STUDY OF PIPELINE PIGGING OPERATIONS DURING MULTIPHASE FLOW THROUGH AN INNOVATIVE EXPERIMENTAL BY-PASS PIG MODEL

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CHAPTER - 1

INTRODUCTION

1.1. OVERVIEW

Multiphase flow through horizontal/inclined pipeline network is the most commonly encountered fluid flow in upstream oil and gas industry. Multiphase flow is highly complicated and unpredictable especially during pigging operations. Tremendous changes in the flow regimes due to flow and terrain induced slugs and phase separation makes the flow phenomenon highly complex to predict without rigorous theoretical/empirical modeling. Effective removal of wax and accumulated water from pipelines without production loss and process upset is the real challenge for Production Engineers. Software simulation models and empirical equations based on experimental results helps engineers to assess the risk involved and choose the most suitable pigging solution for multiphase pipeline cleaning operations

Pigging operation is generally used for cleaning pipelines at various phases of its construction and operational life. Frequent pigging operation is essential to maintain the operating efficiency and integrity of any pipeline. This involves cleaning of solid debris/deposits such as wax/asphaltene/sand and also removing settled water which may lead to pipeline corrosion. Pigging is considered as a vital flow assurance and integrity tool in the oil industry. Pigging is also used for product separation, corrosion inhibition and inspection purposes.

Pigging operation of multiphase flow pipelines is very common in the upstream oil & gas industry at Offshore and Onshore fields. However it is associated with production loss due to imposed flow restriction while pigging operation of multiphase lines. Pigging of single phase flow pipeline carrying compressible gas flow (natural gas) or with incompressible liquid flow (oil & water) is relatively easier compared to multiphase flow consisting oil water emulsion, gas and fine solid particles such as sand and wax. Wax removal is one of the most essential objectives of pipeline pigging during its operational life. Bypass pigging, as compared to the conventional pigging, reduces the damaging effect of the pig generated liquid slug by distributing the liquid hold up in the pipeline.

1.2. ABBREVIATIONS / DEFINITIONS

PIG	Pipeline Inspection Gauge
BY-PASS PIG	PIG which has provision to allow flow of fluid across the pig
MULTIPHASE	More than one phase
OLGA	State of the art software programme used for Dynamic & Transient flow Analysis
PLAC/TACITE	Multiphase flow analysis software programme

1.3. RESEARCH MOTIVATION

All types of pipeline cleaning operations lead to operational upset unless the receiving facility is designed or equipped to contain such abnormalities. In case of multiphase flow pigging where oil, gas and water flow in long distance subsea pipelines, the receiving facility shall be equipped with huge additional handling capacity compared to the normal operating capacity, in order to process the large instantaneous volumetric flow/slugs of incoming fluid. A pigging operation in multiphase oil and gas pipeline will create a total upset of liquid flow to the separator and gas flow to the compressor. A highly conservative design could be very costly affair with a low capacity utilization factor during normal operation. The pipeline sizing shall also be decided considering the flow assurance aspectsacross the pipeline operation life cycle. Due to these reasons pigging operations of multiphase pipelines are always associated with inherent production losses. The facility can be optimally designed and pigging operations can be effectively and safely carried out by minimising the production loss by developing innovative solutions making use of various modeling and simulation techniques. The innovative BY-PASS PIG MODEL developed through this research work will attempt to find a reasonable solution to address this problem.

1.4. RESEARCH QUESTION & OBJECTIVES

This comprehensive Research Study has the following major Objectives;

- To develop Mathematical Model to predict Multiphase Flow behaviour in offshore pipeline during pigging operations.
- To address the special application feature of BY-PASS pigging solution for multiphase pipeline and to design an innovative new BY-PASS pig Geometry/Profile for Multiphase pipeline pigging operation.
- To develop an empirical equation based on field testing of conventional by-pass pigging. Evaluate the performance of new by-pass pig profile through field testing. In this research, the effectiveness of the introduced solution will be compared with OLGA Simulation results.

1.5. OVERVIEW OF RESEARCH MODEL

Broadly speaking there are two major types of research models or research paradigms viz. quantitative and qualitative. Quantitative is also known as traditional, positivist, experimental or empiricist whereas qualitative is known in other names such as constructivist, naturalistic, interpretive, post positivist or post-modern perspective etc.

There are several reasons for choosing a model such as the following:

- World view or assumptions of each paradigm
- Training and experience
- Psychological attributes
- Nature of the problems
- Audience for the study

In this study Quantitative Model is adopted and followed in general.

1.6. OVERVIEW OF RESEARCH APPROACH

When conducting a research it is necessary to determine which approach is being implemented, because "scientific inquiry in practice typically involves alternating between deduction and induction. Both methods involve interplay of logic and observation. Research approach can be divided into two categories viz., Deductive and Inductive approaches.

Main distinction between inductive and deductive research approach relates to the existence and placement of hypotheses and theories. Specifically, if the researcher adopts a range of hypotheses the research is aimed to explore, then it will be deductive research. On the other hand, if hypotheses are absent at the start of the research then it will be the case of inductive research.

In other words, the relation of hypotheses to the study can serve as the main point of difference between these two approaches. Specifically, it has been noted that two important functions that hypotheses serve in scientific inquiry are the development of theory and the statement of parts of an existing theory in testable form (Singh and Bajpai, 2008).

A deductive approach is concerned with developing a hypothesis (or hypotheses) based on existing theory, and then designing a research strategy to test the hypothesis (Wilson, 2010).

Deductive approach can be explained by the means of hypotheses, which can be derived from the propositions of the theory. In other words, deductive approach is concerned with deducting conclusions from premises or propositions. Deduction begins with an expected pattern that is tested against observations, whereas induction begins with observations and seeks to find a pattern within them (Babbie, 2010).

It has been stated that deductive means reasoning from the particular to the general. If a causal relationship or link seems to be implied by a particular theory or case example, it might be true in many cases. A deductive design might test to see if this relationship or link did obtain on more general circumstances (Gulati, 2009).

In other words, when a deductive approach is being followed in the research the author formulates a set of hypotheses that need to be tested. Then, through implementation of relevant methodology the study is going to prove formulated hypotheses right or wrong.

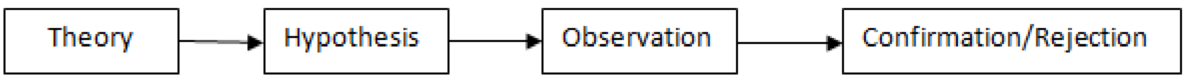

Fig 1.1

Beiske (2007) informs that deductive research approach explores a known theory or phenomenon and tests if that theory is valid in a given circumstances. The deductive approach follows the path of logic most closely. The reasoning starts with a theory and leads to a new hypothesis. This hypothesis is put to the test by confronting it with observations that either lead to a confirmation or a rejection of the hypothesis (Snieder and Larner, 2009).

Moreover, deductive reasoning can be explained as reasoning from the general to the particular (Pelissier, 2008), whereas inductive reasoning is the opposite. In other words, deductive approach involves formulation of hypotheses and their subjection to testing during the research process, while inductive studies do not deal with hypotheses in any ways.

Generally, studies using deductive approach follow the following stages:

1. *Deducing* hypothesis from theory
2. *Formulating* hypothesis in operational terms and proposing relationships between two specific variables
3. *Testing* hypothesis with the application of relevant method(s)
4. *Examining* the outcome of the test, and thus confirming or rejecting the theory.
5. *Modifying* theory in instances when hypothesis is not confirmed.

In this research study the deductive approach is followed.

1.7. RESEARCH METHODOLOGY

In this research work has been carried out in two parts. The first part deals with theoretical study of the multiphase flow and by-pass pigging operation followed by development of an empirical correlation based on a number of conventional by pass pigging tests/operations carried out in the field. The empirical equation prediction results are compared and verified. An OLGA Software simulation study is carried out and results are discussed.

In the second part, based on the multiphase flow & dynamic pig modelling study a new innovative bypass pig profile/geometry is designed and engineered. The new profile is fabricated and field tests conducted. Results are validated and also compared with OLGA Simulation.

During research the following theory works are undertaken;

I. Detailed study of multiphase fluid flow through pipeline network.

a) To have general understanding about fundamentals of multiphase flow of oil/water/gas/sand through a pipeline.
b) Study of various flow regimes & correlations
c) Study of wax deposition in Oil/Gas/Water multiphase flow pipeline
d) Study of multiphase flow through convergent divergent section and its special flow characteristics
e) Understand the dynamic behaviour of the pig in multiphase flow.
f) Review of pig dynamic equation in oil & gas multiphase flow.
g) Solve the governing nonlinear hyperbolic partial differential equations of flow together with pig dynamic equation

II. Model Development & Simulation

Derivation of Mathematical model

Fluid flow Modeling

a) List down assumptions
b) Develop Unsteady Multiphase fluid flow model based on mass / momentum / energy conservation equations for different phases for upstream and downstream conditions

Pig Dynamic Modeling

a) Derive the dynamic equation for pig motion from Newton’s Second Law

III. Design and Development of Bypass pigging solution

a) Sizing of bypass holes

b) Analysis of bypass-hole geometry factors

c) Flow modelling& simulation with various liquid and gases flow rates through various sections at normal pigging velocity and constant pressure conditions

d) Flow simulations for establishing fluid flow behavior through these sections at various pressures and flow rates.

e) Generation of performance curves, performance estimate etc.

f) Development of mathematical models and empirical correlation and software program.

1.8. CONTRIBUTION OF RESEARCH

Various operational and engineering challenges while implementing the commonly known bypass pigging solutions include prediction of pig velocity, pig generated slug volume, slug duration, back pressure increase in the pipeline, process plant upset etc. Control of these parameters is very difficult during bypass pigging operation due to its transient nature. The fluid behaviour through bypass holes, subsequent down stream flow regime and the nature of turbulence are unknown. Transient modelling and simulation results of bypass pigging with help of OLGA Software do not match with actual field results. Wax blockage of bypass holes also leads to erroneous results. In this study effort is made to develop empirical correlations to approximate various parameters based on experimental results vis-a-vis simulation model prediction. Lateron an innovative bypass geometry/profile is proposed, designed and experimental results are evaluated.

This modified and newly developed by pass pigging solution for multiphase flow can be helpful in many ways like the following;

1. Minimum process upset and production loss during cleaning operation

2. Existing process facilities can be fully utilized without going for a highly conservative/high design capacity and existing facility can be retrofitted.
3. Attain the critical bypass mass flow rate (maximum flow rate) at a very low differential pressure (say 0.8) compared to the normal ratio of 0.53 which in turn can help effective cleaning.

1.9. OUTLINE OF THESIS CHAPTERS

The chapters of this thesis are written such that they can be read independently with a general knowledge of the relevant background. Additional theoretical and experimental details are given as they pertain to each chapter. Due to this format, there may be some repetition of introductory material from chapter to chapter. An overview of the main chapters is given below:

ChapterII. This chapter provides a review of multiphase and pigging literature and relevant analysis techniques. The pigging review aims to discover what is already known in the industry regarding the motion of the pipeline pigs. Based on the review areas of further attention have been highlighted for future research.

Chapter III. This chapter provides overview and background of the multiphase flow through pipelines and review of various multiphase flow regimes. The physics of wax deposition phenomena and wax deposition under turbulent flow conditions are explained. The chapter details about bypass pigging operation and principles.

Chapter IV. This chapter elucidates the research outline, the research methodology, the experimental set up and hardware design and systematic methodology for the field testing and result evaluation.

Chapter V. This chapter investigates the extend of scale development in this work. How the study from the concept stage to implementation stage and the battery limits for wide range of applicability. Model with both lab scale and with large scale Field pigging experimentation is achieved.

Chapter VI details about the Fluid flow modeling, pig motion analysis, field pigging operation data collection, interpretation, result evaluation and empirical formula development. Result validation through OLGA Software simulation is demonstrated. This chapter shows that the new empirical correlation can successfully predict the pipeline back pressure and the pig travel time. This chapter introduces the innovative and new by-pass pig geometry/profile and explains the Design and Engineering of the new profile. Field test runs and result validation and comparison. By comparing the results of new by-pass geometry with conventional by-pass pig geometry it imperative that the pig operation is substantially improved and better flow bypass and slug control is achieved.

Chapter VII discusses about the conclusion, recommendation and future research work possibilities based on the presented study. The future application and its wide range of field implementation aspect are also discussed.

CHAPTER - 2

LITERATURE SURVEY

2.1 OVERVIEW

Theoretical developments for multiphase flow or for simply transient two-phase gas-liquid flow in pipes can be classified into three categories. No-slip flow or homogeneous models slip mixture flow or drift-flux models, and separated flow or two-fluid models. Homogeneous mixture models are too simplified and in general do not performs well in comparison with experimental data.

The drift flux models are sometimes called diffusion models. The basic concept of this formulation is to consider the mixture as a whole, rather than two phases separately. This is obtained by using a mixture momentum equation that results from the combination of the gas and liquid linear momentum equations. The mixture momentum equation does not contain the interfacial transfer terms, because they cancelled out in the summation process. Some additional manipulations to convert phase velocities into mixture and drift velocities are also done to express the mixture velocity, the pressure, and the liquid hold-up as dependent variables. This formulation is simpler than two-fluid models.

Two-fluid formulations are very complex. The equations describing the conservation of mass and linear momentum equations for each phase are obtained by averaging the respective local instantaneous partial differential equations over the phase sub-volume in a fixed control volume. Several closure relationships are needed. These include relationships for the shear stress at the pipe wall and at the interface, the mass transfer rate between the phases, which usually depends on the pressure and temperature. One of the problems that arises when using the two-fluid formulation is to properly account for the momentum and mass transfer phenomena taking place at the interface, mainly for flow patterns with a complex interfacial surface. The two-fluid formulation can be successfully developed, however the computer codes are relatively large and complex.

While the homogeneous models have been shown to be always well-posed as an initial-value problem, the drift flux and two-fluid models have been shown to sometimes result in ill-posed initial-value problems and convergence is not attainable. The most relevant works on transient gas-liquid flow in pipes, pigging dynamics of single phase and two-phase pipelines are reviewed in this section. Special attention is given to those related to hydro-carbon transportation and production.

Although there are many studies and research works have been carried out in the area of pigging and much experience have been gained in selection and flow behavior of pigs in single phase lines, little literature relating the dynamic pig motion and flow behavior through multiphase pipeline exists. Quantifiable performance data, experimental and practical application data is scarce, calculation uncertainties, selection criteria for pigs and their applications have not been formally documented. Immense initiatives however have been taken to develop advanced pigging tools with sophisticated mechanisms and control functions. Many improvements are based on trial and error random experiments/empirical approach. The subject of pig dynamics is still elusive and left to the operator’s imagination.

2.2 CHRONOLOGICAL ORDER OF RESEARCH

2.2.1 TRANSIENT GAS LIQUID FLOW

A broad description of gas-liquid flow categories was given by Scoggins (1977), who was one of the first investigators on this subject in the oil industry. Scoggins presented a relatively comprehensive literature survey, after which he decided to use a drift flux formulation in his model for horizontal two-phase transient flow. Homogeneous mixture models were discarded as being too simplified and for not performing well in comparison with experimental data. Two-fluid models were discarded for the ill-posed consideration of the equation sets (Lyczkowski et al.1975), and for the lack of practical and reliable means to account for the flow regime dependent interfacial friction and transient flow forces.

Scoggins determined the slippage between liquid and gas phases through commonly accepted steady-state empirical liquid hold-up correlations. The concepts of slip velocity and slip ratio, both used in earlier works, were not considered. The Eaton (1967) and Dukler et al. (1964)
correlations were used as closure relationships. Fluid physical properties and mass transfer between phases were calculated by the black-oil model approach.

The polynomial characteristic equation of the Scoggins model yielded all real-valued roots for abroad range of operating conditions common to gas-oil two-phase flow pipeline operations. This non-linear equation was solved using a finite difference method, and an implicit sequential
solution algorithm, which was based upon a Newton-Raphson iterative procedure. Finally, a comparison between measured transient flow data and the prediction of the model tended to validate the proposed formulation.

Taitel et al. (1978) developed a theory to predict flow pattern transition under transient conditions using two-fluid flow model equations. Comparison with experimental data was also presented. It was found that under transient conditions, flow pattern transitions can take place at flow rates substantially different from those occurring under steady-state conditions. It was also concluded that certain unexpected 'spurious' flow with slugging would temporarily occur when the gas and liquid flow rates were suddenly increased after the establishment of a steady-state flow. This occurred even though the initial and the final steady-state flow patterns were stratified for both conditions. They have also showed that if the flow rates were increased gradually, slugging would not have been observed.

A theoretical and experimental work on two-phase transient flow in pipes was carried out by Dutta-Roy (1982). He compared the formulations used by Scoggins (1977) and Taitel et al.(1978), and concluded that the Scoggins formulation did not include all the interfacial terms in the mixture momentum equation. The two-fluid model formulation used by Taitel el. al. (1978) was coded and compared with the experimental results. Transients were created by increasing the flow rates after steady-state condition was reached. The comparison showed that the Taitel et al. (1978) transient flow pattern prediction method did not accurately predict the time period for the slug formation, but gave the same trends as the experimental data. The Scoggins transient model and the two-fluid model for stratified flow were compared with the field data of Cunliffe (1978). The results of the comparison show that the Scoggins formulation performed better than the two-fluid model.

The use of a two-fluid model with the inclusion of the pressure differential term was attempted by Sharma (1983). The inclusion of such a small scale flow property has been shown by several researchers to improve the stability of the equation set Banerjee and Chan (1981), Roy and Ho(1980). The analysis of the characteristic polynomial equation for the two-fluid equation set showed that all characteristics were real in the range of parameters investigated, indicating that the inclusion of the phase pressure difference indeed yielded a hyperbolic and well-posed set of equations. The numerical results were consistent with other stratified transient flow formulations, but the predictions were poorer than the ones obtained from the Scoggins drift flux model. No significant difference in results between unequal and equal-phase pressure formulations was found, although the last is known to yield an ill-posed set of equations.

Sharma (1985) proposed a transient slug flow model based on the coupling of an unequal phase velocity and unequal phase pressure two-fluid model with the hydrodynamic slug flow model developed by Dukler and Hubbard (1975). His method included averaging techniques for the slug flow parameters in order to allow the use of the separated flow model. The proposed formulation, however, was not evaluated against any experimental transient slug flow data.

The well-known and one of the few commercially available two-phase transient computational codes, OLGA, resulted from a joint research program conducted by the Institute for Energy Technology (IFE) and SINTEF in Norway (Bendiksen et al. 1986,1991). This code has been continuously updated since 1983 and is now comprised of tens of thousands of code lines. It is based on an 'extended two-fluid model', which assumes the existence of three separate phases, namely, gas, liquid film, and liquid droplets. Separate continuity equations are applied to each of these phases, and two momentum equations are used- a combined equation for the gas and the liquid droplets, and a separate equation for the liquid film. A mixture energy conservation is also used. The possible flow patterns are grouped into two major categories, separated (stratified and annular) and distributed (dispersed bubble and slug). Equations for the interfacial terms and slippage between the phases were given for each of these two categories. Switching between the two sets of equations is done using the minimum slip concept, that is, the roots yielding the minimum liquid hold-up were picked as the correct ones. Although transition criteria for determining the flow pattern at a specific location and time were presented, this information was used as an indication only and was not utilized in the transient calculations.

Other commercially available two-phase transient codes are PLAC and TACITE. PLAC (AEA Technology - 1996) was developed from the nuclear reactor code TRAC. The PLAC code solves mass, momentum and energy equationsfor each phaseusing a one-dimensional-finite differencescheme. The SETS (Stability-Enhancing Two-Step) method, used in PLAC, is a semi-implicit method which treats the convective terms implicitly. SETS is a two step method, consisting of a basic step and a stabilizing step. The basic step is a semi-implicit equation set which provides information about pressure wave propagation. The second step is thus added as a “stabilizing"step and it provides information about the propagation of density, energy and momentum. PLAC has flow regime maps for vertical and horizontal pipes. The flow regime boundaries in vertical flow are mainly based on void fraction: bubbly, plug, churn and annular. In horizontal flow the transition from stratified flow to other flow regimes is determined using the method devised by Taitel & Dukler (1976), based on gas velocity and the transition between slug flow and annularflow are based simply on void fraction. Studies by Mahaffy (1982) showed that in some circumstances numerical instabilities can arise and so the method is stability enhancing rather than totally stable.

TACITE (Pauchon et al. 1993) has been developed under a joint research program between IFP, TOTAL and ELF AQUITANE. The TACITE code is based on numerical resolution of a drift flux model. The time advancing scheme is explicit. Due to the proprietary nature of OLGA, PLAC and TACITE software it is difficult to know the details of these codes.

Taitel et al. (1989) presented a new simplified approach for modeling two-phase transient flow in pipes. This model assumes that the gas phase can be considered in quasi-steady condition. Thus, the time dependent term in the gas continuity equation can be neglected. Local momentum equilibrium between the gas and liquid phases is also assumed. In order to compensate for some inaccuracies incurred in the simplification process, Minami (1991) used mechanistic models for predicting flow pattern, the slippage between phase and the pressure drop. Minami performed an extensive experimental program showing this simplified approach is physically sound for some flow conditions. However the quasi-steady state gas flow assumption is considered a serious restriction in situations where there is a considerable gas accumulation as proposed in this work.

Vigneron et. al. (1995) carried out an experimental programme to acquire multiphase transient data. Comparisons were presented between the data and predictions with TUFFP simplified Model Minami (1991), PLAC and OLGA. The results show that further work should be done in order to have a better prediction. Even in a simple 420 m horizontal loop, the models predictions were not so good.

2.2.2 SINGLE PHASE LIQUID / GAS PIPELINE PIGGING

The Following is a treatise of papers and research work dealing with Modeling of pipeline pigging operations in Single-phase Pipelines.

McDonald and Baker (1964) were probably the first investigators to present a study on pigging. They assumed a successive steady-state approach to model the phenomena. The pipeline under the pigging operation was divided into four flowing zones. The front of each zone has moved at every time-step based on a volumetric material balance. Using steady-state correlations average pressure drop and average liquid hold-up were calculated. The pig velocity was determined through a gas volumetric balance, assuming no gas leakage through the pig. A pressure drop correlation through the pig was also provided. The successive steady-state assumption is the main weakness of Mc Donald and Baker pigging model. It fails to predict the hydrodynamic flow behavior after the delivery of the liquid slug and the pig into the downstream liquid handling facility.

Barua (1982) pursued an attempt to improve the McDonald and Baker pigging model. He proposed a procedure to model the liquid slug acceleration during its delivery into the separator. He considered that the pig was moving at the gas phase velocity immediately behind it, and used his own empirical correlation for predicting pressure drop across the pig. However, Barua did not remove the main weakness of successive steady-state conditions.

Sullivan (1981) studied Many variations from a typical solid pig including those featuring a concentric uniform annulus, a concentric hole of constant or varying diameter, or both a hole and annulus.

Rahe and Weingarten et al. (1986) solved the case of a solid pig and a pig with by-pass hole in a quasi-steady state manner in a pipeline. A major assumption made in their model was that the compressible flows upstream and downstream of the pig were assumed to behave in a quasi- steady manner while this is an acceptable assumption for far-upstream and downstream flows, it is a crude simplification for flow behavior close to the pig.

