at a single point under the slug through an injection pressure-operated gas lift valve located as deep as possible in the well. The liquid slug is propelled upwards by the energy of the sudden released, expanding and pushing gas beneath it.

In order to conserve the injection gas, the gas-lift valve is so designed that it closes as soon as the liquid slug is displaced. Due to the pressure in the surface-gathering facilities and the difference in the density of the liquid and gas phases, the faster-moving gas constantly tends to penetrate or overrun the bottom of the liquid slug; deforming the gas-liquid interference surface, resulting in a continuously decreasing slug length. This process leaves an annular film of liquid on the tubing wall called 'fallback'. Such as condition prevails in intermittent gas-lift after the liquid slug has surfaced, the suspended liquid “afterflow” will fall back as unrecovered liquid as soon as gas flow has ceased and join the next liquid reservoir-feeding, into an almost empty tubing string, at the beginning of the second formation production period, the only back pressure to be overcome by the reservoir pressure, that is the rest of the preceding liquid column below the injection valve; resulting in new accumulation until the pressure-operated valve opens again to start a new cycle.

The total back pressure increases during the feeding period, as the length of the liquid slug in the tubing increases. For this reason all restrictions in and near the wellhead should be eliminated to reduce the losses and the number of gas-injection cycles should be adjusted to maximize the amount of liquids produced with the minimum injection gas to liquid ratio (GLR).

Too few cycles per day lead to a low, daily production rate because of the long periods during which the formation is producing against a high liquid head. Too many cycles per day lead to a low production rate because the formation is almost or completely shut in during the gas-injection stages. It is usually of importance, then, to operate at or close to the optimum cycle frequency, which results in the maximum rate of production.

Intermittent gas-lift is typically applicable to mature fields where the reservoir pressure and well productivity declines, causing discontinuous flow, less energy available from the well as low-productivity or low and high-productivity with low reservoir pressure, so more energy in the form of injected gas must be used. However, the injection GLR is lower if the well produces on intermittent-flow gas-lift rather than on continuous-flow gas-lift. For this reason to save on compression requirements is recommended to shift from CGL to IGL.

Types of intermittent-flow gas-lift installations

There are a number of alternate designs of intermittent-flow gas-lift installations. The most common types of these installations:

- Conventional intermittent-flow gas lift designs are the most common type of as they generally include less downhole equipment.

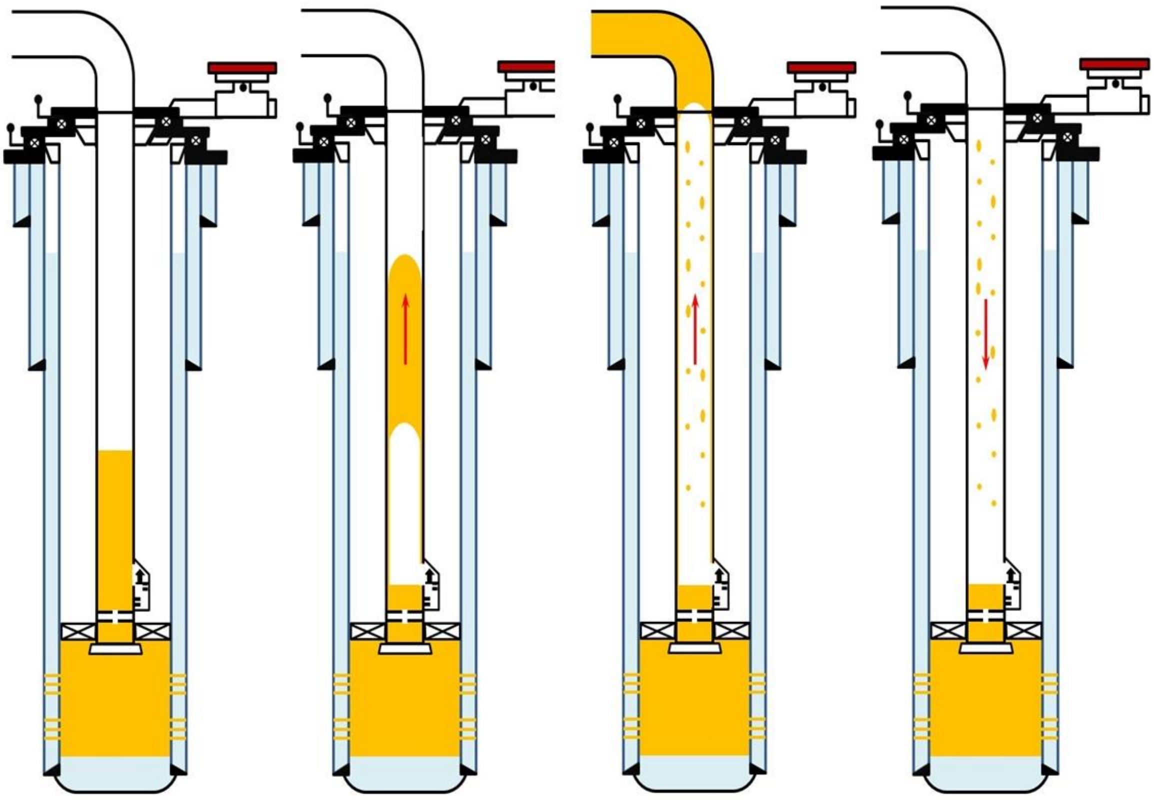
- Intermittent-flow Chamber design may be beneficial for wells with low-flowing-bottom hole-pressure, particularly those wells with a high productivity index. The downhole accumulation chamber provides greater capacity than the nominal tubing string.

- Intermittent-flow gas lift plunger design, the plunger provides a solid interface between the starting liquid slug and the displacing injection gas. The plunger practically eliminates liquid fallback as a result of gas penetrating the liquid slug.

- Intermittent-flow gas lift Accumulator design, Accumulator section provides greater capacity for liquid accumulation and remains it as a simple completion design.

- Intermittent-flow gas lift Dual completion design, utilized for production from a single well with multiple formations having independent operating tubing strings.

However, the subject of this study is the conventional intermittent gas-lift system and in order to study the dynamics and stability of the cycles for this system, the cyclic process divided into four distinct consecutive stages. Loading, Elevation, Production and Decompression, Figure 1. 1 shows a scheme illustrated the sequence of intermittent-gas-lift stages in one cycle.



Loading Elevation Production Decompression

Figure 1.1 - Sequence of conventional intermittent-gas-lift stages in one cycle

Conventional Intermittent Gas-Lift Cycle Stages.

The conventional intermittent gas lift cycle can be divided in four distinct stages:

Loading (Pressure build-up): this stage starts once the pressure-operated gas-lift valve closes, fallback losses from the previous cycle and new reservoir feeding begin to form liquid slug above the gas-lift valve. Gas injection into the casing-tubing annulus continues, this stage ends when the annulus pressure and the pressure inside the tubing are sufficiently high enough to open the pressure-operated gas-lift valve.

Elevation: this stage starts when the pressure-operated gas-lift valve opens allowing gas from the annulus to enter the production tubing and lifting the liquid slug upwards.

Production: after the liquid slug is lifted to the top of the tubing, this stage begins as soon as the tip of the slug reaches the surface and ends when the entire liquid slug has been produced to the flowline.

Decompression: this stage begins when the entire liquid slug has produced into the surface flowline and ends when all the liquid has reached the separator or when the liquid velocity becomes negligible.

If such a condition prevails in intermittent gas lift after the liquid slug and (afterflow) have surfaced, the suspended liquid will fall back as unrecovered liquid after gas flow has ceased.

Here should be note a special case when gas is venting to surface, and this case takes place if the pressure-operated gas-lift valve is still open when the entire liquid slug has completely surfaced. At this moment, gas is being injected from the gas supply line to the casing-tubing annulus and then into the tubing. This status will end as soon as the pressure-operated gas-lift valve closes.

1.2 Objectives

The general objective of this study is to examine a physical IGL-well model in laboratory scale; gathering and analyzing experimental data, in order to investigate and obtain a better understanding of the dynamics and stability of gas-injection cycles when gas lifting liquid-slug in real conventional intermittent gas-lift (CIGL) system for oil wells, since this kind of experimental data is rare in the literature, this study specifically aimed to fulfill the following three objectives:

1. To analyze the main variables that influence the CIGL production system.

2. To conduct experimental investigations on how cycle frequency affects on model behavior and therefore on daily production optimization.

3. To identify the appropriate stability conditions for the CIGL cycles.

To fulfill these objectives, three research phases were undertaken.

Phase I: This phase was intended to:

1. Design and build a laboratory scale model (carried out by Lara) where a set of laboratory apparatus suitable for this study, assembled based on past researches (conducted by Carvalho).

2. According to the old design, former results were subject of analyzing and some parts of the apparatus were tested and proposed to be replaced.

3. Further development and modifications on the design of laboratory scale model were carried out.

Phase II was intended to apply different experimental design methods to test CIGL model.

The phase II goals were:

1. To observe the model performance according to varied operational parameters by means of increasing or decreasing the reservoir pressure through changing the tank elevation, reservoir productivity index using a variable flow valve provides a range of productivity index for the mock up reservoir, different tubing diameters and injection operating-valve's closing and opening pressures, under special conditions with neglecting the temperature effect.

2. To monitor the stability conditions for the CIGL cycles through verifying cycle's frequency and injection time intervals for the intermitter.

In Phase III of this research, analysis the obtained experimental results to suggest further improvement on the model to gain data may be extended to develop a mathematical model to be used at field for a real intermittent gas-lift system. This phase involved 2 steps:

1. The fallback for various operational parameters and concurrent stages was determined, the repeatability of the cycles was verified and the operating conditions for stable CIGL cycles were identified.

2. Propose and recommend further developments on the laboratory-scale model.

3. Evaluate the results from this study in order to develop a mathematical simulator for the CIGL in the future. Such simulator may be extended for mature oilfield wells and be applied to design the CIGL cycles and the injection gas volume per cycle to achieve optimum production rates.

1.3 Experimental Methods Used in This Study

In this research, the experimental methods for dynamics and stability studies of injection-gas cycles for intermittent gas-lift system in laboratory scale model are classified into three categories: preliminary tests, one-shot tests and cycle's stability tests. These three methods were applied to examine the influence of the operational parameters on the performance of the CIGL system. The preliminary tests were conducted on the model in order to prepare the system and calibrate the key parts of the apparatus for the next stage of tests, while in the one-shot experiments, there are several controlled parameters that correspond different aspects of the model should be tested separately. For instance, the measurement of fallback can be used to provide a general description of gas penetration tendency over low injection pressures or short period of injection time. In comparison, the third one is cycle's stability measurements which provide a full time record during the process under specific operational conditions in order to analyze the cycle's stability, repeatability and daily production optimization. However, fallback for various operational parameters and concurrent stages was determined; the repeatability of the cycles was verified. The results from this study will help to develop a mathematical simulator for the CIGL. Such simulator may be extended for mature oilfield wells and be applied to design the CIGL cycles and the injection gas volume per cycle to achieve optimum production rates.

1.4 Thesis Outline

This thesis is arranged into five chapters. Following this introductory chapter, a literature review is presented in Chapter 2. The review is divided into two basic compartments: the previous studies and the main principles in the intermittent gas-lift system, while the experimental techniques conducted in this research and the results are covered in Chapters 3 and 4, respectively. Finally, Chapter 5 contains the conclusions from this research and some recommendations for future studies in this area. However, additional detailed information of chapters 4 and 5 is presented in appendices as follows:

Appendix A: (Equipment) some of the equipment used in this study are not included in chapter 3 will be presented in this section

Appendix B: (Plotted results) Some results and levels are not included in chapter 4 will be provided in this section, because they do not show any changes outside of those induced through the variation in test conditions

Appendix C: (Log data) some log data examples will be provided in this section.

CHAPTER 2

LITERATURE REVIEW AND BASIC CONCEPTS

2.1 Overview

Intermittent-flow gas-lift has been used for artificial lift in oil wells for decades, considering the economic optimization as the main motivation; especially when the gas from a nearby plant is being used and the additional use of gas is a critical as it could be for IGL systems. Accordingly, a cost estimate shows the financial losses due to the usage of excess gas. Despite of the advances achieved so far, by the studies had already published in this field, presently, this kind of experimental data is rare in the literature which covers some of the IGL design methods and system behavior predictions. However, most of the existing studies are experimental; the few predictive models are system dependent and are not valid to be applied in general. Furthermore, none of the studied models that developed using experimental data are incorporate all of the system components.

2.2 Previous Studies

There have been several attempts to remedy the situation stated chronologically as follows:

In 1962. Brown and Jessen, did extensive field experiments to develop an experimental foundation for intermittent-flow gas-lift systems. By conducting experiments on (244 m) experimental well equipped with 2``. tubing. They attempted, but no analytical solution. A method of calculating the average bottom-hole flowing pressure and pressure stabilization time for a lift cycle in a 2-in. tubing was presented to aid design considerations. On the other hand, they studied the injection-pressure-operated gas lift valve as one of the main factors that have most strongly influenced the IGL production system; testing the effect of valve-port size on the IGL process, and coming to the following conclusions:

- Using larger port size increases the efficiency and decreases the injection-gas liquid ratio (IGLR); lower the load restoration period thanks to lower pressure exerted on the reservoir; and increased pressure beneath the slug and thus higher speed of slug;

- A larger gate size will result in higher recovery ratio. However, when an excess of gas is used, the size of the door loses influence on the percent recovery;

- The column pressure at the depth of the valve operator seems to decrease while the area of the door increases. Brown and Jensen accepted the importance of economic analysis in the energy balance of the IGL method; Brown described the advantages of IGL with chamber for reservoirs with low static head and low productivity index, and provided a simplified procedure to estimate the average flow pressure at the bottom of the well.

In 1963, White *et al.* developed the first form of mathematical relationships for the conventional intermittent-flow gas lift and did experiments on laboratory apparatus, with vertical pipes of 28 m, used dimensional analysis and dynamic similarity to model IGL. The mathematical simulation was simplified by assuming that the liquid slug velocity rapidly reached a constant value and that the velocity of gas bubble penetration into the liquid slug was a constant. Experimental results confirmed the conceptual model with considered the gas expansion energy is sufficient to produce liquid volume equals to the starting slug length that lifted to the surface. The model was subsequently applied to a real well with 823 m depth.

In 1967, Brill *et a1.* conducted a wide-ranging of intermittent flow gas-lift experiments on an 457.2 m experimental well. Based on the results, agreed on there is a noteworthy acceleration of the liquid slug at the moment the injection-gas valve opens and along the tubing to the surface. And rising slug velocity drops rapidly after the pressure-operated valve closes, stated that there are several factors that tend to promote the penetration of gas in the liquid, resulting in the net production loss. The authors stated that, due to density difference between the gas and liquid there is an upward buoyancy force that causes the gas ascends at a velocity greater than the slug forming a transition zone between the liquid slug and the gas, assuming that the existence of the gas-liquid interface below the liquid slug represents an ideal situation. However, a high velocity slug leads to a very low gas penetration. Finally, an empirical fallback correlation was developed in conjunction with a conceptual model that combined basic fluid-flow equations with the empirical liquid fallback correlation. The results compared favorably with the rest data and verified the model.

In 1972, Doerr, conducted an experimental study with 0.95``. tubing. Testing Fallback in an intermittent-flow gas-lift system and developed a theoretical approach for liquid loss. The results showed considerable discrepancy with the liquid fallback data of Brill.

In 1973, Neely *et a1.* conducted a field experiments on a monitored well 1482 m intermittent-flow gas lift system and obtained different results to White (1963) and similar to Brown and Jessen (1962), in terms of liquid recovery, while White did not consider the amount liquid produced after the slug surfaces in form of mist with the gas which called (afterflow).However, it represents the justification of the difference in recovery efficiency results compared between Brown *et al* and While *et al*.

While Nelly et al. agreed with the premise of White (1963) for the slug velocity, stating that, after an initial acceleration, the slug velocity remains reasonably constant along the tubing to the surface. In addition, they correlated the average gas velocity below the liquid slug with liquid holdup compared with continuous-flow correlations. A different view of the fallback was given, which defined the fallback as a function of gas velocity, and stating that some liquid droplets remains suspended in the gas in form of mist which settle down after slug surfaced causing recovery increase .

Finally, an analytical method for calculating intermittent-flow gas-lift behavior was developed that assumed a constant liquid velocity. Results showed good agreement with test data and confirmed the suggested liquid fallback correlation.

In 1984, Schmidt *et al*. presented a dynamic model for the conventional intermittent-flow gas-lift cycle, based on the conservation equations of mechanics. Comparisons between numerical calculations and measurements in an experimental test facility supported the validity of the model. Moreover, they agreed with Nelly *et al*. (1973) giving attention to the importance of afterflow.

In 1995 Liao *et al*. produced a mechanistic model for the conventional intermittent-flow gas-lift cycle, obtained good agreement results with the previous experimental studies. In order to simulate the conventional IGL cycle, the cycle was divided into 4 stages, each one with its own complete set of ordinary differential equations. Then the sequential stages were simulated in a standalone fashion, through an iterative numerical procedure

In 1997, Santos conducted a fallback study for several cycles, results showed that the impact of fallback may not be as adverse as proclaimed in previous studies, where the fallback was estimated only for one cycle, and concluded that larger initial slug length results in lower fallback per cycle. However, the daily recovery will be smaller.

In 2001, Santos *et al.* improved Liao's modeling approach, and extended it to other variants of the intermittent-flow gas-lift methods: the IGL with chamber, the IGL with plunger (ideal case) and the IGL with pig (pig-lift); including the gas injection stage on the simulation.

In 2003, Carvalho and Bordalo produced a new approach of modeling the IGL. They postulated the occurrence possibility of overlapping of the stages in the IGL cycle according to the system dynamics. However, Carvalho (2004) stated that in certain conditions the stages of injection and feeding can be simultaneously rather than sequentially as was assumed in the previous studies. Also conducted an analysis on the cycle’s stability which identified to be strongly related to the intermitter timing (motor valve) and the calibration of the pressure-operated gas-injection valve.

In 2013, Lara and Bordalo, developed a physical simulator with three vertical pipes of 15 meters and diameter ranging from 1 to 2 inches, for the conventional intermittent-flow gas-lift (IGL) and the Zadson pneumatic pump (ZPP), to validate numerical simulators proposed by previous studies, few and limited experiments have been carried out.

Due to the few experimental tests, the construction of the laboratory-scale model requires further experimental studies. However, is intended to encourage further experiments and to investigate aspects related to the theoretical models.

This work suggests some topics to be studied as factors affecting intermittent gas-lift including altering both of the reservoir pressure and formation productivity, fallback, operating gas injection valve performance and slug length. In addition to identifying the stability conditions for the production cycles.

For this reason, further development have been applied on the above-mentioned laboratory scale model including partially changes on the design to improve the model performance.

2.3 Inflow Performance Relationship

The Inflow Performance Relationship (IPR) for a well is the relationship between the flow rate of the well Q_f and the pressure drawdown ΔP, which is the difference between bottom-hole static pressure P_{sbh}, and the bottom-hole flowing pressure of the well P_{wf}. However, IPR equations, such as Vogel or Fetkovich, can be used to get an approximation of the production potential, but are not quite correct to apply these equations for wells on intermittent gas-lift while they were developed for wells producing at a constant flowing bottom-hole pressure. Equation (2.1) in single phase flow this is a straight line under-saturation conditions, but under unsaturated conditions, at a pressure below the bubble point, this is not a linear relationship. Therefore, the factors influencing the shape of the IPR are the pressure drop and the relative permeability k across the reservoir.

$$Q_f = PI\ (P_{sbh} - P_{wf}) \tag{2.1}$$

Where (PI) *is* the productivity index taken in average for intermittent gas-lift operations, when usually the bottom hole pressures less than 40 % of the bottom hole static pressure. In this case, defining the productivity index is constant will be valid. Figure 2.1. illustrates a comparison between “average” PI and “true” PI, where “true” PI is the slope of the IPR curve at some specific flowing bottom-hole pressures P_{wf} and flow rates Q_f. The daily production rate can be expressed as:

$$Q_f = Vc\ (dh/dt) \tag{2.2}$$

Where

Vc; is the volumetric capacity; m^3/m, of the production conduit; h is the liquid slug length in the production conduit above the point of gas injection, m.

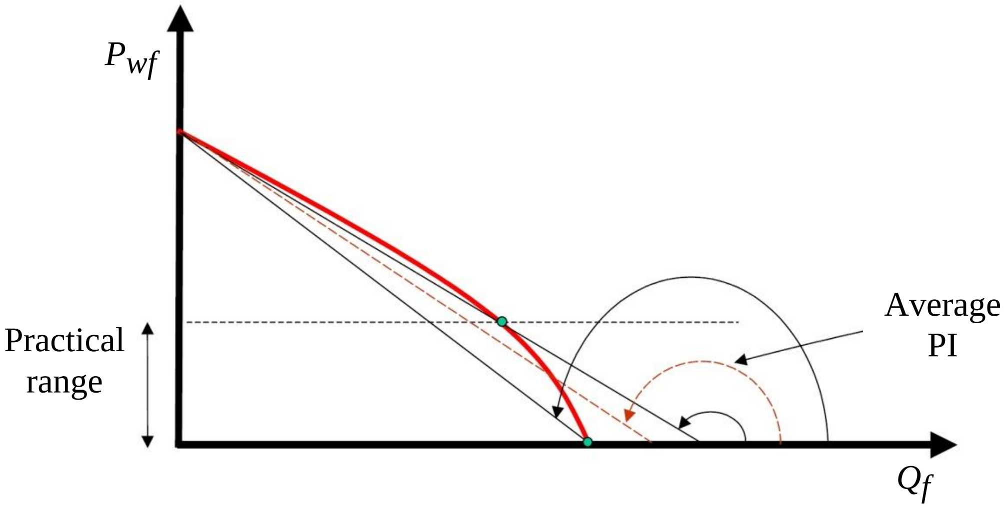


Figure 2. 1- Practical range for intermittent lift operation

On the other hand, the pressure along the production formation in the conventional intermittent gas-lift system as it the case study, dropped down permitting the necessary drawdown while the gas is constantly being vented to the tubing and transmitted directly to the wellhead which is preventing gas accumulation along the production interval. Thereby no blocking liquid inflow from the reservoir resulting in the pressure in the upper part of the perforations is low and high toward the bottom-hole, what matches the hypotheses in this laboratory experimental study where no gas associated with the reservoir fluids.

2.4 Cycle Optimization

After an installation is unloaded, the time cycle controller should be adjusted for a given cycle time, which should maximize the daily liquid production and minimize the gas injection GLR. A practical way of finding the required volume of gas per cycle should be applied at field. Obviously, the primary purpose of applying intermittent gas-lift system is to optimize the oil production, which means to produce optimum amount at an acceptable cost in terms of excess gas usage. This comparing with the term of maximizes oil production which means produce more oil but at an unacceptable cost. Therefore, the optimum oil production does occur when the profitability of the intermittent gas-lift system is maximized. For this reason, the time cycle controller at surface should be adjusted for an optimum cycle time as well as ensures minimum injection GLR. Figure 2.2 shows how the intermitter function affects the cycle dynamics and therefore the volume of the injection gas per cycle and as a result the profitability while taking in consideration the oil production.

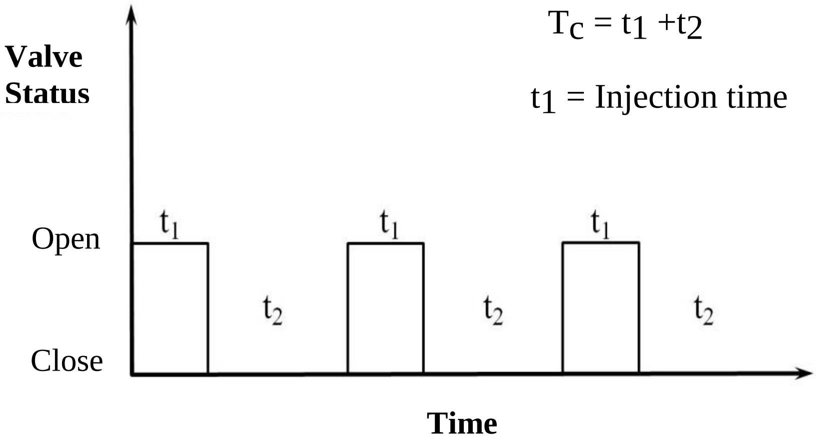


Figure 2. 2- Function of the intermitter valve

On the other hand, since the cycle time should takes in consideration the productivity index, therefore the maximum drawdown at the production interval determines the range of the cycle time. For this reason, an experimental approach to determine the optimum cycle time is to test the system for different cycle frequencies and examine its stability at the same time. However, the optimum cycle time defined as the cycle time for which the profitable daily fluid production is maximized. In light of this, to avoid producing liquid below the potential of the well, there is a tradeoff between liquid slug load and accumulation time and this relation should be defined. The bigger the liquid slug the longer the accumulation time the lower the number of cycles per day. For this reason, the optimum cycle time depends on the well productivity index (PI) at maximum drawdown, and not on the static bottom-hole pressure. Therefore, an experimental way to determine the optimum cycle time is to test the apparatus several times for different liquid slug loads and reservoir productivity index. As shown in Figure 2.3 wells have the same reservoir pressure with different productivity indexes, where well-1 has the greatest productivity index with the lowest accumulation time to get maximum slug load in comparison with wells with the same reservoir pressure but different productivity indexes.

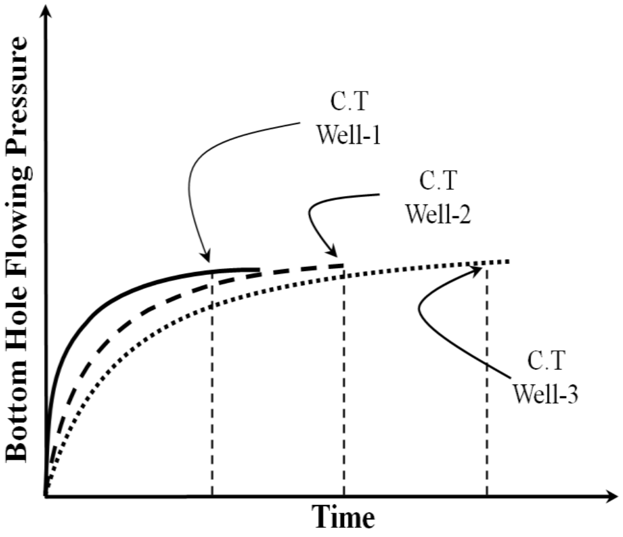


Figure 2. 3- Same reservoir pressure vs. different productivity indexes

In the previous example, well-1 has the greatest productivity index what matches the lowest accumulation time for maximum slug load, in comparison with the same reservoir pressure and different productivity indexes.

2.5 Gas-lift Valve.

One of the most important factors that affects on the intermittent liquid-slug lifting system is the operating gas lift valve performance. For this reason, It should be taken into consideration the gas lift valve specifications, for instance, its mechanism supposes to not open slowly and providing a small gas injection rate into the tubing to avoid aerate the liquid slug and lead to an ineffective slug displacement, in comparison with a large port of the operating valve which opens rapidly to provide a plentiful injection-gas volume to ensure maximum liquid slug displacement efficiently. However, the difference between valve opening and closing pressures should be relatively acceptable to avoid any extra gas usage in some cases which associated with large casing space volume comparing with small tubing space volume. However, in the course of improvement of gas lift system several types of gas lift valves were developed, a simple valve representation shown in Figure 2.4 the function of this model of gas-injection valve depends on the combination between the casing pressure, the pressure inside the production string and the dome pressure.

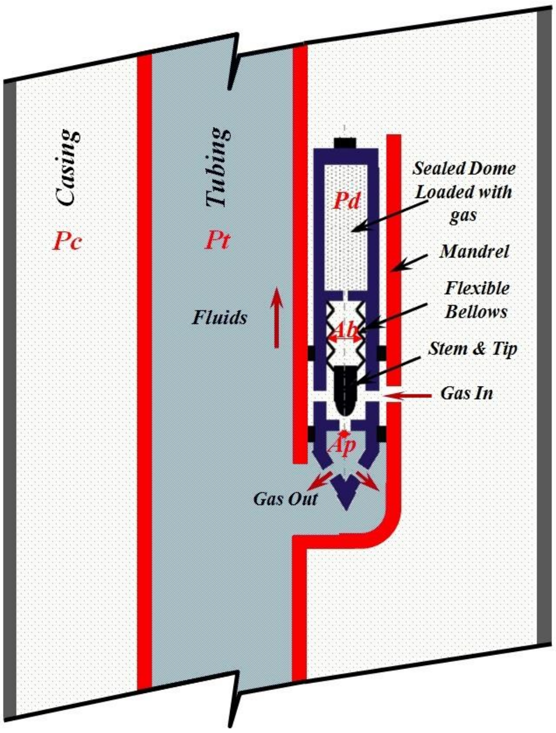


Figure 2. 4- Scheme of Gas-lift valve

Hence, analyzing the gas injection valve mechanism and studying the forces take place in the above-mentioned model, presented in the equations (2.3) and (2.4), where the upstream pressure should be increased to be over the threshold of the valve initial opening pressure in order to permit gas injection into the tubing string.

$$F_O = \quad P_C \times (A_b \; - \; A_p) + P_t \times \; A_p \tag{2.3}$$

$$F_C = P_d \; \times A_b \tag{2.4}$$

Where,

Ab, is the effective Area of the bellows; Ap, is the area of the valve seat; P_d, is the valve operator dome loading pressure; P_C, is the valve upstream pressure; P_t, is the valve downstream pressure.

Valve's Opening Pressure

The required condition that leads to the valve opens depends on balance between forces *Fo e Fc* states:

$$P_d \times A_b = \quad P_c \times (A_b \; - \; A_p) + P_t \times \; A_p \tag{2.5}$$

Thus, to determine the threshold upstream pressure that opens the valve:

$$P_{co} = \quad \frac{P_d - (P_{to} \; \times \; R)}{1 - R} \tag{2.6}$$

However, the flow condition is $P_C \geq P_t$, *Where:*

Pco, is the upstream pressure at the moment of the valve opens; *R*, is the Ratio of the valve areas bellows versus seat's area. $(R = A_p/A_b)$

Valve's Closing Pressure

In the open position, assumed that the pressure acting on the shutter of stem is match the casing pressure and therefore the force which tends to keep the valve open is given by:

$$F_O = \; P_C \times (A_b \; - \; A_p) + \; P_C \times A_p \tag{2.7}$$

At valve closing position, the balance of the forces on the valve stem can be written as follows:

$$P_d \times A_b = \; P_{cc} \times (A_b \; - \; A_p) + P_{cc} \times \; A_p \tag{2.8}$$

Valve closing condition occurs when the upstream drops down to match the valve dome loading pressure; *Pcc is* the upstream pressure at the moment of the valve is closing. Thus, we can write:

$$P_{cc} = P_d \tag{2.9}$$

However, the valve closing condition is obtained when the casing pressure decreases to match the dome loading pressure. Figure 2.5 shows the dynamic of one cycle and defines the valve spread as the difference between the moment when the operating valve opens and closes.

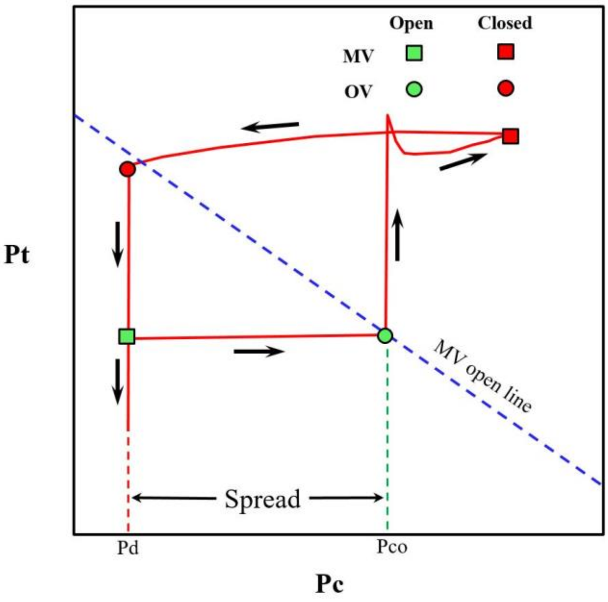


Figure 2. 5- Cycle dynamics (Carvalho, 2004)

When the cycle starting with reservoir feeding at the lowest bottom hole pressure, Pt increases during the liquid accumulation above the operating valve, until the casing pressure Pc reaches the operating valve opening point, as defined by the equation of the gas-lift valve, then the valve opens and the gas flow into the tubing causes an increase of the pressure Pt. By ending the injection time the motor valve closes and pressure decreases inside the casing due to the emptying of the casing through the gas-lift valve, consequently, Pt decreases until the operating valve closes at lowest casing pressure which matches the valve’s dome loading pressure, then (Depressurization stage) Pt decreases until the subsequent cycle begins.

2.6 Fallback.

It has defined that the fallback in vertical pipe is the difference between the initial -liquid-slug volume and the final surface produced slug volume. However, there are other two ways to define the fallback according to Santos (1997):

- Fallback is the ratio between the mass of liquid film on the pipe wall after the liquid slug surfaced, and mass of the initial accumulated liquid slug inside the production conduit, in this case the fallback increases with the number of cycles, indicating that the film thickness on the pipe wall increases with each cycle until getting stabilized.

$$\text{Fallback} = \frac{\boldsymbol{m}_{film}}{\boldsymbol{m}_{initial}}$$

- Or the fallback can be calculated as the difference between mass of the initial liquid slug and mass of the surface produced liquid divided by mass of the initial liquid slug.

$$\text{Fallback} = \frac{\boldsymbol{m}_{initial} - \boldsymbol{m}_{produced}}{\boldsymbol{m}_{initial}}$$

It occurs due to the injection-gas penetration or gas slippage and results in a decrease of the liquid recovery per cycle. *Brill*, stated that, due to density difference between the gas and liquid there is an upward buoyancy force that causes the gas ascends at a velocity greater than the slug forming a transition zone between the liquid slug and the gas, assuming that the existence of the gas-liquid interface below the liquid slug represents an ideal situation.