Kohda et. al. (1988a, 1988b) proposed the first pigging model based on full two-phase transient flow formulation. Their model includes both the Kohda et al. (1987) drift flux transient code, which is based on the Scoggin's study, and a pigging model. The pigging model composed of a correlation for the pressure drop across the pig, a correlation for liquid hold-up in the slug zone, a correlation for the pigging efficiency as a function of the pig to pipe diameter ratio, a pig velocity model, and a gas and liquid mass flow boundary condition applied to the slug front. The resulting set of equations was solved numerically by finite difference method, using two coordinate systems, one fixed and the other adaptive. No detail was given on how the different equations were coupled and solved simultaneously. In the experimental part of the study, two pigging test results were reported that were obtained from a 1436.5 m long, 105.3 mm diameter, low pressure horizontal pipeline, using compressed air and water as the two-phase flow mixture. The experimental data compared relatively well with the predicted values from the numerical simulator. Other than the fact that the Kohda et al. (1988) pigging model is still based on a drift flux model, and that it uses flow pattern independent steady-state liquid hold-up and pressure drop correlations, no other deficiencies are apparent.

Minami (1991) developed a pigging model and coupled it with the Taitel simplified transient Model. A Eulerean-Lagrangean approach using a fixed and moving co-ordinate system is used. He used mechanistic models for predicting flow pattern, the slippage between phases and the pressure drop. Minami performed an extensive experimental program showing, this simplified approach is physically sound. However the quasi-steady state approach is not suitable for pipeline-riser system gas pump and pigging due to the high accumulation of gas upstream the pig.

Azevedo et al. (1995) Considered incompressible, quasi-state flow through a bypass hole in a simple-geometry pig. They employed Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) to provide the basis for a more simplified model of the pig motion. They also provided some experimental validation in Kruyer et al. used an analytical approach in solving a similar problem for infinitely long liquid-borne cylinders flowing freely in pipes. The focus of this work was on the radial position of the cylinder, i.e. its eccentricity with respect to the pipe. Campo and Rachid developed a simple model for incompressible transient flow and demonstrated a specific problem that showed some peculiar behavior of the pig motion.

Nguyen et al. and Kim et al. (2001) developed a model based on solving the 1-D flow equations (mass and momentum only) coupled with the pig equation of motion accounting for a bypass hole. They used “the method of characteristics” for solving the flow equations and with a regular rectangular grid , while the Runge-Kutta method was used to solve the equation of motion of the pig.

Pipeline Research Ltd.(2001) developed several computer modules, posted on their website, which deal not only with the dynamics of pig motion but also to examine the interaction of the pig with pipeline components such as straight pipe with ovality, bends and reducers, seal water etc. Nieckele et al. developed a model which includes heat transfer to the surroundings in 1-D compressible flow formulation and accounts for two distinct friction regimes that prevail depending on whether the pig is stopped or in motion; hence their model is called a "skip/slip" model.

Esmaeilzadeh et al. (2006,2009) developed two separate models, one for gas and another for liquid flows, based on solving the full 1-D flow equations using again the method of characteristics, while the equation of motion of the pig was solved using the standard Runge-Kutta method. They assumed that the pig velocity was equal to the flow velocity, hence neglected any flow by-pass.

Mathews et al (2008) referred to a general pig dynamic model developed by California Institute of Technology (Caltech), which is claimed to have been validated using 50 mm and 250 mm diameter pipe loop tests. The basis for this model is not clear.

Both Rahe and Weingarten et al.solved the case of a solid pig and a pig with by-pass hole in a quasi-steady state manner in a pipeline. A major assumption made in their model was that the compressible flows upstream and downstream of the pig were assumed to behave in a quasi- steady manner while this is an acceptable assumption for far-upstream and downstream flows, it is a crude simplification for flow behavior close to the pig.

2.2.3 TWO PHASE / MULTIPHASE FLOW PIGGING

The number of papers on two-phase/multiphase flow is very few due to the complexity of the subject. Out solved the problem of a slug liquid between two sealing pigs in an isothermal 1-D flow field by using the standard Lax-Wendroffscheme with equally expanded grid intervals behind the pig. In this way, the intervals in each volume, upstream or downstream of the pigs/slug train, were of equal size, which helped in improving the stability of the numerical scheme.

McDonald and Baker (1964) are among the initial investigators to present a study on pigging of gas-liquid pipelines. They opined that pigging can increase transportation efficiency by 30-70%. Pig Model assumed standard steady state teo phase empirical correlations for both liquid hold up and pressure drop for successive time steps. This caused errors.

Barua (1982) attempted to improve McDonald and Baker (1964) Model by removing some limiting assumptions of original model and proposed a procedure to model the liquid slug acceleration during its delivery into the separartor/slug catcher.

Kohda et al. (1988) proposed the first pigging model based on full 2 phase transient flow formulation. Model include the drift flux transient code, which is based on the Scoggins'(1977) study. The pigging model is composed of correlations for pressure drop across the pig, slug hold up, pigging efficiency, pig velocity model and a gas and liquid mass flow boundary condition applied to the slug front. This model uses flow pattern independent steady state hold up and pressure drop correlations to account the slip between the phases.

Their model included a drift flux transient code for the flow field in the pipe, as well as several correlations to couple the pig motion to the flow, e.g. correlation for the pressure drop across the pig, one for the liquid hold up in the slug zone, etc. The resulting set of equation was solved by a finite difference method, using two coordinate systems, one fixed and the other adaptive. Taitel et al (1989) Simplified transient two fluid model.

Minami and Shoham (1989) Developed a pigging model and coupled it with Taitel et al. (1989) simplified transient model assuming quasi-steady state gas flow. They used a mixed Eulerian-Lagrangian approach in the solution of the transient two phase gas/slug system. The descretisation of the flow model equation was performed using an Eulerian (fixed) coordinate grid system, but the pigging model equation employed a Lagrangian (moving) grid system. They have also conducted thorough experimental work to validate the model.

Yeung and Lima (2002) proposed where the quasi steady state approach is not suitable for such systems due to a high accumulation of gas upstream of the pig . For this purpose, a new transient two fluid model has been developed by Yeung and Lima (2002), which is appropriate for estimating two phase flow pigging hydraulics, especially in pipeline riser systems. Lima et al. used a two fluid model to determine the transient behavior of fluids during pigging operations. Although they accounted for the various flow regimes in the pipeline, they assumed that the velocity of the pig is given by the velocity of the mixture pushing the pig in the previous time step. This may only be true if there is no bypass flow through or around the pig.

Nguyen's et al (2004) in their work dealt with PIG dynamic problem in more detail when it moves under several operational conditions of the pipeline. Theoretical model for the pig dynamics was derived and computational scheme using MOC was proposed. The reliability and accuracy of that proposed solution using MOC was certified through only simulation results because fabrication of the pig and as well as a field application is very difficult.Therefore actual pigging is required to verify the reliability of solution.

A good overview of current knowledge of pigging technology and importance of individual parameters was provided by McNulty et al.(2007). They clearly advocated for the need to develop guidelines for pigging practices and the codification of knowledge to help design pigging operations that will deliver the most benefits.

A simple model to simulate transient flow behavior in a two phase flow pipeline under pigging operation has been presented by Minami (1991). In this model, Minami assumed that the gas phase can be considered to be flowing in a quasi-steady condition and then coupled it with the Taitel et al. (1989) simplified transient two fluid model. The model, however needs significant modifications in order to be used for simulating transient flow in a pipeline riser system, where the quasi steady state approach is not suitable for such systems due to a high accumulation of gas upstream of the pig . For this purpose, a new transient two fluid model has been developed by Yeung and Lima (2002), which is appropriate for estimating two phase flow pigging hydraulics, especially in pipeline riser systems.

The number of papers on two-phase/multiphase flow is very few due to the complexity of the subject. Out solved the problem of a slug liquid between two sealing pigs in an isothermal 1-D flow field by using the standard Lax-Wendroffscheme with equally expanded grid intervals behind the pig. In this way, the intervals in each volume, upstream or downstream of the pigs/slug train, were of equal size, which helped in improving the stability of the numerical scheme.

Minami and Shoham(1989) used a mixed Eulerian-Lagrangian approach in the solution of the transient two phase gas/slug system. The descretisation of the flow model equation was performed using an Eulerian (fixed) coordinate grid system, but the pigging model equation employed a Lagrangian (moving) grid system. They have also conducted thorough experimental work to validate the model.

The first pigging model based on a full two-phase transient flow formulation was developed by Kohda et al.(1988) Their model included a drift flux transient code for the flow field in the pipe, as well as several correlations to couple the pig motion to the flow, e.g. correlation for the pressure drop across the pig, one for the liquid hold up in the slug zone, etc. The resulting set of equation was solved by a finite difference method, using two coordinate systems, one fixed and the other adaptive.

Lima et al. (2002|) used a two fluid model to determine the transient behavior of fluids during pigging operations. Although they accounted for the various flow regimes in the pipeline, they assumed that “the velocity of the pig is given by the velocity of the mixture pushing the pig in the previous time step” This may only be true if there is no bypass flow through or around the pig.

A good overview of current knowledge of pigging technology and importance of individual parameters was provided by McNulty et al. (2007). They clearly advocated for the need to develop guidelines for pigging practices and the codification of knowledge to help design pigging operations that will deliver the most benefits.

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2.2.4 CONCLUSIONS

The following conclusions can be made based on the Literature Review:

The complexity of the gas-liquid transient flow has raised difficulties in the development of easy-to-use and proven codes for the oil industry to design and operate pipelines under transient conditions.

The drift-flux model requires the use of empirical correlations to account for the slippage between the phases limiting the degree of confidence of this formulation. It also suffers from ill-posedness problems.

The quasi-steady state gas flow assumed in the Taitel et al. (1989) simplified model is a serious restriction for pipeline-riser pigging. The existing pigging models are not suitable for pipeline-riser systems.

The above considerations show that further studies should be done for predicting gas-liquid transient flow and pigging in multiphase pipeline systems. The objectives of the present work are to collect experimental data on gas-liquid/multiphase pigging, transient gas-liquid flow in pipeline-flow and to develop a model to predict these complex phenomena. The model should be a transient two-fluid model avoiding the complexity of highly non-linear momentum equations of OLGA or PLAC and the simplicity of Taitel et al., drift flux or homogenous flow models

2.2.5 GAP IN LITERATURE AND RESEARCH DOMAIN

Following are major areas of focus where more studies and deliberations are required:

1. Overall, it is evident that the public domain mathematical models are inadequate. The differential pressure across the pig is one of the main parameters in controlling and determining the efficiency of the pigging operation for pipeline cleaning activities. The cleaning operation becomes more effective as the differential pressure increases. The pig velocity is also a deciding factor for the success of pigging operation. It appears from the literature that the models developed for velocity control using by-pass ports have been based primarily on a quasi-steady assumption for the single phase flow through the ports. This assumption is considered to be acceptable only for the slow transients inherent in the relative motion of the flow around the pig which is not the case in multiphase flow pipeline pigging.

2. In most of the previous research and study works, efforts are focused on single phase flow dynamics. Multiphase flow considerations and their behaviour did not gain much attention due to extremely complicated and very difficult nature of the flow. The flow pattern upstream and downstream of the pig will be totally different unlike a flow stream without a pig.

3. By-pass pigging of single phase flow has been subject of interest for many researchers and bypass flow & area requirement have been theoretically worked out in such flow conditions. But, neither the effect of by-pass flow in changing the flow regime nor different bypass hole geometry did get much attention and are less highlighted in previous literature works.

4. The adequacy of bypass gas quantity and ways to achieve the differential pressure required across the ports to attain this flow quantity during multi-phase pigging in practical field application was not studied in detail. The geometry requirement to achieve maximum flow rate (critical flow rate) at minimum differential pressure need to be thoroughly assessed and geometry needs to be finalized. Evidence is also not available to indicate that the multiphase flow behaviour through the bypass port is studied well.

5. Pig speed calculation in Multiphase flow pipeline needs to be formalized. The effect of back flow and leakage of fluid and wax through bypass holes are not addressed in detail. Pig stability and stalling condition shall also need detailed analysis during bypass pigging.

6. The effectiveness of wax removal with bypass pigs, effectiveness of wax disintegration ahead of the pig, etc. shall be studied and compared with simulated prediction results.
7. The bypass pigging solution for effective slug control and smooth process operation at receiving end needs more attention. Bypass pigging for back pressure reduction and production loss also needs to be addressed.

8. The mixture velocity and pig velocity is assumed to be equal in the multiphase flow. This assumption is a simplification of the complexity and brings error in the model. The gas compressibility factor and pressure are critical factors in this assumption which needs to

be further analysed. This assumption may be true if there is no by-pass flow through or around the pig.

9. The literature shows that most of the developed models are based either on isothermal set of governing equations i.e. 1-D mass and momentum or the complete set of equations including the energy equation with heat transfer to surroundings. These equations are typically formulated in partial differential forms or are treated in quasi-steady manner. Some models are related to Compressible flow and others to incompressible flow. But multiphase flow aspects are neglected due to its complexity. The intention is to carry out field experiments and formulate empirical equations to find out best matching model.

   Results of research on the motion of PIG in pipeline are scarcely found in the literatures. It is a fact that most research results give more commercial information than the necessary technical information about pigging process.

2.3 CHAPTER SUMMARY

This Chapter introduced review of pigging literature and various theories on single phase and multiphase flow throgh pipeline at steady state and transient conditions. Various models developed by scholars under varrying assumptions and simplifications discussed in the chapter. Different theories are applicable at different conditions. In fact there is very little hard data available on the steady state and transient motion of pigs in the literature. The literature search focused on simplified techniques which could be easily incorporated into fluid flow model and pig dynamics model.

Multiphase flow studies have sought to develop a technique with which the pressure drop can be calculated. Pressure losses in two-phase, gas-liquid flow are quite different from those encountered in single-phase flow, in most cases an interface exists and the gas slips past the liquid. The interface may be smooth or have varying degrees of rough ness, depending on the flow pattern. Therefore, a transfer of energy from the gaseous phase to the liquid phase may take place while energy is lost from the system through the wetting phase at the pipe wall. Such an energy transfer may be either in the form of heat exchange of acceleration. Since each phase must flow through a smaller area than if it flowed alone, amazingly high pressure losses occur when compared to single-phase flow.

Most investigators of horizontal two-phase flow phenomena have chosen to separate their experimental data into several groups of observed flow patterns or regimes. Separate correlations were then developed for each flow regime. This appears to be a logical approach to correlate widely scattered data, The problem arises in determining which particular flow pattern exists for a certain set of flow conditions, and in selecting the correct correlation for that pattern, An additional problem is the existence of several correlations for any one particular flow regime. The number of reported flow mechanisms for gas-liquid mixtures varies from 4 to 10, depending on the method by which the regimes were separated. Several investigators have measured a quantity defined as “liquid holdup”, Liquid holdup is that fraction of a unit volume of pipe that is occupied by flowing liquid. A knowledge of the variation of liquid holdup permits calculation of the average linear velocities of each phase and their difference, known as the “slip velocity”. Slippage of gas over the liquid is responsible for energy transfer across the interface between phases. Liquid holdup is an important parameter in multiphase flow situations. Literature on the subject of multiphase flow is voluminous. Unfortunately, understanding of the problem is not directly proportional to the quantity of subject literature. Several reviews of the literature have been published.

CHAPTER - 3

RESEARCH PROBLEM

3.1. OVERVIEW

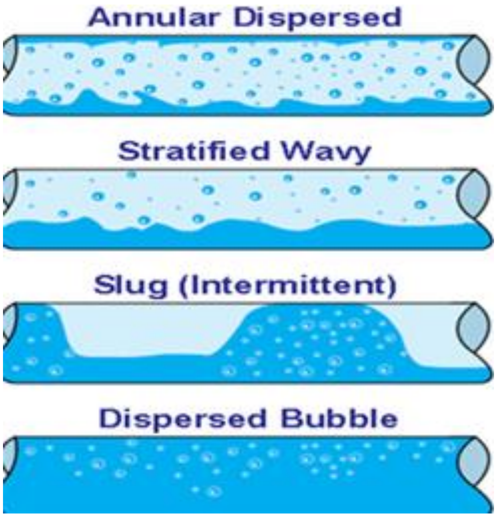
Most of the time bypass pigging is not fully effective in waxy crude oil and gas flow pipelines. Blockage of bypass holes with wax is a common problem while adopting such pigging solution, A very careful pig motion analysis, bypass design and scheme is a mandatory requirement avoid pig stalling and effective cleaning of the pipeline eliminating the risk of pipeline blockage. Also concern is the oil and gas production rate while pigging and the liquid withdrawal capacity/capacity of slug handling facility at the receiving end. High liquid slug flow to the receiving end/separator makes it difficult for further oil treatment like heating and emulsion breaking to maintain the crude oil quality.

This paper addresses various operational and engineering challenges while implementing the commonly known bypass pigging solutions. These challenges include prediction of pig velocity, pig generated slug volume, slug duration, back pressure increase in the pipeline while pigging operation, process plant upset etc. Control of these parameters are very difficult during bypass pigging operation as the operation is transient in nature. The fluid behavior through the bypass hole, subsequent down stream flow regime and the nature of turbulence are unknown. Transient modeling of bypass pigging operation with help of OLGA Software also do not support very well as compared to actual field results. There are variations in most of the above mentioned parameters. Due to the presence of wax blockage of bypass holes prediction of effectiveness is erroneous. In this paper efforts are made to formulate empirical correlations to approximate various parameters based on experimental results vis-a-vis simulation model prediction. Bypass pigs of different hole sizes to provide various flow bypass percentage have been field tested with various multiphase flow rates.

3.2 MULTIPHASE FLOW REGIMES

Multiphase flow is a complex phenomenon that is difficult to understand, predict and model. Common single-phase flow characteristics such as velocity profile, turbulence and boundary layer are thus inappropriate for describing the nature of such flow. The flow structures are rather classified in flow regimes, whose precise characteristics depend on a number of parameters. Flow regime varies depending on operating conditions, fluid properties, flow rates, orientation and geometry of the pipe through which the fluid passes. The transition between different flow regimes may be a gradual process. Due to the highly non-linear nature of the forces that rule the flow regime transitions, the prediction is nearly impossible. The distribution of the fluid phases in space and time differs for the various flow regimes and is usually not under the control of the pipeline designer or operator.

There are different flow regimes encountered in horizontal/vertical/inclined pipeline network system viz. Stratified (smooth and wavy) flow, Intermittent (slug and elongated bubble) flow, Annular flow, Dispersed Bubble flow, Churn flow etc. To stress again there is no permanent flow regime in the pipeline but it varies depending on the Gas Liquid Ratio, pipeline profile, the terrain and length at large.



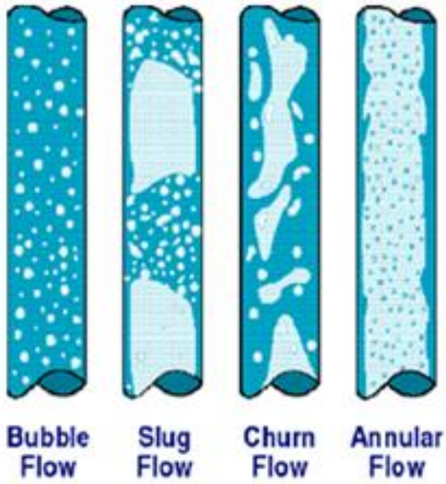


Fig 3.1 Flow pattern in horizontal pipeline **Fig 3.2 Flow pattern in vertical pipeline**

(Bratland, Ove 2010) **(Bratland, Ove 2010)**

Theoretical developments for transient two-phase gas-liquid flow in pipes can be classified into three categories: no-slip flow or homogeneous models, slip mixture flow or drift-flux models, and separated flow or two-fluid models.

Homogeneous mixture models are too simplified and in general do not performs well in comparison with experimental data. The drift flux models are sometimes called diffusion models. The basic concept of this formulation is to consider the mixture as a whole, rather than two phases separately. This is obtained by using a mixture momentum equation that results from the combination of the gas and liquid linear momentum equations. The mixture momentum equation does not contain the interfacial transfer terms, because they cancelled out in the summation process. Some additional manipulations to convert phase velocities into mixture and drift velocities are also done to express the mixture velocity, the pressure, and the liquid hold-up as dependent variables. This formulation is simpler than two-fluid models. Two-fluid formulations are very complex. The equations describing the conservation of mass and linear momentum equations for each phase are obtained by averaging the respective local instantaneous partial differential equations over the phase sub-volume in a fixed control volume. Several closure relationships are needed. These include relationships for the shear stress at the pipe wall and at the interface, the mass transfer rate between the phases, which usually depends on the pressure and temperature. One of the problems that arises when using the two-fluid formulation is to properly account for the momentum and mass transfer phenomena taking place at the interface, mainly for flow patterns with a complex interfacial surface. The two-fluid formulation can be successfully developed, however the computer codes are relatively large and complex.

While the homogeneous models have been shown to be always well-posed as an initial-value problem, the drift flux and two-fluid models have been shown to sometimes result in ill-posed initial-value problems and convergence is not attainable. The most relevant works on transient gas-liquid flow in pipes, pigging dynamics of two-phase pipelines and intermittent gas lift are reviewed in this section. Special attention is given to those related to hydrocarbon transportation and production.

3.2.1 FLOW REGIME MAPS

Simulating pipes of any elevation involves determining what kind of flow regime we are facing as well as doing calculations for that particular regime. Flow regime maps of the sort shown in figure Fig 3.3 are useful when we want to gain insight into the mechanisms creating the flow regimes.

Along the horizontal axis the superficial gas velocity $\alpha G v G$ has been plotted. That parameter is more thoroughly defined later, but for now, let us just consider it a way to quantify the volumetric gas flow (or, by multiplying with the density, the gas mass flow). Along the vertical axis we have plotted the superficial liquid velocity.

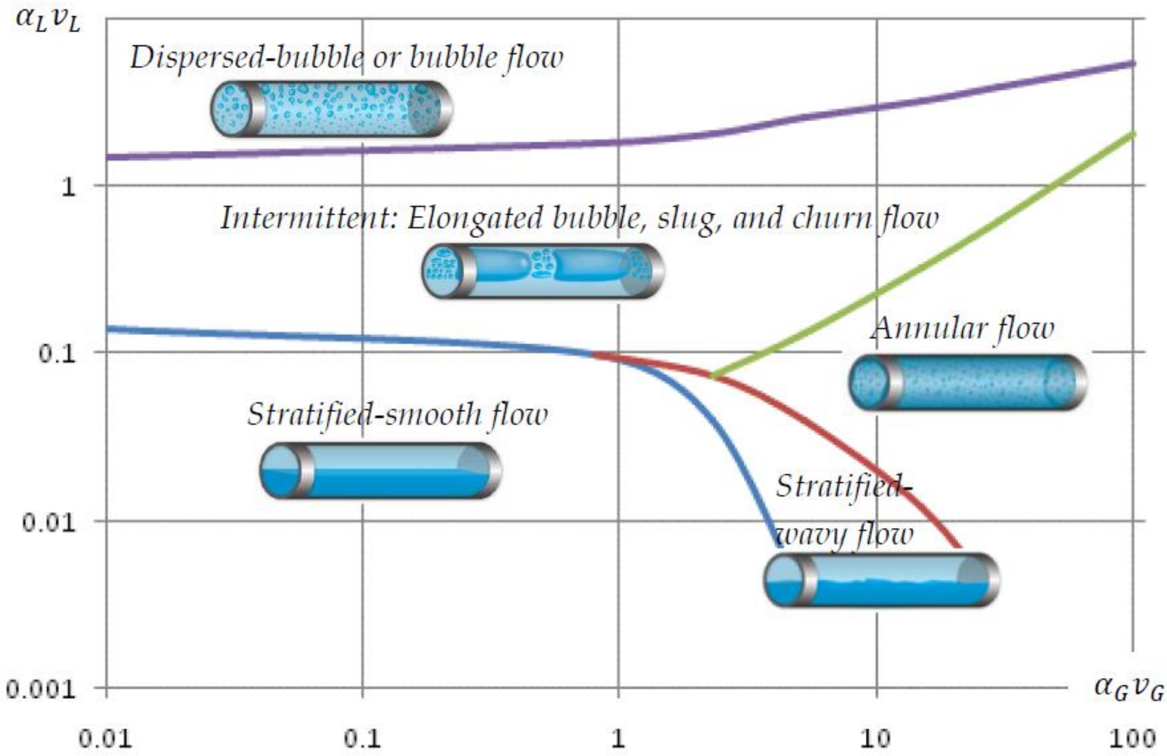


Fig 3.3 Flow regime map (Bratland, Ove 2010)

We see that for very low superficial gas and liquid velocities the flow is stratified. That is not surprising: As the velocities approach zero, we expect the pipe to act as a long, horizontal tank with liquid at the bottom and gas on top. If we increase the gas velocity, waves start forming on the liquid surface. Due to the friction between gas and liquid, increasing the gas flow will also affect the liquid by dragging it faster towards the outlet and thereby reducing the liquid level. If we continue to increase the gas flow further, the gas turbulence intensifies until it rips liquid from the liquid surface so droplets become entrained in the gas stream, while the previously horizontal surface bends around the inside of the pipe until it covers the whole circumference with a liquid film. The droplets are carried by the gas until they occasionally hit the pipe wall and are deposited back into the liquid film on the wall. We will later learn how to model this process.