White, studied the interface surface between the gas and the liquid as in an ideal case. As shown in Figure 2.6, observed during their experiments.

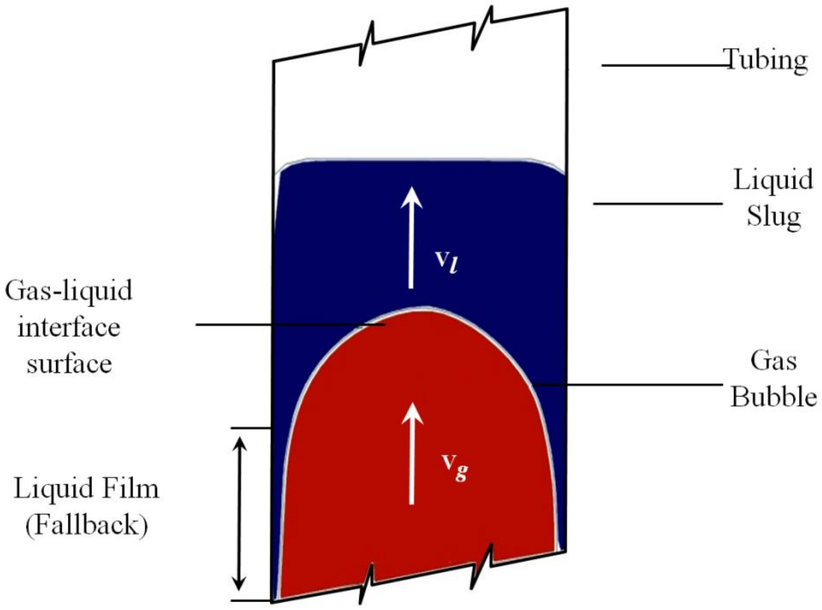


Figure 2. 6- Gas-liquid interface below the liquid slug

However, a high velocity slug leads to a very low gas penetration (*Brill*). Therefore, it is vitally important to minimize the fallback effect or to increase the recovered portion of the initial liquid-slug length which determines the success of the intermittent gas-lift installation design.

Nelly defines the fallback as a function of gas velocity, thus, the upward liquid-slug velocity must be maintained above a certain value and avoid the velocity being reduced before the entire liquid slug length surfaced and trapped into the flowline. On the other hand, the liquid level inside the production string instantly after the operating gas-injection valve opens, is not at the same depth of the valve due to the accumulation of liquid fallback during the displacement process. Consequently, results in, the minimum bottom-hole flowing-production pressure between injection-gas cycles will be greater.

Finally, as the knowledge about this phenomenon still not complete and the inability to predict the fallback factor, is a big motivation to test the laboratory scale model in order to figure out the main indications that could solve CIGL design problems in many installations.

CHAPTER 3

EXPERIMENTAL TECHNIQUES

3.1 Overview

This chapter provides a detailed description of the experimental apparatus which was designed and constructed to test the performance of a CIGL laboratory-scale model. However, the dimensional analysis and design intended to scale this apparatus has been explained in depth elsewhere (Sobolewski 2008, Lara 2013), and therefore this chapter begins with an overall description and schematic of the experimental set-up, followed by a detailed description of each of the main components installed. Last, a description of the data acquisition system and all of the instrumentation installed within the system. The experimental apparatus was constructed in the Petroleum Experimental.

Laboratory (Lab Petro) at University of Campinas. The detail design, drawings, certification and construction of the laboratory loops were completed by a consulting engineer and certified contractor as per Campinas University's regulations. This includes the gas compressor installation and all connections to the system (height-controlled skid-mounted tank). Once complete, the compressed air and water supply lines were connected to the experimental apparatus. However, after a brief review of these details, it will be focused on the apparatus modification, experimental diagnostics and techniques crucial to the topic of this dissertation. These topics include providing the apparatus with new technique to alter some operational parameters, such as reservoir pressure and productivity index.

3.2 Experimental Apparatus

The experimental apparatus was designed to model the performance of an CIGL as an oil well production system in a laboratory-scale. The experimental CIGL set-up is consists of three main loops Figure 3.1 representing, the oil reservoir feeding system, the well production vertical section and the injection gas system.

These loops are equipped by data acquisition and control instrumentations which record the inlet and outlet gas injection pressure as well as the reservoir production rates in order to use the data collected for determining and controlling the apparatus performance and therefore surface production rates. In addition to the three primary loops, the experimental apparatus contains a secondary manual sub-system which provides vertical multi-position setting for the reservoir feeding system so as to provide various levels of the initial reservoir pressure.

This includes a hand-operated wire rope winch, secondary vertical multi-position skid-mounted mini-tank (open to the atmosphere), and laser distance meter.

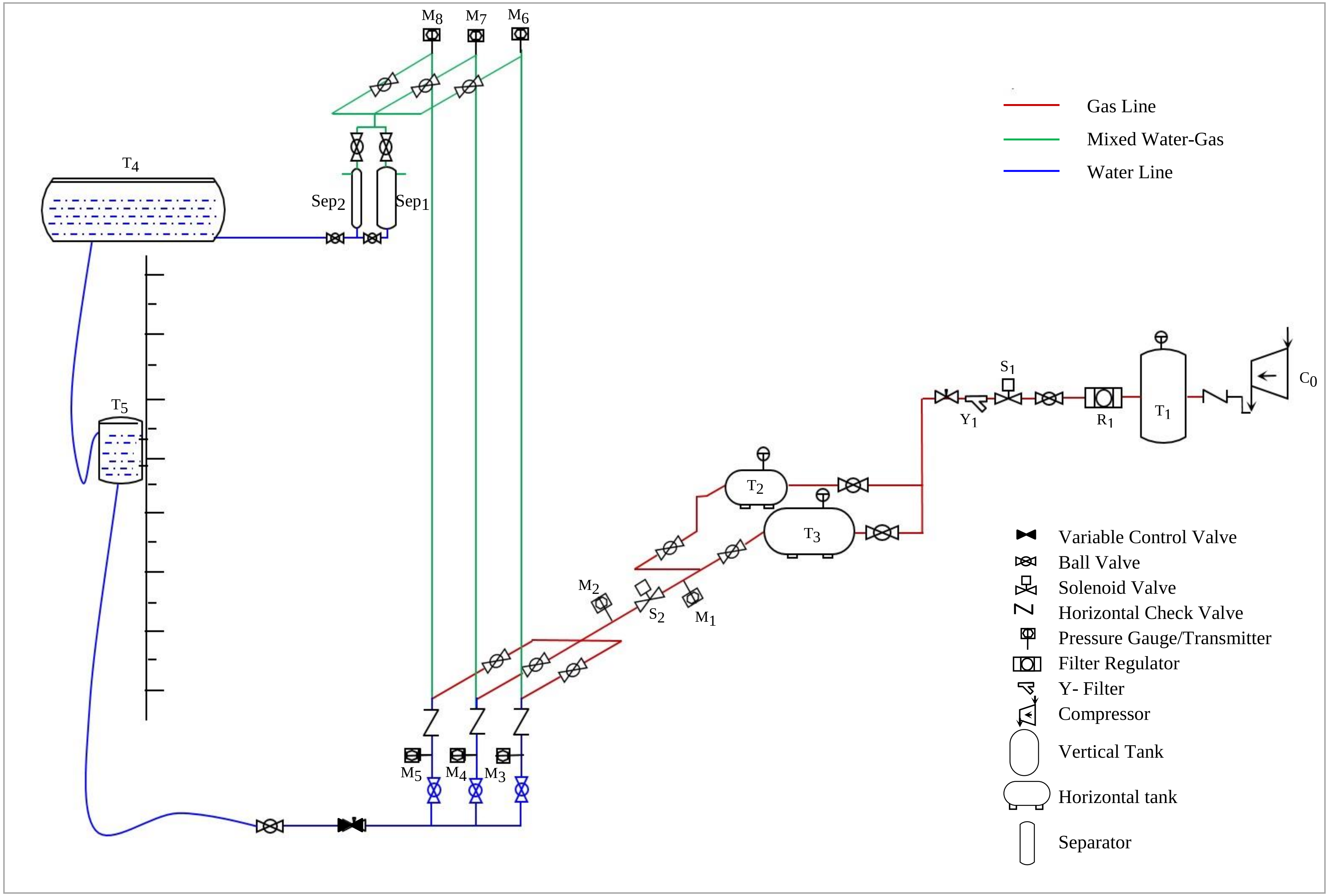


Figure 3. 1- Schematic of experimental test set-up for intermittent gas-lift

Before any design work could be conducted, a set of design parameters had to be determined. As the goal of this experimental apparatus is to test the CIGL system at various cycle frequencies, different productivity indexes (PI's) and gas injection pressure, therefore, the system has to be adaptable and be able to function over the entire range of test conditions. To start, the inlet and outlet conditions as well as the calibration for pressure transducer and control valves were determined depends on the specifications provided by the manufacturer of the unit. In addition to the design parameters, it was also important to ensure that all of the components of the system function are able to provide the desired pressure and flow rate ranges for each of the three gas and hydraulic loops.

3.2.1 Gas injection system

The gas injection loop has been designed to supply the experimental apparatus with the lifting energy that will be used to elevate the liquid slug to the surface. However, the air was used as an injection gas instead of the natural gas while it is a controllable, available and cheap source that as well as permits to be handled safely and without any environmental risks. Main Components of the gas injection loop was built out of a number of individual components piped together.

Compressor

The starting point of the loop is the compressor C_0, the gas input loop uses the compressor as the main gas source, where the compressor specifications of injection gas system are listed in Table 3.1 below.

Table 3. 1 - Compressor specifications of gas injection system

Compressor	CSI7.4/50
theoretical displacement	5.4 cu ft /min; 153 l/min
Opt. pressure	Min: 6.9 bar; Max: 9.7 bar
Air End	No. Stages: 1; No. piston: 1
RPM	2275

A photograph of the compressor and its place on the schematic of the experiment are shown in Figure 3.2 and Figure 3.1, respectively.

Figure 3. 2- Photograph of the compressor and air storage tank

Air storage tank

To prevent gas injection shortage, a Vertical cylindrical leg mounted gas tank T_1 Figure 3.2 was piped to the compressor, with maximum working pressure of 9.28 bar and volume capacity of (0.2 m^3), which is sufficient to provide the system by the required injection air volume for several sequential cycles. Once the pressurized air exits the air tank, it passes to pressure regulator valve with direct command, in order to avoid pressure fluctuation and maintain the pressure outlet at a given value with working pressure from (0-16 bar) and offers manometer to indicate the outlet pressure, which represents the gas supply line pressure on a real system. Figure 3.3 shows a photograph of the pressure regulator valve.

Figure 3. 3 - Photograph of the pressure regulator.

Since the pressurized air is available at a certain pressure, a solenoid valve (surface intermitter) installed on the gas line which was placed to control the gas injection cycle’s frequency between several predetermined time intervals and represents the surface intermitter valve on the gas supply line. It should be noted that all gas lines being used in the gas loop system were 1.5" pipe diameter.

Figure 3. 4- Casing space tank.

In order to control the gas injection flow rate and to eliminate gas humidity, a configuration of the Y-strainer Y_0, followed by a needle valve V_1 was installed. Then the compressed air enters optionally two casing-space air tanks T_2 or T_3 Figure 3.4 represent the tubing-casing annular space in this model. Optionally T_2 and T_3 connected to the system separately or together, whiles they provide a capacity of 0.03 m^3 and 0.09 m^3, respectively.

Then the compressed air reaches the end of the gas-line, which instrumented by a second solenoid valve S_2, represents the gas injection operating valve Figure 3.5 this valve responsible for injection of the gas into the production conduit to lift the liquid-slug that has already accumulated during the feeding time.

Moreover, the solenoid valve does not only control the injected gas through the tubing, it also should have a large port that opens quickly to ensure ample injection-gas volumetric throughput for efficiently displacing the liquid slug. This valve was supported by two pressure transmitters M1 and M2 to log the pressure upstream inside the casing-space tank (Pc) and downstream inside the tubing (Pt), respectively. At the moment the magnitude of a given pressure difference between M1 and M2 occurs, the valve opens and closes as a result of a programmed process used by the data acquisition system, which will be explained later.

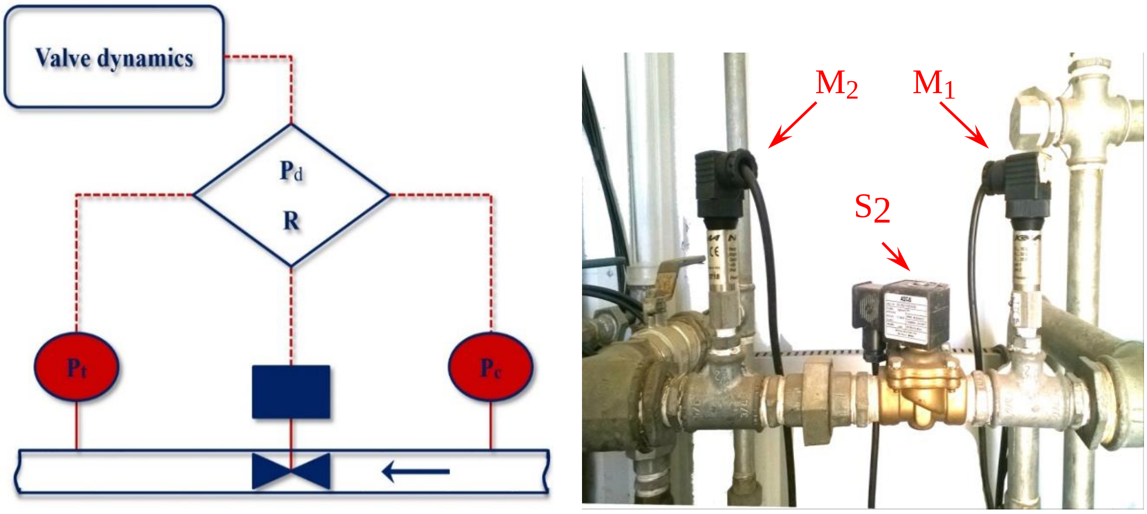
Valve port size

In this laboratory model, it was used one operating valve seat size Table 3.2 illustrates the solenoid valve specifications which was used in this study, in comparison with three options for the operating valve seat diameters (19/64", 13/32" and 1/2") were used in the work of White (1963) combined with a production conduit of 28 m in height, while it is only 15 m. in this laboratory-scale model,

Table 3. 2 - Solenoid valve specifications as an operating-valve

Connection NPT	Orifice (mm)	Pressure Diff. (Kgf / cm^2)	
		Min.	Max. (Air/Water)
¾"	19	0.34	9

However, the solenoid valve which installed on the gas line and used as an operating valve in this apparatus Figure 3.5-a shows the solenoid valve mechanism and its function in the experimental model. On the other hand, Figure 3.5-b below illustrates a photograph of the valve position in the system.



(a) (b)

Figure 3. 5- (a) Scheme of the operating valve mechanism (b) Solenoid valve with pressure transmitters M1 and M2

The control mechanism which depends on the measured pressure values, tubing pressure Pt and casing-space tank's pressure Pc to be used according to the opening and closing valve's equations (2.6) and (2.9) corresponding to the dynamics of a real operating gas-lift valve, in addition to the dome pressure Pd and R ratio of valve's areas which already set for the control system depends on the desired operational parameters. However, this mechanism facilitates the study by permitting varying the dome pressure and the areas ratio R. For the occurrence of gas injection from the casing-space tank into the tubing, the upstream injection pressure on the operating valve must be greater than the dome pressure.

This means:

$$\mathrm{Pinj} > \mathrm{Pco} \tag{3.1}$$

Soon:

$$\mathrm{Pinj} = \mathrm{B} \times \mathrm{Pco} \quad ; \qquad \mathrm{B} > 1 \tag{3.2}$$

According to Carvalho (2004), an applicable value for the dimensionless factor B

It is: B = 1.054

3.2.2 Reservoir system

The main Component of the reservoir feeding loop is an open to atmosphere water tank T4, Figure 3.6 with capacity of 1 m^3, which is located at 13.5 m elevation. Once the liquid "water" leaves the tank, by the gravity, enters a flexible hose descended to a suspended height-controlled skid-mounted tank which also connected directly to another flexible hose downing to the ground at the end where located a variable flow valve provides a range of productivity index (PI) for the mock up reservoir as the function of the well PI through controlling the valve opening port, representing the formation-borehole flow resistance during the reservoir fluids being produced.

Figure 3. 6- Water main tank

Tank Volume

The volume of the liquid feeding reservoir is designed to withstand 30 cycles with the maximum liquid load taking into consideration maximum height of the vertical column 15 m completely filled with water. However, it was calculated depends on the volumetric capacity of each column. Table 3.3 shows the variety of conduit's volume according to the diameter.

$$V_R = n_c\, V_{max} \tag{3.3}$$

Where:

$h_{max} = 15\text{m}$

Table 3. 3 - Conduit volume capacity

Nominal Diameter (in.)	Inside Diameter (in.)	Volumetric Capacity (m^3/m)	Voulme required (m^3)
1	1.049	$5.6\ 10^{-4}$	0.25
1.5	1.61	$13.1\ 10^{-4}$	0.59
2	2.067	$21.6\ 10^{-4}$	0.98

In light of this, Table 3.3 the reservoir is designed to provide a volume of 1 m^3, which ensures sufficient reservoir supply of water for the CIGL cycles using any of the three production columns.

3.2.3 Vertical production system

This section was built out of three individual conduits, were selected in three different diameters 25.4 mm, 38.1 mm, 50.8 mm (1", 1.5" and 2") respectively, the three conduits were built to be standing vertically and laterally supported by the lab building wall, with a length of 14.66 m. In order to determine the bottom pipe flowing pressure (*Pwf*); the lower end of each of which, was instrumented by a pressure transmitter M3, M4, M5, respectively. Figure 3.7, as well as to determine the pipe-head pressure (*Pwh*); the head of each pipe, was instrumented by a pressure transmitter M6, M7, M8, respectively, Figure 3.8. Although, the three pipes made of galvanized steel, a visual observation is only available through the lower section of the 1.5" pipe since it was made of acrylic transparent material,

The purpose of transparent lower section of the 1.5" is to determine whether the liquid slug is being driven by gas expansion energy or the gas penetrates completely through the slug. Furthermore, once the slug is surfaced and the operating-valve closed, the fallback liquid or the slug portion that is not produced can be measured directly by the height in the transparent lower section of the production conduit.

Figure 3. 7- Pressure transmitters M3, M4, M5

Figure 3. 8- Vertical production section with pressure transmitters M6, M7, M8

Separator

As soon as the tip of the slug reaches the surface, the produced water will be accumulated in a separator opened to the atmosphere pressure and located at the same elevation of the water reservoir feeding tank, Figure 3.9. However, it consists of two cylinders with height of (2 m) and volume capacity in total (0.11 m^3), each of which is provided by a transparent graduated tube to measure the water height inside the separator, consequently, the water produced volume after each slug reaches the surface will be measured.

Figure 3. 9- Surface Separator

In order to measure the production rate of each run of the experiments, it was not practical to have a continuous liquid meter at the separator liquid outlet during testing the laboratory model. The liquid level in the separator has to be continuously monitored from which the average volume of liquid per cycle and as a result the daily production rate can be calculated. Figure 3.10 shows an expected behavior chart where the liquid level inside the separator as a function of time.

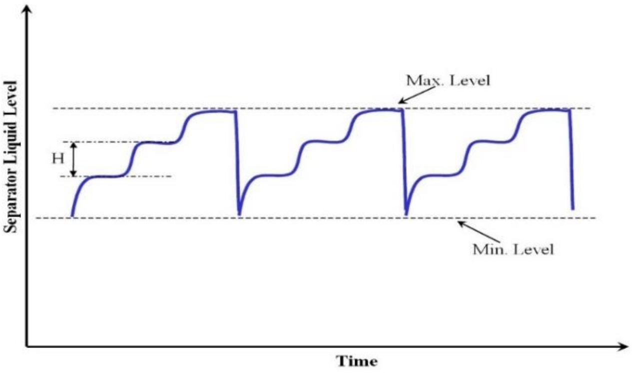


Figure 3. 10- Expected separator behavior - Liquid Level vs. Time

As it illustrated in the Figure 3.10, every time a liquid slug is surfaced, the liquid level inside the separator increases by a distance "*H*." which correspond the volume of liquid produced by single cycle. However, when the liquid level inside the separator reaches a maximum value, the manifold with two valves located at the inlet and outlet of the test separator opens and the liquid flow switched to the secondary separator by the time the main separator emptied of fluids to the main water reservoir until it matches the minimum liquid level. As the experiment proceeds, the level difference "*H*" and the time needed to fill the separator will reach constant values. However, for the first few slugs, the level difference "*H*" might be higher or lower than the final approaching until the system being stable. As soon as an average constant value of the level difference is reached, the average daily production can be calculated. However, it could be calculated while the total volume of the separator between its maximum and minimum level is known, associated with the measured time for the number of separator liquid discharges.

Vertical Rail

As a secondary manual sub-system, the purpose of the vertical slider rail is to provide multi-position setting for the height-controlled skid-mounted tank which feeds the system so as to provide various options of initial reservoir pressure less than the potential hydrostatic pressure which provided by the main water tank (13 m) elevation. However this manual sub-system includes a hand operated wire rope winch, secondary water mini-tank opened to the atmosphere T5 and laser distance meter. Figure 3.11 presents a scheme of all components of this sub-system.

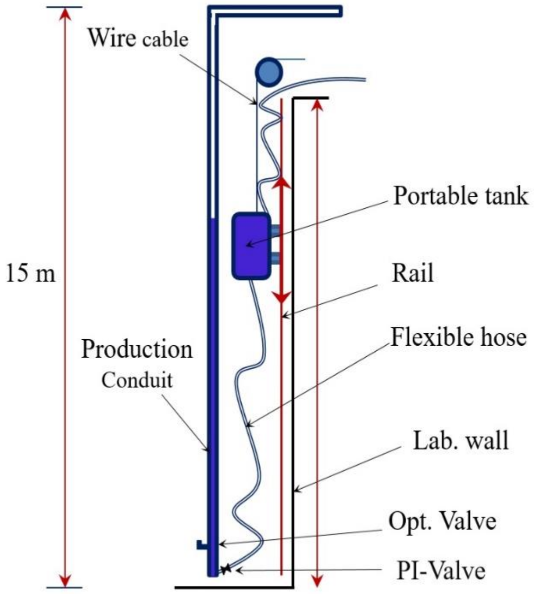


Figure 3. 11- Scheme of the vertical rail with movable tank

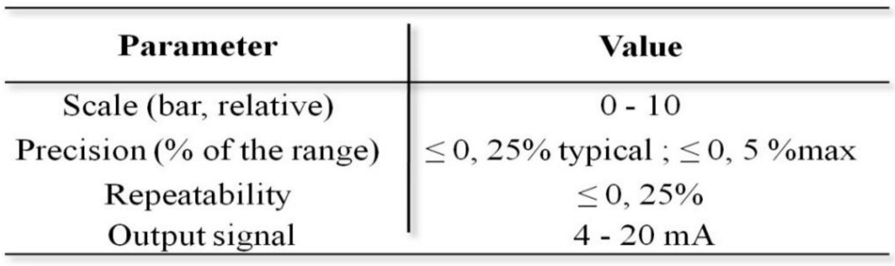
3.2.4 Data Acquisition System

To monitor all of the instrumentation installed within the two former gas and hydraulic loops, as well as to provide the control signals during experimental tests to the control solenoid valves, each loop is instrumented to determine the pressure variation performance through the components. In addition to determine the performance of the gas flow rates into and out of the gas casing-tank and the gas line, several pressure transmitters and solenoid valves were installed within the experimental set-up. This system uses the output signals from the pressure transmitters which placed at key pressure nodes of the inlet and outlet of the gas and hydraulic loops. The signals are converted to pressure values and recorded at set time interval (every 0.4 s) in a text file format (.txt file) which exported later to Microsoft Excel and converted to a Microsoft Excel® worksheet.

Pressure Transmitters

To achieve full function performance, each loop is instrumented by pressure transmitters to measure and log pressure magnitude through the set-up system. Table 3.4 shows the specifications of pressure transmitters were used in this study.

Table 3. 4 - Pressure transmitter specifications



Parameter	**Value**
Scale (bar, relative)	0 - 10
Precision (% of the range)	≤ 0, 25% typical ; ≤ 0, 5 %max
Repeatability	≤ 0, 25%
Output signal	4 - 20 mA

However, equation (3.4) explains the relation between the electrical signal of the transmitter and the measured pressure.

$$I(mA) = 1.6 \times P(bar) + 4 \qquad (3.4)$$

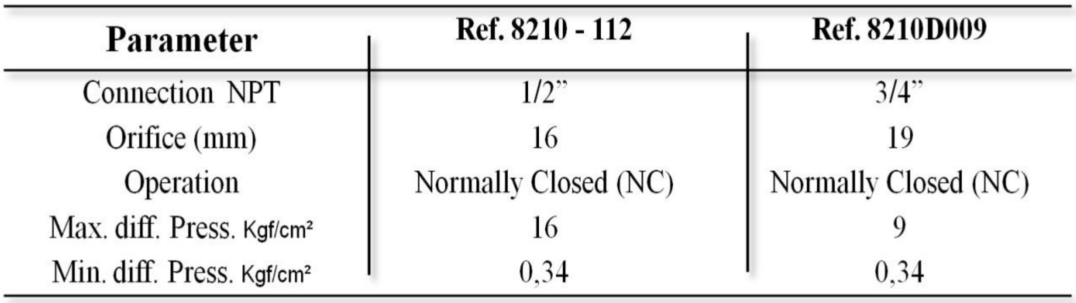
Where:

P (bar); is the manometric pressure.

Control valves

To control the flow within the experimental system, two automated control valves were installed within the system. S_1 and S_2 were installed within the gas loop. The function of the first solenoid valve which represents the intermitter is to inject the gas flow from air-storage supply tank to the gas line when it opens, while the second one represents a gas injection valve to pass the gas flow from the casing-space tank to the vertical production conduits. These control valves were used in the study are solenoid valves, brand ASCO with the specifications outlined in Table 3.5.

Table 3. 5 - Solenoid valves specifications



Parameter	Ref. 8210 - 112	Ref. 8210D009
Connection NPT	1/2”	3/4”
Orifice (mm)	16	19
Operation	Normally Closed (NC)	Normally Closed (NC)
Max. diff. Press. Kgf/cm^2	16	9
Min. diff. Press. Kgf/cm^2	0,34	0,34

The function of the solenoid valve which used as an operating gas injection valve presented in Figure 3.12 illustrates the valve diagram.

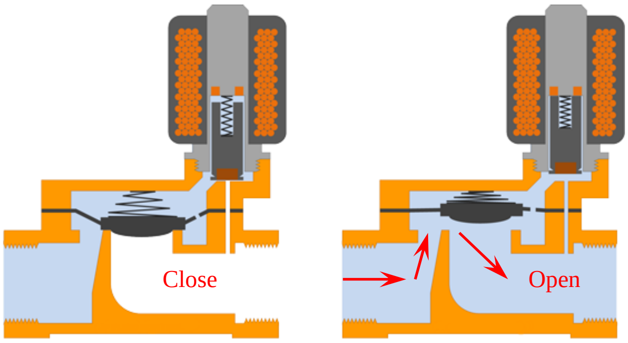


Figure 3. 12- Diagram of the solenoid valve function

Microcontroller board

A microcontroller board with specific processor was developed to control and operate the IGL system. The system function depends on receiving the inputs as electrical signals from pressure transducer located at the key points of the apparatus in order to record pressures signals and other apparatus variables, and sending outputs as electrical signals to control and activate the solenoid valves which open and close depends on the microcontroller outputs signals Figure 3.13 shows a photography of the microcontroller board.

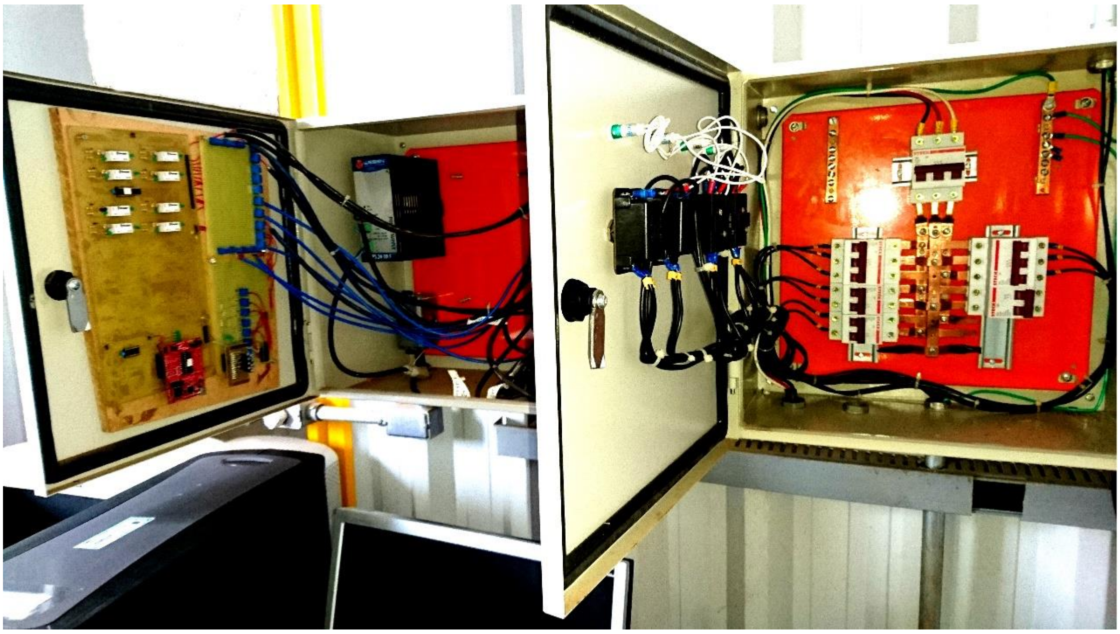


Figure 3. 13- Photography of the microcontroller board

For simplicity and compactness, this microcontroller board receives input signals were issued by the pressure transmitters as electric current (4 to 20 mA), then will be measured and sent to a PC unit, to be received as commands through a USB port. Therefore, the PC Software which was programed using C++ for Windows environment will convert these commands to be visible readings (0- 1023) (10 bits).

Depending on the acquired data, the program implements a logic process which is compatible with a given designed operational parameters conditions for the CIGL method.

Due to having pressure transmitters and solenoid valves in different parts of the experimental apparatus, it was expected to install the sensors at key pressure nodes of inlet and outlet at various level of the system so as to measure the pressure accurately.In light of this, it is possible to apply various operational parameters to conduct the tests using this experimental apparatus for multiple operating cycles and to facilitate analyzing other process variables such fallback time, liquid build up during reservoir feeding period and gas loading into casing-sapce tank.

In addition to setting a relation between number of gas injection cycles and the liquid feeding time to achieve production stability. As shown in Figure 3.14 a photo of the software interface environment, in which could set some input variables to run the system, having the option to collect data every (0.4) seconds to generate a file with (.txt) extension to analysis the test performance.

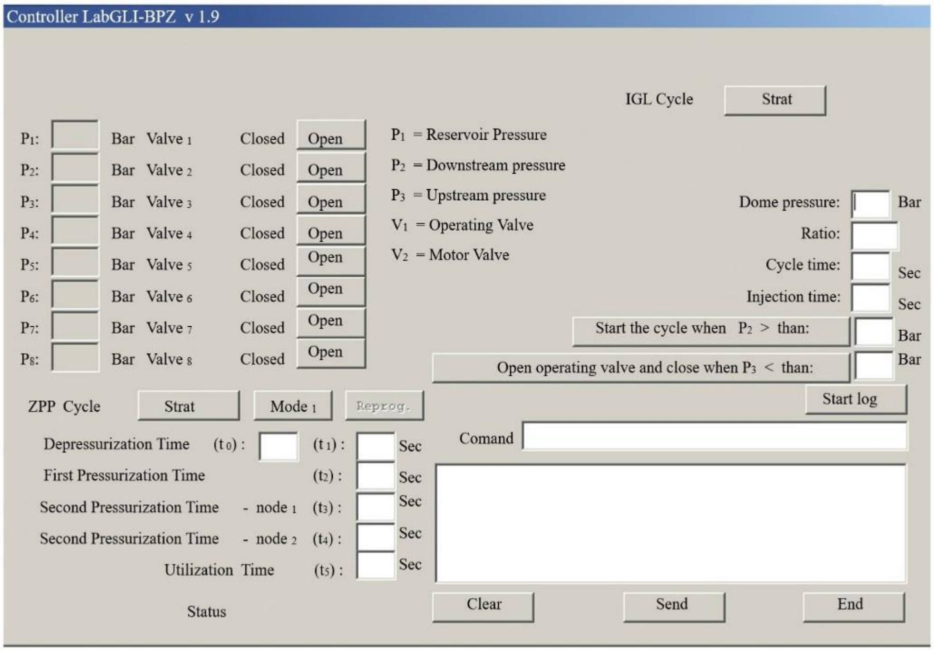


Figure 3. 14- Software interface – IGL system

Pressure transmitter adjustment.

The purpose of using transmitters is to be sensors that log the pressure magnitudes at key points of the system. However, the pressure transmitters were used in this study operate within range of (0 to 10 bar) and produce a power output of (4 to 20 mA), which will be converted later to signals from (0 to 1023) units. Based on that, the system will recognize the maximum pressure magnitude 10 bar pressure value recorded by the transmitter and emitted as a current of 20 mA then will be diverted to 1023 sign value.

The data acquisition system through the microcontroller board has an option to adjust the pressure operating range of the pressure transmitters. Since the circuit has the option to reduce the maximum current I_{max} depending on the maximum pressure as it recorded by the pressure transmitter. This way takes advantage of the full signal range 0 - 1023 for each transmitter.
Hence, before conducting any experiments, the pressure transmitter should be prepared, the preparation process procedures can be done as the following, Starting by:

- Applying the maximum predicted pressure value on the transmitter;
- Calculating the maximum current according to the transmitter equation :

$$I_{max} = 1.6 \times P_{max} + 4$$

- Adjusting the corresponding resistance meter in the microcontroller board until it matches the maximum current, in other word gets 1023 value;

- By using a multimeter, applying the minimum current and use the command <point_a # transmitter Current_value > to set the software that this is the point 'a' of the line that defines the relationship between reading and current;

- By using a multimeter, applying the maximum current and use the command <point_b # transmitter Current_value > to set the software that this is the point 'b' of the line that defines the relationship between reading and current

$$y = aI + b$$

To check if the adjustment already made in the pressure transmitters is valid, Type: “exhibit_constantes” which displays the values of the constants *a* and *b* and maximum current (*Imax*).

However, there are some other commands available in the software:

- To display the pressure values: Type “Exhibit_pressure”, then the software interference displays the value of the pressures for all the pressure transmitters.

Also to display the current values:

- Type “Exhibit_current”, then it displays the value of the measured currents in each pressure transmitter.

- Using the same manner, the reading values are displayed, by typing: “Exhibit_value”, which displays the value of the reading as units.

System Log Data

Log data set is a tool to monitor all of the instrumentation installed within the system, which present the pressure variation performance through several pressure transmitters and status of the solenoid valves installed within the experimental set-up. This system uses the output signals from the pressure transmitters placed at key pressure nodes of inlet and outlet of the gas and hydraulic loops. The signals are converted to pressure values and recorded at the set time interval (every 0.4 s) in a text file format (.txt file), Table C.1 and Table C.2 will be found in Appendix C, Show an example of the log data of bottom pipe flowing pressure and log data of full time cycle record, respectivily. However, the output file will be imported and converted later to a Microsoft Excel® worksheet.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

The bulk of this dissertation focused on measurements of many aspects of the CIGL regime, still not understood yet, since the operational parameters have been studied previously, the experiments reported here are the first to be done in conjunction with altering both of the formation productivity and reservoir pressure during the course of performing these experiments.

This chapter presents the main results and analysis of measurements made to improve the experimental results, it is a particular interest to investigate how various operational parameters affect the CIGL regime. However, the results are presented here in graph and table forms, while variables and responses displayed including the variables changes in the experimental process, their relationships, effects, and interactions, all they are measured, analyzed and mapped.

First, the experimental methods for dynamics and stability of gas -injection cycles for CIGL system in laboratory scale model are classified into three categories: preliminary tests, no time one-shot tests and cycle's stability tests. These three methods were applied to examine the influence of the operational parameters on the performance of the CIGL system. The preliminary tests were conducted on the model in order to prepare the system and calibrate the key parts of the apparatus for the next stage of tests; while in the second stage of one-shot measurements, there are several controlled parameters that represent different aspects of the model should be tested separately.

For instance, the measurement of fallback can be used to provide a general description of the gas penetration tendency over low injection pressures or short period of injection time. In comparison with the third stage of tests; cycle's stability measurements which provide a full time record during the process under predetermined operational conditions in order to analyze the cycle's stability, repeatability and daily production optimization. Therefore, fallback for various operational parameters and concurrent stages was determined and repeatability of cycles was verified.

However, measurements of various cycle frequencies were performed, with the following goals:

1. Identify any instabilities present in production cycles and determine their characteristics,

2. Determine the influence of these instabilities on the production process of CIGL system.

On the other hand, some results and levels were not included in this section and will be provided in the appendix, because they do not show any changes outside of those induced through the variation in test conditions.

4.2 Experimental Procedures

First, some experimental terms related to this study must be defined as it shown in the time log Figure 4.1:

Initial power level:

Since the production conduit started empty, the variable flow valve opens to feed the tubing by the liquid, hence while increasing the liquid level inside the conduit and then reaches a specified level; this level is called “Initial power level”, which in some cases will allow the injection valve opens giving start to the first cycle. On the other hand, it should be noted that while the pipe initially is empty, thus the time for reservoir feeding the first cycle is greater than the following cycles.

Injection time:

The time needed to pressurize the gas tank (annulus) until reaches a given magnitude that is sufficient to open the operating gas-lift valve, (*tinj*)

Cycle time:

It refers to the time interval between two sequential runs of the intermitter -surface controller- (*tc*).

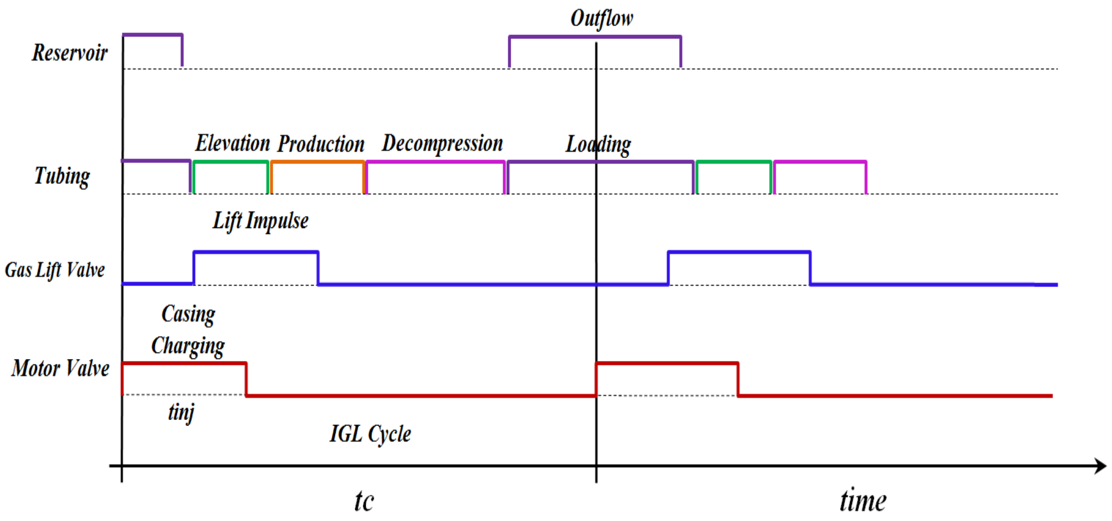


Figure 4. 1- Time log for IGL stages

Finally, during the application process, there was a need to follow the safety precautions for conducting the experiments which achieved by following the occupational health and safety rules. Therefore, in such workplaces, it must be mentioned that the working at heights regulations were adhered during preparing and conducting some experiments. As well as, in such laboratory environment where there was very little or nothing one can do to reduce compressor noise, the hearing protectors had to be used to reduce the amount of noise reaching the ears in addition to wearing proper personal protective equipment including goggles and gloves.

While, this chapter provides an opportunity to determine which operational parameters stand for an essential part of CIGL cycle stability and before investigating other properties of the CIGL regime, it was necessary to indicate that there were some parameters selected to be held during the course of this study with respect of their significant effect on the performance, but varying these parameters would be beyond the scope of this effort.

4.2.1 Parameters Held Constant

Varying large number of parameters was considered to be too inconsistent and difficult to work with the given goals and objectives of this dissertation. For this reason, Table 4.1 lists the parameters that were held constant during the study including operating gas-lift valve's port size, separator pressure, liquid density, gas density, feeding source air-water ratio, temperature and operating gas-lift valve depth which is represented here by the distance between the operating valve and the top-pipe at the laboratory surface. However, varying these parameters in addition to the parameters selected for varying in this test (discussed in next Section) would comprise a very large study and be beyond the scope of this effort. Hence, it is envisioned that these parameters could be investigated in future laboratory studies, especially the liquid density and operating valve's port size.

Table 4. 1- Parameters held constant

Parameter	Test level
GLV depth	13.5 m
GLV/ port size	19 mm
Seperater pressure	1 bar
Liquid density	997 kg/m^3
Gas density / @ 25 °C	1.1839 kg/m^3
Liquid viscosity / @ 25 °C	0.89 mpa.s
Gas-liquid ratio	0
Temperature	25 °C

4.2.2 Parameters Varied

To span the range of parameters that have most strongly influenced the CIGL production system, nine different operational parameters with various levels were chosen. Table 4.2 lists the parameters that were varied in this study; Reservoir pressure, formation productivity, slug length, tubing diameter, dome pressure, injection pressure-valve to open, injection time, cycle time and valve's area ratio. However, the levels were chosen for each Parameter in these tests are discussed in the following sections.

Table 4. 2 - Parameters Varied

Parameter	**Values**
Reservoir pressure	0.7-1.1 bar
Reservoir productivity index	4.5 – 37.6 m^3/d.bar
Slug load	0.2 - 0.7 bar
Tubing diameter	25.4, 38.1, 50.8 mm
Valve closing pressure	0.34 – 4.5 bar
Valve opening pressure	1 – 6 bar
Injection time	1 -10 s
Cycle time	10-200 s
Gas injection volume	0.03 – 0.12 m^3
Valve Area Ratio	0.025-0.255

4.3 Experimental Methods

It was planned to test several variables combinations organized in different sets of runs. Therefore, observations of variables effect on the response, as the variables are changed in the process, their relationships and interactions will be measured, in order to:

- Quantifying the uncertainty in test results for the previous studies.
- Increasing the accuracy and precision of results, and
- Assessing the goodness-of-fit of the equations that will be developed from the data to relate response to the corresponding variables.

Sources of errors

It was very important to avoid mistakes during the data collection, however, it was not possible to avoid other circumstances which seemed to be beyond our control; among other noticeable source of errors were measuring the load level inside the tubing because it was not visible in the all cases to be measured, it was depends on the pressure transducer accuracy, However, we tried to take multiple readings for better comparison and when uncertainty was very high, a particular experiment was repeated.

- Pressure transducer accuracy reaches 0.05 bar and to minimize the effect of this value the mean of multipoint log during a designed time was chosen to keep this value as small as possible.

- Produced water volume measured using two cylindrical graduated separators at the surface with an accuracy of measuring 47.6 cm^3 for main separator and 9 cm^3 for the secondary one.

- Time scale: the system programmed to log the pressure each 0.4 s, which makes it difficult to have the exact set value, leads to delay of 0.4 s as a maximum level of time shift away from the true moment for the control system to process the input data and transmit the orders to the solenoid valves to close or open.

- Reading fluctuates: the other source of error, which ranges in 0.04 bar, although it was small but in some cases is big enough to disturb the pressure recording. Thus, this effect reduced by averaging multiple measurements where multiple readings were recorded for a determined period of time.

The pressure recordings were extracted from the output data as text files then imported to excel. The very high aberrant data points which are do not consistent with the recorded points in the curve were eliminated after repeating the test and data corrected for each point.

4.3.1 Exploratory testing.

Preliminary exploratory testing was conducted to understand the behavior of the model against varying reservoir pressure as well as different productivity indexes which match different variable-flow valve settings. The object of this test was to determine the limitations range for both of the preceding mentioned parameters, which helps in selection of parameter levels for the designed tests. The process flow and the factors levels selection are illustrated in Figure 4.2.

However, selected results from the preliminary tests which have better precision will be used subsequently to choose variables combinations and parameters levels for the following experimental stages. Thus, it was decided that a better preliminary tests precision would be strongly affect on the direction of the course of this study and therefore on the final results of this work due to the dependence of the subsequent experiments on the first runs indications.

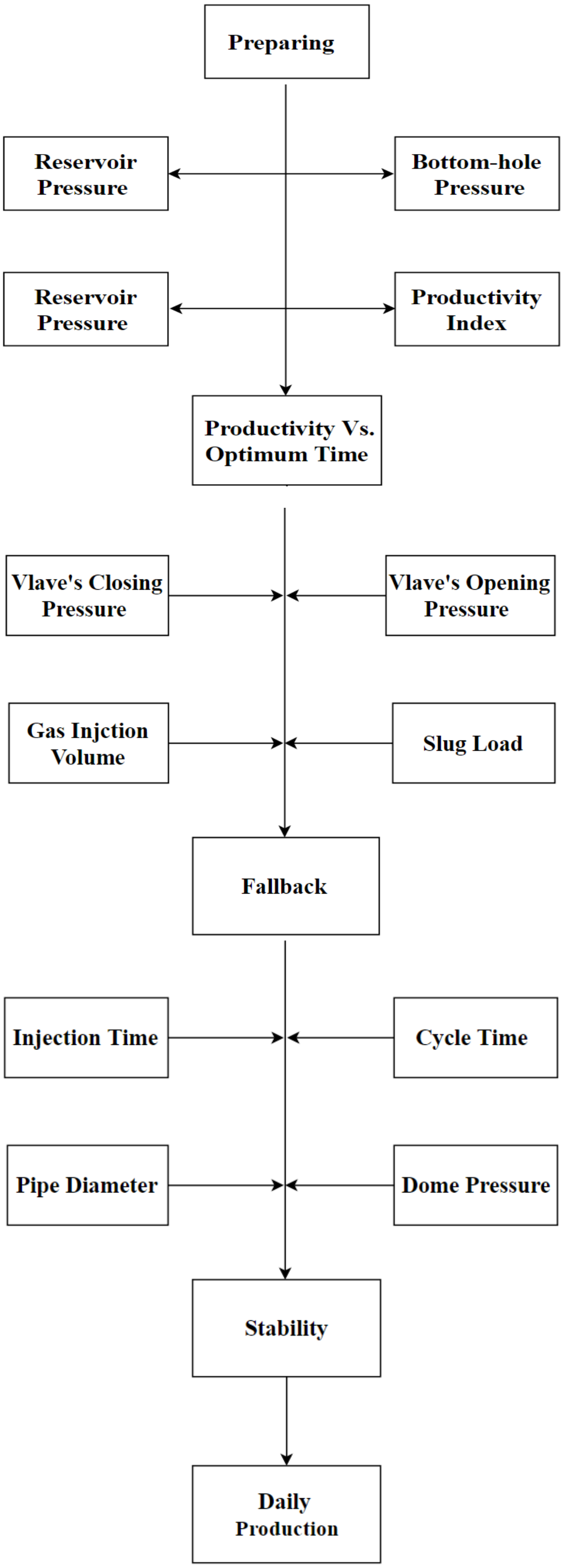


Figure 4. 2- Process flow chart of experiments overview

2 - Bottom pipe Pressure

Depends on the length of the liquid column accumulated inside the tubing, the pressure at the bottom of the production conduit was estimated using equation (4.1).

$$P_{wf} = P_{wh} + H_{sl} \tag{4.1}$$

Where:

P_{wf}, is the bottom-pipe pressure; P_{wh} is the pipe-head pressure; H_{sl} is the slug load, Figure 4.3 shows the calculated and measured bottom-pipe pressure related to the liquid slug length inside the production conduit.

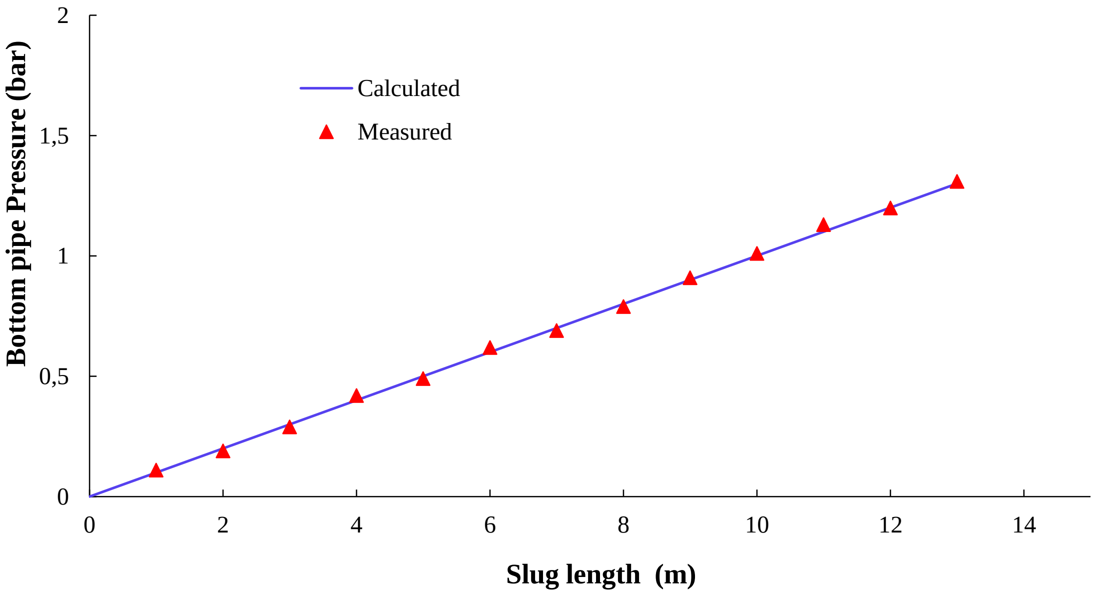


Figure 4. 3- Measured bottom-pipe pressure

It was observed that the measured pressure value ranges within 1.3 bar, therefore, to differentiate between pressure magnitudes within this range was difficult without re-adjusting the pressure transmitter to adapt with low values by setting the maximum pressure for the transmitter as the highest level of pressure change in order to increase its precision, thus the working pressure for pressure transmitter (M2) in the control system was adjusted to be range from 0 to 1.5 bar.

3 - Productivity Index

Here two sets of experiments were studied depends on the characteristics of the model feeding reservoir, the first set has the measured bottom pipe flowing pressure normalized against the time for three different reservoir pressures under same productivity index. In comparison with the second set, where planned to test the model against the same reservoir pressure with different levels of productivity index. The productivity indexes were simulated by throttling the variable flow valve, thus varying the inlet flow resistance; the PI values are shown in Table 4.3 (the opening refers to the position of the wheel of the valve, as read in the collar). The PI values were measured independently before the experiments were run. However, it was selected to test the model during the exploratory testing stage under specific levels of the productivity indexes, Table 4.3.

Table 4. 3 - Productivity indexes tested in the exploratory stage.

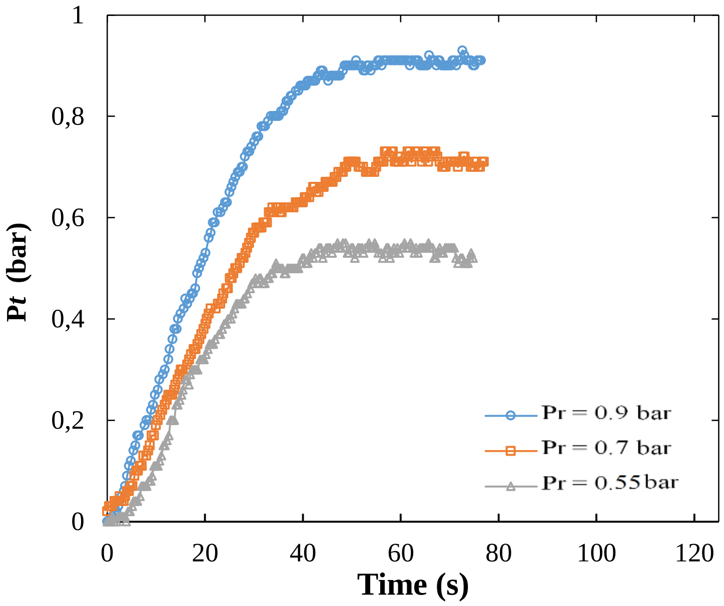
Opening	PI(m^3/d.bar)
90°	37.6
80°	29.3
60°	19.1
50°	13.4
40°	10.1
30°	4.5

The results of the initial round of tests are seen in Table 4.4

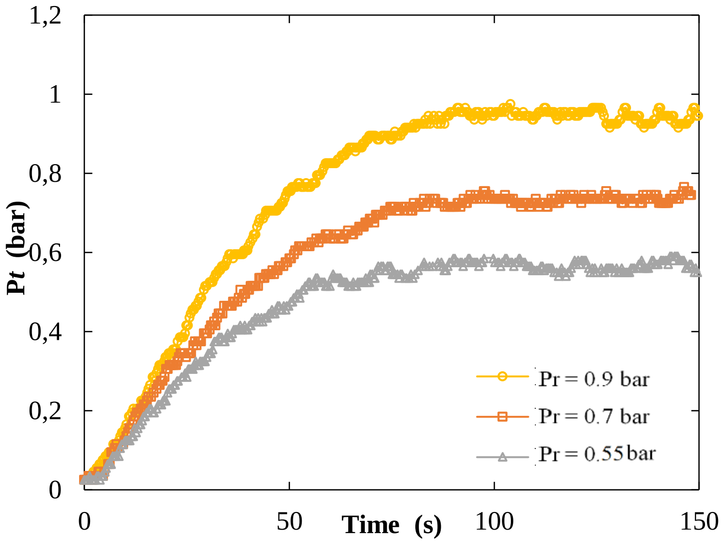
Table 4. 4 - Varied reservoir pressures vs. held productivity index.

Diameter (in)	Productivity Index(m^3/d.bar)	Reservoir Pressure (bar)	Max. Slug Length (m)	Time (s)
1 in	19.1	0.9	9	48
		0.7	7	48
		0.55	5.5	48
	10.1	0.9	9	85
		0.7	7	85
		0.55	5.5	85

and plotted in Figure 4.4. It can be analytically shown that the feeding time which corresponds to a desired liquid load inside the tubing and consequently the theoretical optimum cycle time depend on the productivity index and not on the reservoir pressure. Figures (4.4 (a, b) -4.5) show a consequence of this fact where the model was tested using 1" diameter of production conduit under two different productivity indexes 19.1- 10.1 m^3/d.bar. As it shown in Figure 4.4 –a, results for 1" tubing and productivity index of 19.1 m^3/d.bar, the feeding time for the liquid slug inside the tubing to reach the maximum load was 48 s for three different reservoir pressures (0.9, 0.7, 0.55 bar) in the test, which illustrates the independence between the maximum load time and reservoir pressure. It should be noted that the time to reach a given percentage of the theoretical maximum slug load (for instance, 90 %) is practically independent of Pr, but depends on PI.



(a) (1". diameter, PI = 19.1 m^3/d.bar)



(b) (1" diameter, PI = 10.1 m^3/d.bar)

Figure 4. 4- Held productivity index vs. varied reservoir pressure, 1" diameter

While in Figure 4.4 –b, shows the results of repeating same test under different productivity index 10.1 m^3/d.bar, the feeding time needed for the liquid slug to reach the maximum load was 85 s.

In comparison with the second set of experiments, the model tested against constant reservoir pressure under varying levels of productivity index. Results for this round are summarized in Table 4.5 and plotted in Figure 4.5.

Table 4. 5 - Held reservoir pressure with varied productivity indexes.

Diameter (in)	Reservoir Pressure (bar)	Productivity Index(m^3/d.bar)	Max. Slug Length (m)	Time (s)
1	0.9	4.5	9	145
		10.1	9	85
		19.1	9	48

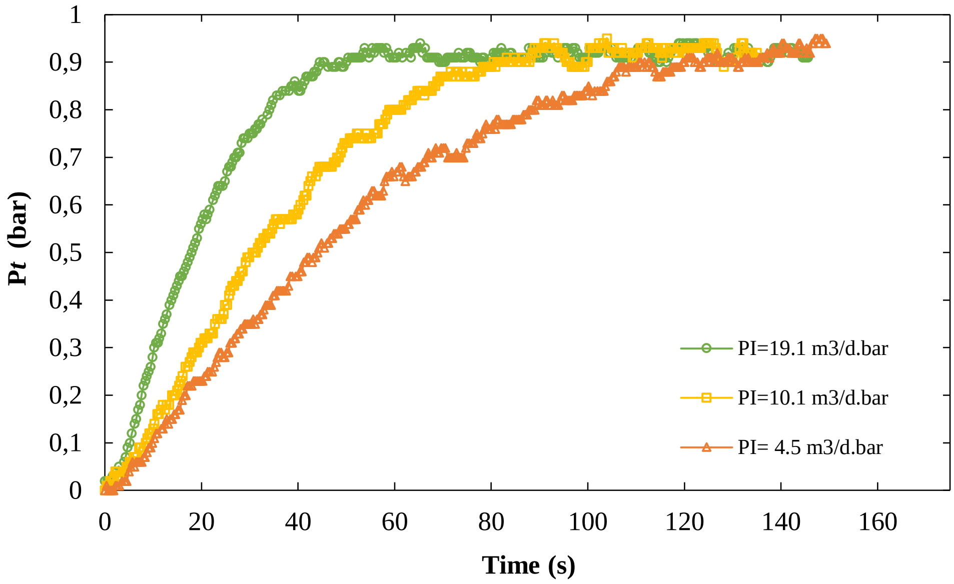
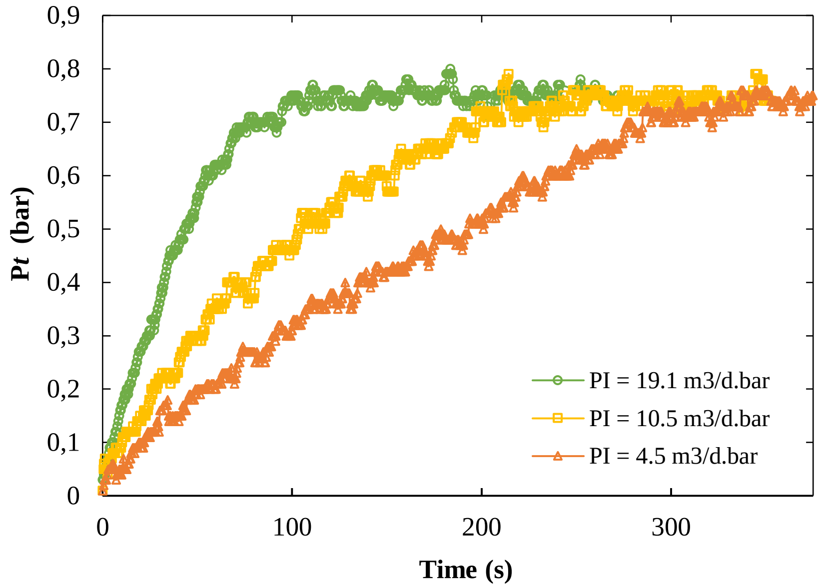
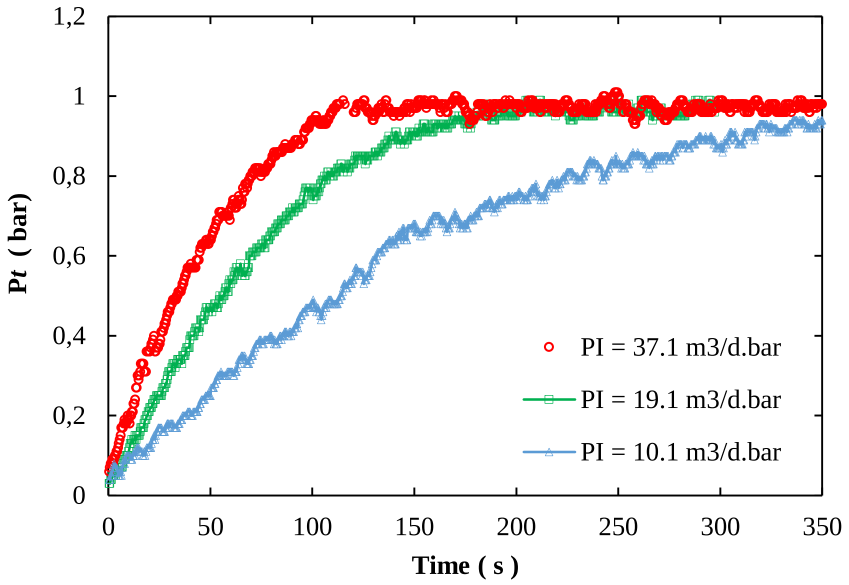


Figure 4. 5- Held reservoir pressure vs. varied productivity indexes (1", Pr 0.9 bar)

As it shown in Figure 4.5, under constant reservoir pressure, the feeding time needed for the liquid slug to reach the maximum load was different (48, 85, 145 s) for the three different productivity indexes (19.1, 10.1, 4.5 m^3/d.bar) respectively, which illustrates the dependence between the feeding time for maximum liquid slug load inside the tubing and productivity index. However, for both sets under same test conditions for productivity index, three different production conduits diameters were tested Figure 4.6-(a and b) show results of the first test using diameters (1.5" and 2") respectively.



(a) (1.5", Pr =0.75 bar)



(b) (2", Pr = 0.95 bar)

Figure 4. 6- Held reservoir pressure vs. varied productivity indexes (2")

The object of measuring the bottom pipe flowing pressure versus time, is to present the effect of altering reservoir pressure and productivity index on the feeding time needed for the liquid slug to build up and reach the maximum load inside the tubing, thus will be used later to determine the optimum cycle time due to the direct influence relationship between the period of time needed to the reservoir feeding the system and the length of cycle time.

4 - Preliminary test observations

It was observed from the preliminary exploratory tests that the feeding time which corresponds to the maximum liquid load level inside the tubing depends on the productivity index and not on the reservoir pressure. As it was shown in the previous section, under various experimental parameters, through altering combinations both of the reservoir pressure and productivity index with three different tubing diameters, therefore, it was observed that 19.1 m^3/d.bar for the productivity index is the mean value which is applicable for this laboratory model considering the three different diameters for the production conduits as shown in Figure 4.7. While the other productivity induces have an individual good results related to certain diameter of the tubing, but not valid for the other diameters. For this reason, it was decided to hold the parameter at this value for the second round of the tests.

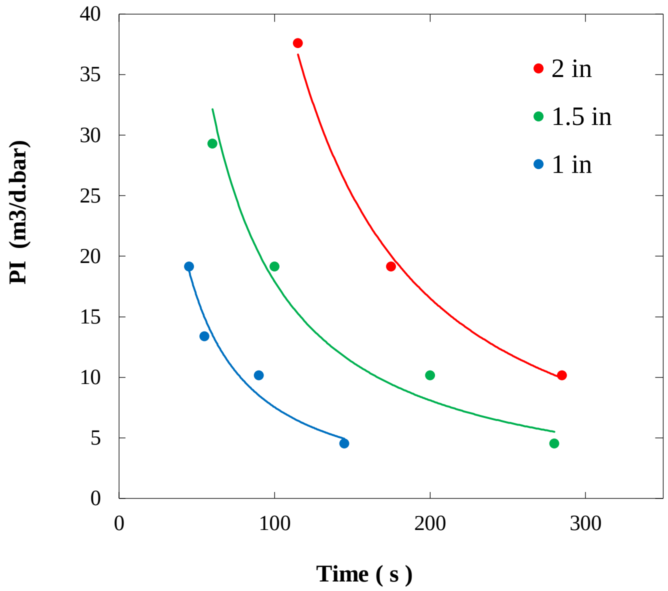


Figure 4. 7- Productivity index vs. time for different diameters.

It was observed from the former section as it shown in Figure 4.8, under a constant productivity index (19.1 m^3/d.bar), the feeding time needed for liquid slug to reach the maximum load was (48, 125, 180 s) for three different Diameters (1", 1.5", 2") respectively, which illustrates the dependence between the maximum load time and productivity index with the conduit diameter.

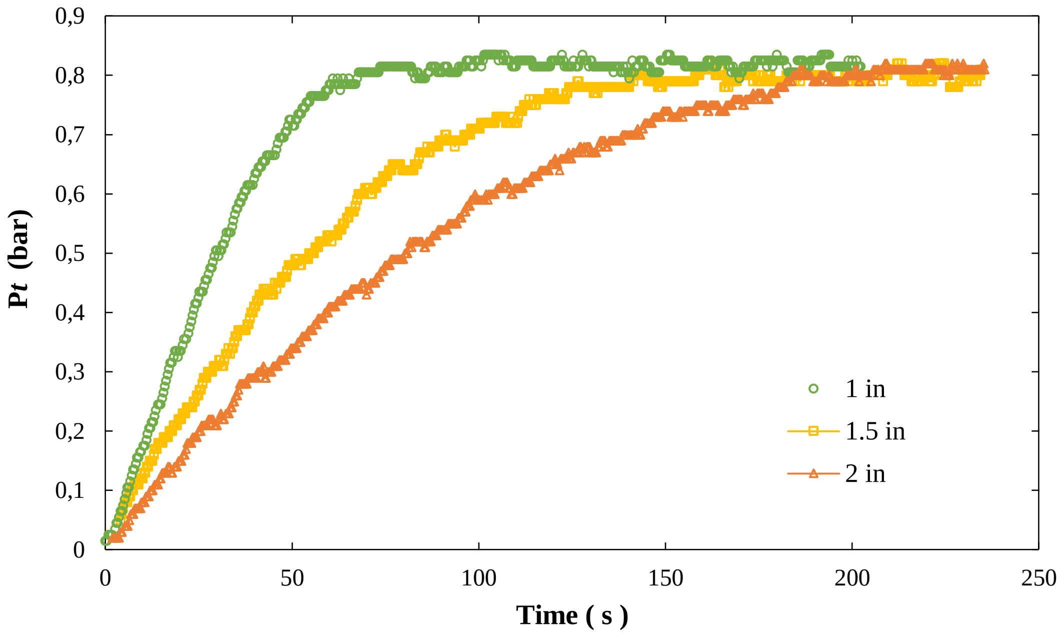


Figure 4. 8- bottom-pipe pressure vs. time for varied diameter, PI =19.1 m^3/d.bar

4.3.2 Factors affecting CIGL

Second testing round was conducted to analyze the fallback factor behavior of the laboratory model to differentiate the function of operational parameters, and here experiments have conducted under several combinations of parameters in order to determine the best operational conditions by measuring the effect of each parameter on the model performance. In light of this, the operational parameters at various levels have tested are: upstream pressure of gas injection valve to open, downstream pressure of gas injection valve to close, liquid slug load and gas injection volume for three different production conduits sizes. The object of this test was observing the behavior of the model under different levels of the operational parameters and consequently could be used later in the production systems design and production optimization.

1 - Fallback

In this section, different experiments have conducted measuring the influence of the fallback factor by varying the operational parameters through designed sets of parameters combinations, such as the operating valve pressure to close and pressure to open respectively, liquid slug load, production conduit diameter and gas injected volume. However, during this round of experiments, runs have conducted randomly and data collected separately by maintain the level of one or more parameters held constant associated with altering other parameters, therefore, fallback has studied considerably and the results from this section cover testing the effect of most levels of the operational parameters which varying in a very well designed range.