If the liquid flow is very high, the turbulence will be strong, and any gas tends to be mixed into the liquid as fine bubbles. For somewhat lower liquid flows, the bubbles float towards the top-side of the pipe and cluster. The appropriate mix of gas and liquid can then form *Taylor-bubbles*, which is the name we sometimes use for the large gas bubbles separating liquid slugs.

If the gas flow is constantly kept high enough, slugs will not form because the gas transports the liquid out so rapidly the liquid fraction stays low throughout the entire pipe. It is sometimes possible to take advantage of this and create operational envelopes that define how a pipeline should be operated, typically defining the minimum gas rate for slug-free flow.

Similar flow regime maps can be drawn for vertical pipes and pipes with uphill or downhill inclinations. Notice that even though numerous measured and theoretically estimated such maps are published in literature, and although they can be made dimensionless under certain conditions (Taitel & Dukler, 1976), no one has succeeded in drawing any general maps valid for all diameters, inclinations and fluid properties. Therefore a diagram valid for one particular situation (one point in one pipeline with one set of fluid data) is of little help when determining the flow regime for any other data set. That is why we need more general flow regime criteria rather than measured flow regime maps.

Characterizing flow regimes from visual observations in the laboratory is complicated as well, and the transitions are difficult to define accurately. To make matters worse, the flow regimes in figures 3.1 and 3.2 are not the only ones one may include when defining horizontal and vertical gas-liquid flow. Different researchers define different number of flow regimes during laboratory categorization, and the number of regimes implemented in simulations models is sometimes kept lower for simplicity. The flow regime selection shown here constitute therefore only one example of how they may be defined. Predicting the flow regime can be the least accurate part of multi-phase flow calculations.

Another difficulty comes from the fact that measurements, which are most abundant for small diameter pipes, are hard to scale up to larger diameters. This problem effects both flow regime determination and the modeling of each specific regime

3.2.2 TYPES OF 3-PHASE AND QUASI 4-PHASE FLOW

Three phase flow is most often encountered as a mixture of gas, oil and water. The presence of sand or other particles can result in four-phase flow, or we may have three-phase flow with solids instead of one of the other phases. Although sand has the potential to build up and affect the flow or even block it, the most common situation if sand is present is that the amounts are tiny. If we keep the velocities high enough, the sand is quickly transported out of the system, and we can often get away with neglecting the particles in the flow model. Instead, it is only taken into account in considerations to do with erosion or to establish minimum flow limits to avoid sand buildup. The three-phase flow our simulation models have to deal with are therefore primarily of the gas-liquid-liquid sort, and sand is only included – if at all - indirectly.

Three-phase flow regimes

Creating flow regime illustrations similar to those for gas-liquid flow in figures 3.1, 3.2, and 3.3 is very difficult for three-phase flow. Some authors have done so, but they end up with very complex illustrations of limited validity, and the pedagogical value is questionable. It may be more convenient to illustrate three-phase flow as shown in figure 3.4 below.

The diagram has been plotted in three dimensions, one for each phase. The vertical axis contains the gas superficial velocity as a fraction of the total superficial velocities. That superficial velocity fraction has been defined so that it becomes *1* for pure gas flow. For pure liquid (oil-water) flow, which corresponds to a straight line in the oil-water plane, the gas fraction is zero. Similarly, if the water content is zero, our operation point will be located somewhere on a line in the gas-oil plane, and so on for zero oil content. Operation points inside the triangle will correspond to three-phase flow.

The zero oil and zero water content planes in figure Fig 3.4 correspond to gas-liquid flow regimes similar to those discussed in figure Fig 3.3. In the oil-water plane, the liquid-liquid mixture can show a very interesting property we have not mentioned yet: The oil can occur as isolated droplets dispersed in the continuous water. If we increase the oil content, the flow can suddenly switch to the opposite situation in a process called *phase inversion*. The dispersion's viscosity tends to be quite similar to the continuous phase's viscosity, which normally is much higher for oil than for water. Whether we have an oil-in-water or water-in-oil dispersion is therefore very important to the mixture's viscosity, and we can observe significant viscosity 'jumps' when a phase inversion occurs. If we take a look at the modified Moody diagram, we see that the consequences of using inaccurate viscosity (and thereby inaccurate Reynolds number) in the friction calculations depend on where in the diagram our operational point is located – for relatively high Reynolds numbers and/or high surface roughness, it may have little or no influence.

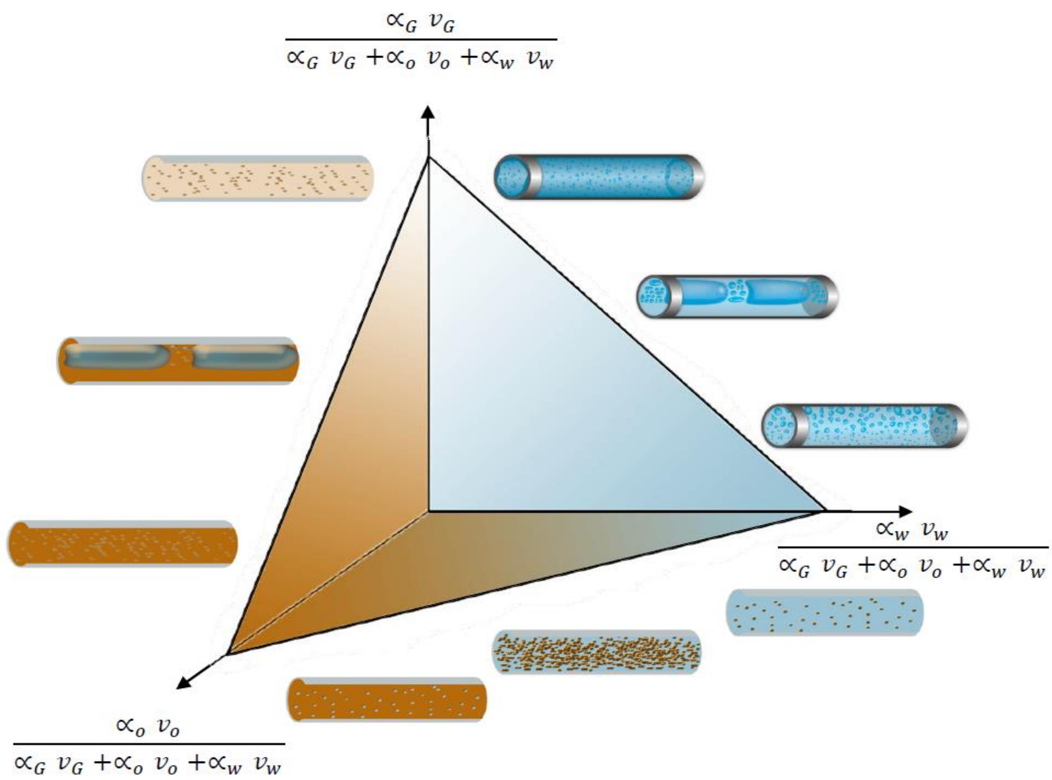


Fig 3.4 Three dimensional flow regime map (Bratland, Ove 2010)

We can also experience other liquid-liquid flow regimes, and the number of possible regimes becomes very large when we move upwards in the three-phase diagram. As a general rule, it is likely the liquids appear as one dispersed in the other if they occur in very different quantities. In some cases we can get reasonable results by treating the two liquids as one averaged liquid and reduce the problem to two-phase gas-liquid flow. Some of the commercial software treats three-phase gas-liquid-liquid flow in this way in all situations, but it can lead to quite inaccurate results for some flow regimes.

Equation of motion

It was implicitly assumed that there existed an infinitesimal volume of dimension such that the volume is not only very much smaller than the typical distance over which the flow properties varied significantly but also very much larger than the size of the individual phase elements (the disperse phase particles, drops or bubbles). The first condition is necessary in order to define derivatives of the flow properties within the flow field. The second is necessary in order that each averaging volume contain representative samples of each of the components or phases. It is required to develop the effective differential equations of motion for multiphase flow assuming that these conditions hold.

However, one of the more difficult hurdles in treating multiphase flows, is that the above two conditions are rarely both satisfied. As a consequence the averaging volumes contain a finite number of finite-sized particles and therefore flow properties such as the continuous phase velocity vary significantly from point to point within these averaging volumes. These variations pose the challenge of how to define appropriate average quantities in the averaging volume. Moreover, the gradients of those averaged flow properties appear in the equations of motion that follow and the mean of the gradient is not necessarily equal to the gradient of the mean.

In fluid dynamics heat of conduction and viscous dissipation are avoided/neglected to reduce co mplication and to simplify. Energy equation for multiphase flow is very complicated. In single phase flow it is generally assumed that the fluid is in equilibrium thermodynamic state at all points in the flow. In many multiphase flow , the different phases/components are often not in equilibrium and thermodynamic arguments are no longer valid.

Interaction with Turbulence

Turbulent flows of a single Newtonian fluid, even those of quite simple ex- ternal geometry such as a fully-developed pipe flow, are very complex and their solution at high Reynolds numbers requires the use of empirical models to represent the unsteady motions. It is self-evident that the addition of particles to such a flow will result in:

1. complex unsteady motions of the particles that mayresult innon-uniformspatial distribution of the particles and, perhaps, particle segregation. It can also result in particle agglomeration or in particle fission, especially if the particles are bubbles or droplets.

2. modifications of the turbulence itself caused by the presence and motions of the particles. One can visualize that the turbulence could be damped by the presence of particles, or it could be enhanced by the wakes and other flow disturbances that the motion of the particles may introduce.

In the last twenty five years, a start has been made in the understanding of these complicated issues, though many aspects remain to be understood. The advent of laser Doppler velocimetry resulted in the first measurements of these effects; and the development of direct numerical simulation allowed the first calculations of these complex flows, albeit at rather low Reynolds numbers.

Dynamic multiphase flow instabilities

At higher frequency, the effective resistance could become a complex function of frequency and could depart significantly from the quasi static resistance. It follows that there may be operating points at which the total dynamic resistance over some range of frequencies is negative. Then the system would be dynamically unstable even though it may be quasi statically stable. Such a description of dynamic instability is instructive but overly simplistic and a more systematic approach to this issue is required to be detailed. It is nevertheless appropriate at this point to describe two examples of dynamic instabilities so that reference to these examples can be made during the description of the transfer function methodology.

Intense Modelling Efforts

The past 3 decades have seen intense modelling efforts to improve our ability to predict multiphase flow behaviour with greater accuracy. The empirical approach typically involves flowing fluids at carefully measured flow rates through a pipe, observing the flow pattern, and measuring liquid holdup and pressure drop. Different diameters, pipe inclinations, and fluids can be used, but all tests are at steady-state conditions (constant gas and liquid flow rates). Using the measured data, empirical correlations are developed for predicting flow patterns, liquid holdup, and friction factor. A pressure gradient equation is also developed that uses these empirical correlations. A computer program can then be written that numerically integrates the pressure-gradient equation along a pipe to predict the pressure drop. The modelling approach is much more sophisticated. In addition to the measurements made in the empirical approach, one must measure variables such as liquid-film thickness and entrainment fraction for annular flow, film thickness around a Taylor bubble in slug flow, and film thickness and with curvature in stratified flow. Empirical correlations must then be developed to predict these phenomena (often called closure relationships). These relationships are then used in more complicated pressure-gradient equations that capture the flow behaviour much better than in the empirical approach. A vital key to the modelling approach is a mechanistic model for predicting flow pattern. Past attempts in the modelling approach used different conservation equations for predicting flow pattern and pressure gradient. The latest attempts to develop multiphase- flow models have recognized that the same conservation equations must be used for predicting both flow pattern and pressure gradient. Although some of the better empirical correlations have survived the test of time, they all suffer from significant errors in some ranges of input variables and cannot be improved because of their simplistic nature.

The mechanistic models are more accurate, more sophisticated, and more difficult to understand. An example of the power of mechanistic models has emerged with current research on multiphase flow involving heavy (viscous) oils. Early empirical correlations fail to predict pressure drop for heavy oils accurately. Flow patterns for heavy oils have different transition boundaries than conventional oils. Some of the closure relationships for lighter oils fail to predict these relationships with acceptable accuracy for heavy oils. However, current heavy-oil multiphase flow research will soon result in an accurate mechanistic model. Identifying limitations like this in existing models and then being involved in successful research to improve predictions is exhilarating, knowing that your efforts will be used by others as they design and operate complex production systems. Successful operation of production systems also requires the ability to predict flow behaviour when flow rates change in pipes. This occurs frequently when adding production from new wells and fields into a pipeline, or reducing production because of flow-assurance problems, maintenance issues, hurricanes, or other factors. Simulating these time-dependent behaviours requires a sophisticated commercial multiphase-flow simulator like OLGA that is based on conservation equations that retain time-dependent terms. OLGA also involves flow-pattern predictions and requires closure relationships similar to steady-state flow.

3.3 SIGNIFICANCE OF WAX IN OIL & GAS PIPELINES

Multiphase flow can be severely affected by the deposition of organic solids, usually in the form of wax crystals, and their potential to disrupt production due to accumulation in the production/transmission systems. The wax crystals reduce the effective cross sectional area of the pipe and increase pipeline roughness, resulting in an increase in pressure drop which indirectly necessitates high pressure requirement at the start point. The deposits also cause subsurface and surface equipment plugging and malfunction especially when oil and gas mixture is transported during cold weather and subsea conditions. Wax deposition leads to more frequent and risky pigging requirements in pipelines. If the wax deposits get too thick, they often reduce the capacity of the pipeline and cause the pigs to get stuck. Wax deposition in well tubing creates more pressure drop in the tubing leading to loss in oil production.

The effect of wax deposition in the pipeline with a focus on the total heat transfer coefficient will be evaluated in this thesis. As the wax layer increases, the total heat transfer coefficient changes/reduces and this affects the further wax deposition.

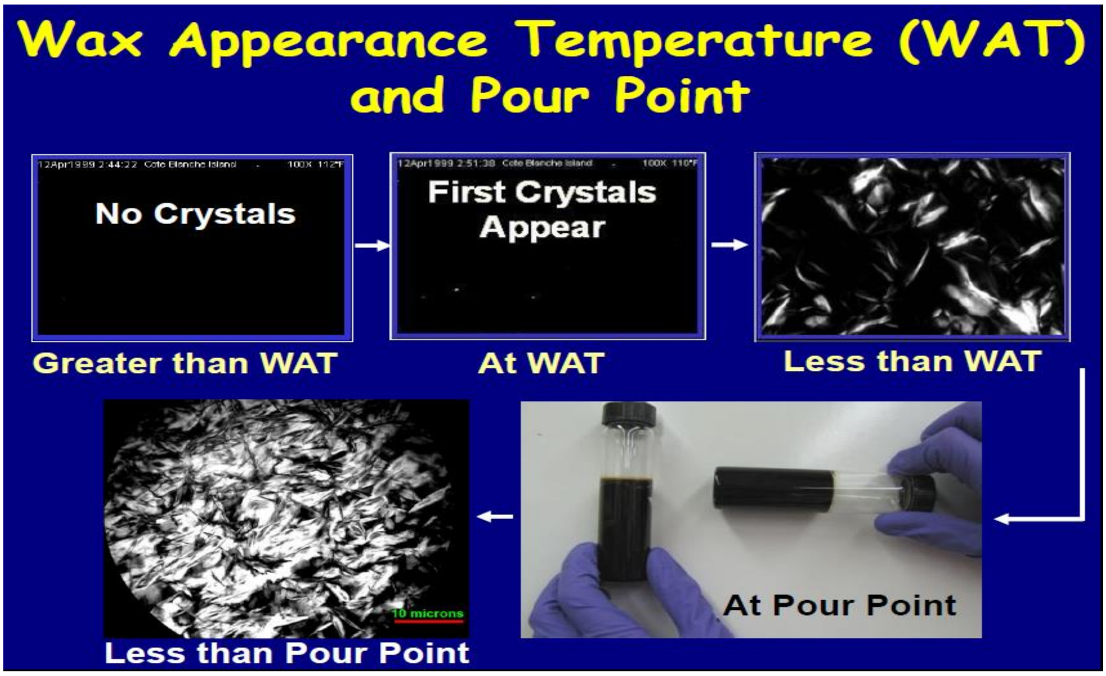


Fig 3.5 Wax crystalization (Venketesan, 2003)

Precipitation of wax from petroleum fluids is considered to be a thermodynamic molecular saturation phenomenon. Paraffin wax molecules are initially dissolved in a chaotic molecular state in the fluid. At some thermodynamic state the fluid becomes saturated with the wax molecules, which then begins to precipitate. This thermodynamic state is called the onset of wax precipitation or solidification. The wax precipitation depends primarily on fluid temperature and composition and is dominated by Vander Waals or London Dispersion type of molecular interactions. It is analogous to the usual dew point or condensation phenomenon, except that in wax precipitation a solid is precipitating from a liquid, where as in condensation a liquid is precipitating from vapor. In wax precipitation, resin and asphaltene micelles behave like heavy molecules. When their kinetic energy is sufficiently reduced due to cooling, they precipitate out of solution but they are not destroyed. If kinetic energy in the form of heat is supplied to the system, these micelles will desegregate to unstable suspension and Brownian Motion. As the paraffin wax starts to deposit on the wall, the pipe cross sectional area will decrease. This decrease leads to pressure drop and flow restrictions, and can be an extensive challenge in the oil production.

As mentioned above the wax layer will build up in layers and can block the line if not removed. As the wax layer builds up, it becomes more difficult to pig the line. The forces needed to push the pig through the pipeline increases with increasing wax layer. With decreased pressure and flow in the line, and a large wax layer, there is a risk of the pig to get stuck. The wax thickness must be known to evaluate the likelihood of stuck pig.

3.4 MULTIPHASE FLOW PIPELINE PIGGING

During a pigging operation several flow zones prevail in a pipeline. An undisturbed multiphase flow regime exists at far downstream of the pig. In this area the effects of the pig launch is not felt so far. As the pig moves, a liquid slug region forms and grows by scooping the liquid from the downstream of the pig gradually extending to the undisturbed region. As slug growth increases, the farther downstream becomes transient. However behind the pig, the liquid hold up is very less, forming a gas zone as the pig removes most of the liquid phase sooner it is launched. The last zone is redeveloping the multiphase flow regime. All these different region inside the pipeline move from upstream to downstream at different velocities bringing the pipeline subject to pigging operation under transient condition.

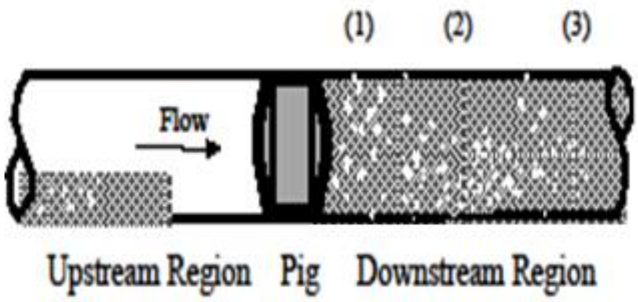


Fig 3.6 Normal pigging operation

Once the pig is launched, the downstream pressure including the separator tends to decrease because the pig starts to block the gas and liquid to generate the liquid slug downstream of the pig in starting from the front. The inlet pressure doesn't change much as long as the pig is in the horizontal terrain as the liquid slug grows further. However, when the terrain changes or pipeline profile changes from horizontal to hilly or riser sections and the liquid slug front reaches the riser, the liquid slug has to travel against the head and the back pressure starts increasing and the inlet pressure starts increasing. This period is also considered as a gas accumulation time which means low pig velocity. This pressure increase continues till the back of the liquid slug reaches the riser when the riser is filled with gas and the head is dramatically reduced. During this time the pig gets accelerated and the liquid slug flow to Separator increases followed by high flow rate of gas pressure and the separator pressure increases. After some time the system stabilize up on receipt of the pig. The stabilization time depends on the transient nature of the operation and the back pressure increase during the pigging operation.

The velocity profile or response of the pig to a restart, resulting acceleration, peak velocity and eventual slowing down for a low pressure gas is much higher than the same for a high pressure gas. Low pipeline pressure or high pig differential can result in high accelerations and therefore elevated velocities.

A simple pig with mass “m” can have accelerations/decelerations due to force “F” (due to differential) as follows:

$$V = F/m \qquad \text{- Eqn (3.1)}$$

3.5 OPERATIONAL CONCERNS& CHALLENGES

One of the operational concerns during pigging of multiphase production pipeline is the restriction of production during pigging operation. Production loss is encountered due to high back pressure, restricted pigging speed, insufficient slug handling facility at downstream, process upset etc. Operational risks include a slug catcher / Heater-treater trip caused by a surge in liquid level, solid blockage, high liquid carry over with gas, improper process heating, crude oil quality issues etc. The potential for lost production due to a stuck pig in offshore pipeline is also very much on card.

Handling of high flow rate and high back pressure during pigging operation is a major challenge for engineering and operations. Since pigging is a major and most cost effective solution in cleaning operation of paraffinic oil and gas multiphase pipelines, oil industry started focusing on these critical issues to suggest solutions. The conventional ways of tackling the issue is one by reducing the production level while pigging to a practically acceptable level based on the liquid hold up and slug recovery at the receiving end. The second solution is to build huge slug handling facility at the receiving end. Both have the disadvantage of either production loss while pigging or huge initial capital investment. Still both solutions are incomplete and only partially resolve the problems.

3.6 BY-PASS PIGGING SOLUTIONS

In order to reduce the liquid/solid surge and high back pressure risks in long pipelines, by-pass pigging solutions has been deployed. Properly designed by-pass pig can effectively control the situation by distributing the collected liquid and debris in front of the pig.

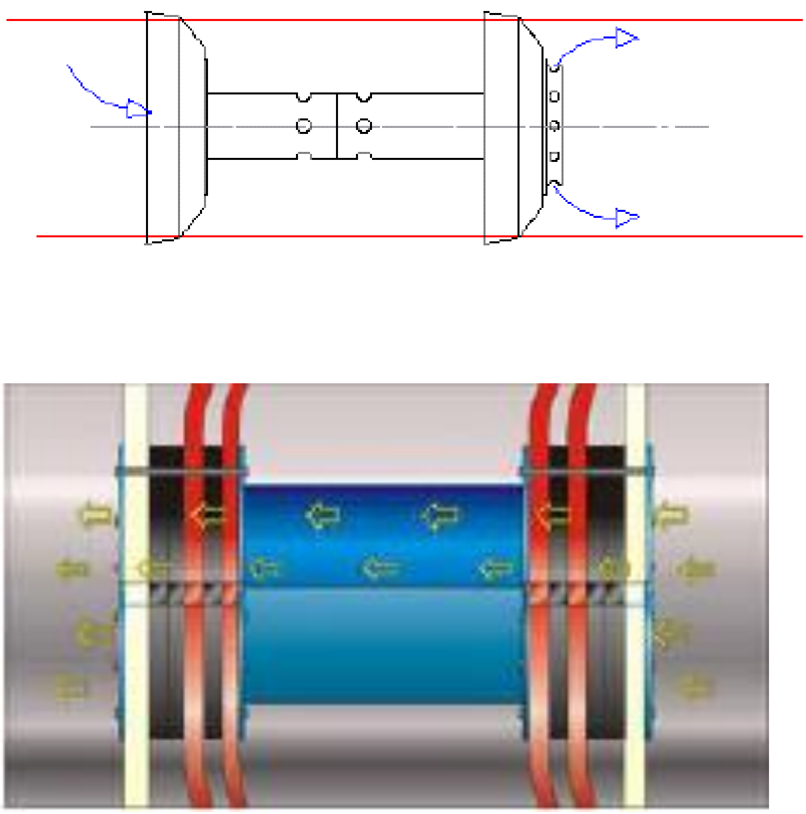


Fig 3.7 Bypass pigging operations

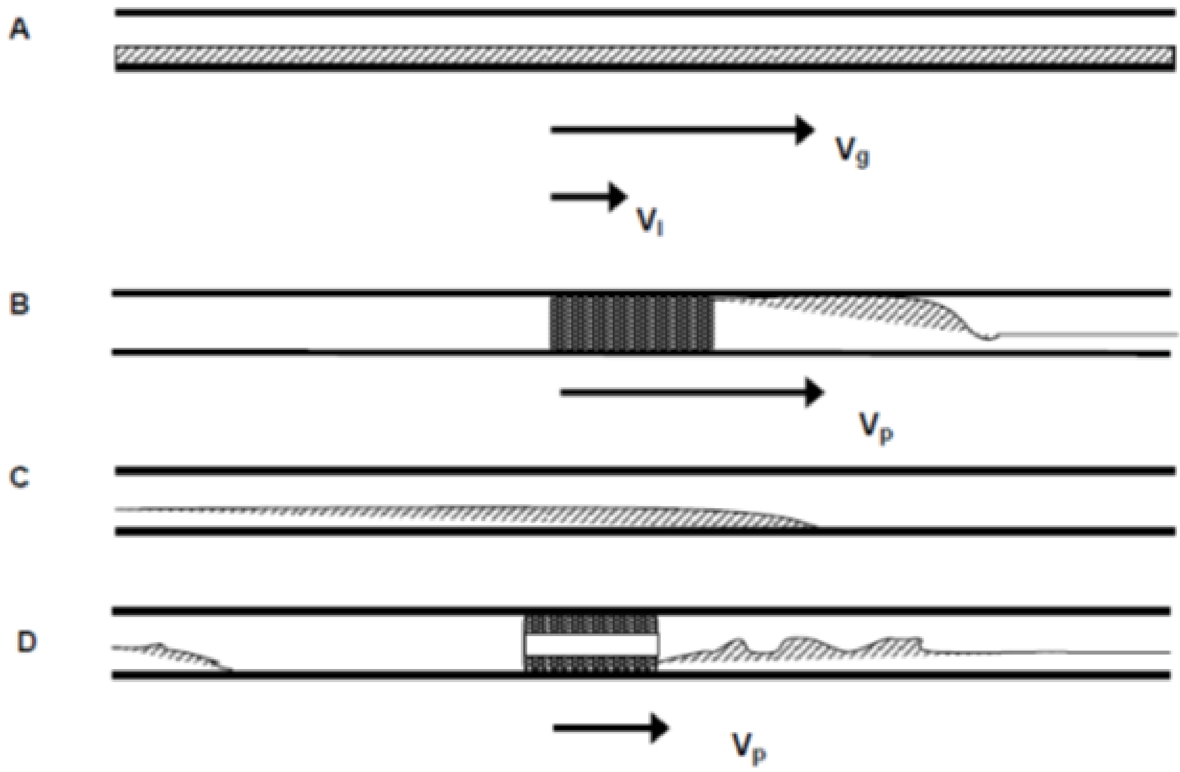


Fig 3.8 Comparison between Normal and By-pass pigging

(A- Steady state flow prior to pigging ; B- A normal pig piles up liquid in front and leaves a dry stretch behind ; C- Delayed rsumption to equilibrium steady flow condition after passage of the pig ; D- The by-pass pig moves at a reduced velocity; piles up less liquid in front and leaves a shorter dry stretch behind).

In bypass pigging, some quantity of the upstream multiphase fluid/gas is bypassed through the pig towards the font so that the downstream liquid slug is aerated gradually as the pig moves. This solution has the following major advantages;

i) Helps in controlling undue increase in the back pressure in the pipeline at hilly terrains and riser portion.

ii) Helps to deliver a constant rate of oil and gas to the separator unlike the long liquid or gas slug in the conventional pigging.

iii) The gas /fluid jet coming through the bypass holes cleans and clear the wax/solid debris in front of the pig and pushes it away and avoid any piling up in front of the pig and leading to pig stuck up.

iv) Helps in increasing the production rate (oil and gas) while pigging simultaneously keeping the required low pig velocity to ensure an effective pipeline cleaning.

v) Helps to optimize the liquid slug handling facility capacity requirements.

Most of the time bypass pigging is not fully effective in waxy crude oil and gas flow pipelines. Blockage of bypass holes with wax is a common problem while adopting such pigging solution. A very careful pig motion analysis, bypass design and pig selection scheme is a mandatory requirementto avoid pig stalling and effective cleaning of the pipeline eliminating the risk of pipeline blockage. Also concern is the oil and gas production rate while pigging and the liquid withdrawal capacity/capacity of slug handling facility at the receiving end. High liquid slug flow to the receiving end/separator makes it difficult for further oil treatment like heating and emulsion breaking to maintain the crude oil quality.

3.6.1 BY-PASS PIGGING AND ENGINEERINGCHALLENGE

Recent innovations in Bypass pigging have significantly reduced the problems in single phase lines, however multiphase pipelines need more careful analysis and custom made solutions after rigorous pig modeling. A close analysis of the pig motion in the pipeline based on pigging model and field application program is essential to minimize the production loss and also to improve the pigging efficiency. The uncertainty of flow regime

& liquid hold up in the pipeline and the pipeline profile are major influencing factors in multiphase pigging operation.

Multiphase flow through pipeline is a complicated domain of fluid dynamics. Various flow parameters, fluid properties and physical considerations like pipeline diameter, profile and terrain are most important aspects which influences the flow regime. Steady state and transient flow conditions are defined very differently in the multiphase pipeline flow. Three equations viz. Continuum equation of mass, continuum equation of momentum and equation of conservation of energy are very important in describing /defining the Multiphase flow. The mass, momentum and energy conservation principles of different phases in the flow stream have to be correlated to solve the problem. Energy equation in multiphase flow becomes quite complicated. In single phase flow it is generally assumed that the fluid is in equilibrium thermodynamic state at all points in the flow. In many multiphase flows, the different phases/components are often not in equilibrium and thermodynamic equilibrium is not possible.

Multiphase Pipeline sizing is generally based on the erosion velocity criteria as per the API RP 14E Code requirement. An optimum mixture velocity is maintained. Pipeline performance curve is also made use to optimize the pipeline size by maintaining the most effective flow regime to minimize slug flow conditions. Frictional pressure loss, Reynold's number, Viscosity are also taken care during the pipeline sizing. Pigging velocity requirement is not considered at this juncture though the pipeline is mechanically designed to accommodate pigging operation. Similar is the design capacity of the receiving facility (Slug catcher/Separator). As mentioned earlier suitable bypass pig design is a great challenge to oil industry especially for multiphase flow with oil, gas, wax &sand

components. Each pigging operation is different in a multiphase flow line at different GLR and wax content. Operating pressure, temperature, liquid viscosity, pipeline profile, liquid hold up in the line are playing important roles. Simulations, Experiments and Modeling are important steps for better design of by-pass pigging.

The level of complexity for a multiphase (mainly oil/gas) pigging model is considerable due to the content of basic equations such as (i) Gas continuity (ii) Gas momentum (iii) Liquid continuity (iv) Liquid momentum (v) Energy equations for each phase to account the temperature efforts. These result is nine simultaneous Partial Differential Equations with gas velocity, liquid velocity, pressure and temperature and gas fraction.

The main drivers for a simplified pigging model is as follows

i) Multiphase pipeline pigging is the most commonly encountered production operations for pipeline cleaning. The liquid and gas content affects the speed of the pig in many ways.

ii) The wax deposit in the pipeline wall and fine wax particles and sand particles challenge the pigging efficiency and the amount fluid available to carry away these components

iii) Comparison of output with commercially available software such as OLGA would allow a check to be carried out from a pigging point of view on the output. These simulations consider many complex matters but little comparison is available with pigging data matching

iv) Knowledge of the flow of fluid (oil/gas) to the surface handling facility (slug catcher/separator)

The following aspects are considered :

a) Development of stable solution method

b) Comparison with field data and published data

c) Comparison with OLGA

d) Integration with pigging model

3.7 INTRODUCTION TO RESEARCH PROBLEM

3.7.1 ELEMENTS OF PIGGING OPERATIONS IN MULTIPHASE FLOW

Pigging of multiphase flow pipelines is highly complicated compared to single phase flow pipeline.Bypass pigging, as compared to the conventional pigging, reduces the damaging effect of pig generated liquid slug by distributing gas and liquid in the pipeline. Allowable Oil and Gas production rate while pigging, high liquid slug flow to the slug catcher, high pipeline back pressure, liquid withdrawal rate/capacity of slug handling facility at receiving end etc. are major considerations for designing a suitable bypass pigging solution. Most of the time, bypass pigging is not fully effective in waxy crude oil due to blockage of bypass holes with wax.

The operating efficiency of a pig is dependent up on number of factors such as the differential pressure across the pig, pig relative velocity with respect to the mean flow velocity, by-pass and sealing efficiency, mass and geometry of the pig, pipe internal diameter, surface roughness and internal pipe condition. Based on the above literature survey an attempt is made through this research work to bridge the gap by improving the by-pass pig geometry and develop a new model to predict the pig velocity & the by-pass fluid quantity.

3.7.2 EVOLUTION OF MULTIPHASE PIGGING

This research work is to study the pigging requirement of multiphase flow pipelines in oil and gas production and processing systems which encounter wax deposition problems as it was rarely addressed in previous research studies and sufficient details are unavailable.Through this work the effect of by-passing of flow to disintegrate the deposited wax will be addressed and bypass geometry will be adjusted to get optimum results.

Quasi-steady state assumptions in multiphase pigging needs to be reviewed and elaborated/verified. The quasi-steady state flow assumption inside the bypass port i.e. the assumption that no relative acceleration of the fluid inside the port, shall be re-visited. This assumption eliminates the effect of any by-pass port in the pig dynamic motion inside thepipeline. This shows that the bypass holes do not have any effect in the stability of the pig or the pig motion, the force balance, its acceleration& deceleration or stalling. This inference shall be reviewed.

The effect of relative acceleration of the fluid inside the bypass port shall be created by the use of a Converging diverging Nozzle profile which will also increase the bypass gas quantity near to the critical flow rate at a very low differential pressure across the pig.In actual field application cases, the effect of bypassing fluid is not realized/obtained, though the bypass area is available. The bypass quantity is negligible and not in line with the calculation based on Thorn-Hill- Craver equation.

The effect of sand/solid back flow through the bypass port and the gap between the pipe inner diameter and the pig disc will also be addressed during the study.

The frictional force (static and dynamic) is the major deciding factor in pig motion analysis. The effect of wax deposit in the pipeline inner wall and the wax shear friction in the gap is unknown in deciding the frictional force.

Cleaning-pigging frequency and type of pigs are selected based on the wax and scale deposition pattern/nature in the pipeline. During normal pigging operation, there is a phase separation phenomenon which results alternate gas and liquid surges followed by a continuous gas phase at the end. Tackling the instantaneous flow of discrete phases is the concern of operation engineers. By introducing a bypass pig in the system some of the gas quantity can be passed through the bypass holes ahead of the pig to lighten the liquid stream in front of the pig and accelerate. It also helps to create a jetting action of gas ahead of the pig travel and remove the wax deposit from the pipe wall. Bypass pig design is very complicated and is tried by few skilled manufacturers who have put in lot of effort to fabricate the geometry and estimate the performance through rigorous testing. Improper bypass pig design may cause stalling of the pig leading to blockage and production loss and even loss of pipeline. Moreover, the efforts were mainly limited to single phase with square edge orifices and on the other hand the case of multiphase fluid is still more elusive and uncertain because of the peculiar fluid and thermodynamic properties. However, no results of research on the experimental certification for dynamic behavior of the PIG could be found.

Fluid composition, flow conditions like pressure, temperature, pipeline profile, flow quantity are some of the critical factors which makes the multiphase flow process complex. Pigging solution is well established in the oil & gas industry for mechanical cleaning of the pipeline for single phase fluid like oil or gas. It is also commonly carried out in 3 phase flow. However, the design, development and application of BY-PASS PIG solutions is still proprietary to very few manufacturers or specialized engineering companies based on case studies. Its wide and general applications in the upstream oil and gas industry still need more investigation, research studies and experimentation.

Some crude oil (paraffinic) has a tendency to form wax as they cool. The wax crystalizes onto the pipe wall reducing the diameter and making the surface rough. Both effects reduce the flow efficiency of the pipeline. A variety of cleaning and scraping pigs are available in the market to alleviate this problem.

In pigging operations where the pipe content is unloaded, the liquid holdup builds up as a slug ahead of the moving pig. The arrival of a slug at production/processing equipment/facility is problematic. It causes both mechanical problem (like high velocity and momentum) and process problems (such as increasing liquid level causing surges and trips).

The pigging operation in multiphase pipeline is a transient operation. Transient flow is observed not only during the pig running time, but also for a long time after the pig exits the pipeline. This situation occurs even if the inlet liquid, gas rate and pressures are kept constant. Analysis of such transient flow behavior in a pipeline is necessary not only for designing the downstream processing facilities, but also for establishing safe operating procedures. Hence, there is a definite need to develop reliable and comprehensive pigging model for better understanding of transient behavior of fluids during these operations.

Most of the time bypass pigging is not fully effective in waxy crude oil and gas flow pipelines. Blockage of bypass holes with wax is a common problem while adopting such pigging solution. A very careful pig motion analysis, selective bypass design and scheme are mandatory requirements to avoid pig stalling and effective cleaning of pipeline eliminating the risk of pipeline blockage. Also concerns exists in the oil and gas production rate while pigging and the liquid withdrawal capacity/capacity of slug handling facility at the receiving end. High liquid slug flow to the receiving end/separator makes it difficult for further oil treatment like heating and emulsion breaking to maintain the crude oil quality.Flow bypass percentage have been field tested with various multiphase flow rates.

3.8 IMPLICATION OF RESEARCH PROBLEM

This study addresses various operational and engineering challenges while implementing the commonly known bypass pigging solutions. These challenges include prediction of pig velocity, pig generated slug volume, slug duration, back pressure increase in the pipeline while pigging operation, process plant upset etc. Control of these parameters are very difficult during bypass pigging operation as the operation is transient in nature. The fluid behavior through the bypass hole, subsequent down stream flow regime and the nature of turbulence are unknown. Transient modeling of bypass pigging operation with help of OLGA Software also do not support very well as compared to actual field results. There are variations in most of the above mentioned parameters. Due to the presence of wax blockage in the bypass holes, prediction of pigging effectiveness is erroneous. In this research work efforts are made to formulate empirical correlation to approximate various parameters based on experimental results vis-a-vis simulation model prediction. Bypass pigs of different hole sizes to provide various by-pass quantity are used for testing and data collection.

3.9 INFLUENCE OF RESEARCH PROBLEM ON SYSTEM'S PERFORMANCE

Selection of bypass pig geometry/profile has special significance in the pigging operation due to its high influence on the production & process system. While finding the optimal pigging solution, it is important to find out the criteria that needs attention. This thesis illustrates the forces acting on a bypass pig in operation. Expressions for both the bypass gas quantity & back- pressure to the system along with liquid & gas surge volume have been presented.

One of the operational concerns during pigging of multiphase production pipeline is the restriction of production during pigging operation. Production loss is encountered due to high back pressure, restricted pigging speed, insufficient slug handling facility at downstream, process upset etc. Operational risks include a slug catcher / Heater-treater trip caused by a surge in liquid level, solid blockage, high liquid carry over with gas, improper process heating, crude oil quality issues etc. The potential for lost production due to a stuck pig in offshore pipeline is also very much on card.

Handling of high flow rate and high back pressure during pigging operation is a major challenge for Engineering and Operations. Since Pigging is a major and most cost effective solution in cleaning operation of paraffinic oil and gas multiphase pipelines, oil industry started focusing on these critical issues to suggest solutions. The conventional ways of tackling the issue is one by reducing the production level while pigging to a practically acceptable level based on the liquid hold up and slug recovery at the receiving end. The second solution is to build huge slug handling facility at the receiving end. Both have the disadvantage of either production loss while pigging or huge initial capital investment. Still both solutions are incomplete and only partially resolve the problems.

3.10 SUMMARY

Pigging operation is commonly used in the pipeline industry in which special devices called pigs are sent into a pipeline for cleaning the pipe interior or inspection. This operation is most commonly used for cleaning the pipelines at various phases of pipeline life cycle. Pigging is an important step after hydro-test and flushing during construction phase in the pre-commissioning stage for debris removal/de-watering/gauging. Frequent pigging operation is essential to maintain the operating efficiency and integrity of any pipeline by removing the scale that builds up on the pipe interior surface from years of operations, removing pafaffin and sand build up in crude oil pipeline, removing settled water which may cause pipeline corrosion. Removing these materials from the pipe by pigging not only results in a cleaner fluid or product going through the pipeline, it also increases the pipeline diameter and reduces the pipeline roughness. Consequently, the pipeline becomes more efficient-being able to transport larger quantity of product with same or less energy. It is also considered as a flow assurance and integrity tool in the oil industry. Pigging is also used for product separation, corrosion inhibition and inspection purposes.

Fluid composition, flow conditions like pressure, temperature, pipeline profile, flow quantity are some of the critical factors which makes the multiphase flow process complex. Pipeline cleaning operation is one of the most vital operations to maintain the operational efficiency throughout life cycle. Pigging solution is well established in the oil & gas industry for mechanical cleaning of the pipeline for single phase fluid like oil or gas. It is also commonly carried out in 3 phase flow. However, the design, development and application of BY-PASS PIG solutions is still proprietary to very few manufacturers or specialized engineering companies based on case studies. Its wide and general applications in the upstream oil and gas industry still need more investigation, researchstudies and experimentation.

In pigging operations where the pipe content is unloaded, the liquid holdup builds up as a slug ahead of the moving pig. The arrival of a slug at production/processing equipment/facility is problematic. It causes both mechanical problem (like high velocity and momentum) and process problems (such as increasing liquid level causing surges and trips).

The pigging operation in multiphase pipeline is a transient operation. Transient flow is observed not only during the pig running time, but also for a long time after the pig exits the pipeline. This situation occurs even if the inlet liquid, gas rate and pressures are kept constant. Analysis of such transient flow behavior in a pipeline is necessary not only for designing the downstream processing facilities, but also for establishing safe operating procedures. Hence, there is a definite need to develop reliable and comprehensive pigging model for better understanding of transient behavior of fluids during these operations.

CHAPTER - 4

RESEARCH OUTLINE

4.1 OVERVIEW

Field testing, experimentation and empirical correlation development are major steps in any research project. Suitable and adequate experimental facility shall be planned and built up. In this section the field testing facility is properly described and the various hardware requirements such as mechanical, instrumentation & control system, software and other requirements are mentioned and set up.

4.2 EXPERIMENTS AND SIMULATIONS

4.2.1 EMPIRICAL CORRELATIONS BASED ON FIELD TEST RESULTS

Correlations to determine the pig travel time based on the production flow during pigging, the speed reduction due to by-pass, expected slug reduction with help of bypass, back pressure conditions in the pipeline, etc. can be evolved based on a correlation developed from experimental results.

The liquid hold up in a long distance pipeline is a function of the Gas Liquid Ratio(GLR) prevailing in the pipeline which is an indication of production level. GLR has got an inverse relation with the liquid hold up. Based on liquid hold up in the pipeline, the back pressure starts increasing earlier or later while pigging. A simple correlation for the inventory collected during pigging is proposed in this paper. Empirical equations were developed to describe the flow characteristics of by-pass pig. Slope of best fit was done. Regression fit is developed based on the data using straight line model

$$Y= m X + C. \qquad - \text{Eqn } (4.1)$$

4.2.2 FIELD TESTING SYSTEM HARDWARE DEVELOPMENT

There are few major facility requirement for carrying out pigging operations and field testing. Following are the main hardware requiremnent:

- Pipeline with Riser System
- Pig Launcher & Pig Receiver Facility
- The PIG
- Pig Tracking System
- Data Gathering System

Following figures shows a typical long distance offshore subsea pipeline profile and pigging operation set up in the field. The subsea in filed pipeline transports multiphase fluid (oil,gas,water,with little sand and wax particles) from wellhead platforms to the nearest Block collection platform. From the Block collection platform the multiphase fluid is transported to Onshore processing plant through a subsea trunk pipeline. The offshore riser portion is in the order of 30-40 meter long. The flow pipeline profile has high potential for slugging at sub optimal flow rate.

Fig 4.1 provides the elevation profile of a typical 30” subsea pipeline. The pipeline starts from the top deck of platform which is approximately 20 meter above the sea level. The approximate water depth in the area is 25 meter. The pipeline terrain is non uniform. Various colours are used for indicating Riser, Offshore and Onshore portion of the pipeline. The receiving end also has very bad profile which leads to severe slugging phenomenon.