2 – Operating-valve closing pressure

Here, three different sets of experiments have conducted in order to determine the effect of the lift-valve closing pressure on the fallback, by maintain the same level of liquid slug load constant (0.4 bar) during this phase, and altering between three different diameters (1", 1.5", 2") applied with two levels of operating-valve opening pressure (2.5 - 5 bar) and at the same time ranging the operating valve closing pressure from (0.5 to 4.5 bar) with repeating similar operational parameters for different production conduit diameters 1" (a), 1.5" (b) and 2" (c), respectively. As shown in Figure 4.9.

Procedures

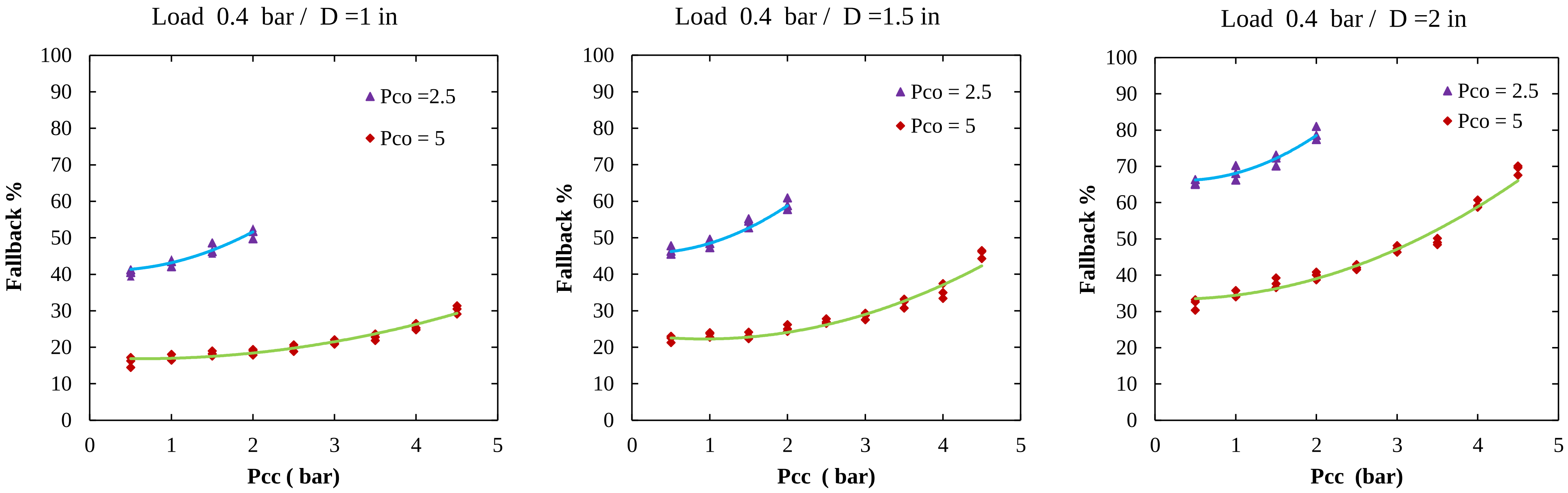
Since the inlet valve (ball–valve) and the variable flow valve are located at the bottom of the tubing and they are operated manually, both of them provide a method of separating the vertical pipes from the water reservoir. Therefore, for the single shot experiments, the variable flow valve set on full open position and for each run the inlet valve opens to provide a desired liquid load then closes before gas injection begins. The inlet valve remains closed until the tail gas dissipated and the fallback recorded for each run. Then a new load permitted to flow into the tubing and another run to be done. Generally, each test is consisted of several steps:

1. Opening the inlet valve until filling the tubing to a desired load using the pipe pressure transducer at the operating-valve’s depth.
2. Closing the tubing inlet valve;

3. Adjust the pressure regulator to a desired pressure (2.5 -5 bar);
4. From the software interference, opening the first solenoid valve, representing the surface intermitter, and gas injection begins from the air-storage tank into the casing-space tank until a desired pressure obtained “operating valve opening pressure”, then adjusting the pressure inside the tank to be stable by re-injecting gas inside the tank or venting the air from the tank manually;
5. Opening the second solenoid valve “operating valve” and gas injection begins and the pressure into the “casing” space tank drops down to a predetermined closing pressure (0.5 – 4.5 bar) then the operating valve closes.
6. Measuring volume of the liquid produced at the surface for each run;
7. Measuring the fallback visibly if it’s available (the lower transparent section of the 1.5") and using logged pressure on the bottom of each vertical pipe.
8. Calculating gas volumes injection into the “casing” space tank.
9. Repeat each set multiple runs (at least three) and measure the liquid produced very accurately and take the mean of the results; and consequentially calculating the fallback and recovery.

It was observed from Figure 4.9 for first set of parameters combinations under held level of slug load 0.4 bar and operating-valve opening pressure at (P_{co} = 5 bar), that the fallback increased in range up to 12% for 1" pipe diameter and up to 20% for the 1.5" pipe diameter in comparison with 33% for 2" pipe diameter by increasing the operating valve closing pressure (P_{cc}) from 0.5 to 4.5 bar.

From results of the second run, the fallback increased in range from (10-15%) for the level of operating-valve opening pressure (Pco = 2.5 bar), by increasing the operating valve closing pressure from 0.5 bar to 4.5 bar. At the same time was observed that depends on the production conduit diameter, the fallback effect increased by increasing the production conduit diameter (1", 1.5" and 2") respectively.



(a) (b) (c)

Figure 4. 9- Fallback vs. operating valve closing pressure.

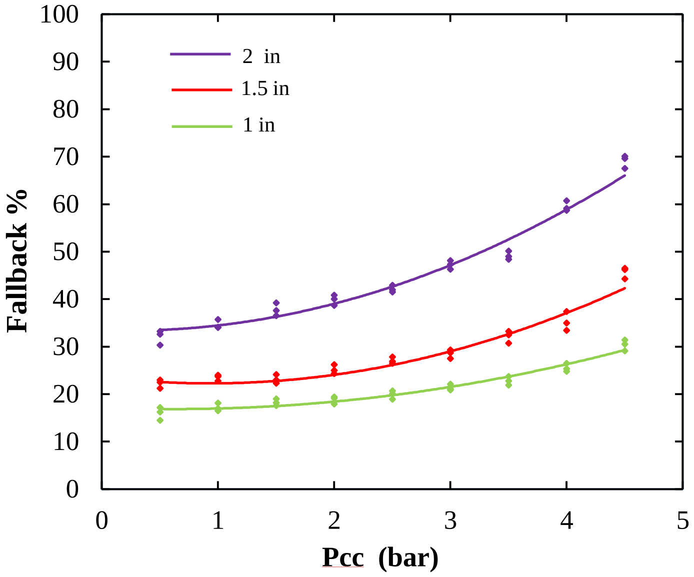
Pcc*:* is the upstream pressure at the moment of the operating valve closes

Test observations

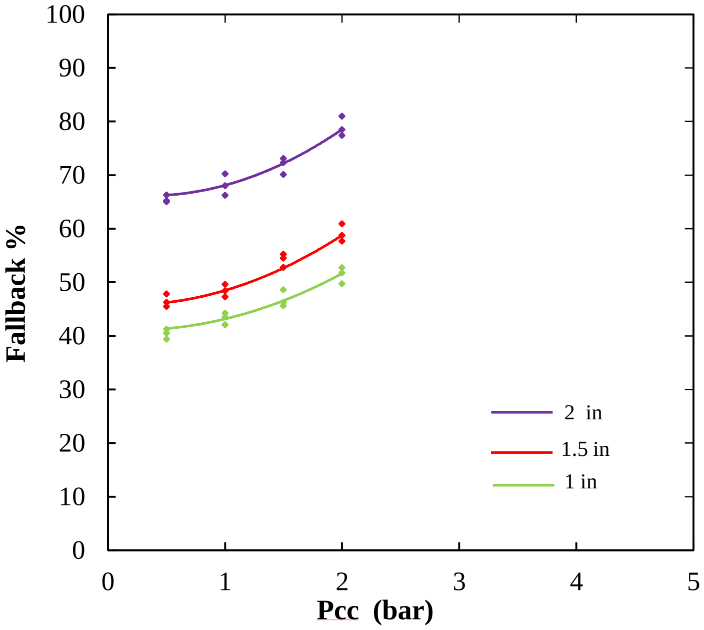
It was observed from Figures 4.9 -a, b and c, the fallback effect under same liquid slug load, does significantly increases by increasing the size of the production conduit and at the same time fallback will be higher with lower operating valve opening pressures in comparison with lesser fallback effect associated with higher operating valve opening pressures Figure 4.10.

- From Figure 4.10-a and b with energy of the injection gas at a level of 5 and 2.5 bar as pressure of opening the operating valve, while altering the pipe's diameter between three sizes 1", 1.5" and 2" leads to higher fallback effect:
- For the size of 2" , fallback ranges in (15-20%) higher than using 1.5" under same slug load, while the volumetric capacity of the pipe increases upto 39.4% by altering 1.5" by 2"
- For the size of 1.5" fallback ranges in (8-12%) higher than using 1" under same slug load, while the volumetric capacity increases upto 57.5% by altering 1" by 1.5".
- In this case Figure 4.10-a with high sudden released energy of the injection gas associated with opening the operating valve at a high level 5 bar, thus, increasing the operating valve closing pressure leads to less time giving for the gas to support the entrainment in the gas phase which results in large portion of the suspended liquid droplets will fall down without recovering as a result of reducing the time of the gas being injected inside the pipe. Therefore, increasing the valve closing pressure from 0.5 bar to 4.5 bar for the (Pco = 5 bar and liquid load of 0.4 bar) with different pipes diameters reduces the recovery of the model in range from 12 to 35%.
- From Figure 4.10-b for a sudden released energy of the injection gas at a level of 2.5 bar as pressure of opening the operating valve, while increasing the operating-valve closing pressure from 0.5 bar to 2 bar leads to less time giving for the gas to support the entrainment in the gas bubble phase, which

results in large portion of the liquid droplets to fall down without recovering as a result of minimizing the time giving to gas being injected inside the pipe. Therefore, increasing the valve closing pressure from 0.5 bar to 2 bar for the Pco= 2.5 bar and liquid load of 0.4 bar, for different pipes diameter reduces the recovery of the model by increasing the fallback factor in range from (10 to 15%).



(a) - Pco = 5 bar



(b)- Pco = 2.5 bar

Figure 4. 10- Fallback comparison between three tube diameters

3 – Operating-valve opening pressure

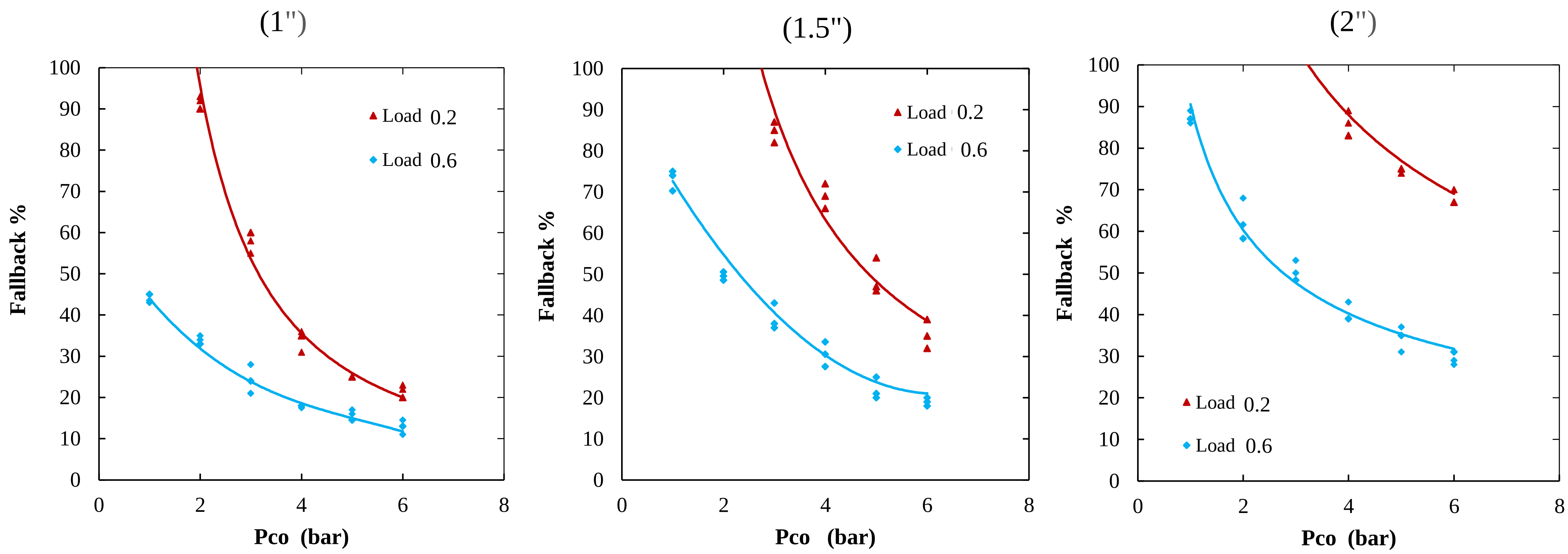
In this section, different experiments have conducted measuring the fallback by using two different liquid slug loads (0.2 - 0.6 bar) during the course of this set of experiments which applied on three different pipe diameters while ranging the operating valve opening pressure from (1 to 6 bar). As shown in Figure 4.11 applying same operational parameters for diameter size 1" (a), 1.5" (b) and 2" (c), respectively.

It was observed from this run for two levels of the slug load and three different tubing diameters that the fallback decreased in range from (95 to 20%) in general, depends on both of the production conduit diameter and the level of the slug load, thus the behavior of the fallback by increasing the operating valve opening pressure, Pco, from (1 to 6 bar), could be summarized in the following points:

- The fallback rapidly decreased in range within (80%) with higher rate for the level of the slug load (0.2 bar) than the level (0.6 bar), with respect that the decreasing rate will be higher for 1" the smaller conduit diameter. As shown in Figure 4.11-a.

- The fallback decreased in range within (40 %) with lower rate for the level of the slug load (0.6 bar) than the level (0.2 bar), with respect that the decreasing rate is lower for larger conduit diameter 2". As shown in Figure 4.12-b and c.

- For injection pressures above a certain value and depends on the liquid slug load, the injection pressure does not affect the liquid fallback, and the fallback curve tends to be stable at this level in independent of increasing the injection pressure



(a) (b) (c)

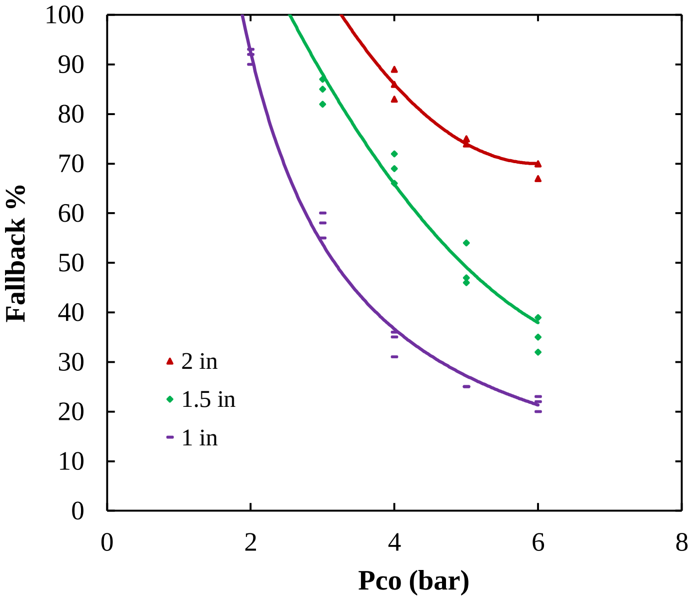
Figure 4. 11- Fallback vs. operating valve opening pressure.

P*co:* is the upstream pressure at the moment of the operating valve opens

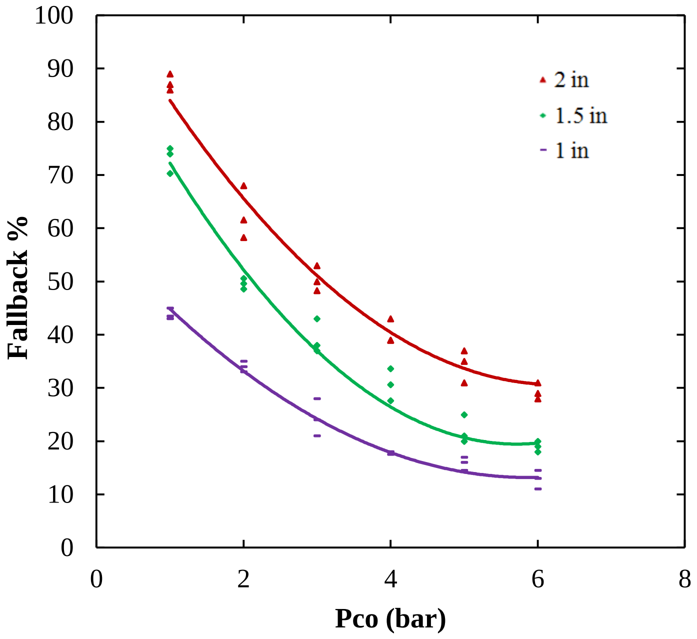
Test observations

It was observed from former Figure 4.11-a, b, c, that the fallback effect under same liquid slug load, does significantly decreases by increasing the operating valve opening pressure with respect of the size of the production conduit and at the same time the rate of fallback decreasing will be higher with low slug loads, on the other hand in comparison between diameters less rate of fallback decreasing associated with larger production conduit diameter Figure 4.12.

From Figure 4.12-a , a held constant operating valve closing pressure with increasing the opening pressure (sudden released energy of the injected gas) gradually from (0.5 bar to 6 bar), thus, increasing the operating valve opening pressure leads to greater time giving for the gas to support the flow of suspended liquid droplets in the gas bubble phase which results in larger portion of the liquid droplets will be produced increasing the recovery. Therefore, increasing the valve opening pressure from 0.5 bar to 6 bar for a fixed constant valve's closing pressure (Pcc = 0.35 bar and liquid load of 0.2 bar) for different pipes diameter reduces the fallback effect of the model and increasing the recovery in range up to 40% .



(a) Slug load (0.2 bar) with different diameters



(b) Slug load (0.6 bar) with different diameters

Figure 4. 12- Fallback factor vs. operating valve opening pressure with different conduit diameters.

- Figure 4.12-b. Here, with a sudden released energy of the injection gas increased gradually for a liquid load held constant at (0.6 bar) and operating valve closing pressure at (0.35 bar) as pressure of closing the operating valve for all runs, It was observed, while increasing the operating valve opening pressure from 0.5 bar to 6 bar leads to greater time giving for the gas to support the suspended droplets of liquid in the gas bubble phase results in larger portion of the liquid droplets will be produced with maximize the time of the gas being injected inside the pipe. Therefore, increasing the valve opening pressure from 0.5 bar to 6 bar for the (Pcc= 0.35 bar and liquid load of 0.6 bar) for different pipes diameter increases the recovery of the model and decreasing the fallback factor in range up to 80%.

- From the former two set of experiments, It was observed that by increasing the liquid load level from 0.2 bar to 0.6 bar the recovery increased in range up to 42%, which means the higher liquid slug load the higher gas penetration resistant which leads to lower fallback effect by giving the slug larger time to reach the surface before the gas totally penetrates the liquid slug the chance of the liquid to be surfaced will be higher depends on the operating valve depth, or the distance that the liquid slug will travel through.

4 - Gas injection volume

The object of this set of experiments which consists of two stages, both of them designed to study the effect of the injection gas volume on the fallback while either, altering the level of the liquid slug load and maintain the tubing diameter held constant, or hold the slug load constant while changing the tubing diameter. applying different levels of gas injection volumes, ranging from (0.03 to 0.12 m^3) with three different levels of operating valve opening pressure, for first stage, the production conduit diameter was kept 1.5" while altering between three different levels of opening pressure of the gas operating valve (3, 4.5, 6 bar) tested for each of the three different runs with levels of liquid slug load (0.3, 0.5, 0.7 bar) respectively, in comparison with the second phase, where the liquid slug load level was held constant at (0.4 bar) for all runs, with altering between three different conduits sizes and three different levels of operating valve opening pressure (2, 3, 4 bar) for each run.

Procedures

Generally, this test is consisted of the following steps:

1. Opening the inlet valve until filling the tubing to a desired liquid load using the bottom pressure transducer which located at the operating valve’s depth.
2. Closing the tubing inlet valve;
3. Adjust the pressure regulator to a desired pressure range (2, 3 ,4.5, 4.5, 6) bar;

4. Opening the first solenoid valve “motor valve” to inject the gas from the air storage tank to a selected “casing” space tank volume (0.03, 0.09, 0.12 m^3) until a predetermined pressure;
5. Opening the second solenoid valve “operating valve” from the program interference and gas injection begins until the pressure into the “casing” space tank drops down to a determined closing pressure (0.35 bar), then the lift-valve closes while time is not being counted.

6. Measuring the produced liquid volume at the surface;
7. Calculating the fallback visibly if it’s possible and using the logged pressure at the bottom of each vertical pipe.

8. Calculating the gas volumes injected into the casing-space tank.
9. Repeat each set (at least three runs for each test) and measure the liquid produced very accurately and takes the mean of the results; and consequentially calculating the recovery.

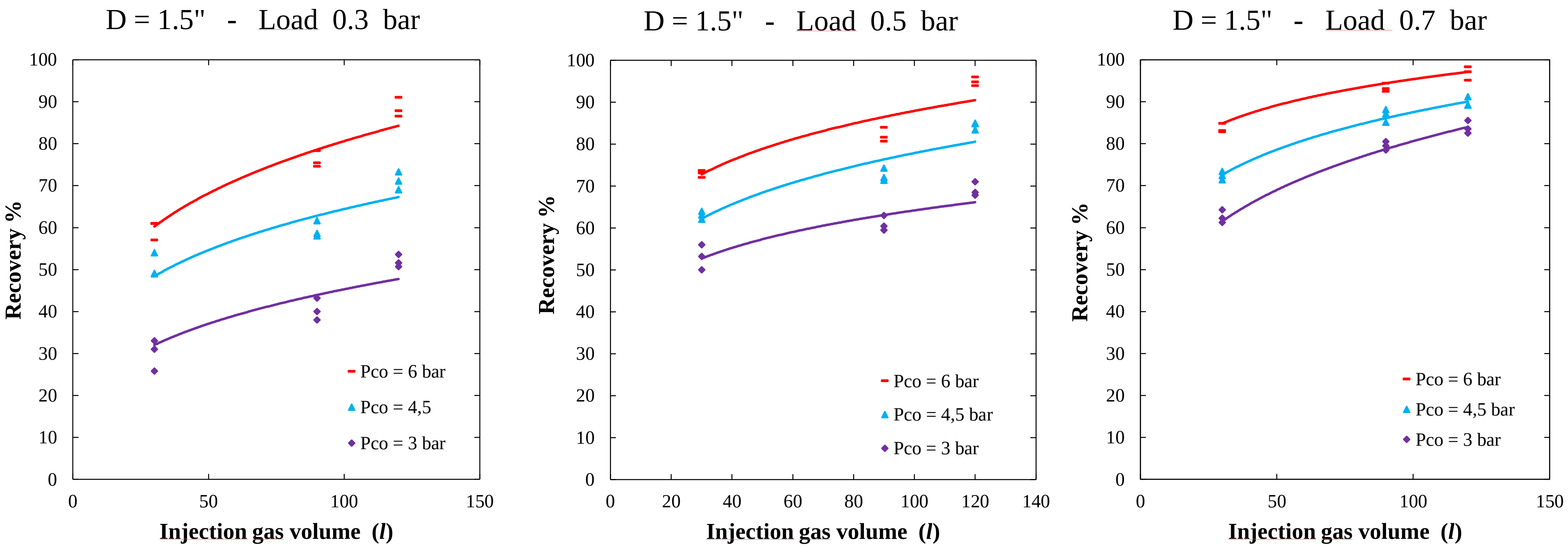
Test observations

It was observed from Figures 4.13-a, b and c, under held three operating-valve opening pressures for same production conduit size 1.5", that the liquid recovery increases by increasing the injection gas volume and at the same time the recovery is higher for higher operating-valve opening pressures as well as obtained lesser recovery associated with lesser liquid loads. However, it was noticed that the rate of increasing the injection gas volume effect associated with higher opening pressure (Pco= 6 bar) is lesser when the liquid slug load increases, on the other hand for lower opening pressure (Pco= 3 bar) the effect of increasing the injection gas volume is greater by increasing the liquid slug load.

- From the first run Figure 4.13-a applying the test for 0.3 bar liquid load associated with operating-valve opening pressure varying at three levels (3, 5.4, 6 bar), then increasing the injection gas volume leads to longer time giving for the gas to support the entrainment in the gas phase which results in larger portion of the suspended liquid droplets will be produced with greater recovery as a result of increasing the time of gas being injected inside the pipe. Therefore, increasing the injected gas volume from 0.03 m^3 to 0.12 m^3 for the Pco= 3 bar the liquid recovery of the model increased in range up to 18% while for the Pco= 4.5 bar the liquid recovery increased in range up to 21% and for the Pco= 6 bar the liquid recovery increased in range up to 25%.

- For the second run Figure 4.13-b, applying test for 0.5 bar liquid load associated with operating-valve opening pressure varying at three previous levels (3, 5.4, 6 bar), then increasing the injection gas volume leads to longer time giving for the gas to support the entrainment in the gas phase which results in larger portion of the suspended liquid droplets will be produced. Therefore, increasing the injection gas volume from 0.03 m^3 to 0.12 m^3 for the Pco= 4.5 bar the liquid recovery increased in range up to 19% while for the Pco= 4.5 bar the liquid recovery increased in range up to 20% and for the Pco= 6 bar the liquid recovery increased in range up to 22%.

- From the second run Figure 4.13-c, applying test for 0.7 bar liquid load associated with operating-valve opening pressure varying at three previous levels, then increasing the injection gas volume leads to larger portion of the suspended liquid droplets to be produced. Therefore, increasing the injection gas volume from 0.03 m^3 to 0.12 m^3 for the Pco= 4.5 bar the liquid recovery increases in range up to 22% while for the Pco= 4.5 bar the liquid recovery increased in range up to 20% and for the Pco= 6 bar the liquid recovery increased in range upto 19%.



(a) (b) (c)

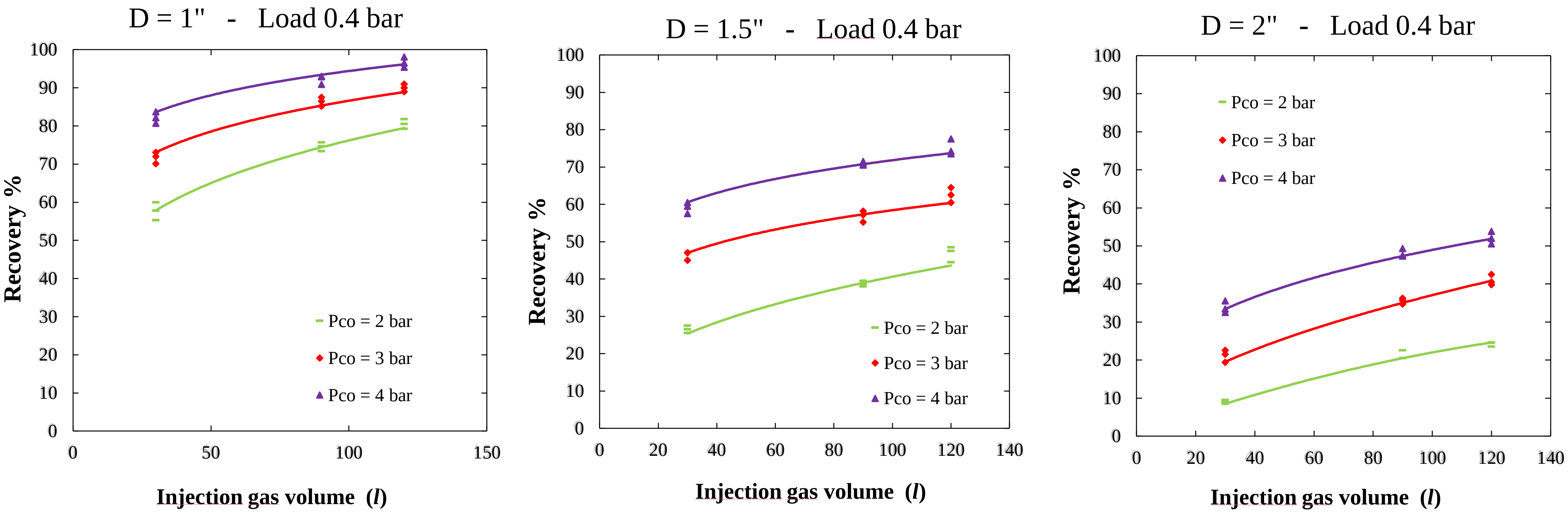
Figure 4. 13- Recovery vs. gas injection volume with different slug loads and operating valve opening pressure.

Test observations

It was observed from Figures 4.14-a, b and c, under held liquid slug load 0.4 bar for three different production conduit sizes (1", 1.5", 2") that the liquid recovery increased by increasing the injection gas volume at the same time recovery was lesser for larger pipe’s diameter. However, it was noticed that the rate of increasing the injection gas volume effect associated with higher valve’s opening pressure (Pco= 4 bar) is greater when increasing the pipe diameter, while for lower opening pressure (Pco= 2 bar) the rate of increasing the injection gas volume effect will be higher for smaller pipe diameter.

- Figure 4.14-a, it was observed for a constant liquid slug load 0.4 bar and 1" pipe diameter with injection gas volume varying from (0.03 m^3 to 0.12 m^3). Higher injected gas volume means increasing the opportunity of delivering the entrainment to surface leads to longer time given to the gas to support the suspended droplets of liquid in the gas bubble phase, results in larger portion of the liquid droplets to be recovered by increasing the time of the gas being injected inside the pipe. Therefore, increasing the volume of the injection gas from 0.03 m^3 to 0.12 m^3 (400%) and liquid load of 0.4 bar for 1" pipe diameter increases the liquid recovery of the model in range up to 15% for Pco 4 bar, 17% for Pco 3 bar and 21% for Pco 2 bar.

- Figure 4.14-b, it was observed for a constant liquid slug load 0.4 bar and 1.5" pipe diameter with varying injected gas volume from (0.03 m^3 to 0.12 m^3), longer time is given to gas to support the suspended droplets of liquid in the gas bubble, which results in larger portion of the liquid to be recovered. Therefore, increasing the volume of the injection gas (400%) increases the liquid recovery of the model in range up to 17% for Pco 4 bar, 16% for Pco 3 bar and 19% for Pco 2 bar.



(a) (b) (c)

Figure 4. 14- Recovery vs. gas injection volume with different conduit diameter and operating valve opening pressure.

- Figure 4.14-c, it was observed for a constant liquid slug load 0.4 bar and 2" pipe diameter with varying injected gas volume from (0.03 m^3 to 0.12 m^3), longer time is given to gas to support the suspended droplets of liquid in the gas bubble which results in larger portion of the liquid to be recovered. Therefore, increasing the volume of the injection gas (400%) increases the liquid recovery of the model in range up to 19% for Pco 4 bar, 15% for Pco 3 bar and 17% for Pco 2 bar.

It should be noted that the major mechanism for liquid production from the liquid film is entrainment of liquid into the moving gas core rather than from a moving liquid film. Observations of Schmidt *et al.* carried out in the test facility confirmed: that after the liquid slug has passed; the film velocity is indeed very small. The fallback volume could be calculated from the equation (4.2)

$$\mathrm{V}_f = \pi(d - 2\mathrm{t}_f)(Z_b - Z) \tag{4.2}$$

Where;

d : is the pipe's diameter and

t_f : is film thickness,

Z_b: is elevation to the bottom of the liquid slug.

Z : is elevation to the operating valve.

Therefore, using a larger pipe diameter the fallback volume is greater, what justifies the reduction of the liquid production by altering the pipe diameter from 1" to 2".However, larger pipe diameter expresses higher volumetric capacity of the pipe while the model production depends on the cycle time which denotes the feeding time and as a result the liquid load inside the tubing, therefore, further tested related to the cycle time and injection time along with operating valve dome pressure will be conducted in the next section.

4.3.3 Dynamics and Stability

After completing the second round of the experiments, the design of the third stage of experiments was established taking in consideration the objective of this stage to analyze the dynamic and stability of the IGL cycles under varied operational parameters. However, the experiments here were conducted under designed sets of parameters combinations. Allowing to determine the model optimum operational conditions, check the process stability and verify cycle's repeatability, which could be obtain by measuring the effect of each parameter's level on the stability and productivity of the model. In light of this and based on the results of the previous tests which have done in the first and second stages, it had decided to hold the level of reservoir pressure at 0.9 bar and the level of the productivity index at 19.1 m^3/d.bar, while varying the other operational parameters at different levels. Thus, parameters have tested here including; operating valve's dome pressure, injection time, cycle time and valve's area ratio.

Where runs in this section divided into three groups, each of them with set of designed parameters combinations, in other words this set of experiments was designed to study the system under production which means testing the working performance of both of the operating valve and surface control valve while varying the dome pressure and holding both of the injection time and the cycle time constant in the first group for 1" pipe diameter, the second group to hold the dome pressure and separately varying the cycle time and the injection time with holding the other constant for the 1.5" and 2" pipe diameter. Finally, the third group is to vary the valve's area ratio with holding the rest of the operational parameters for three different diameters. However, it should be mentioned that during the course of this round of experiments it was held both of the supply line pressure at 6 bar and initial slug load at 0.6 bar, while the measured pressure values range within 6.5 bars, therefore, it had re-adjust the pressure transmitter to adapt with high values by setting the maximum pressure for the transmitter as the highest level of pressure change in order to increase its precision, thus the working pressure for pressure transmitter (M2) was adjusted to be range from (0 to 6.5 bar).