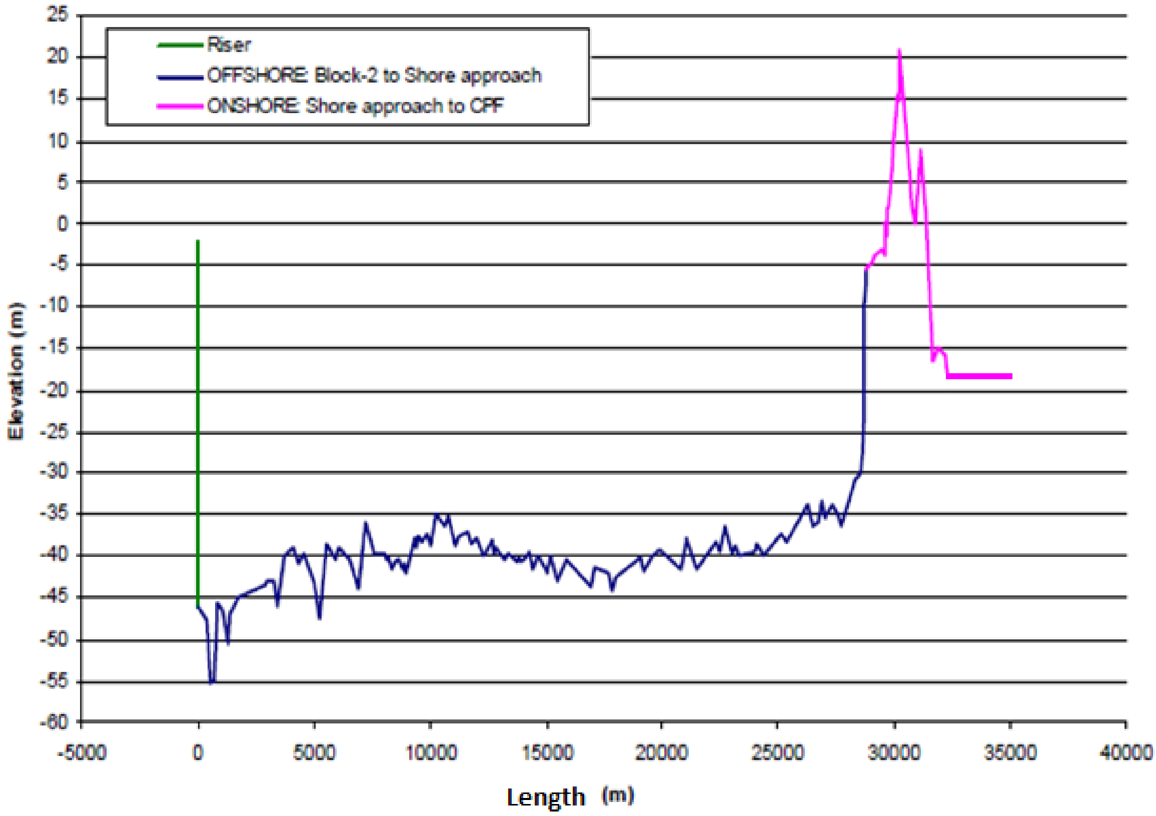


Fig 4.1: Typical 30" pipeline elevation profile

Below figures (Fig 4.2a, Fig 4.2b,Fig 4.2c)shows an overall field arrangement for pigging operations. There are 3 main facilities for carrying out successful pigging operation. First is the pig launching and receiving system with pipeline manifold. Next is the instrumentation and data acquisition system for collecting and recording valuable field dat during actual operation and the third is the advanced pig tracking system for monitoring the pig movement inside the pipeline.

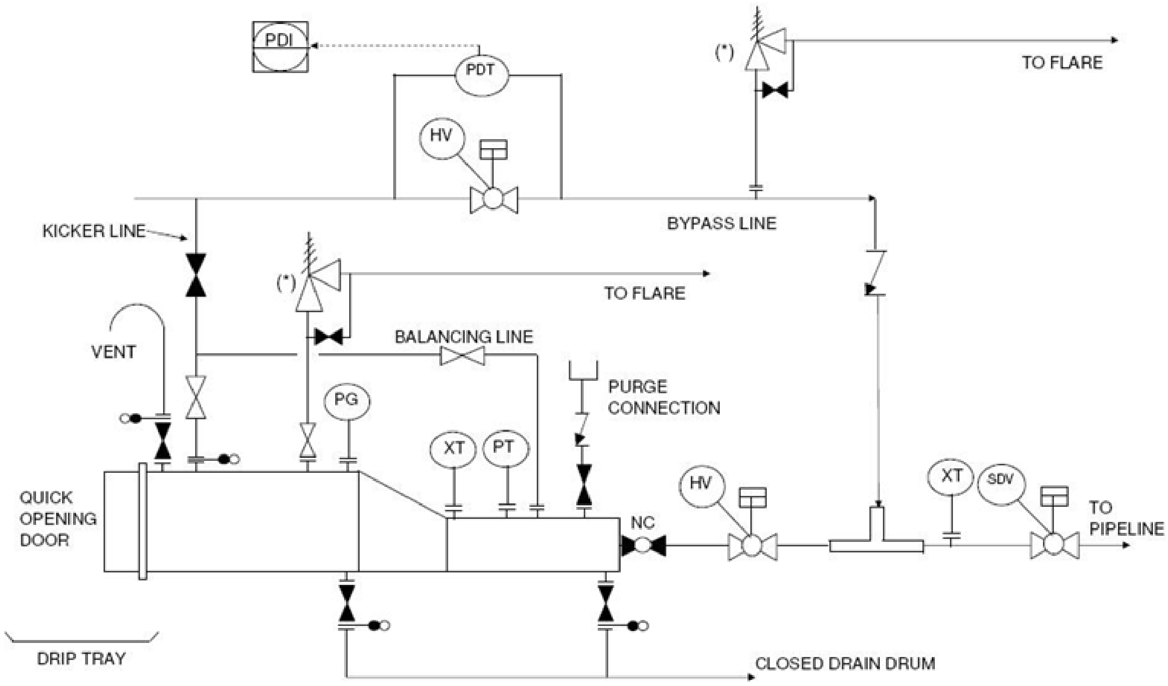


Fig 4.2a: Pigging System Set Up with Pig Launcher/Receiver & Pipeline manifold

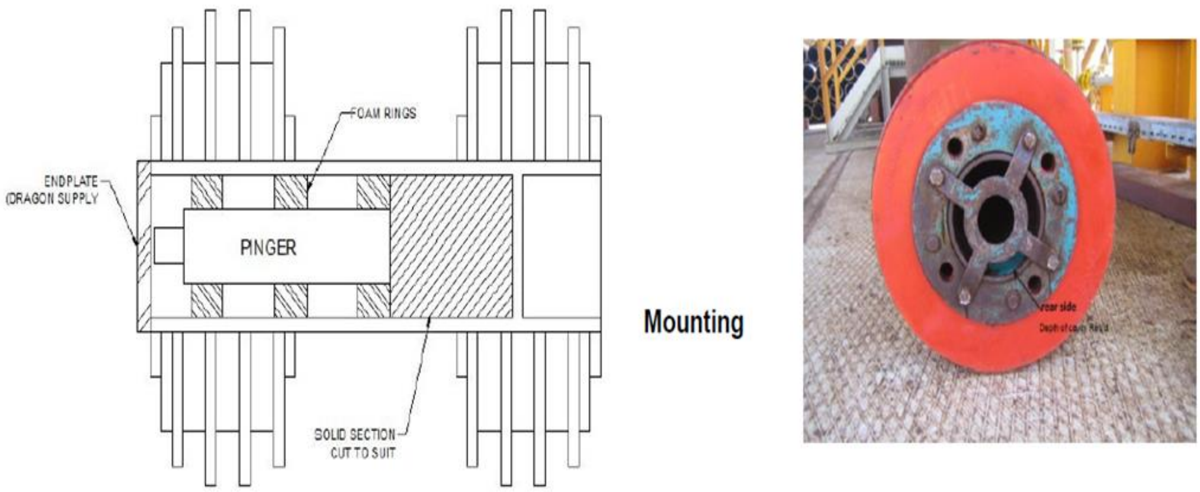


Fig 4.2b: Data Monitoring and Acquisition arrangement with Pinger

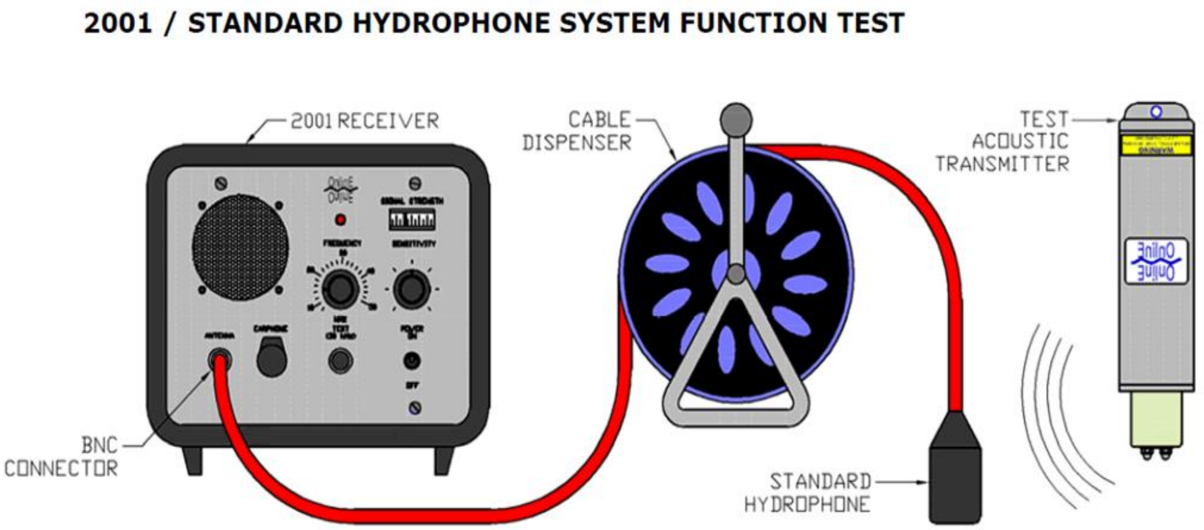


Fig 4.2c: Pig tracking unit

Figure Fig 4.3 below shows the field flow schematic of general pigging operation.

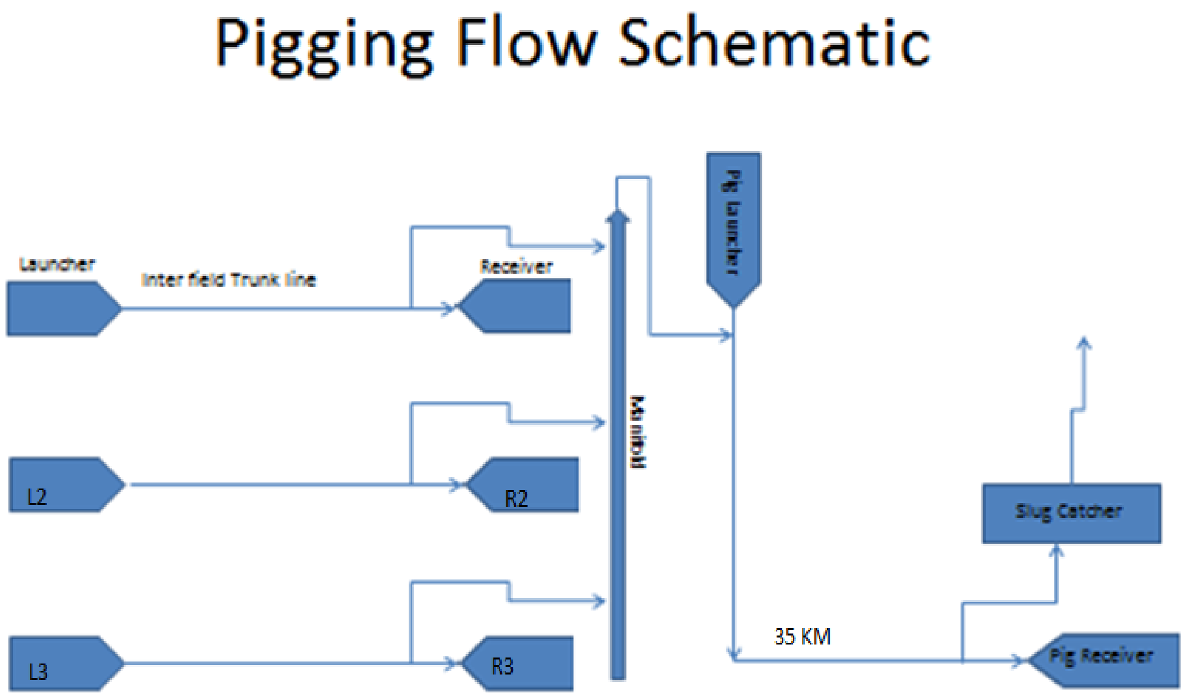


Fig 4.3: Offshore pipeline pigging flow scheme

Key drivers of pigging in a system are wax and sand control specially at winter conditions where the fluid temperature drops down below the Wax Appearance Temperature (WAT). Mechanical Pigging operation is a regular and vital flow assurance tool in the field. Normal bi-directional by-pass pigs are commonly used in the field to reduce production and process upset and to control the pig velocity. Several pigging operations were carried out in many of the selected pipelines with bypass pigs at different operating and flow conditions.Mechanical Pigging operation is a regular and vital flow assurance tool in the field. Normal bi-directional bypass pigs are commonly used in the field to reduce production and process upset and to control the pig velocity. Several pigging operations were carried out in many of the selected pipelines with bypass pigs at different operating and flow conditions.

The PIG

Depending on the purpose of the pipeline pigging operation all cleaning tools can beequipped with different accessories such as:

- Gauge Plate
- Spider nose
- Brushes
- Magnets
- Tool Location Transmitter
- Pressure Bypass Nose

A combination of above-mentioned accessories is also possible

Tool Specifications

Pipeline tools for cleaning, gauging and batching are built using materialsaccording to the following standard specifications (as far as applicable to themodel/configuration concerned):

Guiding Discs: Proprietary polyurethane composition with High Wear Resistance.

Sealing Discs : Proprietary polyurethane composition with High Wear Resistance.

Cups : Proprietary polyurethane composition with High Wear Resistance.

Spacer Discs : Polyethylene

Gauging Plates : Aluminum , AlMg3.

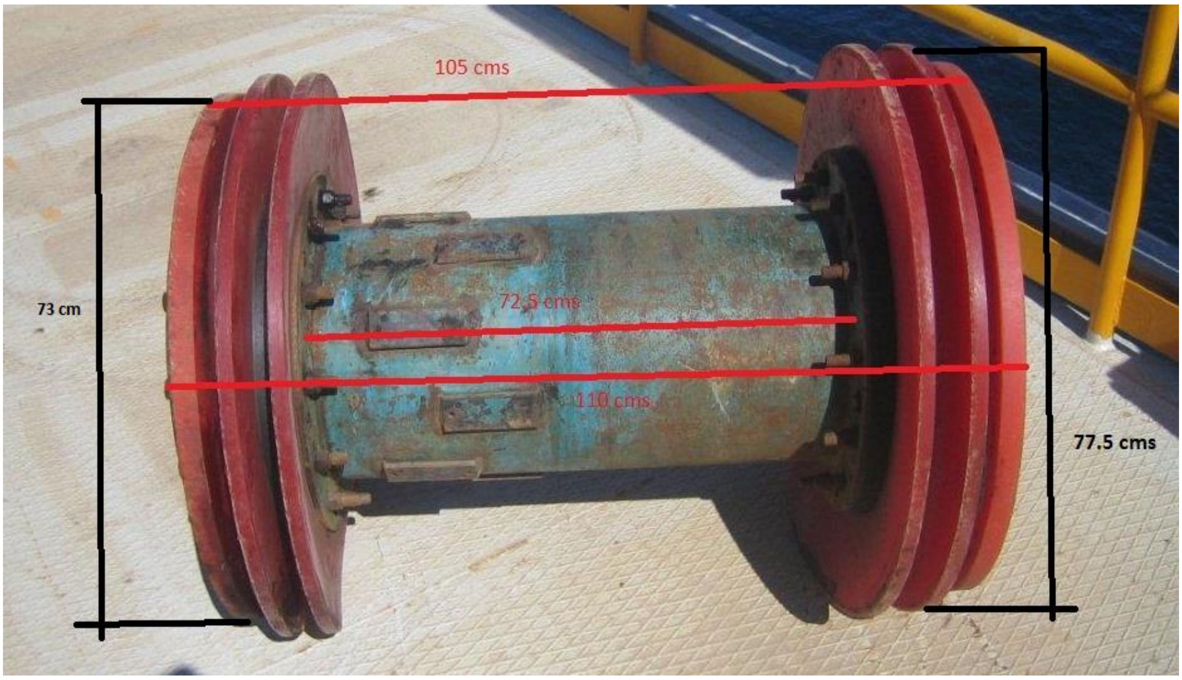


Fig 4.4 Typical BIDI Pig

Gauge Plate

A gauge plate gives a first impression whether larger obstructions are to be expectedin the pipeline and whether the following tools can freely pass the pipeline. The gaugeplate is generally used for the first or second run only.

Spider Nose

The spider nose creates turbulence, thus avoiding accumulation of debris and wax infront of the tool.

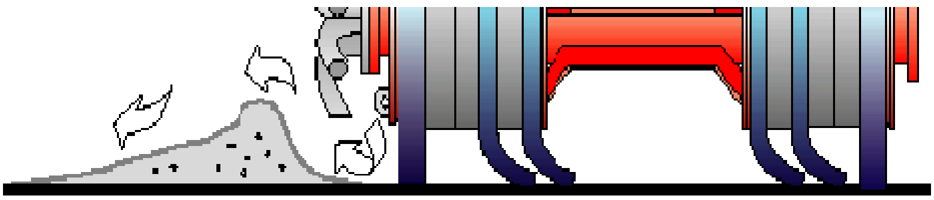


Fig 4.5Pig Spider nose

Brushes

This tool type is very effective in scraping solid debris from the pipe wall.

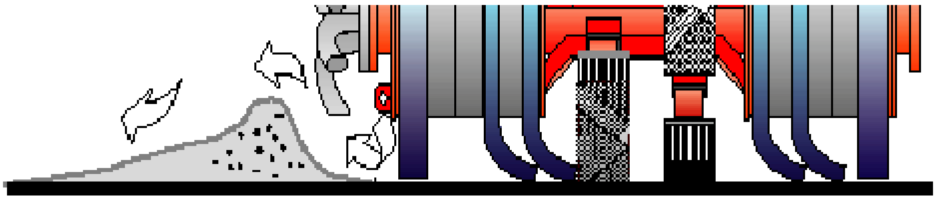


Fig 4.6 Pig Spider nose

4.3 STATISTICAL TESTS TO TEST THE RESEARCH PROBLEM

Pig Launching and Receiving Process for field testing

The following pig launching and receiving procedure is followed for the field testing operations as a general standard.

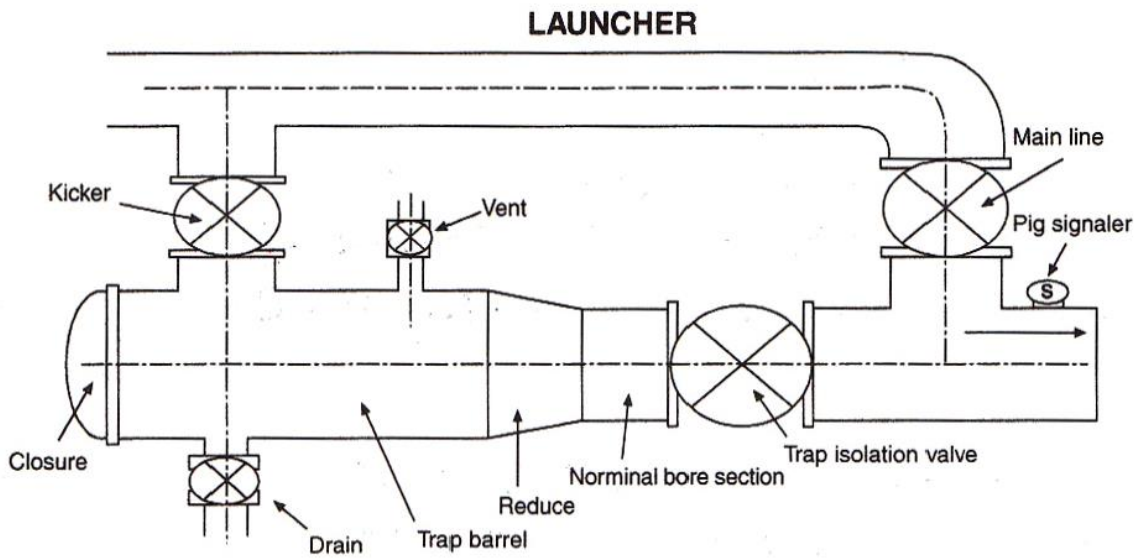


Fig 4.7 Typical Pig Launcher

PIG Launching Procedure

1. Make sure that the isolation valve and the kicker valve are closed.

2. In liquid systems, open the drain valve and allow air to displace the liquid by opening the vent valve. In natural gas systems, open the vent and vent the launcher to atmospheric pressure.

3. When the pig launcher is completely drained (0 psi), with the vent and drain valves still open, open the trap (closure) door.

4. Install the pig with the nose firmly in contact with the reducer between the barrel and the nominal bore section of the launcher.

5. Clean the closure seal and other sealing surfaces, lubricate if necessary, and close and secure the closure door.

6. Close the drain valve. Slowly fill the trap by gradually opening the kicker valve and venting through the vent valve.

7. When filling is complete, close the vent valve to allow pressure to equalize across the isolation valve.

8. Open the isolation valve. The pig is ready for launching.

9. Partially close the main line valve. This will increase the flow through the kicker valve and behind the pig. Continue to close the main line valve until the pig leaves the trap into the main line as indicated by the pig signaller.

10. After the pig leaves the trap and enters the main line, fully open the main line valve. Close the isolation valve and the kicker valve.

11. The pig launching is complete.

PIG Receiving Procedure

1. Make sure the receiver is pressurized.

2. Fully open the bypass valve.

3. Fully open the isolation valve and partially close the main line valve.

4. Monitor the pig signaller for pig arrival.

5. Close the isolation valve and bypass valve.

6. Open the drain valve and the vent valve.

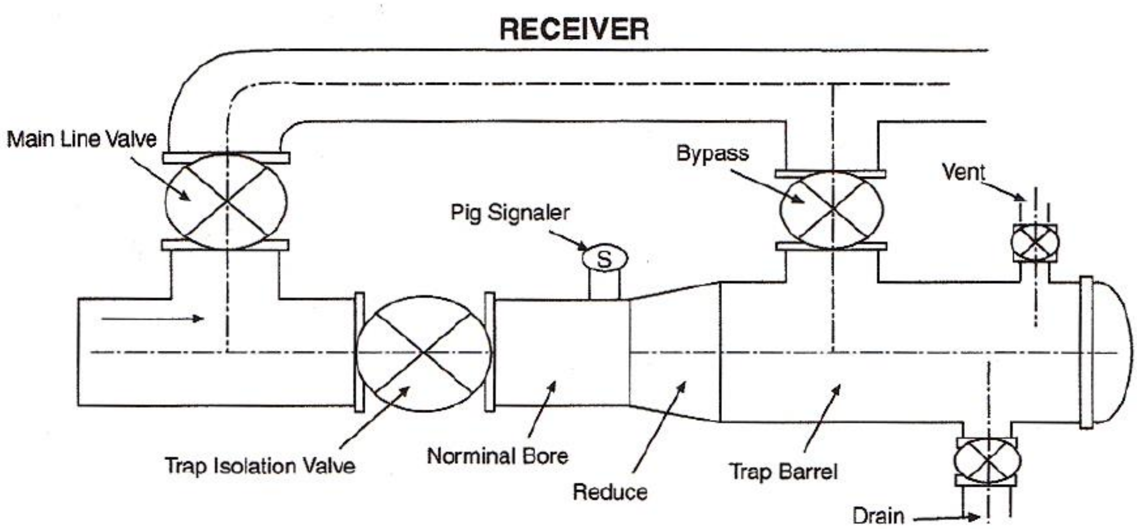


Fig 4.8 Typical Pig Receiver

7. Check the pressure gauge on the receiver to assure the trap is depressurized (0 psi).

8. Open the trap closure and remove the pig from the receiver.

9. Clean the closure seal and other sealing surfaces, lubricate if necessary, and close and secure the trap (closure) door.

10. Return the receiver to the original condition.

Field Data Collection

The Following are main sources of data for this research study project

a) Pipeline and multiphase flow parameters data collection from records

b) Pigging data collection from field experiments & records

c) Primary data collection while field application of the new design BY-PASS pig.

The data were collected during pig run operations with various pigs without by-pass hole and with different by-pass profiles.

4.4 EXPLORATORY ANALYSIS OF CONTINGENT EFFECTS

The following are main reasons for using the Exploratory Data Analysis for this project:

- Detection of mistakes
- Checking of assumptions
- Preliminary selection of appropriate models
- Determining relationships among the explanatory variables, and
- Assessing the direction and rough size of relationship between explanatory and outcome variables.

Pigging input and output data from all the field experiments are generally collected into a rectangular array (e.g.spreadsheet or database), most commonly with one row per experimental subject and one column for each subject identified, outcome variable, and explanatory variable. Each column contains the numeric values for a particular quantitative variable or the levels for a categorical variable. (Some more complicated experiments require a more complex data layout.). The details of the field test data collection is as per APPENDIX-A2. Graphical and non-graphical representations along with single and multivariate analysis are followed with different combinations.

4.5 SUMMARY

The section presented the details of the test facilities and various components that have been used to test different pig profile and develop the empirical correlation and test the new profile and model. Development of proper and adequate field testing set up/facility is very important for model testing and validation. System adequacy and reliability is also very vital to get accurate data. All system components shall be properly calibrated and in good operating condition.

CHAPTER - 5

SCALE DEVELOPMENT

5.1 OVERVIEW

Pigging operation is one of the most prominent concepts in the literature and in short, and indicates the utilization of pipeline inspection gauge tool and its positive impact in the pipeline operation and performance. Despite limited growing body of literature on this concept, the theory & application of multiphase pigging operation is still problematic. Although the literature provides several complicated theories of multiphase flow and pigging operations with simplified solutions through assumptions almost all them have some or other limitations. The purpose of this study is to provide an original, valid, and reliable measure of the innovative solution developed in this research study reflecting the difficulties and impacts.

Based on a proposed conceptual framework of pigging operation, a scale was developed through the systematic scale development process. In the study exploratory factor analysis was conducted to determine the underlying factorial structure of the scale. Data was collected from around 40 number of pigging tests carried out in the offshore oil field. The results of the analysis provided a three dimensional structure/model of by-pass pigging which can be solved with help of mass, momentum and energy conservation equations.

5.2 TECHNOLOGY READINESS LEVEL SCALE

The TRL scale was developed to enable assessment of the maturity of a particular technology and the consistent comparison of maturity between different type of technologies. TRL helps to assess which stage of development a technology is in. This is asystematic approach to communicate thereadiness of technology and forecast implementation between technological research and forecast implementation between the technological research and the mission planning community.

9 levels of Technological development method followed by US DoE is commonly adopted in the Oil Industry. Following are these 9 levels:

1. Basic principles observed
2. Technology/concept application formulated
3. Experimental Proof of concept
4. Component/system validation in lab environment
5. Validation in relevant environment
6. Pilot scale validated in relevant environment
7. Full scale demonstration in relevant environment
8. System complete and qualified(test and demonstration)
9. Actual system operated at full range conditions

In this research work a similar scale of technological development is followed.

5.3 OPERATIONALIZATION OF RESEARCH MODEL'S COMPETENCE

A very important step throughout the study of multiphase flow is the need to model and predict the detailed behavior of those flows and the phenomena that they manifest. There are three ways in which such models are explored: (1) experimentally, through laboratory-sized models equipped with appropriate instrumentation, (2) theoretically, using mathematical equations and models for the flow, and (3) computationally, using the power and size of modern computers to address the complexity of the flow. Clearly there are some applications in which full-scale laboratory models are possible. But, in many instances, the laboratory model must have a very different scale than the prototype and then a reliable theoretical or computational model is essential for confident extrapolation to the scale of the prototype. There are also cases in which a laboratory model is impossible for a wide variety of reasons. In the cases of pigging operations of long distance pipelines this is very obvious. Consequently, the predictive capability and physical understanding must rely heavily on theoretical and/or computational models and here the complexity of most multiphase flows presents a major hurdle. It may be possible at some distant time in the future to code the Navier-Stokes equations for each of the phases or components and to compute every detail of a multi- phase flow, the motion of all the fluid around and inside every particle or drop, the position of every interface. But the computer power and speed required to do this is far beyond present capability for most of the flows that are commonly experienced. When one or both of the phases becomes turbulent (as often happens) the magnitude of the challenge becomes truly astronomical. Therefore, simplifications are essential in realistic models of most multiphase flows.

5.4 SUMMARY

In this research project theoretical models of the new profile is designed and developed. Based on the simulations & initial design calculations laboratory experimental models and prototypes were fabricated and experiments were conducted in the laboratory for various nozzle and throat combinations of convergent divergent nozzle profiles. The profiles were tested at various pressure conditions in the laboratory. After finding favorable results actual profiles were fabricated and field tested in a bigger scale in the field at actual field conditions.

CHAPTER - 6

MODELS FOR RESEARCH PROBLEM'S COMPETENCE

6.1 OVERVIEW

During a pigging operation, several flowing zones prevail in the pipeline. An undisturbed multiphase flow regime exists at far downstream of the pig. In this area the effects of the pig launch is not felt so far. As the pig moves, a liquid slug region forms and grows by scooping the liquid from the downstream of the pig gradually extending to the undisturbed region. As slug growth increase the farther downstream becomes transient. However behind the pig, the liquid hold up is very less, forming a gas zone as the pig removes most of the liquid phase. The last zone is redeveloping the multiphase flow regime. All these different region inside the pipeline move from upstream to downstream at different velocities bringing the pipeline subject to pigging operation under transient condition.

6.2 FLUID FLOW MODELING

A persistent thinking throughout the research work is the need to model and predict the detailed behavior of Multiphase flows and the phenomena they manifest. As mentioned earlier there are 3 ways in which such models are explored:

1. Experimentally through lab sized model or through filed model
2. Theoretically using mathematical equations and models for flow
3. Computationally using the modern computers to address the complexity of flow

In some cases full scale laboratory models are possible. But in many cases the lab model should have very different scale than the prototype and then a reliable theoretical or computational model is essential for confident extrapolation to the scale of the prototype. In some cases laboratory models are impossible. Resolution of multiphase flow is the challenge of coding Navier-Stokes equation for each phases or components and compute every details of a multiphase flow, the motion of all the fluid around and inside every particle or drop, the position of every interface.

Three (3) equations are very important in describing/defining multiphase flow viz. Continuum equation of mass, continuum equation of momentum and Equation of conservation of energy.

In fluid dynamics heat of conduction & viscous dissipation are neglected to reduce complication and to simplify. Energy equation for multiphase flow is very complicated. In single phase flow, it is generally assumed that the fluid is in equilibrium thermodynamic state at all points in the flow. In many multiphase flow, the different phases/components are often not in equilibrium & thermodynamic arguments are no longer valid.

Turbulent flows of a single Newtonian fluid, even those with quite simple external geometry such as a fully developed pipe flow, are very complex and their solution at higher Reynold's number requires empirical models to represent the unsteady motions. The additions of particles such as wax or sand to the flow will result in complex unsteady motions of particles that may result in non-uniform spatial distribution of the particles and particle segregation. It can also result in particle agglomeration or particle fission, especially if the particles are bubbles or droplets.

Mass, Momentum, Energy interaction terms in multiphase flow equations / models remains/represents the core problem in modelling multiphase flow & there exist no universally applicable methodologies that are independent of the topology of flow & flow pattern. Efforts shall be taken to find systems of model equations that would be applicable to a range of flow pattern. The main problem for the researcher is the inability to predict flow pattern and lack of accurate and reliable method to predict flow rate, pressure drops, temperature & other flow parametrs.

Transient multiphase flow in pipelines can occur due to many factors such as pigging, changes in inlet flow rate, outlet pressure, opening or closing of valves, blwdown, ramp up etc. In each of these cases detailed information of the flow behaviour is necessary for design, optimum, economic and safe operation of the pipeline. Model for predicting the overall flow behaviour in terms of pressure, liquid hold up, and flow rate distribution for these different transient conditions would be very useful. Some of the current research challenges in modeling transient flow relate to an understanding and formulation of basic flow models for multiphase and to numerical methods applicable for the solution of transient multiphase flows.

The main equations for transient multi-phase flow with *N* phases are as follows:

- Mass conservation
- Momentum conservation
- Energy conservation
- Mass transfer between phases

Three (3) conservation equations - mass conservation, momentum conservation, and energy conservation – is sufficient to describe the main conservation principles governing transient single-phase flow. For multi-phase flow, the same three equations apply, but for each phase. Therefore, expect to need *6* equations to describe two-phase flow, *9* to describe three-phase flow, and so on. In practice it does not work quite like that, and some phases may occur in more than one form (in annular flow, there can be both liquid droplets carried by the gas and a liquid film on the pipe wall). Additional equations - *closure correlations* –are also to be used to describe how the phases interact with each other and the pipe wall, as well as to describe the fluid properties.

Consider a general case, with *N* different phases. These phases can be distributed in several alternative ways – there can be bubbles, droplets, slugs, and various other sorts of fluid distributions. It is assumed that each phase to be continuous, without necessarily taking up the same cross-section everywhere along the pipe.

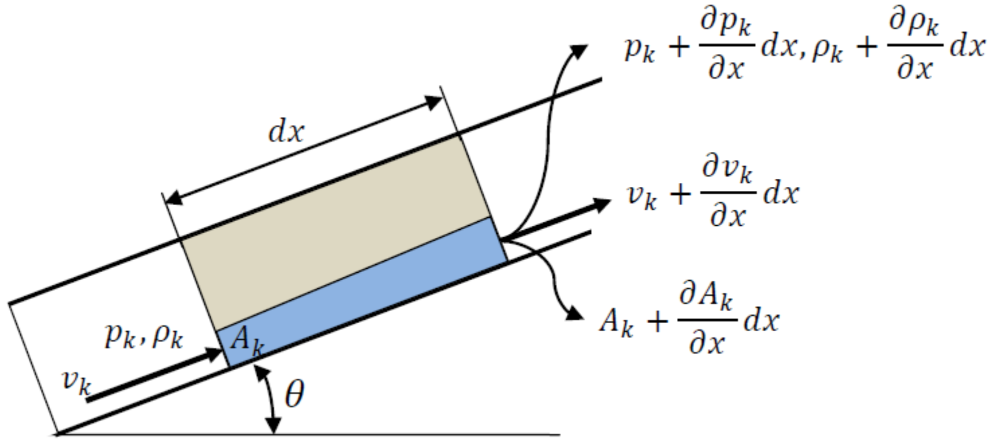


Fig 6.1 Fluid flow analysis (Bratland, Ove 2010)

Transient multiphase flow is traditionally modeled by one dimensional averaged conservation laws, yielding a set of partial differential equations. In this section two models of particular industrial ineterest is described.

- The Two Fluid Model (TFM), consists of a separate momentum equation for each phase

- The Drift Flux Model (DFM), consists of a momentum equation and an algebraic slip relation for the phase velocities.

The TFM is structurally simpler, but involves an extra differential equation when compared to the DFM. They do yield some what different transient results, although the differences are often small (Masella et al., 1998*)*

The following major assumptions have been made in the formulation of differential equations

1. Two immiscible liquid phases (oil and water) that are assumed to be a single fluid with mixture properties
2. Flow is one dimensional in the axial direction of the pipeline
3. Flow temperature is constant at wall, and no mass transfer occurs between gas and liquid phases. Note that most commercial software codes allow phase changes
4. The physical properties of multiphase flow are determined at the average temperature and pressure of flow in each segment of the pipeline.

6.2.1 TWO FLUID MODEL

Problem definition

- Consider only two fluids, one gas and one liquid, and pressures and temperatures are such that evaporation or condensation does not occur. It is also assumed no gas can be dissolved in the liquid (even though this is never quite true, as liquids do take up some gas in the same way oxygen is taken up by water, enabling fish to breathe).
- The pipe has no perforations, so neither liquid nor gas can flow through the pipe wall.
- The flow is stratified – all other flow regimes are neglected for now.

- The flow is isothermal, so do not need the energy equation to keep track of the temperature.

With these simplifications, it is possible to establish all necessary conservation equations. Also, develop closure relationships, which in this highly simplified case are reduced to describing the frictions between the gas and the pipe wall, between the liquid and the pipe wall, and between the gas and the liquid, in addition to some fluid properties. To make the equation system hyperbolic, it is needed to describe the pressure difference between the gas and the liquid.

The two fluid model is governed by a set of four partial differential equations. First two represents the mass conservation for gas and liquid phases as follows:

Mass conservation

for gas phase,

$$\frac{\partial(\alpha_G \rho_G)}{\partial t} + \frac{\partial(\alpha_G \rho_G v_G)}{\partial x} = 0 \qquad \text{- Eqn (6.1)}$$

for liquid phase,

$$\frac{\partial(\alpha_L \rho_L)}{\partial t} + \frac{\partial(\alpha_L \rho_L v_L)}{\partial x} = 0 \qquad \text{- Eqn (6.2)}$$

Where $\alpha_G + \alpha_L = 0$ - Eqn (6.3)

Momentum conservation

For gas phase,

$$\frac{\partial(\alpha_G \rho_G v_G)}{\partial t} = -\frac{\partial(\alpha_G \rho_G v_G 2)}{\partial x} - \alpha_G \frac{\partial p_G}{\partial x} + R_{LG} + R_{GW} + S_{LG} + S_{GW} - \alpha_G \rho_G g \sin\theta \qquad \text{- Eqn (6.4)}$$

R_{LG} is friction force per unit pipe volume from liquid on the gas, and R_{GW} is similarly volume-specific friction force from the wall on the gas. Assuming all surface tension forces acting directly on the gas flow are negligible, a good approximation for stratified flow, we can set S_{LG}=S_{Gw}=0. In addition, the pressure on the interface (the liquid surface) between the gas and liquid can be defined as p, while ΔpG is the extra pressure felt by the gas due to its average elevation being different from that of the interface (ΔpG is obviously going to be negative, given that the gas is on top of the interface).

$$\frac{\partial(\alpha_G\rho_G v_G)}{\partial t} + \frac{\partial(\alpha_G\rho_G v_G 2)}{\partial x} = -\alpha_G \frac{\partial(p+\Delta p_G)}{\partial x} - R_{GL} + R_{GW} - \alpha_G\rho_G g \sin\theta \qquad \text{- Eqn(6.5)}$$

For the liquid phase similarly we get as follows:

$$\frac{\partial(\alpha_L\rho_L v_L)}{\partial t} + \frac{\partial(\alpha_L\rho_L v_L 2)}{\partial x} = -\alpha_L \frac{\partial(p+\Delta p_L)}{\partial x} + R_{GL} + R_{LW} - \alpha_L\rho_L g \sin\theta \qquad \text{- Eqn(6.6)}$$

It can be noticed that the above two equations also satisfy the requirement that the sum of all forces between phases must be zero since R_{GL} occurs with opposite sign in the two equations.

One major limitation for this model is thetreatment of the interfacial coupling. While this is relatively easy for separated flow (stratified and annular) this is intrinsically flawed for intermittent flows.Another drawback is that propagation phenomena, especially pressure waves, tend not to account for satisfactorily(King,1998)

Gas and Liquid pressure difference in stratified flow

In this simple model, it would be tempting to neglect the pressure correction terms (setting ΔpG=ΔpL=0), meaning all pressures in a cross-section would be equal so pG=pL=p. However, this would neglect the mechanisms creating surface waves while creating an unphysical system description which in turn can cause loss of hyperbolic nature and numerical problems

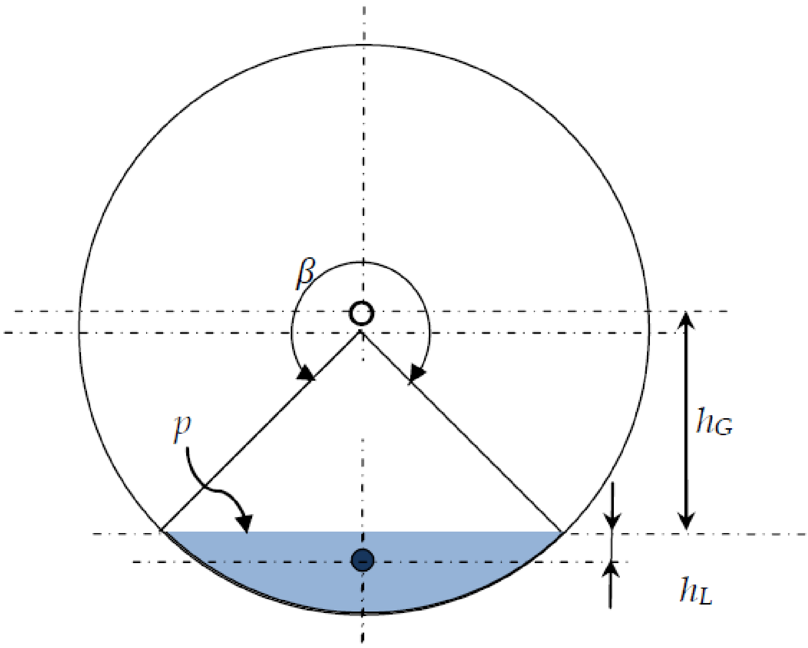


Figure 6.2: Stratified flow. Center of gravity for the gas is above the pipe center, while for the liquid, it is of course somewhere below the interface surface.

A pipe's circular cross-section leads to somewhat different wave conditions compared to the surface of a lake. If a wave-top rises above the pipe's center line, it does so in a diminishing cross-section. Therefore it closes the remaining cross-section relatively fastwhen approaching the upper side of the pipe. That affects the wave pattern significantly, and it is clearly worthwhile implementing a relatively accurate description of the circular geometry to get this right.

For stratified flow we assume the interface in each cross-section to be a straight, horizontal line. That is a good approximation for low gas velocities, but measurements have shown that increasing velocities make the surface bend until the liquid covers the whole wall for fully annular flow.

The pressure at a point *hL* below the interface can be calculated in alternative ways. Some writers propose that the pressure difference is a function only of the difference in static head between interface and liquid area center of gravity (Taitel & Duckler 1976, Watson 1990, Barnea & Taitel 1993, 1996), while others propose taking into account the Bernoulli-effect resulting from the fact that different phases have different average velocities (Tuomi 1996, Coquel et al.1997, Bestion 1990). The former approach seems to be the most correct, since pressure by definition must be the same in all directions – every point in space and time must necessarily comply with this, including points at the interface (at least in our case, where we have decided to neglect surface tension). The conservation equations describe the correlation between pressure and velocity, so the Bernoulli-effect is already built into them as they stand.

Each phase is modeled separately in stratified flow - they are only connected via friction, total cross-sectional area, and pressure. Therefore the pressure correction terms' mission is not to describe a (non-existent) pressure difference at the surface between the two, but the pressure difference between the two phases (at some average point for each phase). If the phases are distributed as shown in figure above, the task comes down to describing the average elevation difference and resulting static pressure head between the phases. It is not self evident exactly what should be taken as average elevation for each phase, since the velocities vary across the cross-section (it is generally lower near the wall than it is elsewhere). For simplicity we use the *area center of gravity* for each phase as our elevation point.

$$h_G = \left[\frac{1}{2}\cos\left(\pi - \frac{\beta}{2}\right) + \frac{1}{3\pi\alpha_G}\sin^3\left(\pi - \frac{\beta}{2}\right)\right] d\cos\theta \qquad \text{- Eqn (6.7)}$$

$$h_L = \left[-\frac{1}{2}\cos\left(\pi - \frac{\beta}{2}\right) + \frac{1}{3\pi\alpha_L}\sin^3\left(\pi - \frac{\beta}{2}\right)\right] d\cos\theta \qquad \text{- Eqn (6.8)}$$

The pressure differences can then easily be calculated as:

$$\Delta p_G = p_G - p = -\rho_G g h_G \qquad \text{- Eqn(6.9)}$$

$$\Delta p_L = p_L - p = -\rho_L g h_L \qquad \text{- Eqn(6.10)}$$

The wetted angle β, as defined on figure Fig 6.1, must be estimated from how full the pipe is, meaning from αG and αL. That angle is also useful when determining the various surfaces involved in the friction calculations. An accurate explicit description of the function $\beta(\alpha G$, $\alpha L)$ is not known, but it is possible to express an equation which can be solved to any required accuracy using Newton-iteration. Given the inaccuracies introduced on various points when developing this model, a more direct but not completely accurate approximation proposed by Biberg (1999) should suffice, it is claimed to be accurate to within ± 0.002 rad:

$$\beta = 2\pi - 2\left\{\pi\alpha_L + \left(\frac{3\pi}{2}\right)^{1/3}\left[1 - 2\alpha_L + \alpha_L^{\frac{1}{3}} - (1-\alpha_L)^{\frac{1}{3}}\right]\right\} \qquad \text{- Eqn(6.11)}$$

When θ=π/2 (vertical pipe), ΔpG=ΔpL=0, which can lead to loss of hyperbolicity

Friction in stratified flow

The friction between gas and pipe wall, RGW, is difficult to express accurately. It is to be noted that the Darcy-Weisbach friction factor can be relatively inaccurate even for circular pipes with single-phase flow. For the friction between gas and liquid, an additional difficulty comes from the fact that we do not know the surface roughness on the interface. Friction errors will also lead to incorrect volume fractions, which again affect the friction calculations. We must therefore expect estimates of the interface friction to be considerably less accurate than previous friction calculations for single-phase flow, where we encountered errors as high as 20%. Keeping these limitations in mind, we will try to develop reasonably accurate estimates for the Darcy-Weisbach friction factors.

The most used empirical correlation to estimate the interfacial friction factor is probably the one proposed by Petalas & Aziz (1997):

$$f_{GL} = (0.004 + 0.5\ 10^{-6}\ Re_{SL}) {F_{rL}}^{1.335} \left(\frac{\rho_L d g}{\rho_G {v_G}^2}\right) \qquad \text{- Eqn(6.12)}$$

Where $ReSL$ is the liquid phase Reynolds number based on superficial velocity =$\alpha L v L$.

The liquid's Froude number is defined by the liquid height hL as:

$$F_{rL} = \frac{v_L}{\sqrt{g}_{h_L}} \qquad \text{- Eqn(6.13)}$$

The gas-wall friction shear τGw becomes:

$$\tau_{GW} = - \left(\frac{f_{Gw}\,\rho_G}{8}\right) v_G |v_G| \qquad \text{- Eqn(6.14)}$$

RGw is defined as friction force $=\tau GwOGW\Delta x$pr. unit volume $=AG\Delta x$:

$$R_{GW} = - \left(\frac{f_{Gw}\rho_G}{8}\frac{O_{Gw}}{A_G}\right) v_G|v_G| \quad \text{- Eqn(6.15)}$$

Similarly for the liquid-wall friction;

$$R_{LW} = - \left(\frac{f_{Lw}\rho_L}{8}\frac{O_{Lw}}{A_L}\right) v_L|v_L| \quad \text{- Eqn(6.16)}$$

If we estimate the relevant gas-liquid velocity difference as $vG{-}vL$, the interfacial friction becomes:

$$R_{GL} = \left(\frac{f_{GL}\ \rho_G}{8}\frac{O_{GL}}{A_G}\right)(v_G - v_{L)}|v_{G-}v_L| \quad \text{- Eqn(6.17)}$$

Steady-state incompressible flow solution

The model:

As a first approach to solving the equations, the following simplifications are introduced (in addition to the ones already listed earlier):

1. The flow is steady-state. That means nothing changes over time, and so the time derivatives in the conservation equations are all going to be zero.

2. All gas and liquid properties are independent of the pressure. This means both fluids are considered incompressible with constant viscosity. That is usually not a good approximation for the gas in pipelines and is only done for convenience at this step in the process of familiarizing with the equations.