Group I

The first group was tested under low valve spread, which means there is a small difference between initial operating-valve opening pressure and closing pressure, where dome pressure here represents closing pressure. From parameters of first-round Table 4.6 the pressure recordings of casing-space pressure recorded associated with both of tubing and pipe-head pressure recordings, which provides the essential data about the laboratory model as well as the operating valve and the time cycle controller performance, which can be inferred. However, it was observed from the recording chart Figure 4.15, a good intermittent operation with a continuous slug being produced and a fast pressure reduction due to a short vertical distance in which the liquid slug travels through the production conduit to be surfaced.

Table 4. 6 - High dome pressure 1".

Dome Pressure	4	bar	Initial Load	0.6	bar
Cycle Time	30	s	Supply Line	6	bar
Injection Time	5	s	Valve's Area Ratio	0.025	

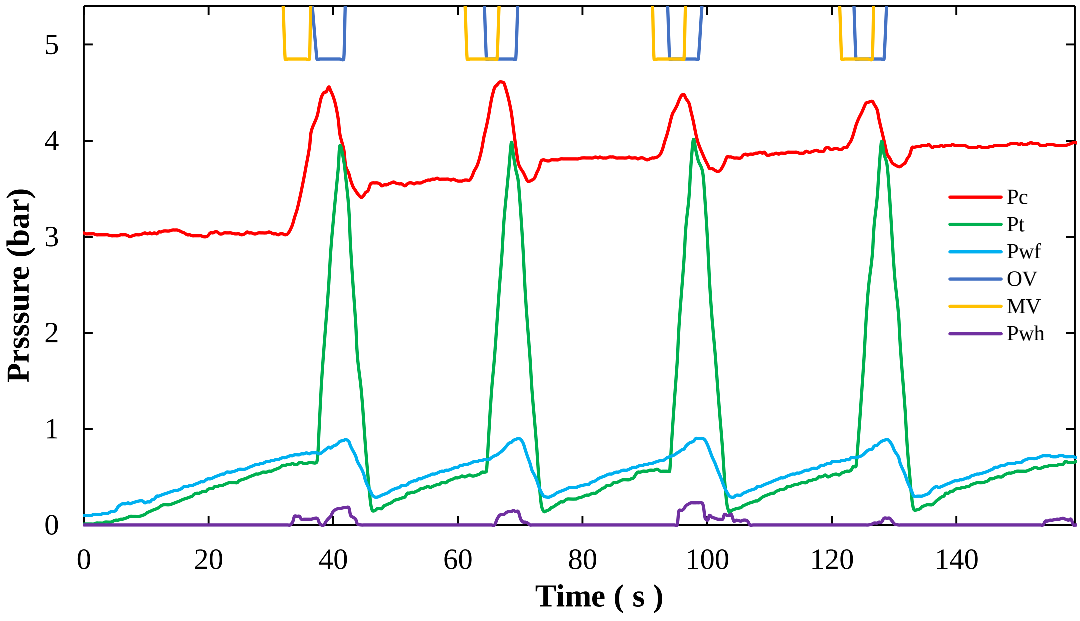


Figure 4. 15- Pressure recording – high dome pressure 1".

Here, the pressure recording gives the first indication about the efficiency of the model and its capacity under the designed parameters. However the maximum pressure and the time required for the pipe-head pressure to descend to the separator pressure must be available to evaluate the model performance. On the other hand, under low dome pressure levels, Table 4.7, it was observed from the results of this test that the operating valve opens and closes repeatedly after each cycle, but in steady behavior along the production process Figure 4.16 indicates that the gas flow rate out of the casing-space tank is greater than the gas flow rate supplied by the air-storage tank, while the pressure of casing-space tank decreases rapidly and makes the operating valve closes prematurely, leads to unstable performance of the operating valve.

Table 4. 7 - Low dome pressure 1".

Dome Pressure	2	bar	Initial Load	0.6	bar
Cycle Time	30	s	Supply Line	6	bar
Injection Time	5	s	Valve's Area Ratio	0.025	

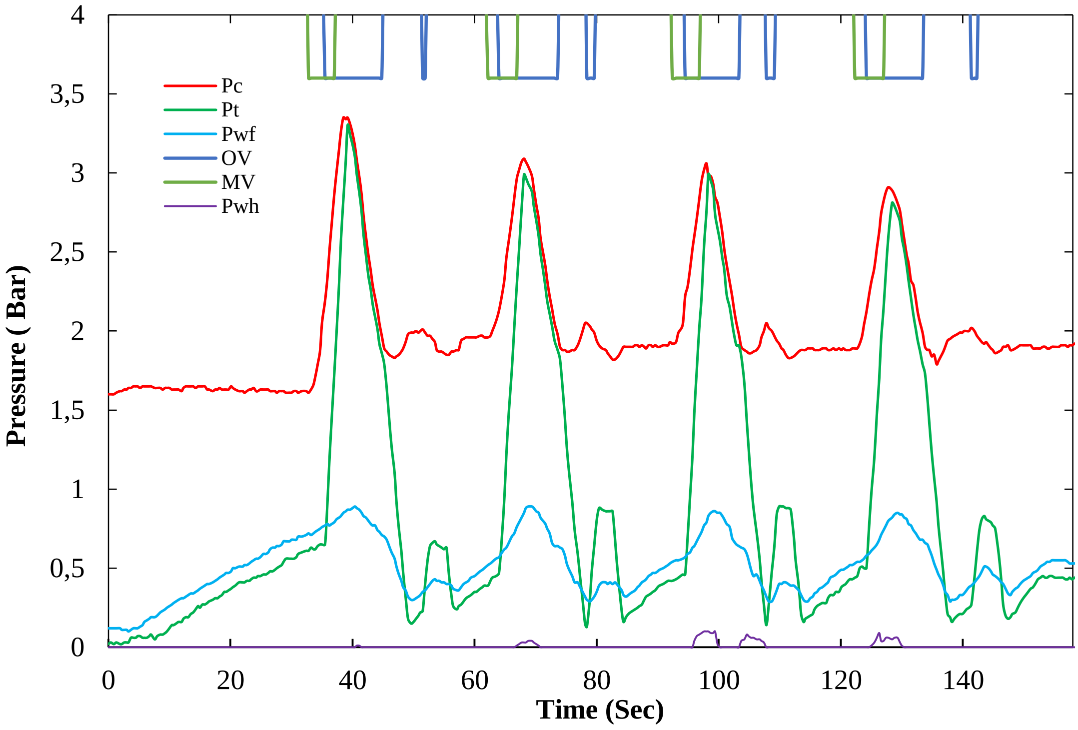


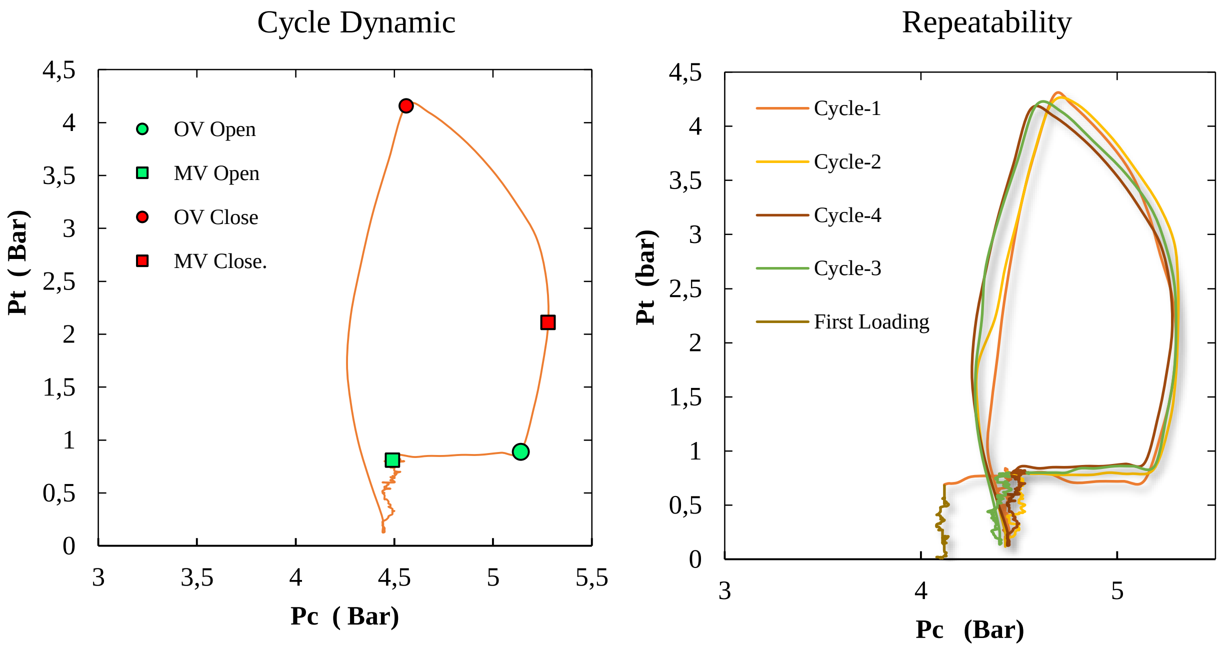
Figure 4. 16- Pressure recording- low dome pressure 1".

Cycle dynamic

Liquid build up in the tubing immediately after the slug reaches the surface due to both the contribution of liquid from water tank and from fallback which is the liquid volume fails to reach the surface and slides down to the bottom of the production conduit, From Figure 4.17-a, represents one cycle under working system and the relation between the upstream pressure Pc (casing-space tank) and the downstream pressure Pt (inside the tubing), where it shows the dynamic status of both of the operating valve and surface controller, respectively. However, it illustrates good valves corresponding, while decreasing in gas injection pressure once the valve opens indicating of high gas flow rate into the tubing and shallow depth of the operating valve. On the other hand, Figure 4.17 b, shows a good repeatability of the cycles under same operating condition Table 4.8.

Table 4. 8 - Parameters combinations - Pc vs. Pt, 1 in.

Dome Pressure	5	bar	Initial Load	0.6	bar
Cycle Time	55	s	Supply Line	6	bar
Injection Time	5	s	Valve's Area Ratio	0.025	



(a) (b)

Figure 4. 17- Cycle dynamic - Pc vs. Pt, 1".

Group II

In the second group, the first run was applying same set of parameters combinations of the dome pressure; cycle time and injection time level, Table 4.9 in comparison with the previous round, using 1.5" pipe diameter with different scenarios of valve’s area ratio. For low valve spread, it was observed the pressure recording chart Figure 4.18 shows good intermittent operation cycles’ repeatability with a continuous slug being produced and faster pressure reduction which also refers to bigger vertical pipe diameter where the liquid slug travels through to reach the surface.

Table 4. 9 - Parameters combinations 1.5". (R = 0.025).

Dome pressure	5	bar	Initial Load	0.6	bar
Cycle time	55	s	Supply Line	6	bar
Injection time	5	s	Valve’s Area Ratio	0.025	

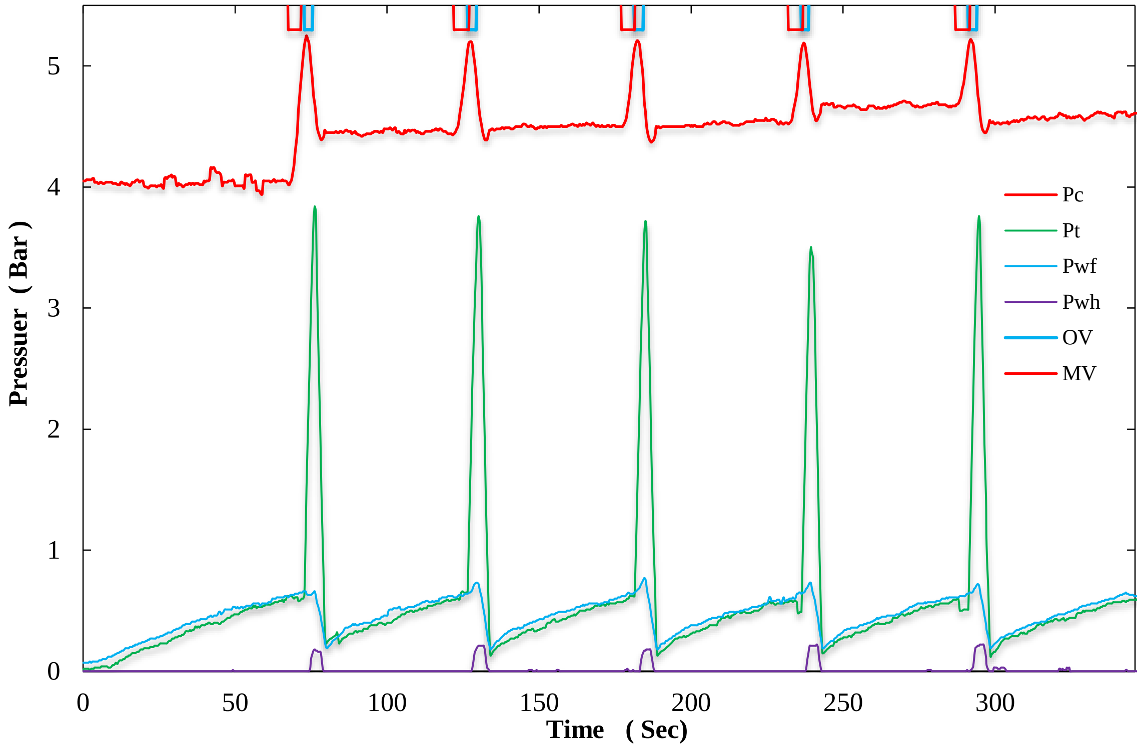
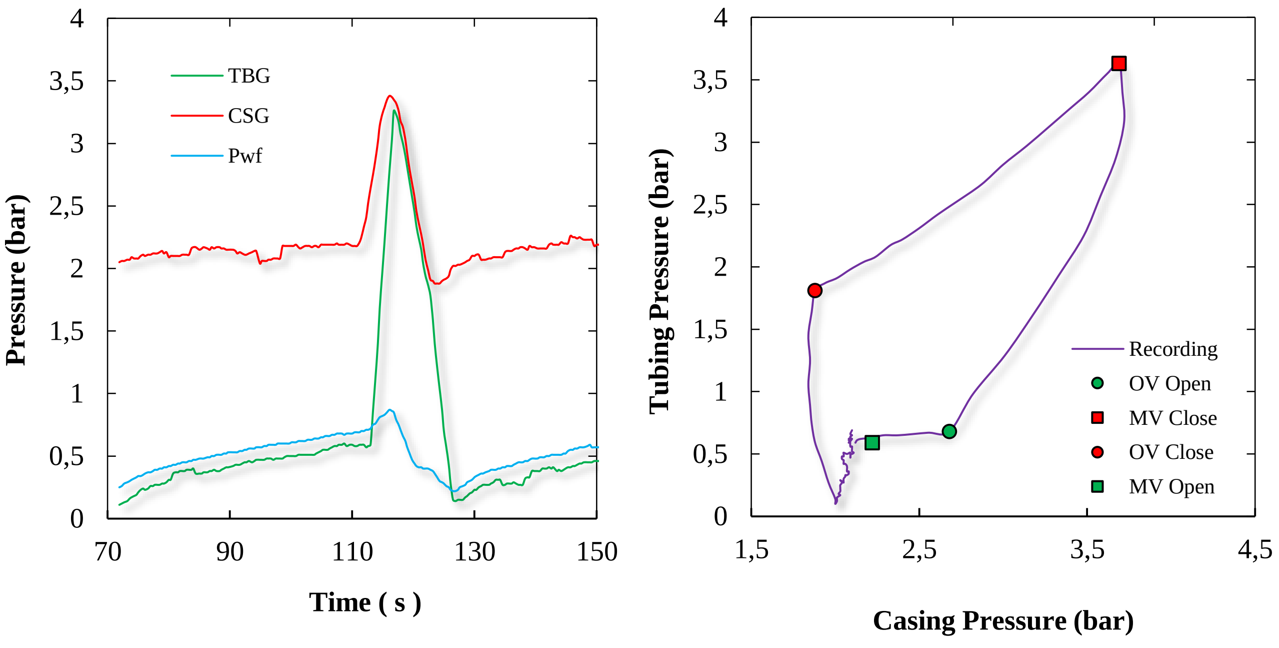


Figure 4. 18- Pressure Recording 1.5" - (R = 0.025).

Stabilization was observed from the curves of the casing-space tank and tubing pressures for five cycles Figure 4.18. Shows the similarity of the cycles in comparison between curves of the casing-space and tubing pressures is a characteristic of stable cycles where a reasonable correspond of the curves is observed. On the other hand, bottom pipe pressure recording shows the increment of liquid slug load is lower than the first round using 1" pipe diameter, due to the larger production conduit size under same productivity and cycle frequency, but higher increment rate of liquid accumulation volumes in comparison with first run, what justifies high daily production increment by using 1.5" pipe in the second run, refers to a better reservoir feeding time selection. In light of this, the cycle time selection effect is greater than the fallback factor effect by increasing the diameter in this case. However, the relationship between the Pc and the Pt Figure 4.19 shows pressure recording for one cycle under designed operational parameters, Table 4.10. Starting with reservoir feeding at the lowest bottom pipe pressure while increasing the pressure inside the tubing during the liquid accumulation above the operating valve, until the pressure of casing-space tank Pc reaches the operating-valve opening point, as defined by the equation of opening the operating valve.

Table 4. 10 - Parameters combinations - Cycle dynamic 1.5 in.

Dome pressure	2	bar	Initial Load	0.6	bar
Cycle time	55	s	Supply Line	6	bar
Injection time	5	s	Valve's Area Ratio	0.255	



(b)

(a)

Figure 4. 19- Cycle dynamic Pc vs. Pt 1.5 in.

Then the valve opens and the gas flow into the tubing causes an increase of the pressure Pt, but in lower rate of increment in comparison with the case low valve spread. Then by ending the injection time the motor valve closes and pressure decreases inside the casing-space tank due to the emptying of the tank through the operating valve, and again the decrease of casing-sapce pressure in lower rate in comparison with the case low valve spread. Consequently, Pt decreases until the operating valve closes at lowest casing pressure which matches the valve's dome loading pressure, then (Depressurization stage) Pt decreases until the subsequent cycle begins. However, it was observed, that the daily production of the system slightly increased by increasing the valve spread due to the casing-space pressure increment for the operating valve to open in this case (5.33 bar) for the ratio (R= 0.069) while it was (5.1 bar) for (R = 0.025) under same other operational parameters Figure 4.20.

Table 4. 11 - Parameters combinations 1.5 in. (R = 0.069)

Dome Pressure	5	bar	Initial Load	0.6	bar
Cycle Time	55	s	Supply Line	6	bar
Injection Time	5	s	Valve's Area Ratio	0.069	

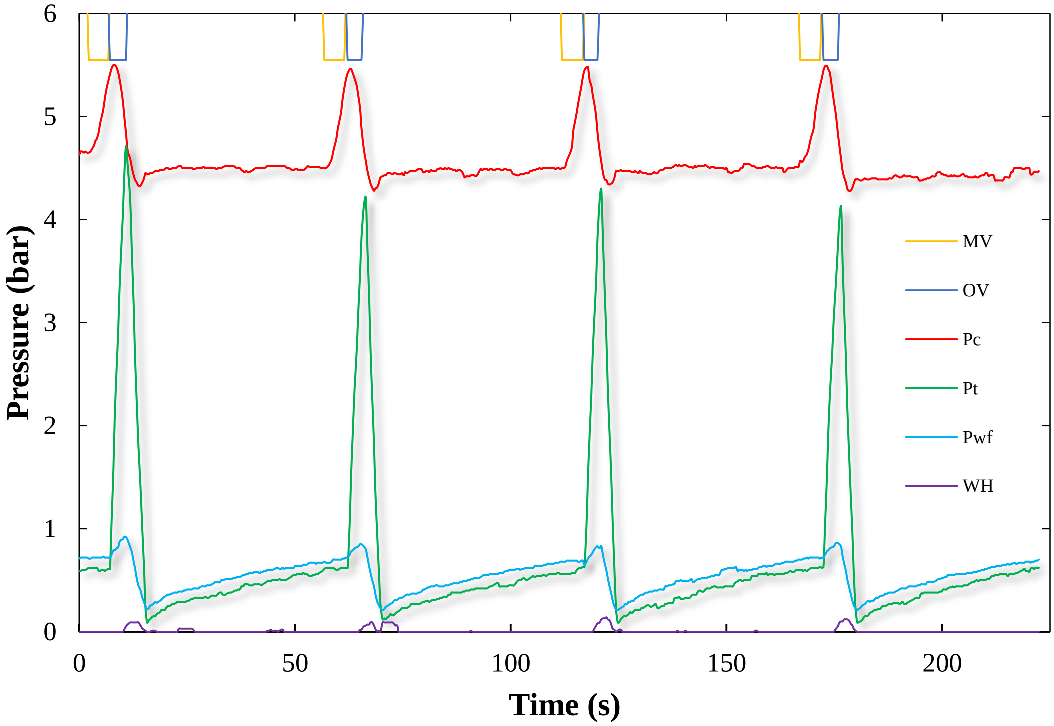
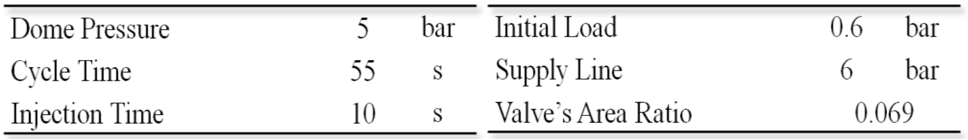


Figure 4. 20- Pressure Recording 1.5 in. (R = 0.069).

For this round, the objective was to test the model under same parameters combinations of the dome pressure and cycle time Table 4.12 while varying injection time levels (5-10 s) and it was observed, that the daily production of the system slightly increased for a higher injection time level, which indicates the low effect of increasing gas injection volume during same cycle time on the model productivity, Moreover, the gas operating valve shows instability under longer injection time Figure 4.21, due to the gas flow rate out of the casing-space tank is greater than the gas flow rate supplied by the gas line system makes the operating valve closes prematurely while the surface controller still open. Therefore, with longer injection time, instability is presented by the mismatch of the operating valve and motor valve: the moment of opening of the operating valve moves away from the opening of the motor valve at each cycle causing the repeatedly opening of the operating valve and not allowing the gas to lift the liquid slug adequately.

Table 4. 12 - Parameters combinations 2 in. (R = 0.069)



Dome Pressure	5	bar	Initial Load	0.6	bar
Cycle Time	55	s	Supply Line	6	bar
Injection Time	10	s	Valve’s Area Ratio	0.069	

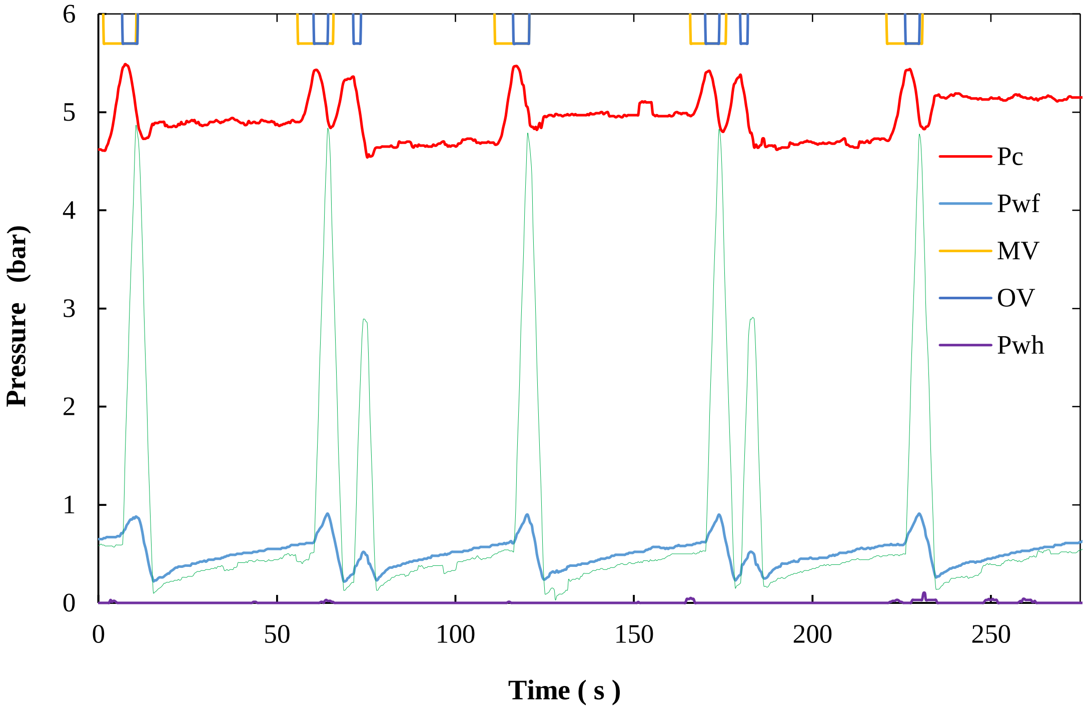


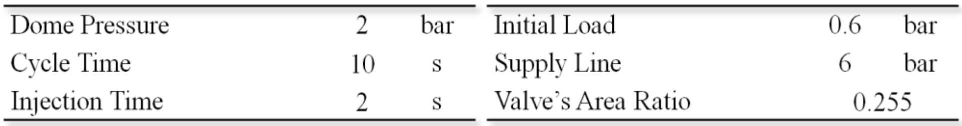
Figure 4. 21- Pressure Recording 2 in. (R = 0.069).

However, the objective of the second round was to observe the model performance under same parameters combinations but with varying injection time, where the effect of parameters combinations on the system stability and consequently on the daily production for configuration of the dome pressure and cycle time, under short and long injection time levels for 1.5 in. tubing diameter.

Short Injection Time

It was observed under set of parameters combinations Table 4.13 and from the pressure recording chart Figure 4.22 the fallback in the tubing increases due to small volumes of the injected gas during short period of time which cannot adequately lift the liquid slug. This results in lower daily production rate, but still shows stable intermittent cycles for a period of time with good repeatability and continuous slug being produced depends on the length of the injection time, then turn to be unstable by the time.

Table 4. 13 - Short injection time, 1.5 in- with varied R.



Dome Pressure	2	bar	Initial Load	0.6	bar
Cycle Time	10	s	Supply Line	6	bar
Injection Time	2	s	Valve's Area Ratio	0.255	

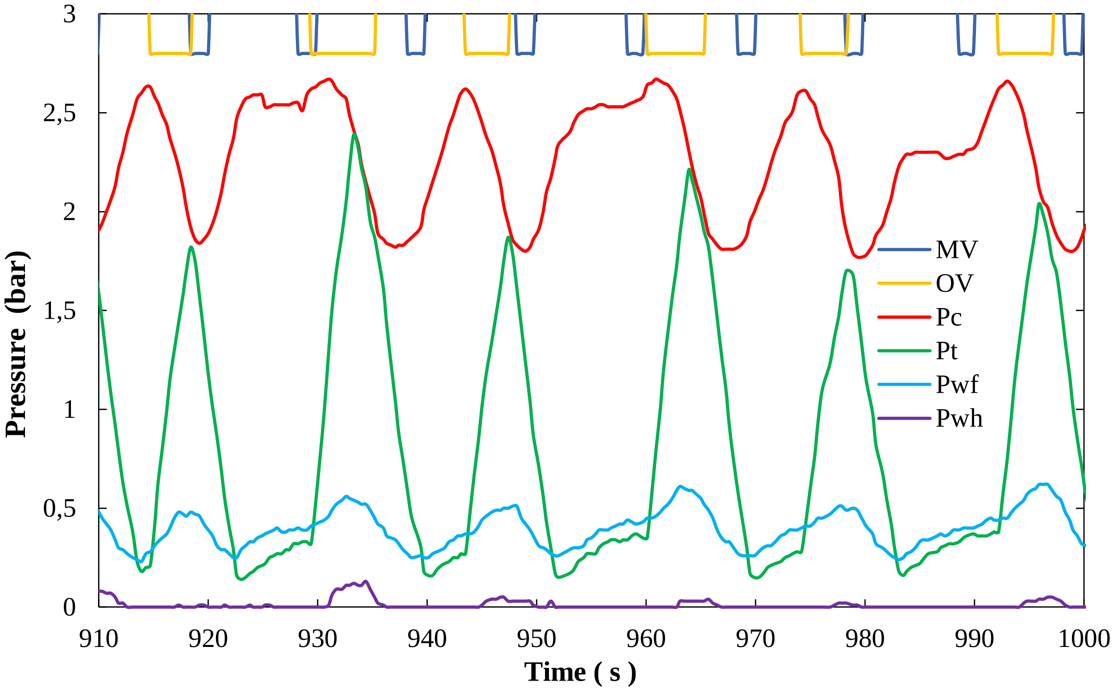


Figure 4. 22- 1st run, Pressure recording- short injection time

In this case, the injection time is not sufficient to increase the pressure inside the casing to match the valve's opening conditions; in this case the model takes two sequential cycles to increase Pc to open the operating valve in unstable behavior what highly affects the productivity of the model. Figure 4. 22-23 show the system repeats same behavior for two or more cycles then back to work normally for one cycle and then back to same performance in the same manner.

Table 4. 14 – Short injection time, 1.5 in - with varied R

Dome Pressure	2	bar	Initial Load	0.6	bar
Cycle Time	10	s	Supply Line	6	bar
Injection Time	1	s	Valve's Area Ratio	0.255	

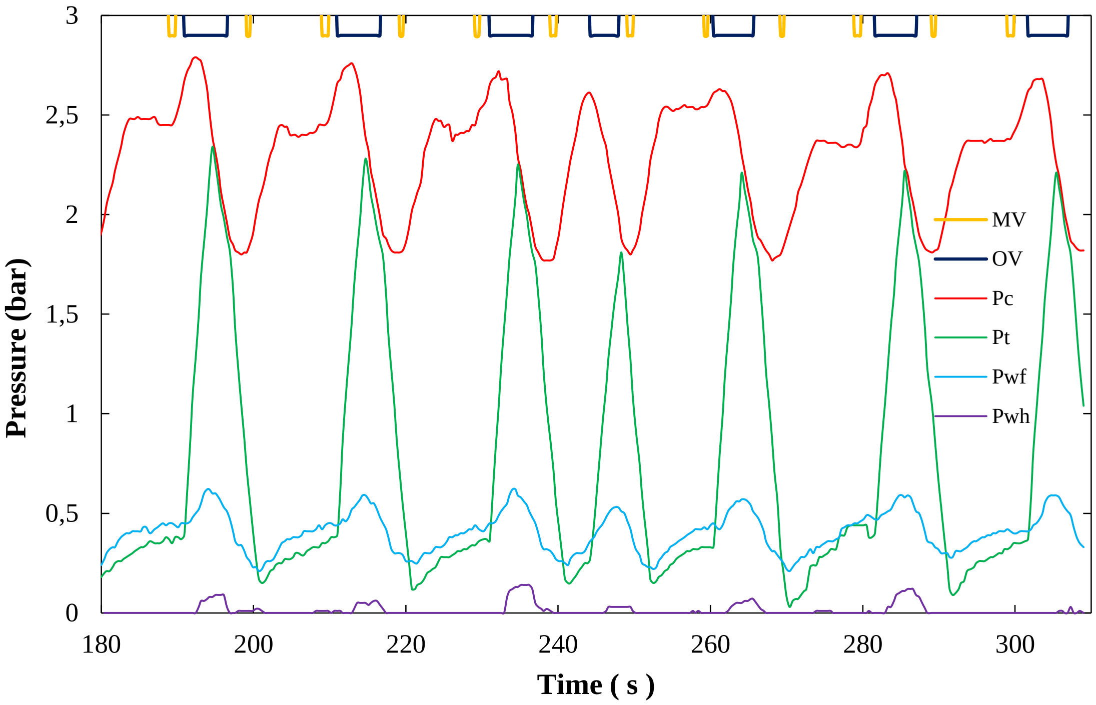


Figure 4. 23– 2nd run, Pressure recording- short injection time

From pressure recordings shown in Figure 4.23 it was observed that depends on the length of the injection time, how many cycles the casing pressure needs to build up slightly again by each cycle until reaches the point when casing pressure able to open the operating valve from only one cycle before to turn be unstable again.

Long Injection Time

Under given valve’s area ratio, Table 4.15, stability is presented by the match of operating valve and motor valve: the gas enters the tubing almost at the same rate that the gas enters the casing, so the injection pressure during the operating valve is open remains constant. This might requires higher GLR during long injection period which is undesirable and the cycle stability in this case depends on the valve’s area ratio. In Figure 4.24 the stages of elevation, feeding and decompression of the cycles remain stable; the difference in the sequential cycles is the moment of opening of the motor valve, which occurs depends on the cycle period length, with a smaller slug of fluid buildup at longer injection time and shorter cycles, results in lower recovery fractions. However, in other cases this kind of pressure recordings chart might indicate to a restriction or the gas-lift system not being able to supply a high flow rate or the opening pressure of the operating valve has set too close to the available pressure at the gas injection manifold.

Table 4. 15 - Long injection time 1.5 in- varied R.

Dome pressure	2	bar	Initial Load	0.6	bar
Cycle length	25	s	Supply Line	6	bar
Injection time	10	s	Valve’s Area Ratio	0.255	

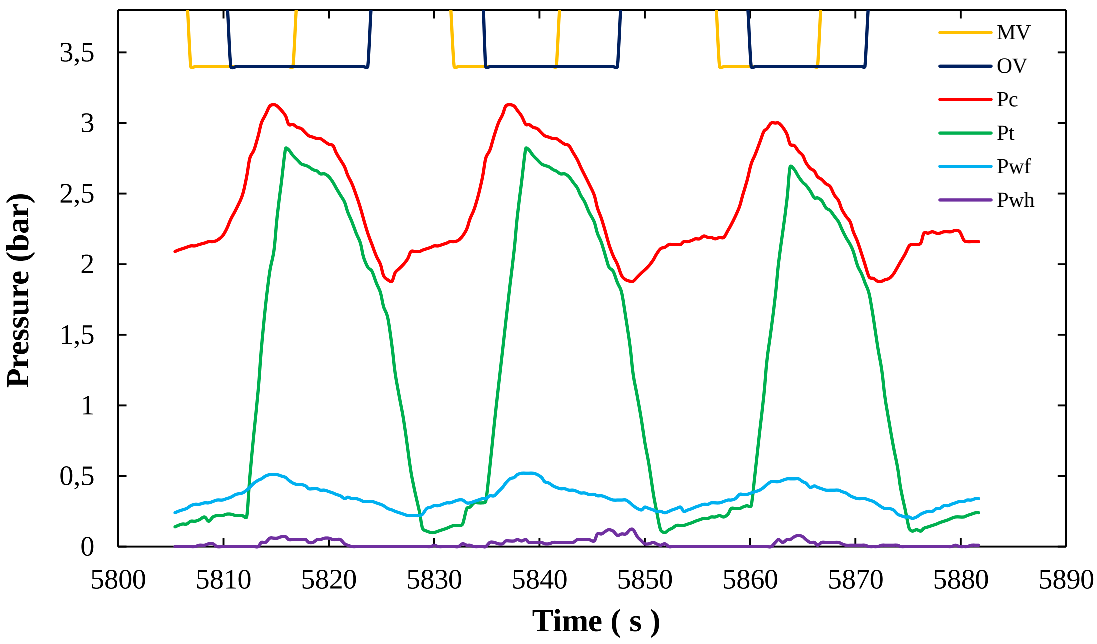


Figure 4. 24- Pressure recording - long injection time 1.5 in.

Long Cycle Time

Under long cycle time Table 4.16 the reservoir will be given more time allowing to more fluid accumulation to occur and the bottom pipe flowing pressure will increase in low rate after a certain time due to both of the reservoir feeding and the fallback as portion from the previous cycle, until the hydrostatic pressure inside the conduit reaches the maximum level, Figure 4.25. Then the deferential pressure will be zero, which means there is no more fluid produced, after this moment every second will be lost without reservoir participating and the daily production will considerably be lower than the maximum production that can be obtained from the model, due to the lower numbers of cycles per day, unless that the increment of the pressure build up inside the tubing matches the valve dome pressure Pd causing the opening of the operating valve, while proper operation for opening the operating valve must occur with increasing of casing pressure, and not from increasing tubing pressure.

Table 4. 16 - Long cycle time 1.5" - varied R.

Dome Pressure	2	bar	Initial Load	0.6	bar
Cycle Time	200	s	Supply Line	6	bar
Injection Time	5	s	Valve's Area Ratio	0.255	

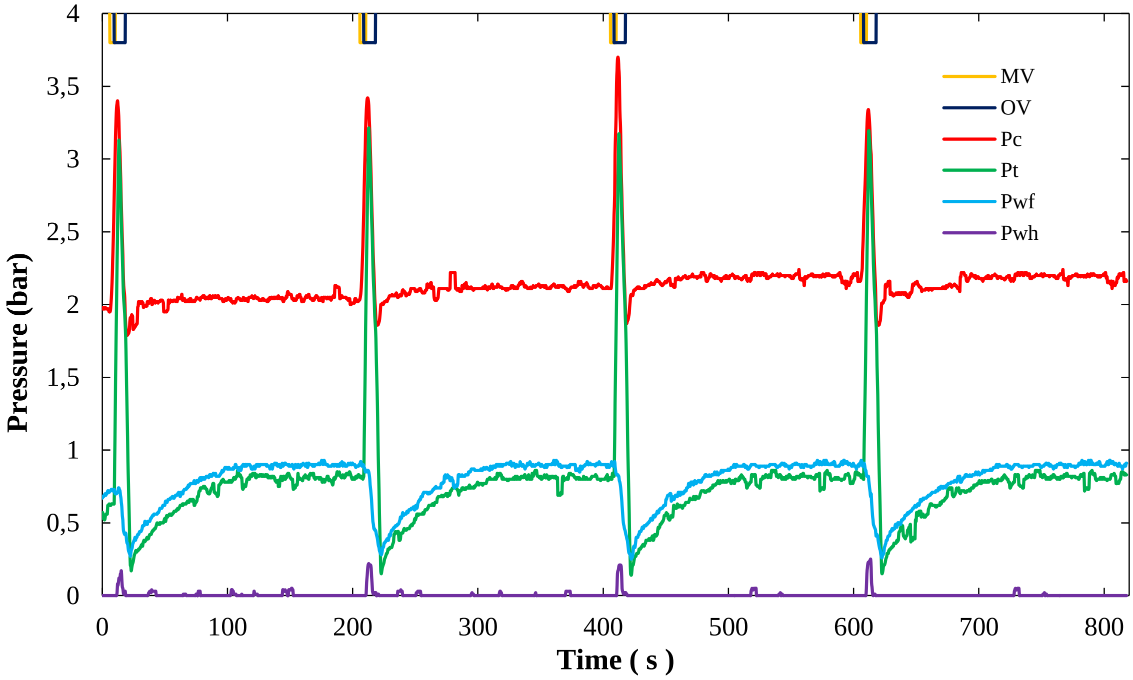


Figure 4. 25- Pressure recording - long injection time 1.5 in.

Short Cycle Time

It was observed under too short cycle period length, Table 4. 17 the injection gas liquid ratio will be high by increasing the cycles' number per day and the daily liquid production will be below the potential of the well depends on the productivity index which governs the relation between column height and accumulation time while the period of time needed to permit adequately gradual increase in liquid slug Figure 4.26 shows bottom pipe pressure recordings no adequate liquid accumulation during the cycle time, which means the model produces below the potential production.

Table 4. 17 - Short cycle time 2" - varied R

Dome pressure	3	bar
Cycle time	30	s
Injection time	5	s

Initial Load	0.6	bar
Supply Line	6	bar
Valve's Area Ratio	0.069	

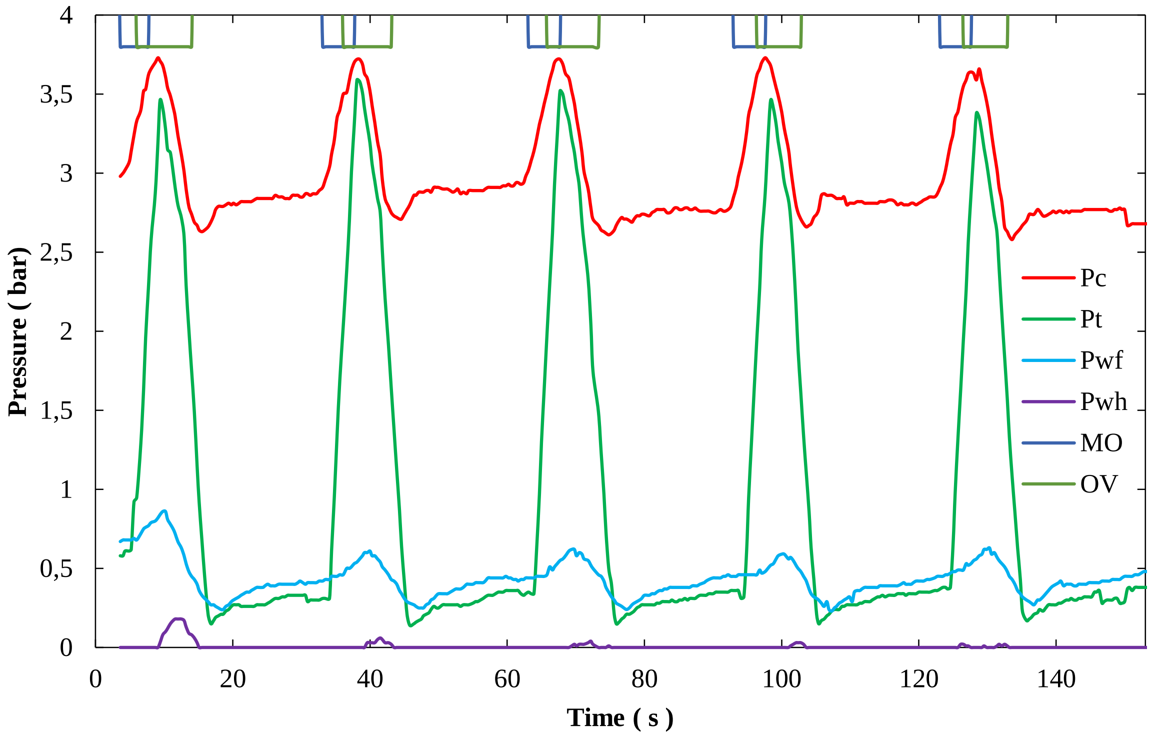


Figure 4. 26- Pressure recording - short cycle time 2 in.

However, a time map is shown in Figure 4.27, summarizes the points tested in this group, and the model performance was verified under various combinations between long and short injection time against long and short cycle time.

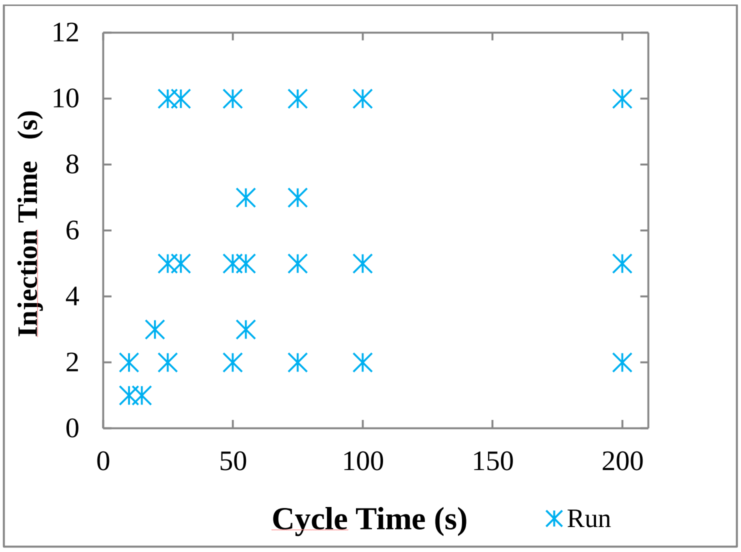


Figure 4. 27- Time map for tested injection time vs. cycle time

Group III

Since the main part of the cycle dynamics depends on the operating valve mechanism, (open-close; positions), the controlling role of programmed relation between valve's area ratio, dome pressure and pressure upstream and downstream the valve, is to hold the valve in the close position at designed conditions, while it allows the valve to open only when the combined forces of the gas injection pressure upstream and the pressure inside tubing matches the valve opening conditions, that means the upstream forces exceeded the valve closing forces. Therefore, at the moment the valve opens, the gas enters into the production conduit and the rate of high-pressure gas expansion are depends on the valve's area ratio which was altered in this group of experiments between two values (0.069 - 0.255).

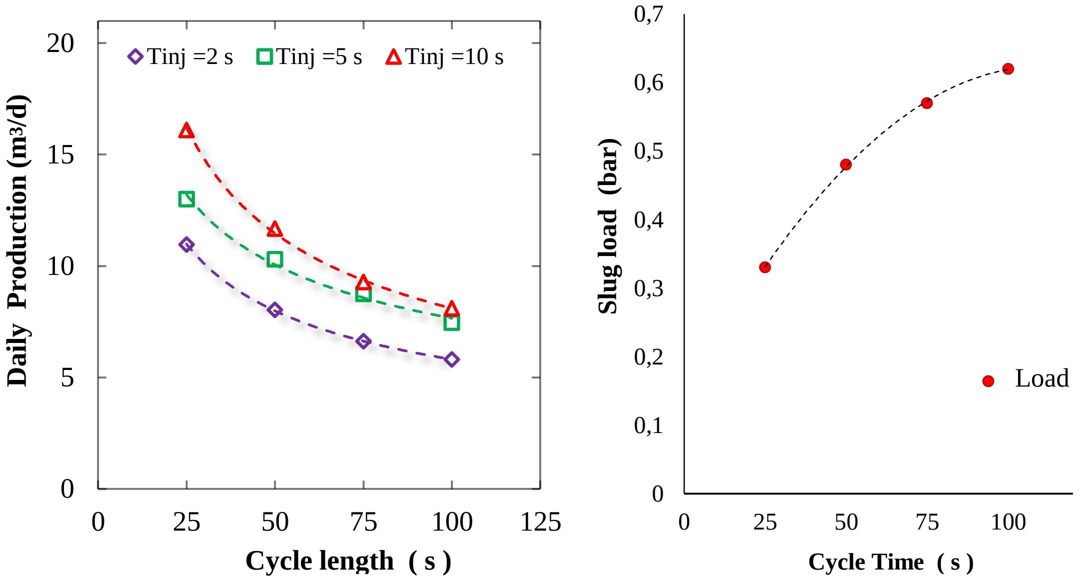
However, the former method was applied in order to measure the average daily production and determine the optimum operational parameters related to the effect of cycle time and injection time using same pipe diameter. On the other hand, was to study the effect of the valve's area ratio and the dome pressure effect on the average daily production by varying alternatively the production conduit diameter under same injection time and cycle time.

The average daily production rate (Q) was calculated from Equation (4.3):

$$Q = \frac{Vc}{Tc}$$

Where Vc; is the average produced volume per cycle (m^3).

Figure 4.28-a, illustrates the average daily production for the 1.5″ pipe for three different injection times (2, 5, 10 s) and four cycle times (25 s, 50 s, 75 s and 100 s). It was noticed that average daily production (Q) decreased (50%), by increasing the cycle length (400%) from 25 to 100 seconds, while Figure 4.28-b illustrates the shorter the column the faster the accumulation time, the higher the number of cycles per day. It should be mentioned here that valve's area ratio was held during this set of experiments at the level (R = 0.255, Pd = 2 bar).



(a) (b)

Figure 4. 28- Daily production for varied cycle times and injection times

On the other hand, the bottom-pipe pressure recording justifies the former results, due to the relationship between the slug increment and the cycle time, where it is for the first runs under 25 seconds cycle time, the bottom-pipe pressure increased 0.33 bar only in 25% of the time needed for the bottom-pipe pressure to increase 0.62 bar in longer cycle period (100 s). On the other hand, it was observed in comparison with the daily production for the three pipe diameters, under same operational parameters combinations of the dome pressure, cycle time, injection time and two different valve’s area ratios, Table 4. 18

Table 4. 18 - Parameters combinations - daily production 1.5"

Dome Pressure	5	bar
Valve’s Area Ratio	0.069	
Cycle Time	55	s
Injection Time	5	s
Initial Load	0.6	bar

Dome Pressure	2	bar
Valve’s Area Ratio	0.255	
Cycle Time	55	s
Injection Time	5	s
Supply Line	6	bar

Figure 4.29, shows the daily production largely increases by increasing the production diameter from 1" to 1.5" and slightly difference between 2" diameter and the 1.5" diameter, where the daily production relatively decreases.

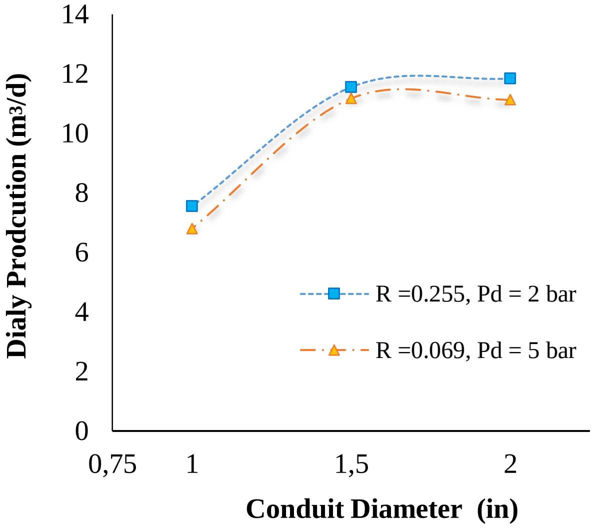


Figure 4. 29- Daily production for three different diameters

Considering that the liquid produced volume per cycle is given by Equation (4.4),

$$V_c = V_i - V_f \tag{4.4}$$

Where, V_i and V_f *are*, respectively, the initial liquid slug volume and the fallback volume,

This was justified by higher accumulated volume for 1.5" tubing size, in comparison with the rate of increase the fallback during the same cycle time with 1 in diameter, but with higher fallback factor associated with the 2 in diameter which results in slightly lower production.

Repeatability

It was observed from this set, under same parameters combinations, Table 4.19 for the dome pressure and pipe diameter, that the pressure recording chart, Figure 4.30, shows stable intermittent cycles with good repeatability and continuous slug being produced with faster pressure reduction depends on the length of the injection period.

Table 4. 19 - Repeatability test 1.5 in.

Dome Pressure	5	bar	Initial Load	0.6	bar
Cycle Time	55	s	Supply Line	6	bar
Injection Time	5	s	Valve's Area Ratio	0.069	

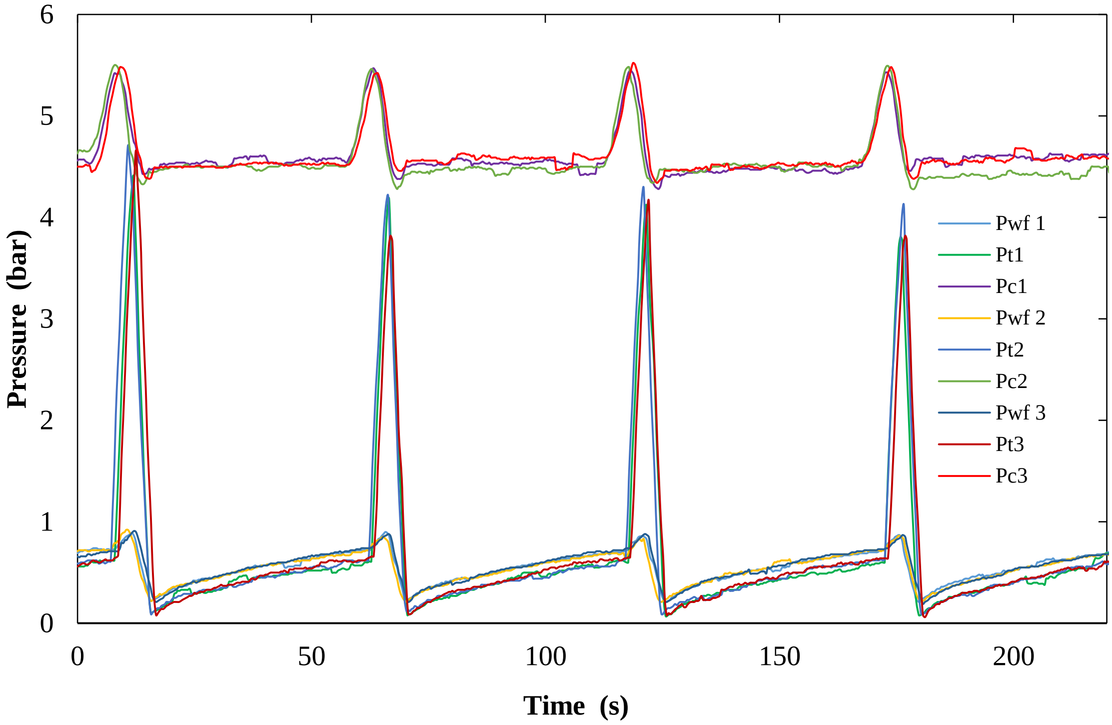


Figure 4. 30- Pressure recording- Repeatability test

Tests were done with under same timings (tc, tinj), The parameters used were: Pinj = 6 bar, Pto = 5.5 bar, and the operating valve was set with Pd = 5 bar and R = 0.069. A stable cycle which is identified by synchronization of the operating valve with the motor valve and stability of fallback over the cycles, therefore the opening of operating valve occurs at the same height of the liquid load for every cycle.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objectives of this study were both revealing and determining the dynamics and stability of a conventional intermittent gas lift system cycles in a laboratory model for different base operational parameters, and prior to performing optimization or virtual simulations, experimental work was conducted to determine the model performance under varying operational parameters, as well as to examine the parameters levels limitations.

Experimental work has been done to investigate the CIGL cycle process; however, the work published to date has been limited. This comprehensive study shows that the model performance significantly improved or degraded depends on the model design and the selected operational parameters.

By conducting multiple test scenarios, it is now understood that this model does not react similar to varied factor levels and cannot be easily predicted from just one study. However, experiments measurements employed for the evaluation and the following conclusions are drawn from this research in two phases: no time one-shot tests and full time record of sequential cycles.

Phase I: One-shot experiments.

The laboratory-scale model provided valuable data which used to evaluate the variation of working parameters limitations such as the production conduit diameter, operating valve mechanism including dome pressure and its effect on the dynamics and stability of operating sequence.

The operating valve being used in this model is a solenoid valve and its function depends on the accuracy of both of the pressure transmitters upstream and downstream the valve, led to influence the dynamics of the CIGL cycles and the model performance as a result. However, two factors have studied fallback and gas injection per cycle.

Fallback:

It has been found that the fallback factor per cycle is a function primarily of the following:

1- **Operating valve**

Valve's closing pressure**:** for the same slug load, it has been found that the fallback increases under held opening pressure by increasing the closing pressure of the valve.

Valve's opening pressure: it has observed that the fallback increases in lower rate by increasing the closing pressure for a lower opening pressure, in comparison with a higher level of the opening pressure.

2- **Production conduit diameter**

The fallback effect under same liquid slug load does significantly increase by increasing the size of the production conduit diameter.

3- **Liquid slug load:**

The fallback rapidly decreases in greater range with higher rate for the lower level of the slug load than the higher level of the slug load, with respect that the decreasing rate will be higher for the smaller conduit diameter.

The fallback decreases in smaller range with lower rate for the higher level of the slug load than lower level of slug load with respect that the decreasing rate will be lower for the smaller conduit diameter.

Volume of gas per cycle:

It has been found that the recovery increases relatively in small range , by extremely increasing the gas injection volume, at the same time was observed that depends on the slug load, the recovery percentage slightly increases by increasing the slug load. While under the same liquid slug load with varying the conduit diameter, the recovery percentage slightly decreases by increasing the tubing diameter size.

Phase II: Full time cycles record.

Here, the pressure recording gives the first indication of the efficiency of the laboratory model and its capacity under determined conditions. However, it was observed during the course of this study, where casing pressure recording associated with both of tubing and pipe-head pressure recording, an essential data have been obtained from which the laboratory model, the operating valve and the time cycle controller performance can be inferred. Therefore recording charts represent when and under which conditions a good intermittent operation with a continuous slug being produced and a fast pressure reduction will occur, determining the optimum conditions from which could be extended to be applied on the field operation.

In light of this, pressure recording measurements employed for model efficiency and cycle’s stability evaluation and the following conclusions are drawn from this study:

- Under same parameters combinations of injection time and cycle frequency, with varying dome pressure levels, the average daily production of the system increases for the lower dome pressure, in comparison with, lower cycle frequency, which results in lower daily production due to the time loss during the feeding time with no high increasing in the rate of the slug level inside the tubing.
- The bottom pipe pressure recording shows the initial liquid slug is lower with bigger production conduit diameter under same productivity and cycle

frequency, but in higher increasing rate of liquid accumulation, what justified by the daily production highly increases by using 1.5 in. in comparison with 1 in. in diameter. On the other hand, it was observed that the daily production slightly decreases by using 2 in. diameter for the tubing, in comparison with the daily production for the 1.5 in tubing size under the same operational parameters, which justified by the higher fallback factor effect for 2 in. tubing size in comparison with lower rate of slug load increase during the same cycle frequency with 1 in.

- The better cycle frequency selection effect is higher than the fallback factor effect by increasing the tubing diameter.

- It was observed, that the daily production of the system increases for a higher injection time level under the same other operational parameters

- The operating valve opens and closes repeatedly after each cycle under low dome pressure levels and depends on the valve’s area ratio, but in steady behavior along the production process without affecting on the system daily production, when the gas flow rate out of the annular space is greater than the gas flow rate supplied by the gas line system,

- At short injection time, the injection gas is not sufficient to increase the pressure in the tubing-casing annulus to match the valve's opening conditions; in this case the model takes two sequential cycles to increase Pc to open the operating valve in unstable behavior what highly affects the productivity of the model.
- Under same parameters combinations for the dome pressure and injection time with varying cycle frequency, it was observed, that the daily production is a function of the liquid slug load accumulated during longer or shorter cycle length, while the daily production will decrease after certain level due to the

effect of increasing or decreasing the number of cycles on the total daily production, in comparison with the slug load in one single cycle.

5.2 Recommendations for future research and program development

This study is only the beginning to help understand the reactions of the laboratory scale model on some of the operational parameters in order to develop a mathematical simulator for the conventional intermittent gas lift system (CIGL). However, such simulator may be extended for mature oilfield wells and be applied to design the CIGL cycles and the injection gas volume per cycle to achieve optimum production rates. Short term future work include testing different fluids varying density and viscosity, will aid in better understanding and mapping the dynamic behavior of the model. However, the following recommendations are made for future study.

Operating configuration

- Currently, it is known that the operating valve mechanism has considerable effect on the cycle dynamics, but the performance of the model to a pressure operated-valve cannot be confidently predicted. As a supplement to this testing, operating valve seat can be installed directly on the production conduit to observe the behavior of gas-liquid interference at the moment the operating valve opens.

- In this study, water and air were used in all experiments as reservoir fluid and injection gas, respectively. Therefore, the system can be tested by varying the fluid’s viscosity and density for more advanced study.

- The accuracy of the measurements used in this research depends on several pressure transmitters and their calibration, and it can improve the data acquisition system performance by increasing the sensors number and by installing further gas and liquid flow meters on the reservoir feeding system and the gas supply line respectively, in order to obtain comprehensive measurements.

Modeling

It was mentioned in the introductory chapter that this study is a part of three stages project and as the second part has done while the objective of the results of current experimental work, is to be used to develop a mathematical model for the CIGL model.
However, some difficulties may be encountered developing such correlations for this model. Since it was assumed to have a surface interference between the two phase gas-liquid, it was noticed during this experimental work that the flow pattern is an annular flow and was not an ideal liquid slug-gas bubble as perfectly assumed in the theoretical studies, which is hard to achieve practically.

However, once a model is developed and prior to be used, its validity has to be under examination, what means, the predictions of the model are confronted with data that have not been used for estimating the parameters of this model. In many cases, model validation process is not that simple one and it is related to the purpose of the model

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Appendix - A

Here, some of the equipment used in this study will be presented in this section.

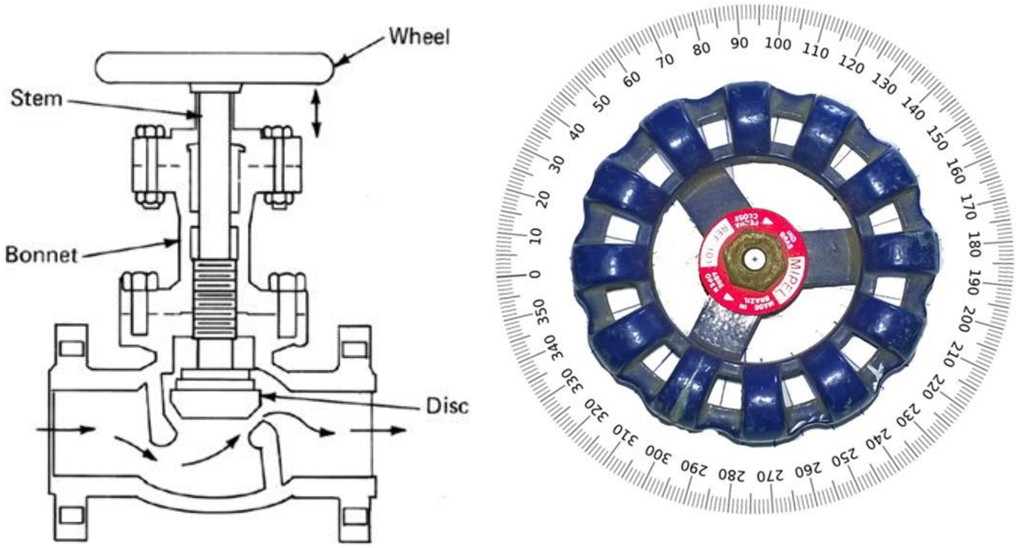


Figure A. 1– Scheme and photograph of the variable flow valve (1 in)

used in this study with the tool used to adjust the opening of the valve and as a result determine the productivity of the valve.

Figure A. 2– Photograph of the pressure transmitter used in this study

Figure A. 3– Photograph of lab-room

Figure A. 4– Photograph of the top of vertical section

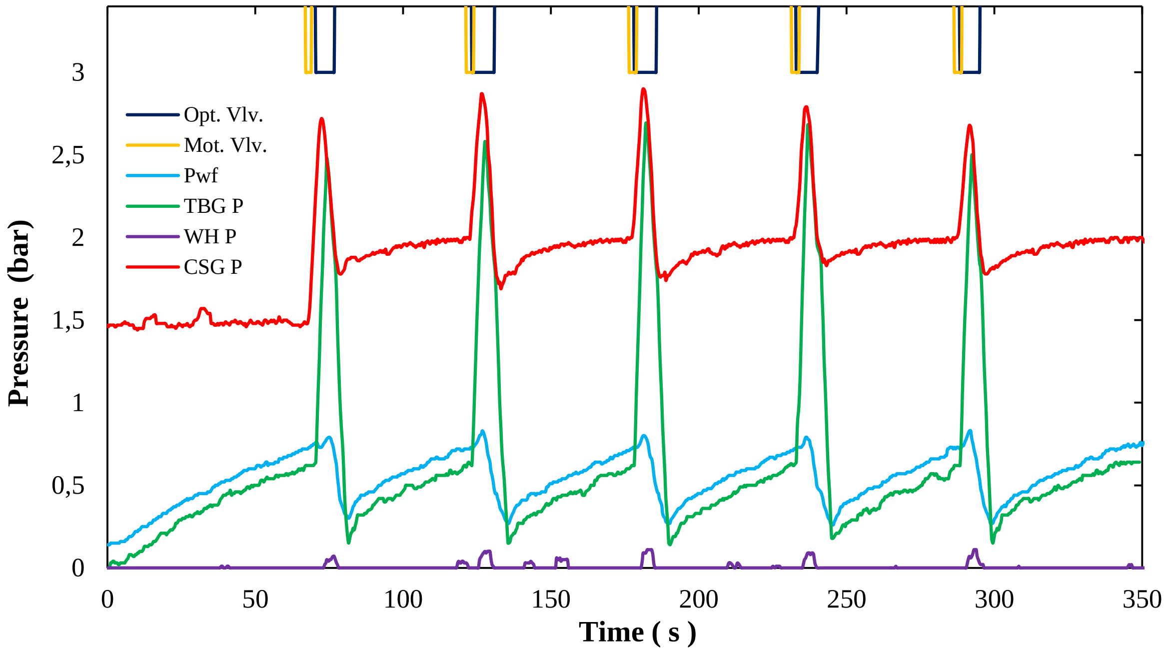
Figure A. 5– Photograph of the vertical section side and top view

Figure A. 6– Photograph on the right portable tank elevation mechanism, on the left the separator

Appendix – B

In this section some results and levels were not included in previous chapters will be provided here, because they do not show any changes outside of those induced through the variation in test conditions.