3. The pipe's elevation angle θ is constant.

As boundary conditions impose constant mass flows for both gas and liquid at the inlet and a constant pressure at the outlet. We can use constants $kGin$ and $kLin$ for defining the inlet boundary conditions:

$$\alpha_L \rho_L v_L = k_{Lin} \quad \text{- Eqn(6.18)}$$

$$\alpha_G \rho_G v_G = k_{Gin} \quad \text{- Eqn(6.19)}$$

Since the flow is steady-state with no phase change and no fluid flows in through perforations, the mass flow must be constant along the entire pipeline. The above Equations are therefore not restricted to the inlet – they are valid everywhere.

Steady state compressible flow, steady state incompressible flow and fully transient flow conditions can be derived and solutions can be arrived from both models with suitable assumptions.

6.2.2 DRIFT FLUX MODEL

The drift-flux model is a simplified form of the full two-fluid model described thus far. Both models are widely used and very similar, but in some ways the drift-flux model is simpler to deal with numerically. In addition, it can be shown that we do not need to include the pressure correction terms ΔpG and ΔpL to maintain hyperbolicity for the drift-flux model.

The drift-flux model combines the two dynamic momentum equations by summarizing them. To maintain closure, the 'lost' momentum equation is replaced by an extra algebraic equation.

The mass conservation equations remain equations Eqn(6.1) – Eqn(6.3). The dynamic momentum conservation equation is created by neglecting the pressure correction terms and summarizing equations Eqn(6.5) and Eqn(6.6) we get as below:

$$\frac{\partial(\alpha_G\rho_G v_G + \alpha_L\rho_L v_L)}{\partial t} + \frac{\partial(\alpha_G\rho_G v_G 2 + \alpha_L\rho_L v_L 2)}{\partial x} = R_{GW} + R_{LW} - (\alpha_G\rho_G + \alpha_L\rho_L) g \sin\theta$$

- Eqn(6.20)

Since this equation contains no information about individual forces on each phase, we realize that it cannot fully describe how the velocity difference between the two phases is going to develop. We therefore create an algebraic equation by eliminating $\partial p/\partial x$ between equations Eqn(6.5) and Eqn(6.6) (after again having neglected the pressure correction terms). We then take the steady-state, incompressible version of the result, which leads to:

$$\left(\frac{R_{GL}}{\alpha_G\alpha_L} - \frac{R_{GW}}{\alpha_G} + \frac{R_{LW}}{\alpha_L}\right) - (\rho_L - \rho_G)\, g\, \sin\theta = 0$$

- Eqn(6.21)

The main advantages of the DF Model are as follows:

1. The equations are in conservative form, which makes their solution by finite volume methods less onerous
2. The interfacial shear term is cancelled out in the momentum equation, although it appears in an additional algebraic relation called the slip law
3. The model is well posed and does not exhibit a complex characteristic
4. The drift flux model is best applied to closely coupled flows such as bubbly flow

6.3 PIG DYNAMICS MODELING

Eulerian & Lagrangian are the most popular polar coordinate grid system. A fixed-in-space coordinate system is called the Eulerian or sometimes the laboratory coordinate system, while the particle-following system is called Lagrangian. The Eulerian system is almost always used to model liquids, while the Lagrangian shines when elasticity is to be considered.

Out solved the problem of liquid between two sealing pigs in an isothermal 1-D flow field by using a standard numerical scheme with equally expanded grid interval behind the pig. Minami and Shoham used a mixed Eulerian-Lagrangian approach in the solution of the transient two phase gas/slug system. The descretization of the flow equation was performed using an Eulerian (fixed) coordinate grid system but the equations for the pigging model employed a Lagrangian (moving) grid system.

The first pigging model based on a full two-phase transient flow formulation was developed by Kohda et al.,. Their model included a drift flux transient representation for the flow field in the pipe, as well as several correlations to couple the pig motion to the flow, e.g. correlation for the pressure drop across the pig,correlation for the liquid hold up in the slug zone etc.

Azevedo et al., considered the incompressible quasi state flow through a by-pass hole in a pig with simple geometry. They employed CFD with finite element techniques to provide the basis for a more simplified model for the pig motion.

Wsu and Van Spronsen demonstrated some successful field trials for the high by-pass pigging. The field results have shown that nearly 100 % reduction of the size of the Pig Generated Slug Volume is possible. They also showed how the reduction in slug size with a by-pass pig could be correlated against the velocity reduction of the pig. One of the most prominent risks is that the by-pass pig gets stuck in the pipeline.

6.3.1 PIG MOTION / DYNAMICS ANALYSIS

The pig motion analysis shows the following results;

$$P_{p} = \Delta C_D \times \frac{1}{2} \times \rho \, (V - V_P)^2 = \frac{1}{2}(C_D \times \rho \times Vd^2) \qquad \text{- Eqn(6.22)}$$

C_D= Drag coefficient of pig; ρ = Density of the transportation medium

V = Velocity of the transportation fluid mixture

Vp = Velocity of the pig

Vd= Velocity difference between the fluid mixture and the pig

The C_D, drag coefficient depends to a large extent on the size of the end disks of the pig and the degree of seal provided by end disks. Accurate determination of C_D requires testing of Prototype capsules in a pipe. Kosugi equation as given below can predict C_D within 20% error margin.

$$C_D = 4 k_d^4 / (1-k_d^2)^2 \qquad \text{- Eqn(6.23)}$$

wherek_d = Disk diameter ratio (diameter of the end disk divided by the internal pipe diameter while the pig is inside the pipe). In the case of By-pass pig, an effective disk diameter shall be calculated by reducing the by-pass opening area. Hence for a by-pass pig the disk diameter ratio will be smaller and correspondingly the Drag coefficient of the by-pass pig will be less compared to a similar size/type pig with no by-pass. This will result in to lesser pressure drop across the pig and also a reduced drag force. The Drag force is calculated as follows for a known cross sectional pipe of area "A" as follows:

$F_D = A * C_D$ - Eqn(6.24)

Pig moves at a constant velocity Vp through a pipeline. Due the presence of large contact friction between the pipe wall and the pig disks, the pig moves at velocity lower than the mean flow velocity of fluid.

$Vd = V - Vp$; or $Vp = V - Vd$ - Eqn(6.25)

During steady state motion, the drag force F_D is equal in magnitude and but opposite in direction to the contact friction force F_f..

$F_D = F_f = \eta * N$;Where "N" is the total normal forces hat the pig exerts on the pipe in the radial direction (Scalar sum of forces) "η" is the contact friction coefficient. "N" can also be considered as the weight of the pig.

From the pig motion analysis and the Newton's second law of motion following results can be obtained for horizontal length of pipeline;

$$V - Vp = Vd = \sqrt{\frac{2 \times \eta \times N}{C_D \rho A}}$$ - Eqn(6.26)

One Dimensional Model for By-Pass pigging

If the acceleration of the by-pass pig is neglected and the mass and momentum balance is applied across the pig in the axial direction it can be shown that the velosity of the pig is as follows:

$$V_p = V - \frac{d^2}{D^2} * \sqrt{\frac{8F_D}{C_D \pi \rho_{bp} D^2}}$$ - Eqn(6.27)

D= Inside diameter of pipeline ; d= By-pass hole diameter ; ρ_{bp} = Density of bypass fluid

The transportation fluid mixture velocity, as obtained from a steady state simulation in the absence of a pig can be used to evaluate the above equation. The residence time of the pig in the pipeline can be calculated as follows:

$$t_R = \int_{l=0}^{l_{pipeline}} (1/V_p)\, dl \qquad \text{- Eqn(6.28)}$$

Here L is the length of the pipeline. The pig residence time can be used to obtain the Pig Generated Volume (PGV) as follows:

$$PGV = H - t_R\, \Phi_L \qquad \text{- Eqn(6.29)}$$

Here Φ_L is the volumetric liquid outflow rate and H is the total liquid hold up in the pipeline at the instance of pig launch. The PGV becomes zero if the by-pass area is chosen such that the average pig velocity becomes equal to the average liquid velocity in the pipeline.

Gas Velocity and Pig Velocity Calculations

It is generally believed that in a multiphase flow pigging without by-pass, the pig velocity is equal to the gas stream velocity. Though this assumption is a fairly good approximation the actual pig velocity is slightly less than the gas velocity /mixture velocity in a long distance pipeline. The initial pig velocity is high compared to the latter part of its travel due to Pig generated liquid displacement. The pig speed is generally calculated based on the Ideal Gas Law acoss a control section as follows;

$$\frac{P_1 \times V_1}{n_1 \times z_1 \times R \times T_1} = \frac{P_2 \times V_2}{n_2 \times z_2 \times R \times T_2} \qquad \text{- Eqn(6.30)}$$

Actual Velosity = V_2/A - Eqn(6.31)

P_1 = Initial Pressure (standard pressure condition)- bar a;

P_2= Final Pressure (Actual Pressure condition)-bar a

V_1= Initial Volumetric flow rate (standard volumetric rate)- m^3/s ;

V_2=Final Volumetric flow rate (Actual volumetric at pressure)- m^3/s

T_1 = Initial or standard temperature- ^oR;

T_2 = Final temperature (Actual)- ^oR ;

n_1,n_2 = Number of moles of gas at different pressures

A = Area of the pipeline – m^2:

R = Gas Constant

z_1, z_2 = Compressibility factor at different pressures and temperatures

The above equation gives the superficial gas velocity which can be approximated to the pig velocity in the pipeline without bypass. With bypass, the pig velocity will be different and shall be calculated by reducing the by passed gas quantity as briefed in the subsequent section below.

Calculation of Bypass gas flow quantity

In multiphase flow, though it is a mixture of oil and gas it is generally assumed and tried to calculate the bypassing gas quantity only. The quantity of gas bypassed is a function of the pressure differential pressure across the pig and the area of cross section for by-pass. Larger the differential across the pig higher the volumetric flow rate. The Gas flow rate is given by the Thornhill-Craver equation through a choke /square edged orifice as follows:

$$Q = 155.5\, C_d\ A\, P \sqrt{\frac{2gk(k-1)(r^{\frac{2}{k}} - r^{(k+1)/k}}{S_g \times T_g}} \quad - \text{ Eqn(6.32)}$$

Where, Q = By-pass Gas flow rate in MMSCFD

$r = P_2/P_1$ (P_1 = Pig Upstream pressure, P_2 = Pig downstream pressure) ;

Sp = Specific gravity of gas

A = Area of cross section of each by-pass hole – sq. inches;

P_1 = Pipeline pressure- Psia

Tg = Temperature of gas – ^{0}R;   k = Specific heat ratio Cp/Cv

Cd = Coefficient of discharge (Accounts for the hole geometry and multidimensional flow effects.

Pig velocity reduction due to bypass

By pass pigging solution for single phase fluid (liquid or gas) generally clean in nature is predictable to a good extent. Things get complicated when the flow is multiphase and all the more when the crude oil is waxy and wax crystallization and precipitation/deposition starts on the pipe wall. It is evident from field experience. At several cases the bypass holes are being plugged by wax. The chance of bypass hole blockage is high when the holes are small and peripheral as the scrapped out sticky wax could easily plug the holes.

6.4 PIGGING EXPERIMENTS &SIMULATIONS

6.4.1 DEVELOPMENT OF EMPIRICAL CORRELATION

Correlations to determine the pig travel time based on the production flow during pigging, the speed reduction due to by-pass, expected slug reduction with help of bypass, back pressure conditions in the pipeline, etc. can be evolved based on a correlation developed from experimental results.

The liquid hold up in a long distance pipeline is a function of the Gas Liquid Ratio prevailing in the pipeline which is an indication of production level. GLR has got an inverse relation with the liquid hold up. Based on liquid hold up in the pipeline, the back pressure starts increasing earlier or later while pigging. A simple correlation for the inventory collected during pigging is proposed in this paper. Empirical equations were developed to describe the flow characteristics of by-pass pig. Slope of best fit was done. Regression fit is developed based on the data using straight line model;

$$Y = m X + C. \qquad - \text{ Eqn}(6.33)$$

Bypass Pig Geometry / Profile

Figures, Fig6.3-6.5 below shows different pig geometry used in the field for pigging operations. These bi-directional pigs have multiple disks and weighs approximately 150 kgs. Bypass holes are drilled in the outer periphery of the pig body. The bypass area is controlled by increasing the number of bypass holes and hole diameter. By this method the bypass area can be increased to a maximum of 3-4 % in a 30" pig. Three types of geometry used in pigging operation is explanined below.

Care shall be taken while designing by-pass pig geometry. Pig stability, pig stalling, mechanical integrity of the pig etc. shall be given the prime importance while designing a bypass pig geometry. In the first stage of experiments, bypass pigs with peripheral holes of 1" and 1.25" on the FRONT and BACK disks have been designed.

Simulation model with different bypass % have been run and pig travel time, pressure conditions, slug volume, slug initiation time, duration etc. have been predicted with help of OLGA Software.

The following are few physical input parameters :

Pipe line diameter = 30"; Pipe wall thickness 12.7 mm;

Total pipeline length = 35 km (running from an offshore manifold platform to onshore process complex). The pipeline is cement coated. The pipeline profile used for modeling is as shown in the previous graph.

A 30” bi-directional PU pig with 2 front disks and 2 rear disks with support disks and upto 12 bypass holes in the front and rear is used. The hole size varied from 25 mm to 34 mm for initial pigging.

The following are operating parameters during pigging :

Total gas flow rate through the pipeline = 80 MMSCFD which is reduced to 60 MMSCFD at least 12 hrs. in advance of pigging to maintain a steady state condition. Total liquid flow rate = 70,000 blpd with 8 % water (approx.)

The inlet pressure at the start of pigging is 17 to 18 barg; Receiving end pressure, which is the normal operating pressure of the plant is 7 barg.

- **Profile 1**: Initial geometry with 6 peripheral holes in the front disc and rear discs with hole size of 25mm. Many experiments with different oil & gas flow rates carried out with various % bypass area(BIDI, 150 kg, 6 disks)

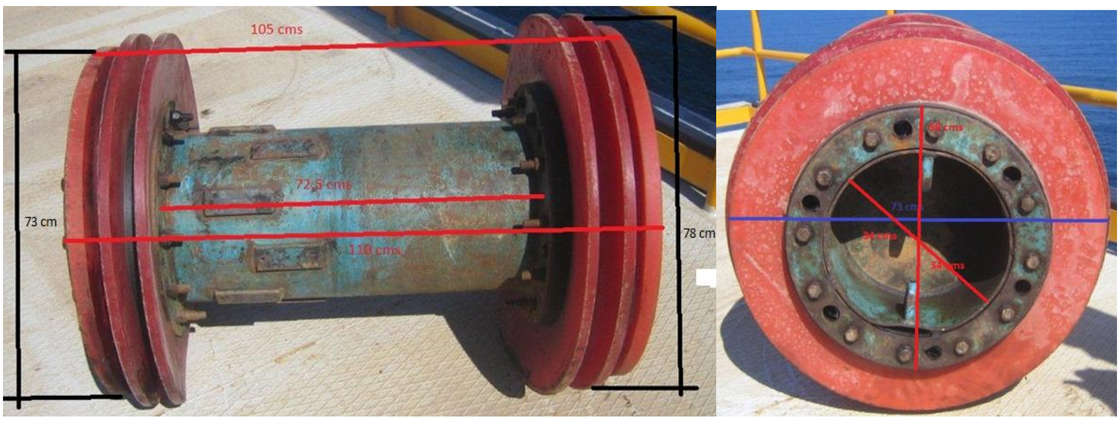


Fig 6.3: Profile 1

Profile 2: Geometry revised with 12 holes in the front disc and rear discs with hole size of 34mm. Many experiments with different oil & gas flow rates carried out with various % bypass area

Fig 6.4: Profile 2

- **Profile 3:** Geometry revised with 12 holes in the front disc and rear discs with hole size of 34mm and a central hole of 75mm. 3 experiments with different oil & gas flow rates carried out with various % bypass area

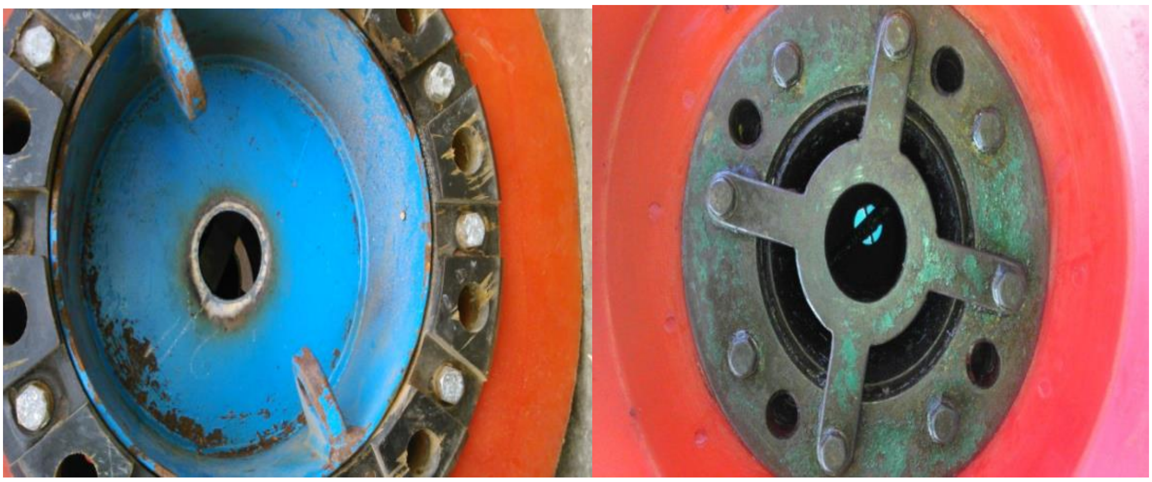


Fig 6.5: Profile 3

6.4.2 PIGGING OPERATION DATA

Many field pigging runs are analysed in this paper based on the 3 cases mentioned above. The pigging operations were carried out with a varying time gap of 1-3 months at different oil & gas production rate. Different production rate resulted in different liquid inventories, back pressure and process conditions during pigging operations. The liquid withdrawal from the pipeline during pigging (Figures 7-10) with different profile is made almost constant based on the design capacity of the processing plant which is assumed to be equal to the trunk pipeline design capacity. The slug catcher capacity at the processing plant is assumed to be equal to the trunk line capacity and very limited slug volume can be handled at the receiving end. It is also important that the incoming flow and slugs are suppressed and controlled using Inlet controll valves. This result into high back pressure in the trunk pipeline during pigging operation which is closely monitored and controlled during pigging operation to maintain withing the MAWP of offshore platforms. Due to this the pigging operation of long distance trunk pipeline always result into some kind of production loss and process upset.