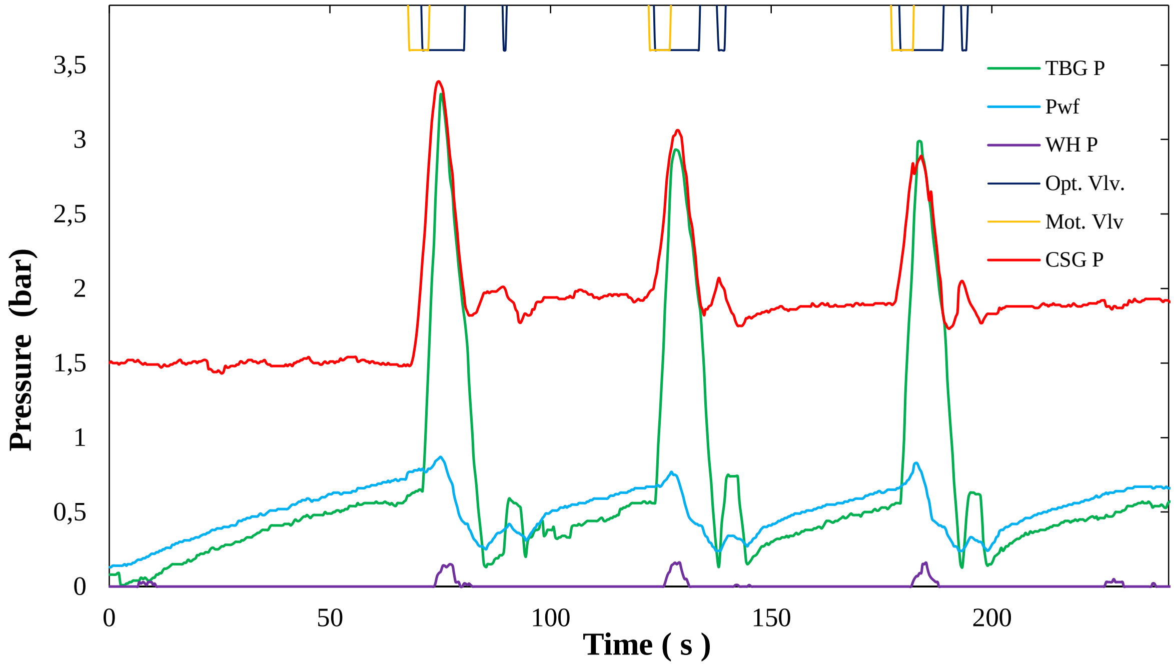
Production Conduit (1.5 in)



Dome pressure	2	bar
Cycle time	55	s
Injection time	3	s

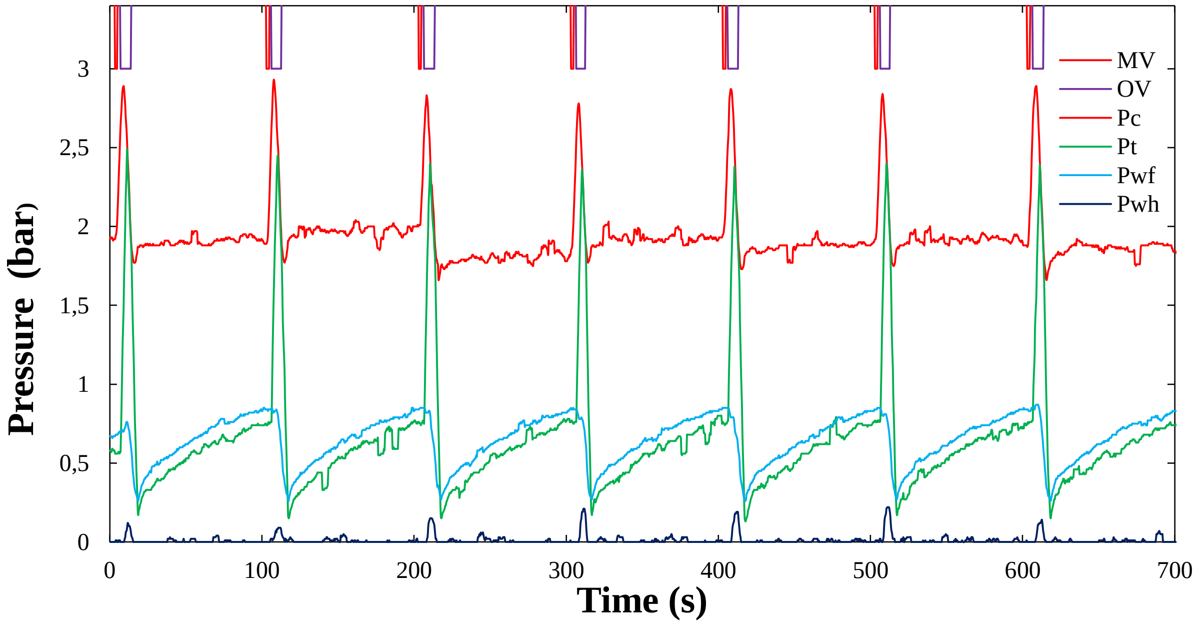
Initial Load	0.6	bar
Supply Line	6	bar
Daily production	65.07	bbl/d

Figure B. 1- Pressure Recordings Pd=2 bar, Ti= 3 s, (1.5")



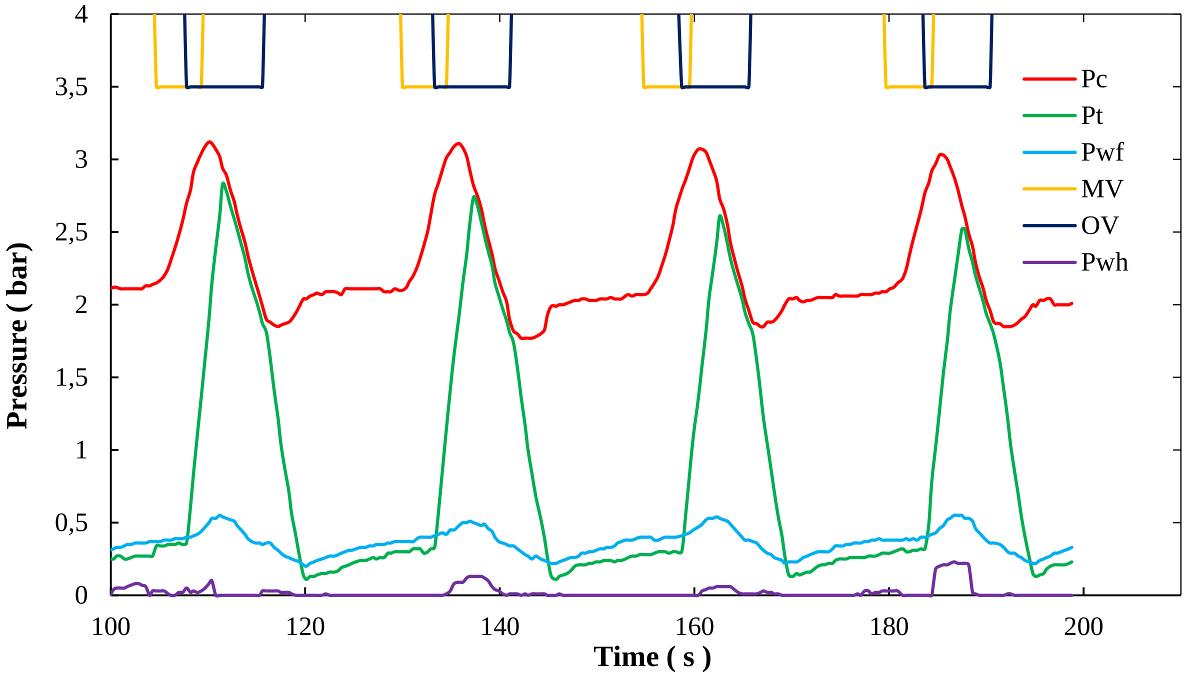
Dome Pressure	2	bar	Initial Laod	0,6	bar
Cycle Time	55	s	Supply line Pressure	6	
Injection Time	5	s	Daily Production	73,30	bbl/d

Figure B. 2- Pressure Recordings Pd=2 bar, Ti= 5 s, (1.5")



Dome Pressure	2	bar	Initial Load	0.6	bar
Cycle Time	100	s	Supply Line	6	bar
Injection Time	2	s	Valve's Area Ratio	0.255	

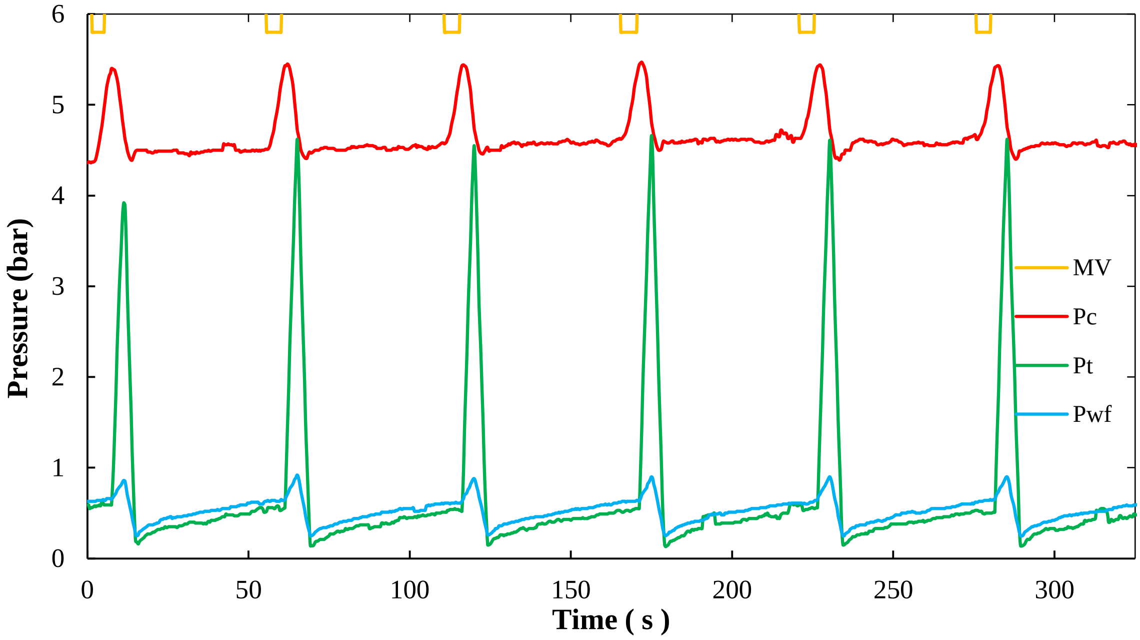
Figure B. 3- Pressure Recordings Pd=2 bar, Ti= 2 s, (1.5")



Dome Pressure	2	bar	Initial Load	0.6	bar
Cycle Time	25	s	Supply Line	6	bar
Injection Time	5	s	Valve's Area Ratio	0.255	

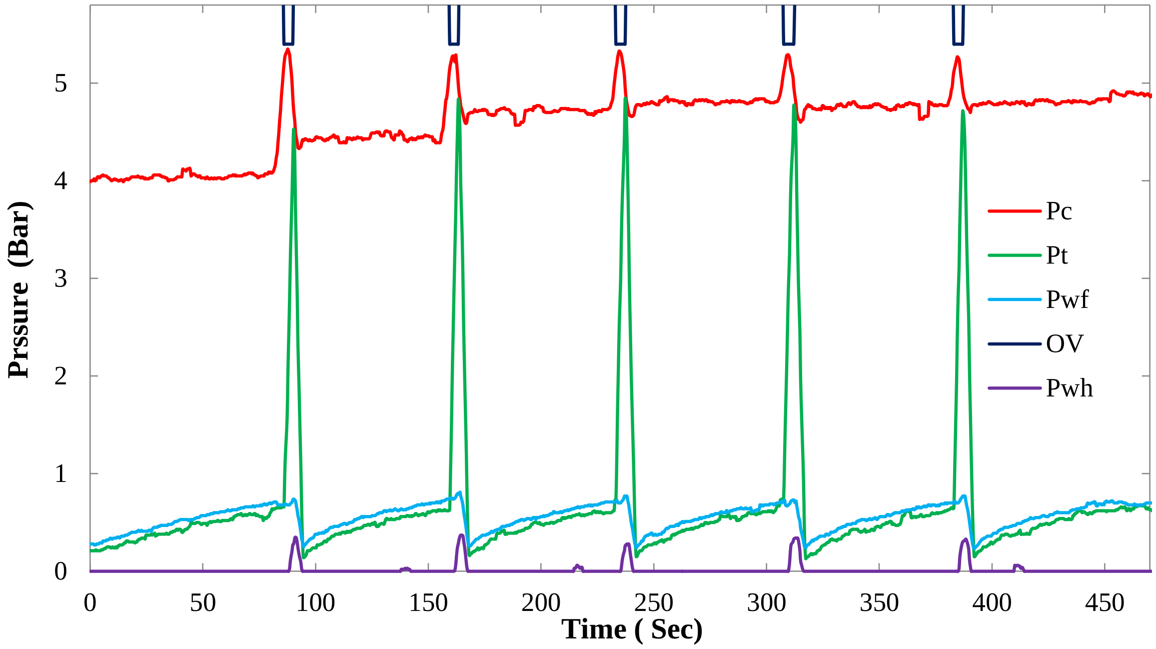
Figure B. 4- Pressure Recordings Pd=2 bar, Ti= 5 s, Tc=25 s, (1.5")

Production Conduit (2 in)



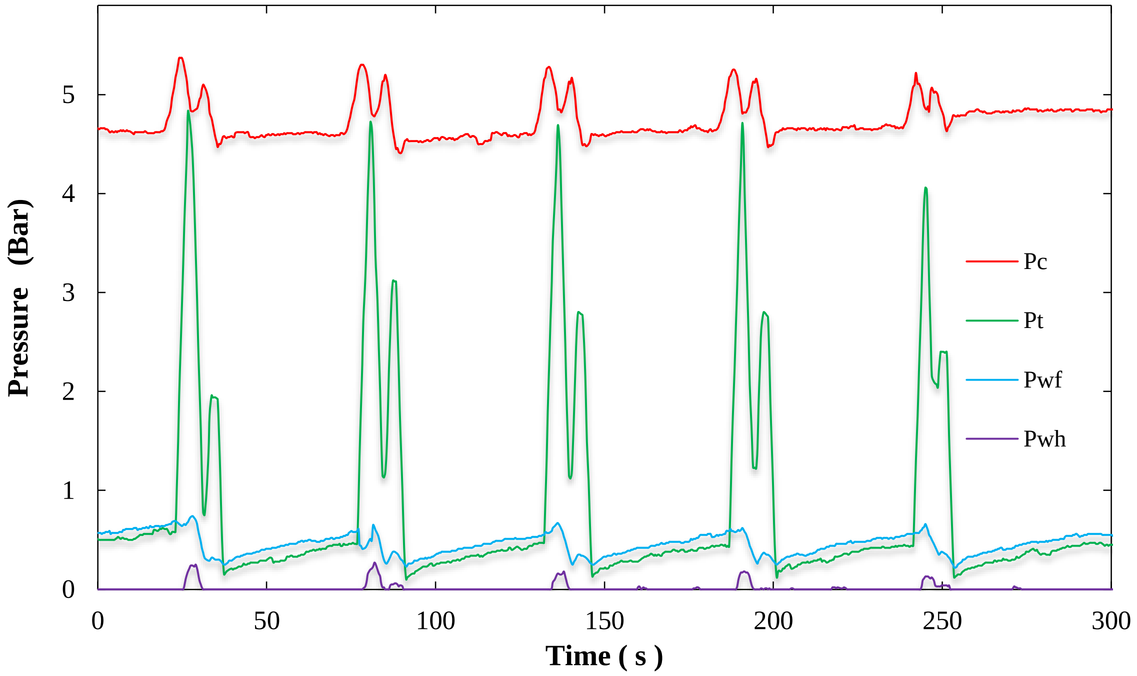
Dome pressure	5	bar	Initial Load	0.6	bar
Cycle length	55	s	Supply Line	6	bar
Injection time	5	s	Valve's Area Ratio	0.069	

Figure B. 5- Pressure Recordings Pd=5 bar, Ti= 5 s, (2")



Dome Pressure	5	bar	Initial Load	0.6	bar
Cycle Time	55	s	Supply Line	6	bar
Injection Time	7	s	Daily Production	66.3	bpd

Figure B. 6- Pressure Recordings Pd=5 bar, Ti= 7 s, (2")



Dome Pressure	5	bar	Initial Load	0.6	bar
Cycle Time	55	s	Supply Line	6	bar
Injection Time	10	s	Daily Production	63.1	bpd

Figure B. 7- Pressure Recordings Pd=5 bar, Ti= 10 s, (2")

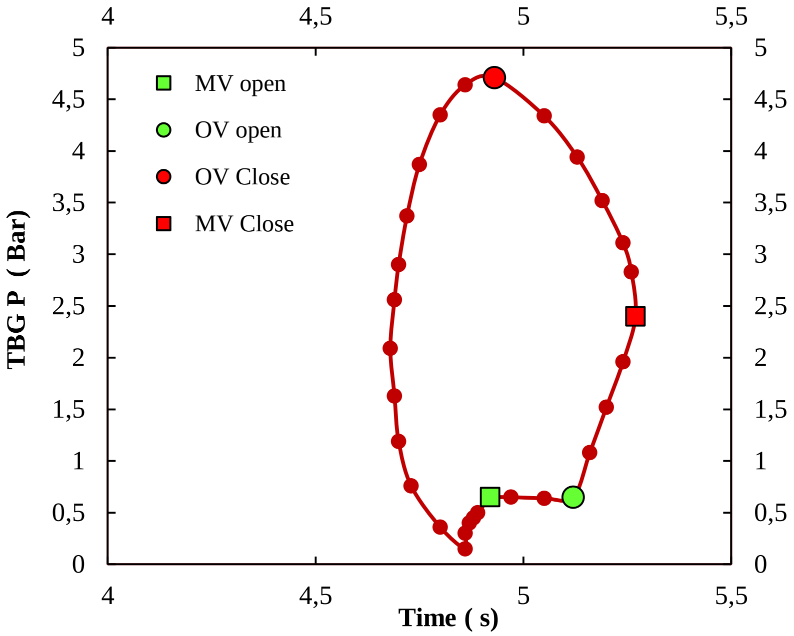


Figure B. 8- Pc vs. Pt (2")

Appendix - C

Table C.1-Bottom-pipe pressure record for three Different diameters

PI = 19.1 m^3/d.bar   Pwf = Bottom-pipe Pressure

2 in		**1.5 in**		**1 in**	
Time	**Pwf** (bar)	**Time**	**Pwf** (bar)	**Time**	**Pwf** (bar)
0	0.06	0	0.045	0	0.045
0.4	0.06	0.4	0.045	0.4	0.045
0.7	0.06	0.8	0.055	0.8	0.055
1.1	0.06	1.1	0.055	1.1	0.055
1.5	0.05	1.5	0.055	1.5	0.055
1.9	0.05	1.9	0.055	1.9	0.055
2.4	0.05	2.6	0.055	2.6	0.055
2.9	0.05	3	0.065	3	0.065
3.3	0.05	3.3	0.065	3.3	0.065
3.7	0.05	4.1	0.085	3.7	0.075
4.1	0.06	4.4	0.095	4.1	0.085
4.4	0.06	4.8	0.105	4.5	0.085
5.2	0.07	5.2	0.115	4.8	0.095
5.7	0.07	5.6	0.115	5.2	0.105
6	0.07	5.9	0.115	5.6	0.115
6.4	0.08	6.3	0.125	5.9	0.125
6.8	0.09	6.7	0.125	6.3	0.125
7.1	0.09	7	0.135	6.7	0.135
7.5	0.09	7.4	0.135	7.1	0.145
7.9	0.1	7.8	0.145	7.4	0.155
8.3	0.1	8.1	0.145	7.8	0.155
8.6	0.1	8.5	0.145	8.2	0.165
9	0.1	8.9	0.145	8.5	0.175
9.4	0.1	9.3	0.155	8.9	0.175
9.7	0.11	9.6	0.155	9.3	0.185
10.1	0.11	10	0.155	9.6	0.185
10.5	0.11	10.4	0.165	10.2	0.195
10.9	0.12	10.7	0.165	10.6	0.195
11.2	0.12	11.1	0.175	11	0.205
11.6	0.12	11.5	0.175	11.3	0.215
12	0.13	11.9	0.185	11.7	0.225
12.3	0.13	12.2	0.185	12.1	0.225
12.7	0.13	12.6	0.185	12.4	0.235
13.2	0.14	13	0.195	12.8	0.235

13.6	0.14	13.3	0.205	13.2	0.245
14.1	0.14	13.8	0.205	13.5	0.255
14.5	0.15	14.2	0.215	14.1	0.265
14.8	0.15	14.6	0.215	14.5	0.265
15.2	0.16	14.9	0.215	14.8	0.265
15.6	0.16	15.3	0.215	15.2	0.275
16.1	0.16	15.7	0.225	15.6	0.285
16.5	0.16	16.1	0.225	15.9	0.295
16.8	0.17	16.4	0.225	16.3	0.305
17.2	0.17	16.8	0.225	16.7	0.315
17.6	0.16	17.2	0.235	17	0.325
17.9	0.16	17.5	0.235	17.4	0.335
18.5	0.17	17.9	0.235	17.8	0.335
18.9	0.17	18.3	0.245	18.3	0.345
19.2	0.17	18.6	0.245	18.7	0.355
19.6	0.18	19.2	0.245	19.1	0.355
20.1	0.18	19.6	0.255	19.4	0.345
20.4	0.18	19.9	0.255	19.8	0.355
20.8	0.19	20.3	0.255	20.2	0.355
21.2	0.19	20.7	0.265	20.7	0.365
21.6	0.2	21	0.265	21.1	0.375
21.9	0.21	21.4	0.265	21.7	0.375
22.3	0.21	21.8	0.275	22.3	0.385
22.7	0.21	22.2	0.275	22.6	0.395
23	0.21	22.5	0.275	23	0.405
23.4	0.22	22.9	0.275	23.4	0.415
23.8	0.22	23.3	0.275	23.7	0.425
24.1	0.22	23.6	0.285	24.1	0.435
24.5	0.22	24	0.285	24.5	0.435
24.9	0.23	24.5	0.295	24.9	0.445
25.5	0.23	24.9	0.295	25.2	0.455
25.8	0.24	25.3	0.305	25.7	0.455
26.2	0.24	25.6	0.305	26.1	0.455
26.6	0.24	26	0.315	26.5	0.465
27	0.24	26.4	0.325	26.8	0.475
27.3	0.24	26.8	0.325	27.2	0.475
27.7	0.25	27.1	0.325	27.7	0.485
28.1	0.25	27.5	0.335	28.1	0.495
28.4	0.25	27.9	0.335	28.5	0.495
28.8	0.25	28.2	0.335	28.8	0.505
29.2	0.24	28.6	0.335	29.2	0.515
29.6	0.24	29	0.345	29.6	0.525
29.9	0.24	29.3	0.345	29.9	0.525
30.3	0.25	29.7	0.345	30.3	0.515
30.9	0.26	30.1	0.345	30.7	0.525

31.4	0.25	30.5	0.355	31.1	0.525
31.8	0.25	30.8	0.355	31.4	0.535
32.3	0.26	31.2	0.345	31.8	0.535
32.7	0.26	31.6	0.345	32.2	0.545
33.1	0.26	31.9	0.355	32.5	0.555
33.4	0.27	32.3	0.365	33.1	0.555
33.8	0.27	32.7	0.365	33.6	0.555
34.2	0.28	33	0.375	34	0.565
34.5	0.28	33.4	0.365	34.3	0.575
34.9	0.29	33.8	0.375	34.7	0.585
35.3	0.29	34.2	0.375	35.1	0.595
35.6	0.3	34.5	0.385	35.4	0.595
36	0.31	34.9	0.395	35.8	0.605
36.4	0.31	35.3	0.395	36.2	0.605
36.7	0.31	35.6	0.405	36.5	0.615
37.1	0.31	36	0.405	36.9	0.615
37.5	0.31	36.4	0.405	37.3	0.625
37.9	0.31	36.9	0.405	37.7	0.625
38.2	0.32	37.3	0.405	38	0.635
38.6	0.32	37.6	0.405	38.5	0.635
39	0.32	38	0.415	38.9	0.635
39.3	0.32	38.4	0.415	39.5	0.635
39.7	0.32	38.7	0.425	39.8	0.645
40.1	0.32	39.1	0.435	40.2	0.655
40.4	0.32	39.5	0.435	40.6	0.655
40.8	0.33	39.8	0.445	41	0.665
41.2	0.33	40.2	0.445	41.3	0.665
41.6	0.33	40.6	0.455	41.7	0.665
41.9	0.33	41	0.455	42.1	0.675
42.3	0.34	41.3	0.465	42.4	0.675
42.7	0.32	41.7	0.465	42.8	0.675
43	0.32	42.1	0.465	43.3	0.685
43.4	0.33	42.4	0.475	43.7	0.685
43.8	0.33	42.8	0.475	44.1	0.685
44.1	0.33	43.2	0.475	44.8	0.685
44.5	0.33	43.5	0.465	45.4	0.685
44.9	0.34	43.9	0.475	45.8	0.695
45.3	0.34	44.3	0.465	46.2	0.705
45.8	0.34	44.7	0.465	46.7	0.715
46.2	0.34	45	0.465	47.1	0.715
46.6	0.35	45.4	0.485	47.5	0.715
47	0.35	45.8	0.475	47.8	0.715
47.3	0.35	46.1	0.485	48.2	0.725
47.7	0.35	46.5	0.485	48.6	0.725
48.2	0.35	46.9	0.485	48.9	0.735

48.6	0.36	47.3	0.495	49.3	0.745
49	0.36	47.6	0.495	49.7	0.745
49.4	0.36	48	0.495	50.2	0.735
49.7	0.37	48.4	0.495	50.6	0.735
50.1	0.37	48.7	0.505	51	0.745
50.5	0.37	49.1	0.515	51.3	0.745
50.8	0.37	49.5	0.515	51.7	0.755
51.2	0.37	49.8	0.515	52.1	0.755
51.6	0.38	50.2	0.515	52.4	0.755
52	0.38	50.6	0.515	52.8	0.765
52.3	0.38	50.9	0.525	53.2	0.765
52.7	0.39	51.3	0.525	53.5	0.765
53.1	0.39	51.7	0.525	53.9	0.775
53.6	0.39	52.1	0.515	54.3	0.775
54	0.39	52.4	0.515	54.7	0.775
54.4	0.4	52.8	0.525	55	0.785
54.8	0.4	53.2	0.525	55.4	0.785
55.1	0.4	53.5	0.525	55.8	0.785
55.5	0.4	53.9	0.525	56.2	0.785
55.9	0.41	54.3	0.525	56.7	0.785
56.2	0.41	54.6	0.535	57	0.785
56.6	0.41	55	0.535	57.4	0.785
57	0.42	55.4	0.535	57.8	0.785
57.3	0.42	55.9	0.535	58.3	0.785
57.7	0.42	56.3	0.545	58.7	0.785
58.1	0.42	56.6	0.545	59	0.795
58.4	0.42	57	0.545	59.4	0.795
58.8	0.43	57.4	0.555	59.8	0.795
59.2	0.43	57.8	0.555	60.1	0.805
59.6	0.43	58.2	0.555	60.5	0.805
59.9	0.44	58.6	0.555	60.9	0.815
60.3	0.44	59.2	0.555	61.3	0.805
60.7	0.44	59.5	0.565	61.6	0.805
61.1	0.44	59.9	0.565	62.2	0.815
61.6	0.44	60.3	0.565	62.6	0.805
62.2	0.45	60.6	0.555	62.9	0.795
62.5	0.45	61	0.565	63.3	0.805
62.9	0.45	61.4	0.565	63.7	0.815
63.3	0.45	61.7	0.565	64	0.805
63.6	0.45	62.1	0.565	64.4	0.805
64	0.46	62.5	0.575	64.8	0.805
64.4	0.46	62.9	0.575	65.2	0.815
64.8	0.46	63.2	0.575	65.5	0.805
65.1	0.46	63.6	0.585	65.9	0.805
65.5	0.46	64	0.585	66.3	0.805

65.9	0.47	64.7	0.595	66.6	0.805
66.4	0.47	65.1	0.595	67	0.805
66.7	0.47	65.5	0.605	67.4	0.815
67.1	0.47	65.9	0.605	67.9	0.825
67.5	0.47	66.3	0.605	68.2	0.825
67.9	0.47	66.6	0.605	68.6	0.825
68.2	0.47	67	0.615	69	0.825
68.6	0.48	67.4	0.625	69.3	0.825
69	0.48	67.8	0.635	69.7	0.825
69.3	0.48	68.1	0.635	70.1	0.825
69.9	0.46	68.5	0.635	70.5	0.825
70.2	0.47	68.9	0.635	70.8	0.825
70.6	0.47	69.2	0.635	71.2	0.825
71	0.48	69.6	0.645	71.7	0.825
71.6	0.48	70	0.645	72.1	0.825
71.9	0.48	70.4	0.645	72.5	0.825
72.3	0.48	70.7	0.645	72.8	0.825
72.7	0.49	71.1	0.635	73.2	0.825
73	0.49	71.5	0.635	73.6	0.835
73.4	0.49	71.8	0.645	73.9	0.835
73.8	0.5	72.2	0.645	74.3	0.835
74.1	0.5	72.6	0.645	74.7	0.835
74.5	0.5	72.9	0.655	75.1	0.835
74.9	0.51	73.3	0.655	75.4	0.835
75.2	0.51	73.7	0.655	75.8	0.835
75.8	0.51	74.1	0.655	76.4	0.835
76.2	0.51	74.4	0.665	76.9	0.835
76.5	0.52	74.8	0.665	77.3	0.835
76.9	0.52	75.2	0.665	77.7	0.835
77.3	0.52	75.5	0.665	78	0.835
77.9	0.52	75.9	0.675	78.4	0.835
78.3	0.52	76.3	0.675	78.8	0.835
78.7	0.52	76.6	0.675	79.2	0.835
79.1	0.52	77	0.685	79.7	0.835
79.4	0.52	77.4	0.685	80	0.835
79.8	0.52	77.8	0.685	80.4	0.835
80.2	0.53	78.1	0.685	80.8	0.835
80.5	0.53	78.5	0.685	81.1	0.835
80.9	0.53	78.9	0.685	81.5	0.835
81.3	0.54	79.5	0.675	81.9	0.835
81.6	0.55	79.9	0.675	82.2	0.825
82	0.54	80.3	0.675	82.6	0.825
82.4	0.55	80.6	0.675	83	0.815
82.8	0.55	81	0.675	83.4	0.825
83.1	0.55	81.4	0.675	83.7	0.825

83.5	0.55	81.8	0.675	84.1	0.815
84.1	0.55	82.1	0.675	84.5	0.815
84.4	0.55	82.5	0.675	84.8	0.815
84.8	0.55	82.9	0.685	85.2	0.815
85.4	0.54	83.2	0.685	85.7	0.815
85.7	0.54	83.6	0.685	86.4	0.825
86.1	0.55	84	0.695	86.8	0.825
86.5	0.55	84.3	0.705	87.2	0.835
86.9	0.55	84.7	0.705	87.5	0.835
87.2	0.55	85.1	0.705	88.1	0.835
87.6	0.56	85.5	0.705	88.5	0.835
88	0.56	85.8	0.705	89	0.825
88.3	0.56	86.2	0.715	89.5	0.825
88.7	0.56	86.6	0.705	89.9	0.825
89.1	0.57	86.9	0.705	90.3	0.825
89.4	0.57	87.3	0.715	90.8	0.835
89.8	0.57	87.7	0.715	91.2	0.835
90.2	0.57	88	0.715	91.6	0.835
90.8	0.57	88.4	0.715	92	0.825
91.1	0.57	88.8	0.715	92.3	0.825
91.5	0.57	89.2	0.715	92.7	0.825
91.9	0.58	89.5	0.725	93.2	0.825
92.3	0.58	89.9	0.725	93.6	0.825
92.6	0.58	90.3	0.725	94	0.825
93.1	0.58	90.6	0.725	94.4	0.825
93.5	0.58	91	0.735	94.7	0.835
93.9	0.58	91.4	0.735	95.3	0.835
94.2	0.58	91.7	0.725	95.6	0.835
94.6	0.59	92.1	0.725	96	0.835
95	0.59	92.5	0.725	96.4	0.835
95.4	0.59	92.9	0.725	96.8	0.845
95.9	0.6	93.2	0.725	97.1	0.845
96.5	0.6	93.6	0.715	97.5	0.845
96.8	0.61	94	0.725	97.9	0.835
97.2	0.61	94.3	0.725	98.2	0.835
97.6	0.61	94.7	0.725	98.6	0.835
97.9	0.62	95.1	0.725	99.1	0.845
98.3	0.62	95.5	0.725	99.5	0.845
98.7	0.62	95.8	0.725	99.9	0.845
99	0.63	96.2	0.735	100.3	0.845
99.4	0.62	96.6	0.735	100.7	0.835
99.8	0.62	96.9	0.735	101.1	0.845
100.1	0.62	97.3	0.735	101.5	0.855
100.7	0.62	97.7	0.735	101.8	0.855
101.3	0.62	98	0.745	102.2	0.855

101.6	0.62	98.4	0.745	102.6	0.855
102	0.63	98.8	0.745	103	0.855
102.4	0.62	99.2	0.745	103.5	0.855
102.7	0.63	99.5	0.745	103.8	0.855
103.2	0.63	99.9	0.745	104.2	0.855
103.6	0.63	100.3	0.745	104.6	0.855
104	0.63	100.6	0.755	104.9	0.855
104.3	0.63	101	0.755	105.3	0.845
105	0.64	101.4	0.755	105.7	0.855
105.4	0.64	101.7	0.755	106.1	0.855
105.8	0.64	102.1	0.755	106.6	0.845
106.1	0.64	102.5	0.755	107	0.855
106.5	0.65	102.9	0.755	107.4	0.845
106.9	0.65	103.2	0.755	107.7	0.845
107.3	0.65	103.6	0.755	108.1	0.845
107.6	0.65	104	0.755	108.5	0.845
108	0.64	104.3	0.755	108.9	0.835
108.4	0.64	104.7	0.765	109.2	0.835
108.7	0.63	105.1	0.765	109.6	0.835
109.1	0.63	105.4	0.765	110	0.835
109.5	0.64	105.8	0.765	110.3	0.845
109.9	0.64	106.2	0.765	110.7	0.845
110.2	0.64	106.5	0.765	111.1	0.845
110.6	0.64	106.9	0.765	111.5	0.845
111	0.64	107.3	0.755	111.8	0.845
111.3	0.64	107.7	0.755	112.2	0.845
111.8	0.64	108	0.755	112.6	0.845
112.2	0.65	108.4	0.755	112.9	0.845
112.7	0.65	108.8	0.755	113.4	0.845
113.1	0.65	109.2	0.765	113.8	0.845
113.5	0.65	109.5	0.755	114.2	0.845
113.8	0.65	109.9	0.755	114.6	0.835
114.2	0.66	110.3	0.755	114.9	0.835
114.6	0.66	110.6	0.765	115.3	0.835
114.9	0.66	111	0.775	115.7	0.835
115.3	0.66	111.4	0.775	116.2	0.835
115.7	0.66	111.7	0.775	116.6	0.835
116	0.66	112.1	0.785	116.9	0.835
116.4	0.67	112.5	0.785	117.3	0.835
116.8	0.67	112.8	0.785	117.7	0.835
117.2	0.67	113.2	0.785	118	0.835
117.5	0.67	113.6	0.795	118.4	0.835
117.9	0.67	114	0.785	118.8	0.835
118.4	0.67	114.3	0.785	119.1	0.835
118.8	0.67	114.7	0.795	119.5	0.845

119.1	0.68	115.1	0.785	119.9	0.845
119.5	0.68	115.4	0.785	120.3	0.845
120	0.68	115.8	0.795	120.6	0.845
120.4	0.69	116.2	0.795	121.2	0.845
120.8	0.68	116.5	0.795	121.6	0.845
121.1	0.68	116.9	0.795	121.9	0.845
121.6	0.67	117.3	0.795	122.3	0.855
122	0.69	117.7	0.795	122.7	0.845
122.4	0.69	118	0.795	123	0.835
122.9	0.69	118.4	0.795	123.6	0.835
123.3	0.69	118.8	0.805	123.9	0.835
123.7	0.69	119.1	0.805	124.3	0.835
124	0.7	119.5	0.805	124.7	0.835
124.4	0.69	119.9	0.805	125	0.835
124.8	0.69	120.2	0.805	125.4	0.845
125.2	0.7	120.6	0.795	126	0.835
125.5	0.7	121	0.795	126.3	0.835
126.2	0.7	121.4	0.795	126.7	0.835
126.6	0.7	121.9	0.795	127.1	0.845
127	0.71	122.3	0.795	127.4	0.845
127.3	0.71	122.7	0.795	127.8	0.855
127.7	0.7	123.1	0.795	128.2	0.845
128.2	0.71	123.4	0.805	128.6	0.845
128.6	0.7	123.8	0.805	128.9	0.845
128.9	0.71	124.2	0.815	129.5	0.835
129.3	0.71	124.5	0.815	129.9	0.845
129.7	0.71	124.9	0.815	130.2	0.845
130	0.7	125.3	0.815	130.6	0.835
130.4	0.7	125.6	0.815	131	0.835
130.8	0.7	126	0.815	131.4	0.835
131.1	0.7	126.4	0.825	131.7	0.835
131.5	0.7	126.8	0.825	132.1	0.835
131.9	0.71	127.1	0.815	132.6	0.835
132.3	0.71	127.5	0.815	133	0.835
132.6	0.72	127.9	0.815	133.4	0.835
133	0.72	128.2	0.815	133.7	0.835
133.4	0.72	128.6	0.815	134.1	0.835
133.7	0.72	129	0.815	134.5	0.835
134.1	0.71	129.3	0.815	135	0.835
134.6	0.71	129.7	0.815	135.3	0.835
135	0.72	130.1	0.815	135.7	0.835
135.4	0.72	130.5	0.815	136.1	0.825
135.7	0.72	130.8	0.805	136.4	0.835
136.1	0.72	131.2	0.805	137	0.835
136.5	0.72	131.8	0.805	137.4	0.835

136.9	0.72	132.1	0.815	137.7	0.835
137.2	0.72	132.5	0.815	138.1	0.825
137.8	0.72	132.9	0.815	138.5	0.825
138.2	0.72	133.3	0.815	138.8	0.835
138.5	0.73	133.6	0.815	139.2	0.825
138.9	0.73	134	0.815	139.6	0.835
139.4	0.73	134.4	0.815	140	0.825
140	0.73	134.7	0.815	140.3	0.815
140.6	0.73	135.1	0.815	140.9	0.825
140.9	0.73	135.5	0.815	141.2	0.845
141.4	0.73	135.8	0.815	141.6	0.825
141.8	0.73	136.2	0.815	142	0.835
142.2	0.73	136.6	0.815	142.3	0.835
142.5	0.74	137	0.815	142.7	0.835
142.9	0.73	137.3	0.815	143.1	0.845
143.3	0.73	138.1	0.815	143.4	0.845
143.7	0.74	138.4	0.815	143.8	0.845
144	0.74	138.8	0.815	144.2	0.845
144.4	0.75	139.2	0.815	144.6	0.835
144.8	0.75	139.5	0.815	144.9	0.835
145.1	0.75	139.9	0.815	145.3	0.835
145.7	0.75	140.3	0.815	145.8	0.835
146.1	0.75	140.6	0.825	146.2	0.825
146.4	0.75	141	0.835	146.8	0.825
146.8	0.76	141.4	0.825	147.3	0.825
147.2	0.76	141.8	0.835	147.6	0.825
147.7	0.76	142.1	0.835	148	0.825
148	0.76	142.5	0.835	148.4	0.825
148.5	0.76	142.9	0.835	148.7	0.845
148.9	0.76	143.3	0.835	149.1	0.845
149.3	0.77	143.6	0.835	149.5	0.845
149.6	0.77	144.2	0.835	149.8	0.845
150	0.77	144.6	0.835	150.4	0.855
150.4	0.77	144.9	0.835	150.8	0.855
150.8	0.77	145.3	0.825	151.2	0.855
151.1	0.77	145.7	0.825	151.5	0.845
151.5	0.76	146.1	0.825	152.1	0.845
151.9	0.76	146.5	0.825	152.5	0.845
152.2	0.76	146.9	0.825	152.8	0.845
152.6	0.76	147.2	0.825	153.2	0.845
153	0.76	147.6	0.825	153.7	0.845
153.4	0.76	148	0.815	154.1	0.845
153.8	0.77	148.4	0.815	154.4	0.845
154.2	0.77	148.7	0.815	154.8	0.845
154.6	0.76	149.1	0.815	155.2	0.835

155	0.77	149.5	0.825	155.6	0.835
155.3	0.77	149.8	0.825	155.9	0.835
155.7	0.77	150.2	0.825	156.3	0.835
156.1	0.77	150.6	0.825	156.9	0.835
156.4	0.77	151	0.825	157.2	0.835
156.8	0.77	151.3	0.825	157.8	0.835
157.2	0.77	151.7	0.825	158.5	0.835
157.6	0.77	152.1	0.825	158.9	0.835
157.9	0.77	152.4	0.825	159.3	0.835
158.3	0.78	152.8	0.825	159.6	0.835
158.7	0.78	153.2	0.825	160	0.835
159.2	0.78	153.6	0.825	160.5	0.835
159.7	0.78	153.9	0.825	160.9	0.835
160.1	0.78	154.3	0.825	161.2	0.845
160.5	0.78	154.7	0.825	161.6	0.845
160.8	0.78	155	0.825	162	0.845
161.2	0.77	155.4	0.825	162.4	0.845
161.6	0.77	155.8	0.825	162.7	0.835
162	0.78	156.1	0.825	163.1	0.835
162.3	0.78	156.5	0.825	163.5	0.835
162.7	0.78	156.9	0.825	163.8	0.835
163.1	0.78	157.2	0.825	164.4	0.845
163.6	0.78	157.6	0.825	164.8	0.845
164.1	0.78	158	0.835	165.1	0.845
164.5	0.77	158.4	0.835	165.5	0.845
164.9	0.77	158.7	0.835	165.9	0.845
165.2	0.77	159.1	0.835	166.3	0.845
165.6	0.77	159.5	0.845	166.6	0.845
166	0.77	159.8	0.845	167	0.835
166.3	0.78	160.2	0.845	167.4	0.835
166.8	0.78	160.6	0.845	167.7	0.825
167.2	0.78	160.9	0.845	168.1	0.835
167.6	0.78	161.3	0.845	168.7	0.825
167.9	0.78	161.7	0.845	169	0.825
168.3	0.79	162.1	0.855	169.4	0.825
168.7	0.79	162.4	0.855	169.8	0.815
169.1	0.79	162.8	0.845	170.1	0.825
169.6	0.79	163.2	0.845	170.5	0.825
169.9	0.79	163.5	0.835	170.9	0.835
170.3	0.79	163.9	0.835	171.2	0.835
170.7	0.78	164.3	0.835	171.6	0.835
171.1	0.78	164.6	0.845	172.2	0.835
171.4	0.79	165	0.835	172.5	0.835
171.8	0.79	165.4	0.835	172.9	0.835
172.2	0.79	165.8	0.815	173.3	0.835

172.5	0.79	166.1	0.815	173.6	0.835
173.1	0.79	166.5	0.825	174	0.845
173.5	0.8	166.9	0.815	174.4	0.845
173.8	0.79	167.2	0.825	174.7	0.845
174.2	0.79	167.6	0.825	175.5	0.845
174.6	0.8	168	0.825	175.9	0.845
175	0.8	168.4	0.825	176.3	0.845
175.3	0.8	168.7	0.825	176.8	0.845
175.7	0.8	169.1	0.825	177.2	0.835
176.1	0.8	169.5	0.835	177.6	0.845
176.4	0.79	169.8	0.835	178	0.845
176.8	0.79	170.2	0.835	178.3	0.845
177.3	0.79	170.6	0.835	178.7	0.835
177.7	0.79	170.9	0.835	179.1	0.845
178.1	0.8	171.3	0.835	179.4	0.845
178.4	0.8	171.7	0.835	179.8	0.855
178.8	0.8	172.1	0.835	180.3	0.845
179.2	0.8	172.4	0.835	180.7	0.845
179.6	0.8	172.8	0.835	181.1	0.845
180.1	0.81	173.2	0.835	181.4	0.845
180.4	0.81	173.5	0.825	181.8	0.845
180.8	0.81	173.9	0.835	182.5	0.835
181.2	0.81	174.3	0.835	182.9	0.825
181.5	0.81	174.6	0.825	183.3	0.825
181.9	0.81	175	0.825	183.6	0.825
182.3	0.82	175.4	0.825	184	0.825
182.6	0.82	175.8	0.825	184.4	0.825
183	0.82	176.1	0.835	185	0.825
183.8	0.82	176.5	0.825	185.4	0.845
184.2	0.83	176.9	0.825	185.8	0.845
184.5	0.83	177.2	0.835	186.1	0.845
184.9	0.83	177.6	0.835	186.5	0.845
185.3	0.83	178.1	0.835	186.9	0.845
185.7	0.83	178.5	0.825	187.3	0.835
186	0.84	178.9	0.825	187.6	0.835
186.4	0.84	179.2	0.825	188.2	0.835
186.8	0.84	179.6	0.825	188.6	0.835
187.3	0.83	180	0.825	189	0.845
187.7	0.83	180.4	0.825	189.3	0.845
188	0.83	180.9	0.825	189.7	0.845
188.4	0.83	181.3	0.825	190.1	0.845
188.8	0.83	181.6	0.825	190.5	0.845
189.5	0.82	182	0.825	191.1	0.845
189.9	0.82	182.4	0.835	191.5	0.845
190.2	0.82	182.8	0.835	191.8	0.855

190.6	0.82	183.1	0.835	192.4	0.855
191.1	0.82	183.5	0.825	192.8	0.855
191.5	0.83	183.9	0.835	193.1	0.855
191.9	0.83	184.2	0.835	193.5	0.855
192.2	0.83	184.6	0.825	193.9	0.855
192.6	0.83	185	0.835	194.2	0.835
193.1	0.82	185.4	0.835	194.6	0.835
193.6	0.83	185.7	0.835	195	0.835
194	0.83	186.1	0.825	195.5	0.835
194.3	0.82	186.5	0.835	195.9	0.835
194.7	0.82	186.8	0.835	196.3	0.835
195.1	0.82	187.2	0.835	196.6	0.835
195.4	0.82	187.6	0.835	197	0.835
195.8	0.82	187.9	0.835	197.4	0.835
196.2	0.82	188.3	0.835	197.8	0.835
196.6	0.82	188.7	0.835	198.1	0.835
196.9	0.82	189.1	0.835	198.5	0.835
197.5	0.82	189.4	0.835	199	0.845
198	0.82	190.4	0.835	199.4	0.835
198.4	0.83	190.8	0.835	199.8	0.835
198.7	0.83	191.1	0.835	200.1	0.845
199.1	0.83	191.5	0.835	200.7	0.835
199.5	0.83	191.9	0.835	201.2	0.845
200	0.83	192.3	0.835	201.6	0.835
200.4	0.83	192.6	0.835	201.9	0.835
200.8	0.84	193	0.835	202.3	0.835

Table C.2- Full time pressure record for short cycle time

Dome pressure	3	bar
Cycle time	30	s
Injection time	5	s

Initial Load	0.6	bar
Supply Line	6	bar
Valve's Area Ratio	0.069	

O = Open
C = Closed
A = Active
Pt = Tubing Pressure
Pc = Casing Pressure

Pwf = Bottom-pipe Pressure
Pwh = Pipe-head Pressure
MV = Motor Valve
OV = Operating Valve
D = Diameter **2 in.**

Time	**Cycle**	**OV**	**MV**	**Pwf** (bar)	**Pt** (bar)	**Pc** (bar)	**Pwh** (bar)
1028.8	A	C	O	0.67	0.58	2.98	0
1029.2	A	C	O	0.68	0.58	3	0
1029.5	A	C	O	0.68	0.58	3.02	0
1030.1	A	C	O	0.68	0.61	3.07	0
1030.4	A	C	O	0.68	0.61	3.14	0
1030.8	A	C	O	0.69	0.62	3.24	0
1031.2	A	O	O	0.68	0.92	3.33	0
1031.8	A	O	O	0.72	0.95	3.4	0
1032.2	A	O	O	0.75	1.29	3.52	0
1032.5	A	O	O	0.76	1.63	3.53	0
1032.9	A	O	O	0.77	1.96	3.62	0
1033.3	A	O	C	0.79	2.27	3.66	0
1033.9	A	O	C	0.8	2.58	3.7	0
1034.3	A	O	C	0.82	2.87	3.73	0
1034.6	A	O	C	0.84	3.2	3.71	0.03
1035	A	O	C	0.86	3.46	3.68	0.08
1035.4	A	O	C	0.86	3.41	3.61	0.1
1035.7	A	O	C	0.81	3.28	3.54	0.12
1036.1	A	O	C	0.78	3.15	3.49	0.15
1036.5	A	O	C	0.75	3.13	3.42	0.17
1036.8	A	O	C	0.72	3.01	3.36	0.18
1037.2	A	O	C	0.67	2.91	3.24	0.18
1037.7	A	O	C	0.63	2.8	3.12	0.18
1038.1	A	O	C	0.58	2.72	3.01	0.17
1038.4	A	O	C	0.53	2.6	2.9	0.13
1038.8	A	O	C	0.48	2.29	2.79	0.09
1039.2	A	O	C	0.45	2.01	2.74	0.08
1039.6	A	C	C	0.43	1.75	2.69	0.06

1040	A	C	C	0.4	1.49	2.67	0.03
1040.3	A	C	C	0.36	1.15	2.64	0
1040.7	A	C	C	0.33	0.92	2.63	0
1041.1	A	C	C	0.31	0.68	2.64	0
1041.6	A	C	C	0.29	0.45	2.66	0
1042	A	C	C	0.27	0.21	2.69	0
1042.4	A	C	C	0.27	0.15	2.73	0
1042.7	A	C	C	0.26	0.17	2.77	0
1043.1	A	C	C	0.25	0.19	2.79	0
1043.5	A	C	C	0.24	0.2	2.79	0
1043.8	A	C	C	0.24	0.21	2.79	0
1044.2	A	C	C	0.26	0.21	2.8	0
1044.6	A	C	C	0.27	0.23	2.81	0
1045	A	C	C	0.29	0.24	2.8	0
1045.3	A	C	C	0.3	0.26	2.81	0
1045.7	A	C	C	0.31	0.27	2.8	0
1046.1	A	C	C	0.32	0.27	2.81	0
1046.4	A	C	C	0.33	0.27	2.82	0
1046.8	A	C	C	0.34	0.26	2.82	0
1047.2	A	C	C	0.35	0.26	2.82	0
1047.6	A	C	C	0.35	0.26	2.82	0
1047.9	A	C	C	0.36	0.26	2.82	0
1048.3	A	C	C	0.37	0.26	2.83	0
1048.7	A	C	C	0.38	0.26	2.84	0
1049	A	C	C	0.38	0.27	2.84	0
1049.6	A	C	C	0.38	0.27	2.84	0
1049.9	A	C	C	0.39	0.27	2.84	0
1050.3	A	C	C	0.4	0.27	2.84	0
1050.7	A	C	C	0.39	0.28	2.84	0
1051	A	C	C	0.39	0.29	2.84	0
1051.4	A	C	C	0.39	0.3	2.86	0
1051.9	A	C	C	0.4	0.31	2.85	0
1052.4	A	C	C	0.4	0.31	2.85	0
1052.8	A	C	C	0.4	0.32	2.84	0
1053.2	A	C	C	0.4	0.32	2.84	0
1053.5	A	C	C	0.4	0.33	2.84	0
1053.9	A	C	C	0.4	0.33	2.86	0
1054.3	A	C	C	0.4	0.33	2.86	0
1054.7	A	C	C	0.41	0.33	2.86	0
1055	A	C	C	0.42	0.33	2.85	0
1055.4	A	C	C	0.41	0.33	2.85	0
1055.8	A	C	C	0.4	0.33	2.87	0
1056.1	A	C	C	0.41	0.33	2.87	0
1056.5	A	C	C	0.41	0.29	2.86	0
1056.9	A	C	C	0.41	0.3	2.87	0

1057.4	A	C	C	0.41	0.3	2.87	0
1057.8	A	C	C	0.42	0.3	2.89	0
1058.3	A	C	O	0.42	0.3	2.91	0
1058.7	A	C	O	0.43	0.31	2.96	0
1059.3	A	C	O	0.43	0.31	3.04	0
1059.6	A	C	O	0.45	0.31	3.12	0
1060	A	C	O	0.45	0.61	3.21	0
1060.4	A	C	O	0.45	0.95	3.35	0
1060.8	A	C	O	0.46	1.34	3.4	0
1061.3	A	O	O	0.46	1.69	3.5	0
1061.8	A	O	O	0.5	2.03	3.51	0
1062.2	A	O	O	0.5	2.38	3.59	0
1062.5	A	O	O	0.51	2.7	3.65	0
1062.9	A	O	O	0.53	3.01	3.7	0
1063.3	A	O	C	0.54	3.3	3.72	0
1063.7	A	O	C	0.56	3.59	3.72	0
1064.1	A	O	C	0.58	3.58	3.69	0
1064.4	A	O	C	0.6	3.51	3.63	0
1064.8	A	O	C	0.6	3.41	3.6	0.03
1065.2	A	O	C	0.61	3.3	3.52	0.03
1065.5	A	O	C	0.58	3.19	3.43	0.03
1065.9	A	O	C	0.58	3.06	3.32	0.03
1066.3	A	O	C	0.56	2.95	3.2	0.05
1066.7	A	O	C	0.54	2.84	3.11	0.06
1067	A	O	C	0.51	2.75	2.96	0.05
1067.4	A	O	C	0.49	2.51	2.84	0.03
1067.9	A	O	C	0.46	2.21	2.79	0.03
1068.3	A	O	C	0.43	1.91	2.75	0.02
1068.7	A	C	C	0.42	1.64	2.73	0
1069.1	A	C	C	0.4	1.38	2.72	0
1069.5	A	C	C	0.36	1.12	2.71	0
1069.8	A	C	C	0.34	0.87	2.71	0
1070.2	A	C	C	0.31	0.64	2.74	0
1070.6	A	C	C	0.29	0.42	2.77	0
1071	A	C	C	0.28	0.21	2.8	0
1071.6	A	C	C	0.27	0.14	2.86	0
1071.9	A	C	C	0.26	0.15	2.86	0
1072.3	A	C	C	0.25	0.16	2.88	0
1072.7	A	C	C	0.25	0.17	2.88	0
1073	A	C	C	0.25	0.18	2.88	0
1073.4	A	C	C	0.27	0.2	2.89	0
1073.8	A	C	C	0.28	0.21	2.89	0
1074.1	A	C	C	0.3	0.22	2.88	0
1074.5	A	C	C	0.31	0.24	2.91	0
1074.9	A	C	C	0.33	0.26	2.91	0

1075.2	A	C	C	0.34	0.25	2.91	0
1075.8	A	C	C	0.34	0.25	2.9	0
1076.2	A	C	C	0.34	0.27	2.9	0
1076.5	A	C	C	0.34	0.27	2.9	0
1076.9	A	C	C	0.35	0.27	2.89	0
1077.3	A	C	C	0.36	0.27	2.88	0
1077.7	A	C	C	0.37	0.27	2.89	0
1078	A	C	C	0.37	0.27	2.9	0
1078.4	A	C	C	0.37	0.27	2.87	0
1078.8	A	C	C	0.38	0.26	2.88	0
1079.3	A	C	C	0.4	0.27	2.87	0
1079.6	A	C	C	0.4	0.27	2.89	0
1080.2	A	C	C	0.4	0.27	2.89	0
1080.6	A	C	C	0.41	0.28	2.89	0
1080.9	A	C	C	0.41	0.29	2.89	0
1081.3	A	C	C	0.41	0.29	2.89	0
1081.7	A	C	C	0.41	0.3	2.89	0
1082	A	C	C	0.42	0.31	2.9	0
1082.4	A	C	C	0.44	0.32	2.91	0
1082.8	A	C	C	0.44	0.33	2.91	0
1083.1	A	C	C	0.44	0.33	2.91	0
1083.5	A	C	C	0.44	0.33	2.91	0
1083.9	A	C	C	0.44	0.34	2.91	0
1084.2	A	C	C	0.44	0.35	2.91	0
1084.6	A	C	C	0.44	0.35	2.92	0
1085	A	C	C	0.45	0.35	2.92	0
1085.4	A	C	C	0.44	0.36	2.93	0
1085.7	A	C	C	0.44	0.36	2.92	0
1086.1	A	C	C	0.43	0.36	2.92	0
1086.5	A	C	C	0.43	0.36	2.94	0
1086.8	A	C	C	0.42	0.36	2.94	0
1087.2	A	C	C	0.43	0.36	2.93	0
1087.6	A	C	C	0.43	0.34	2.94	0
1087.9	A	C	C	0.44	0.33	2.98	0
1088.3	A	C	O	0.44	0.34	3.02	0
1088.7	A	C	O	0.44	0.35	3.08	0
1089.1	A	C	O	0.44	0.34	3.14	0
1089.5	A	C	O	0.45	0.34	3.22	0
1089.9	A	C	O	0.45	0.63	3.31	0
1090.2	A	C	O	0.45	0.97	3.36	0
1090.6	A	C	O	0.45	1.3	3.44	0
1091	A	O	O	0.46	1.64	3.51	0
1091.4	A	O	O	0.51	1.98	3.59	0
1091.8	A	O	O	0.49	2.3	3.65	0
1092.1	A	O	O	0.51	2.62	3.7	0

1092.5	A	O	O	0.53	2.93	3.72	0
1092.9	A	O	O	0.55	3.24	3.72	0
1093.3	A	O	C	0.56	3.52	3.69	0
1093.7	A	O	C	0.58	3.5	3.63	0
1094.2	A	O	C	0.61	3.41	3.6	0
1094.6	A	O	C	0.62	3.33	3.52	0.01
1095	A	O	C	0.62	3.22	3.44	0.02
1095.3	A	O	C	0.58	3.13	3.35	0.01
1095.7	A	O	C	0.6	3.03	3.25	0.02
1096.1	A	O	C	0.59	2.92	3.13	0.02
1096.4	A	O	C	0.56	2.69	3.01	0.02
1097	A	O	C	0.55	2.56	2.9	0.03
1097.4	A	O	C	0.52	2.33	2.78	0.04
1097.7	A	O	C	0.5	2.04	2.71	0.02
1098.5	A	O	C	0.46	1.75	2.67	0
1098.9	A	C	C	0.45	1.49	2.64	0
1099.3	A	C	C	0.42	1.23	2.63	0
1099.6	A	C	C	0.38	0.97	2.62	0
1100	A	C	C	0.35	0.73	2.61	0.01
1100.4	A	C	C	0.32	0.5	2.62	0
1100.8	A	C	C	0.3	0.4	2.64	0
1101.1	A	C	C	0.28	0.21	2.67	0
1101.5	A	C	C	0.27	0.15	2.7	0
1101.9	A	C	C	0.26	0.16	2.72	0
1102.2	A	C	C	0.25	0.18	2.71	0
1102.6	A	C	C	0.24	0.19	2.71	0
1103	A	C	C	0.25	0.21	2.7	0
1103.4	A	C	C	0.27	0.21	2.69	0
1103.7	A	C	C	0.28	0.22	2.71	0
1104.1	A	C	C	0.29	0.23	2.73	0
1104.5	A	C	C	0.3	0.25	2.73	0
1104.8	A	C	C	0.31	0.26	2.74	0
1105.2	A	C	C	0.33	0.27	2.74	0
1105.9	A	C	C	0.33	0.27	2.73	0
1106.3	A	C	C	0.34	0.27	2.75	0
1106.7	A	C	C	0.34	0.27	2.76	0
1107	A	C	C	0.35	0.27	2.77	0
1107.4	A	C	C	0.36	0.28	2.77	0
1107.8	A	C	C	0.36	0.28	2.77	0
1108.1	A	C	C	0.37	0.29	2.77	0
1108.5	A	C	C	0.37	0.29	2.75	0
1108.9	A	C	C	0.38	0.29	2.75	0
1109.2	A	C	C	0.38	0.29	2.76	0
1109.6	A	C	C	0.38	0.3	2.78	0
1110	A	C	C	0.38	0.29	2.78	0

1110.3	A	C	C	0.38	0.29	2.77	0
1110.7	A	C	C	0.38	0.3	2.77	0
1111.1	A	C	C	0.38	0.3	2.78	0
1111.5	A	C	C	0.38	0.31	2.78	0
1111.8	A	C	C	0.38	0.3	2.77	0
1112.2	A	C	C	0.39	0.31	2.77	0
1112.6	A	C	C	0.39	0.31	2.78	0
1112.9	A	C	C	0.39	0.31	2.77	0
1113.3	A	C	C	0.4	0.32	2.76	0
1113.9	A	C	C	0.41	0.33	2.76	0
1114.2	A	C	C	0.42	0.33	2.76	0
1114.6	A	C	C	0.43	0.33	2.76	0
1115.2	A	C	C	0.44	0.34	2.75	0
1115.6	A	C	C	0.44	0.34	2.75	0
1115.9	A	C	C	0.44	0.35	2.76	0
1116.3	A	C	C	0.44	0.35	2.77	0
1116.7	A	C	C	0.45	0.35	2.76	0
1117	A	C	C	0.45	0.35	2.76	0
1117.4	A	C	C	0.46	0.35	2.77	0
1117.8	A	C	C	0.45	0.35	2.79	0
1118.2	A	C	O	0.45	0.36	2.85	0
1118.6	A	C	O	0.45	0.36	2.91	0
1118.9	A	C	O	0.46	0.36	2.98	0
1119.3	A	C	O	0.46	0.36	3.05	0
1119.7	A	C	O	0.46	0.31	3.14	0
1120.1	A	C	O	0.46	0.32	3.26	0
1120.4	A	C	O	0.46	0.61	3.37	0
1120.8	A	C	O	0.46	0.95	3.44	0
1121.2	A	C	O	0.46	1.29	3.53	0
1121.6	A	O	O	0.46	1.63	3.62	0
1122	A	O	O	0.49	1.96	3.66	0
1122.3	A	O	O	0.47	2.27	3.7	0
1122.8	A	O	O	0.48	2.58	3.73	0
1123.2	A	O	C	0.5	2.87	3.71	0
1123.6	A	O	C	0.52	3.2	3.68	0
1124	A	O	C	0.53	3.46	3.61	0
1124.4	A	O	C	0.56	3.41	3.54	0
1124.7	A	O	C	0.58	3.31	3.49	0
1125.2	A	O	C	0.59	3.2	3.39	0
1125.6	A	O	C	0.59	3.07	3.28	0
1126.2	A	O	C	0.56	2.94	3.15	0
1126.5	A	O	C	0.57	2.83	3.04	0.01
1126.9	A	O	C	0.55	2.72	2.91	0.02
1127.3	A	O	C	0.52	2.48	2.8	0.03
1127.6	A	O	C	0.5	2.16	2.75	0.03

1128	A	O	C	0.48	1.88	2.71	0.03
1128.4	A	C	C	0.45	1.61	2.68	0.02
1128.8	A	C	C	0.42	1.34	2.66	0
1129.2	A	C	C	0.37	1.1	2.67	0
1129.5	A	C	C	0.34	0.86	2.68	0
1129.9	A	C	C	0.32	0.63	2.72	0
1130.3	A	C	C	0.31	0.43	2.74	0
1130.6	A	C	C	0.3	0.21	2.77	0
1131	A	C	C	0.28	0.15	2.86	0
1131.4	A	C	C	0.26	0.17	2.87	0
1131.8	A	C	C	0.29	0.18	2.86	0
1132.1	A	C	C	0.24	0.2	2.86	0
1132.5	A	C	C	0.23	0.21	2.86	0
1132.9	A	C	C	0.25	0.23	2.85	0
1133.2	A	C	C	0.26	0.24	2.84	0
1133.6	A	C	C	0.28	0.24	2.84	0
1134	A	C	C	0.29	0.24	2.84	0
1134.3	A	C	C	0.3	0.26	2.85	0
1134.7	A	C	C	0.31	0.26	2.8	0
1135.1	A	C	C	0.32	0.27	2.81	0
1135.5	A	C	C	0.29	0.27	2.81	0
1135.8	A	C	C	0.35	0.27	2.81	0
1136.2	A	C	C	0.36	0.27	2.82	0
1136.6	A	C	C	0.36	0.27	2.82	0
1136.9	A	C	C	0.37	0.28	2.82	0
1137.3	A	C	C	0.38	0.28	2.81	0
1137.7	A	C	C	0.38	0.29	2.81	0
1138.1	A	C	C	0.38	0.29	2.81	0
1138.4	A	C	C	0.38	0.29	2.81	0
1138.8	A	C	C	0.38	0.3	2.81	0
1139.2	A	C	C	0.38	0.31	2.81	0
1139.5	A	C	C	0.39	0.32	2.82	0
1139.9	A	C	C	0.39	0.32	2.82	0
1140.3	A	C	C	0.39	0.33	2.82	0
1140.8	A	C	C	0.39	0.32	2.83	0
1141.3	A	C	C	0.39	0.33	2.83	0
1141.7	A	C	C	0.39	0.33	2.82	0
1142.1	A	C	C	0.39	0.33	2.8	0
1142.6	A	C	C	0.4	0.34	2.81	0
1143	A	C	C	0.41	0.34	2.8	0
1143.3	A	C	C	0.4	0.34	2.8	0
1143.7	A	C	C	0.4	0.33	2.8	0
1144.1	A	C	C	0.4	0.34	2.81	0
1144.4	A	C	C	0.41	0.34	2.81	0
1144.8	A	C	C	0.42	0.34	2.8	0

1145.2	A	C	C	0.42	0.34	2.81	0
1145.6	A	C	C	0.42	0.35	2.82	0
1145.9	A	C	C	0.42	0.35	2.83	0
1146.4	A	C	C	0.43	0.35	2.84	0
1146.8	A	C	C	0.43	0.35	2.85	0
1147.5	A	C	C	0.44	0.35	2.85	0
1147.9	A	C	C	0.45	0.36	2.87	0
1148.3	A	C	O	0.45	0.36	2.91	0
1148.7	A	C	O	0.45	0.37	2.95	0
1149.1	A	C	O	0.46	0.38	3.02	0
1149.4	A	C	O	0.46	0.38	3.09	0
1149.8	A	C	O	0.47	0.37	3.18	0
1150.2	A	C	O	0.48	0.38	3.25	0
1150.5	A	C	O	0.48	0.66	3.35	0
1150.9	A	C	O	0.49	0.98	3.39	0
1151.3	A	C	O	0.49	1.32	3.48	0.02
1151.7	A	O	O	0.49	1.63	3.55	0.02
1152.1	A	O	O	0.53	1.95	3.59	0.01
1152.4	A	O	O	0.52	2.26	3.63	0.01
1152.8	A	O	O	0.53	2.56	3.64	0
1153.2	A	O	C	0.55	2.86	3.63	0
1153.6	A	O	C	0.56	3.13	3.59	0
1154	A	O	C	0.58	3.38	3.66	0
1154.4	A	O	C	0.59	3.35	3.58	0
1154.7	A	O	C	0.62	3.25	3.53	0.01
1155.1	A	O	C	0.62	3.16	3.45	0
1155.5	A	O	C	0.63	3.06	3.35	0
1155.8	A	O	C	0.59	2.94	3.25	0
1156.2	A	O	C	0.6	2.85	3.13	0
1156.6	A	O	C	0.57	2.73	3.02	0.01
1156.9	A	O	C	0.55	2.62	2.91	0.02
1157.3	A	O	C	0.53	2.4	2.82	0.01
1157.7	A	O	C	0.51	2.11	2.66	0.02
1158.1	A	O	C	0.48	1.84	2.63	0.01
1158.4	A	C	C	0.45	1.57	2.6	0
1158.8	A	C	C	0.43	1.33	2.58	0
1159.2	A	C	C	0.4	1.08	2.61	0
1159.6	A	C	C	0.36	0.86	2.63	0
1160	A	C	C	0.34	0.63	2.65	0
1160.3	A	C	C	0.32	0.43	2.67	0
1160.9	A	C	C	0.3	0.23	2.7	0
1161.3	A	C	C	0.29	0.17	2.74	0
1161.6	A	C	C	0.28	0.18	2.74	0
1162	A	C	C	0.27	0.19	2.74	0
1162.5	A	C	C	0.3	0.21	2.77	0

1162.8	A	C	C	0.3	0.22	2.76	0
1163.3	A	C	C	0.32	0.24	2.73	0
1163.7	A	C	C	0.34	0.23	2.73	0
1164.1	A	C	C	0.36	0.25	2.74	0
1164.5	A	C	C	0.38	0.27	2.75	0
1164.8	A	C	C	0.39	0.27	2.76	0
1165.2	A	C	C	0.4	0.27	2.75	0
1165.6	A	C	C	0.41	0.27	2.76	0
1165.9	A	C	C	0.42	0.28	2.76	0
1166.3	A	C	C	0.39	0.28	2.75	0
1166.7	A	C	C	0.4	0.29	2.76	0
1167.1	A	C	C	0.4	0.3	2.75	0
1167.4	A	C	C	0.4	0.3	2.76	0
1167.8	A	C	C	0.39	0.31	2.76	0
1168.2	A	C	C	0.39	0.3	2.76	0
1168.5	A	C	C	0.4	0.3	2.76	0
1168.9	A	C	C	0.4	0.31	2.76	0
1169.3	A	C	C	0.4	0.31	2.77	0
1169.6	A	C	C	0.4	0.32	2.77	0
1170	A	C	C	0.41	0.32	2.77	0
1170.4	A	C	C	0.41	0.32	2.77	0
1170.8	A	C	C	0.41	0.32	2.77	0
1171.1	A	C	C	0.41	0.35	2.77	0
1171.5	A	C	C	0.41	0.35	2.77	0
1171.9	A	C	C	0.42	0.36	2.77	0
1172.2	A	C	C	0.42	0.28	2.77	0
1172.6	A	C	C	0.42	0.29	2.77	0
1173	A	C	C	0.42	0.3	2.76	0
1173.4	A	C	C	0.43	0.3	2.76	0
1173.7	A	C	C	0.43	0.3	2.77	0
1174.1	A	C	C	0.43	0.31	2.77	0
1174.5	A	C	C	0.43	0.31	2.78	0
1174.8	A	C	C	0.44	0.28	2.77	0
1175.2	A	C	C	0.45	0.28	2.77	0
1175.6	A	C	C	0.45	0.29	2.67	0
1175.9	A	C	C	0.45	0.37	2.67	0
1176.3	A	C	C	0.45	0.38	2.68	0
1176.7	A	C	C	0.46	0.36	2.68	0
1177.2	A	C	C	0.46	0.38	2.68	0
1177.6	A	C	C	0.47	0.38	2.68	0