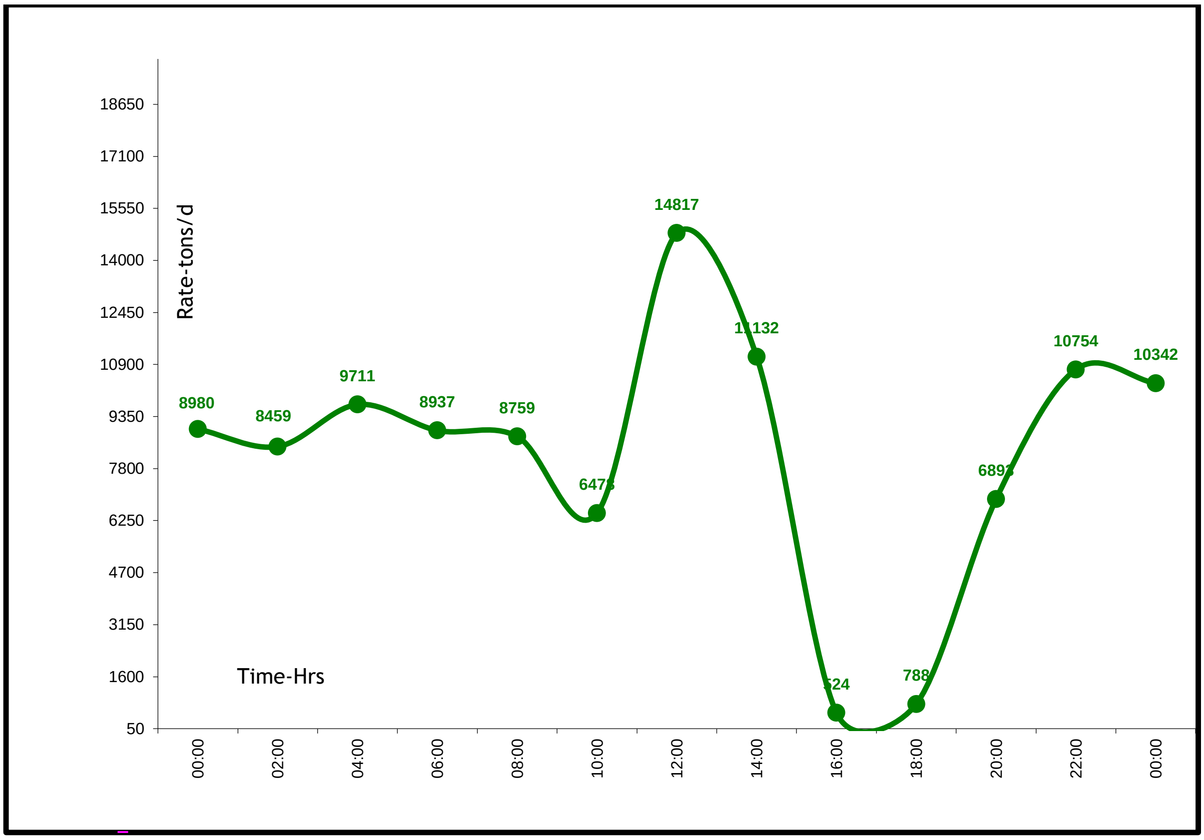


Fig 6.6: Liquid withdrawal during pigging with Profile 1

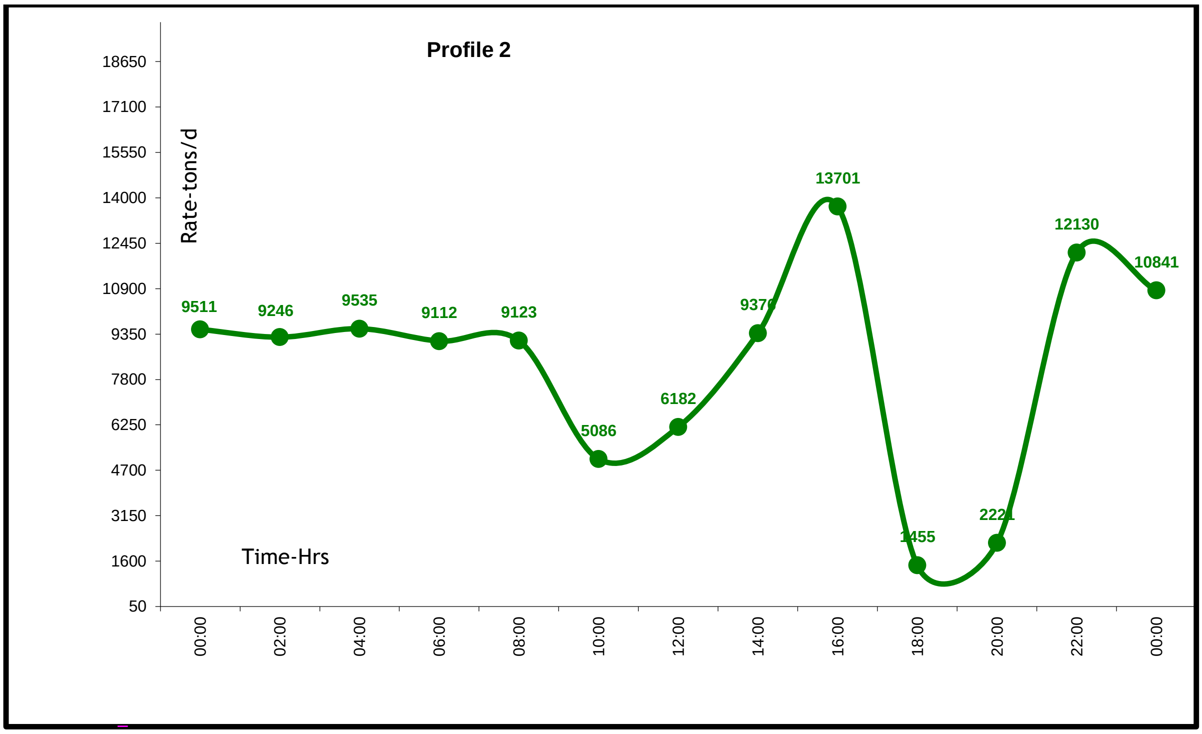


Fig 6.7: Liquid withdralduring pigging with Profile 2

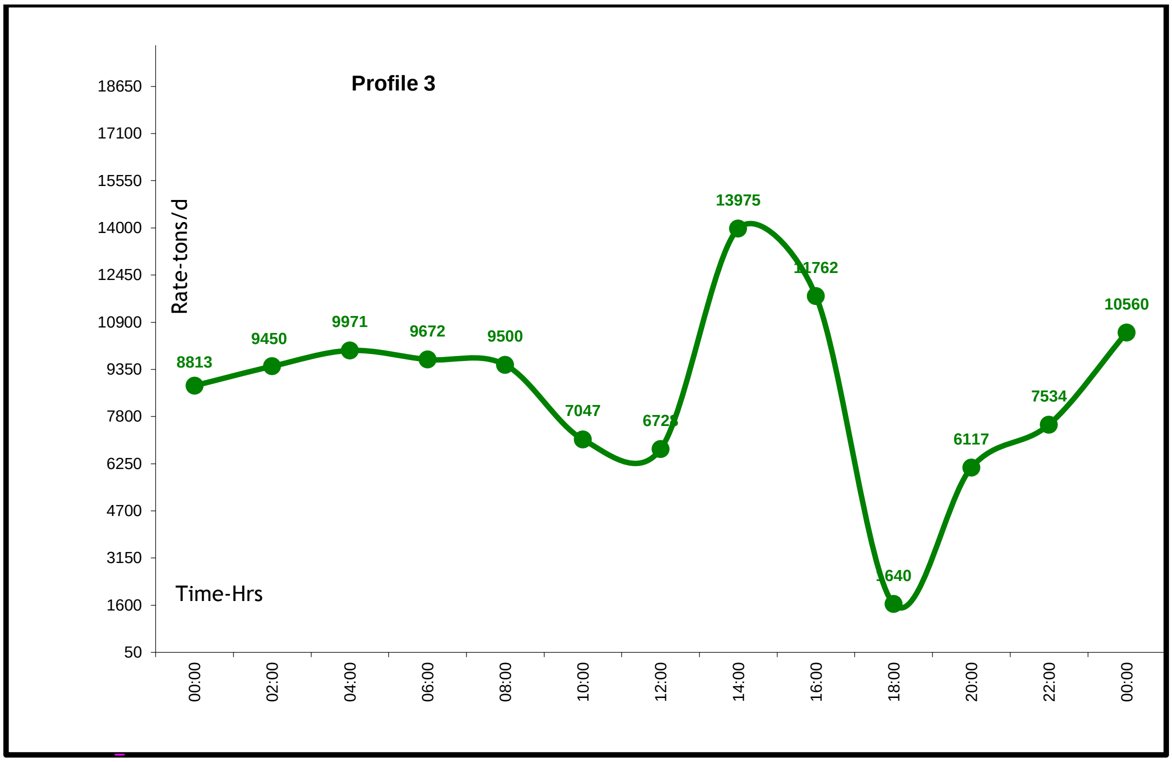


Fig 6.8: Liquid withdraldurng pigging with Profile 3

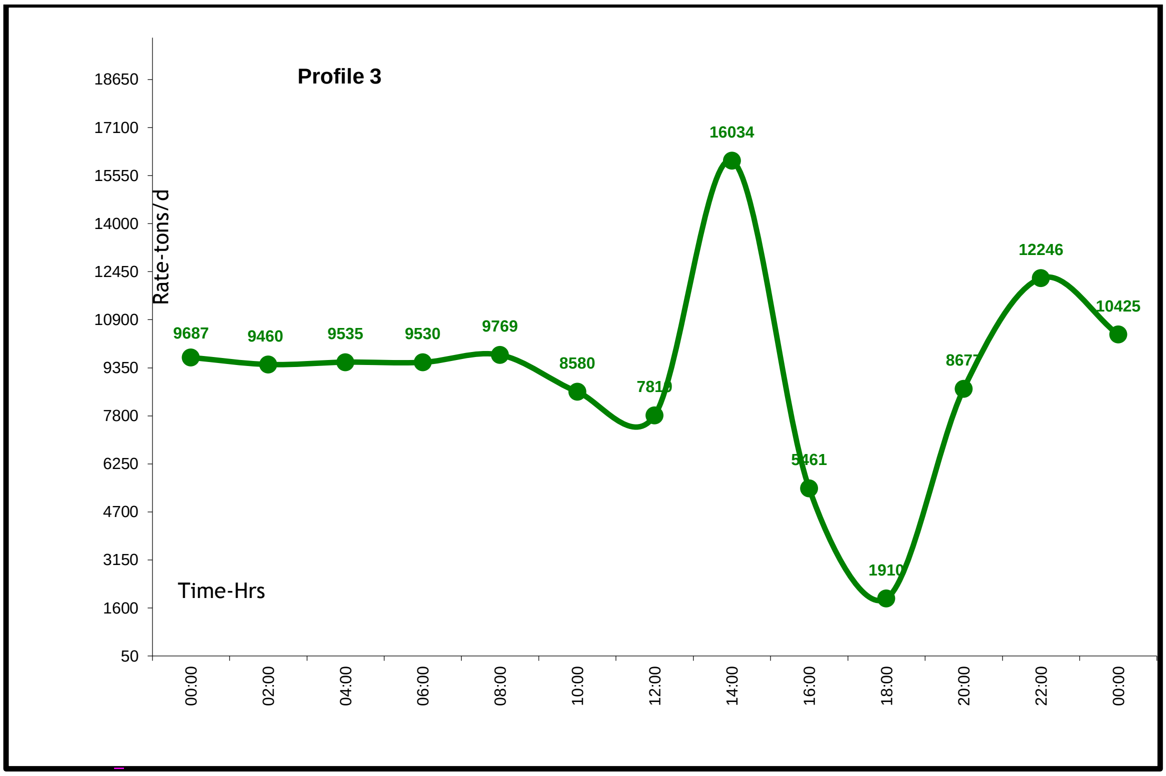


Fig 6.9: Liquid withdraldurng pigging with Profile 3

Figure, Fig6.10 below shows a real time photo of back pressure increase in a trunk pipeline while by-pass pigging operation. The graph indicate a gradual pressure rise in the pipeline even after using a bypass pig.

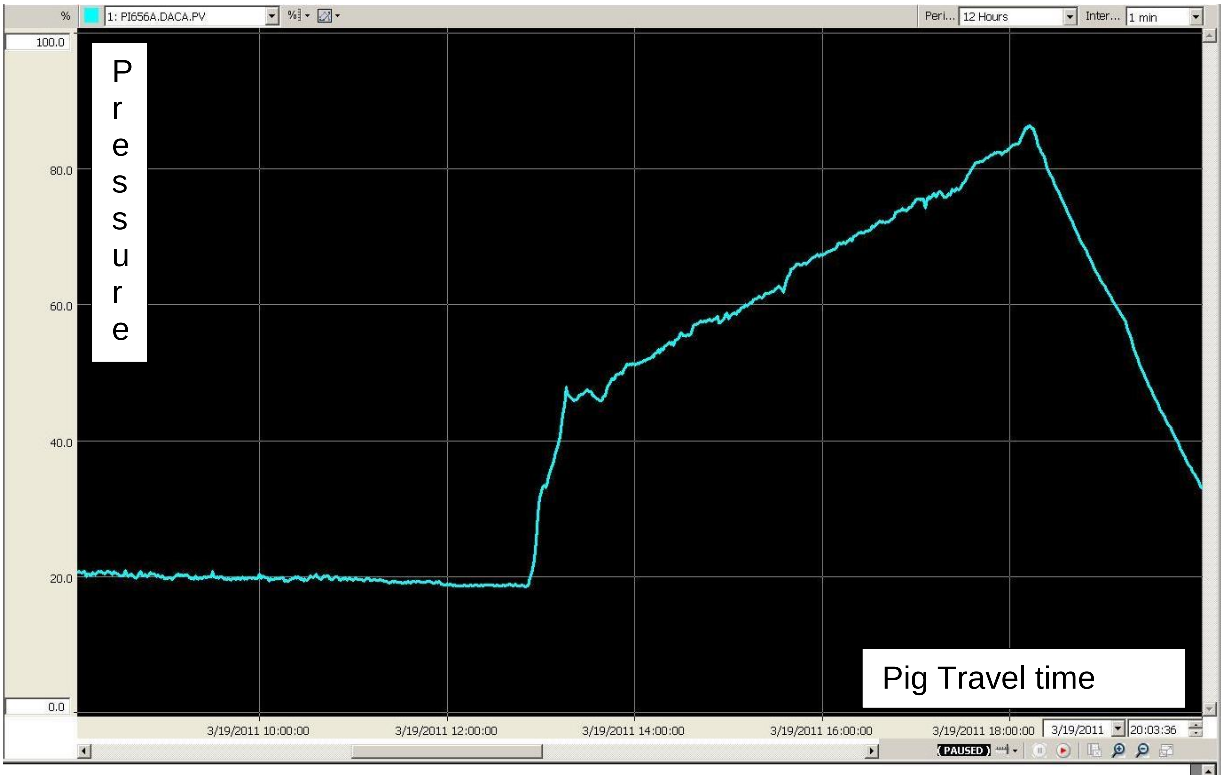


Fig 6.10: Back pressure increase during pigging

The details of of liquid and gas flow rate during pigging and Pig Generated Volume during all the pigging operations are provided in Appendix - A1

Empirical Correlations based on Field Pigging Results

Many field pigging runs were carried out over the past two years with by-pass pigs (bypass area up to 4%) and analysed. Different gas and liquid production rates resulted in different liquid inventories in each run. Each pigging operation was unique and took different pig travelling time. Each run brought different results in terms of wax recovery and gas surge. It is also to be noted that the pressure differential across the source and sink also varied in a small range though efforts were made to control the variation. Another risk in the pipeline pigging was the presence of sand content, though to a smaller percentage, which was unknown. Regular de-sanding operations from the pipeline and downstream process equipment, close monitoring of liquid samples and analysis are routine part of the operation. It is also a fact that enough slug handling capacity is unavailable for handling the total production during the transient pigging operation. The pigging operation has evolved to minimize production downtime and surge risks. For example, in order to achieve a steady state condition and slow down the pig, before starting the pigging operations, the gas flow rate is used to be reduced to certain extent based on simulation results. The gas flow rate has been reduced keeping the liquid flow rate as same to avoid production loss. It is also to be noted that in order to have good control on the process operation in the plant, the liquid drain rate at the process plant inlet has been controlled by throttling the subsea pipeline exit control valve downstream of the pig receiver.

The utilization of a pig tracking system will give authentic information of pig travel and will help locating the pig journey at various time point. This will also give us an idea of the pig travel velocity at different travel segment, its acceleration, deceleration based on the pipeline profile and the terrain conditions. Pig tracking will give an advance indication about any blockage in the system based on the travel speed.

The following input parameters collected:

- % Bypass
- Liquid & gas flow rate before start of pigging
- Pressure, temperature at start and end of pipeline at constant interval
- Liquid and gas flow rate at and of the pipeline at constant interval

- Pigging start time & end time

Output parameters generated are as follows:

- Pig Travel time Vs Pressure graph at source and sink
- Gas Velocity at Start and End
- Pig Travel time calculation based on gas velosity
- Bypass gas quantity Calculation
- Time at which pressure increase started
- Distance travelled by the pig before the pressure rise started
- Surge/Inventory estimation calculation
- Average Liquid hold up in the pipeline (Cunliffe’s Method)
- Distance travelled before pressure increase
- Straight Line Trend fitting
- Slope and Intercept of the pressure curve

Run No	Liquid flow rate-BLPD	Gas flow rate - MMSCFD	Actual pigging time-Hrs	Pig speed -M/s	Max. Pr. At start-Bar g	Cal. Min. pigging time-Hrs	Cal. Max. pigging time - Hrs	Time taken for pressure rise -Hrs	Distance travelled by pig before pressure rise - Km	Upstream "m" Value	Up stream "c" Value	Down stream "m" Value	Down stream "c" Value	Actual Bypass gas rate-MMSCFD	Calculated Bypass Gas Rate-MMSCFD
1	36640	32.0	12.5	0.86	34	8.29	15.95	2.5	12.1	1.7145	14.617	2.306	3.186	0	7
2	49478	56.0	6.5	1.61	28	4.32	7.84	3	27.8	2.3598	12.001	3.159	3.003	0	6.1
3	51478	27.0	10	1.05	25	9.02	14.57	1	4.4	1.213	14.694	1.664	4.071	0	6.1
4	52747	55.0	7.5	1.42	35.2	4.68	9.96	2	17.1	2.7314	12.898	3.545	3.008	0	6.5
5	57522	55.0	7.5	1.43	35.5	4.68	10.04	1.5	12.8	2.8206	12.806	3.651	3.143	0	6.5
6	57663	56.0	8.5	1.31	34	4.46	9.46	1.5	13.5	2.7162	11.789	3.213	3.517	0	6.3
7	65658	57.0	7.5	1.46	34	4.51	9.29	2	17.7	2.6594	12.765	3.581	3.183	0	6.5
8	67180	57.0	9.5	1.17	39	4.01	10.62	1.5	15.0	2.9786	11.131			0	6.2
9	68197	26.0	10.5	1.04	33.9	10.2	20.31	2	7.9	1.5725	15.458	2.134	3.395	0	6.8
10	67642	21.0	13.5	0.8	40	13.7	29.54	1.5	4.4	1.951	16.595	2.430	3.680	0	7.2
11	68819	46.0	7.4	1.42	34	5.59	11.51	1.5	10.7	2.4985	12.765			0	6.5
12	59686	35.3	7.25	1.46	32.8	7.72	14.50	1.5	7.8	2.3711	13.827			0	6.9
13	67708	70.2	7.41	1.41	36	4.09	7.97	3	29.3	2.6593	14.551	3.363	4.696	3	7.2
14	72433	63.5	6.22	1.7	35	3.93	8.58	1.5	15.3	3.2659	12.229	4.122	3.160	4	6.3
15	79044	55.6	6.25	1.69	33	5.14	9.25	1.5	11.7	2.7081	13.534	3.576	3.750	2	8.1
16	78285	59.6	6.17	1.72	29.2	4.83	7.67	1.5	12.4	2.9345	13.606	3.906	3.369	3	9
17	62504	82.4	5.55	1.57	39	3.30	7.34	1.5	18.2	3.7982	13.406	4.925	3.394	2	8.2
18	66691	63.5	6.4	1.63	35.7	4.29	8.75	1	9.3	3.5875	12.76	4.364	3.840	4	8
19	75592	71.5	6.15	1.73	32.8	3.81	7.15	1.5	15.8	3.8242	12.418	4.709	2.956	2	9
20	75447	69.2	5.38	1.92	34	3.94	7.66	1.5	15.2	2.9164	12.293	3.851	2.233	3	7
21	78089	65.3	6.12	1.75	37.2	4.17	8.85	2	19.2	3.4686	12.849	4.459	2.138	2	8
22	77017	66.0	5.55	1.83	35	4.13	8.25	1.5	14.5	3.4399	12.137	4.433	1.974	3	9
23	67479	55.8	8.1	1.32	37.8	4.88	10.51	1.5	12.3	3.0651	13.076	3.734	3.257	11	31
24	63703	44.6	9.16	1.19	30.5	6.11	10.70	1	6.5	2.5396	12.918	3.119	2.071	12	32
25	71655	53.8	7.04	1.53	34	5.06	9.84	1.5	11.9	2.8457	12.836	3.508	2.630	12	32
26	71284	59.1	6.45	1.58	35	4.61	9.22	1.5	13.0	3.0579	12.468	3.848	3.042	14	32
27	68948	60.3	5.33	1.95	35	4.52	9.04	1.5	13.3	3.6612	12.924	4.771	2.957	13	31

28	71024	53.7	7.45	1.39	38	5.07	10.99	2	15.8	3.2431	11.457	3.733	2.822	15	32
29	70839	57.0	7.56	1.36	34.3	4.78	9.37	1.5	12.6	3.2652	13.039	4.047	2.243	19	43
30	81752	61.0	6.35	1.64	30.8	4.47	7.89	1.5	13.4	3.5385	12.5	4.270	2.894	18	43
31	71980	67.0	5.5	1.85	30.6	4.07	7.14	1.5	14.8	3.5242	12.912	4.555	3.435	20	43
										2.9121	**13.072**	**3.740**	**3.092**		

- Empirical formula with average slope and intercept

The following table shows the details of the pigging operations carried out during last 2 years with different bypass pigs and flow parameters. The input and out data are tabulated.

Table 6.1-Tabulation of bypass pigging input and output parameters

Notes: Average regression constants are given in red font above.

Pig runs 1-21 are carried out with Profile-1

Pig runs 22-28 are carried out with profile-2

Pig runs 29-31 are carried out with Profile-3

The details of the all pigging operations are provided in the Appendix – A2

The following typical examples of graph depicting the relation between pig travel time (X-axis. hrs), Pipeline pressure at start and end points (Y-axis, barg), gas flow rate (Y-axis, MMSCFD) observed in the plant during pigging.

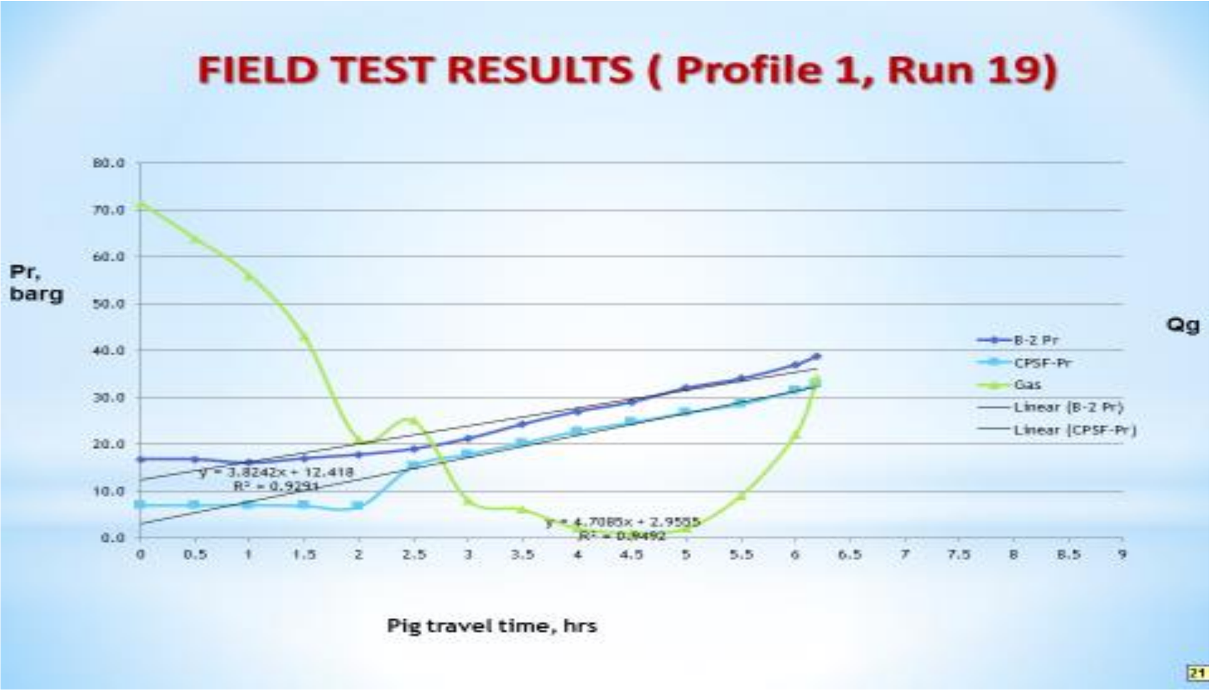


Fig 6.11: Pigging with profile 1

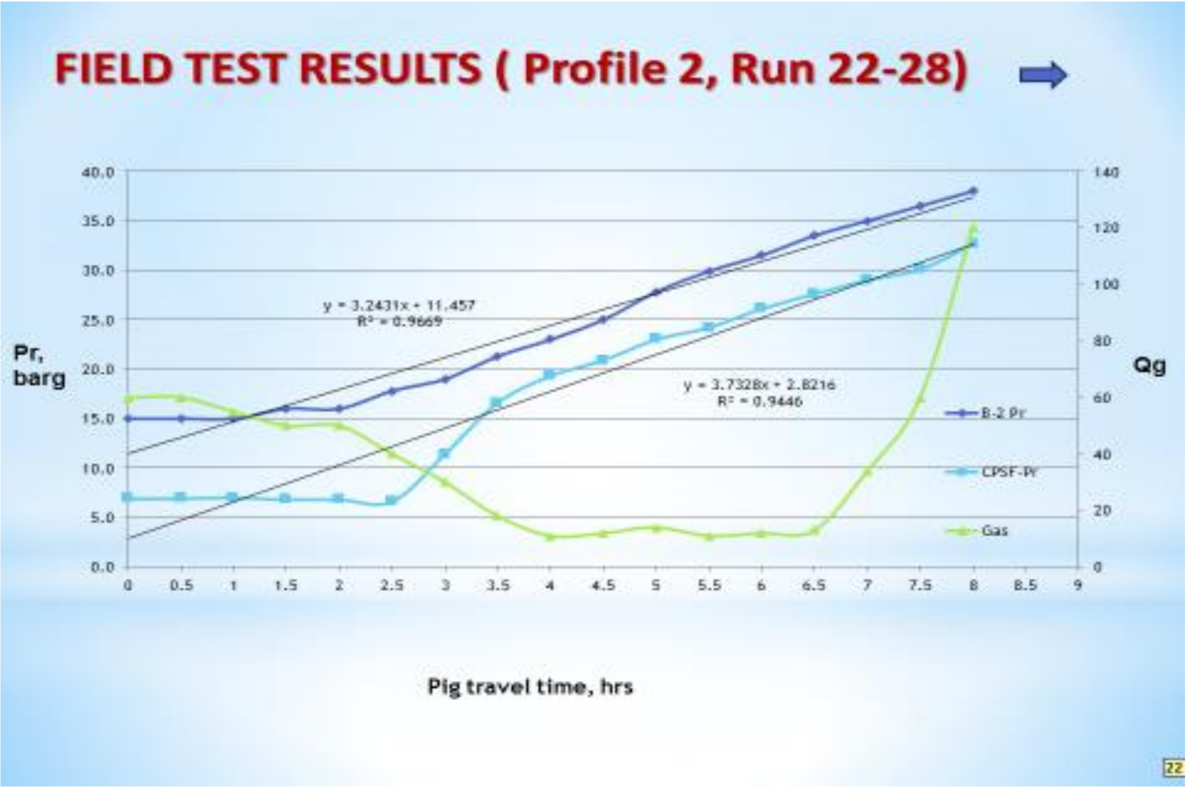


Fig 6.12: Pigging with profile 2

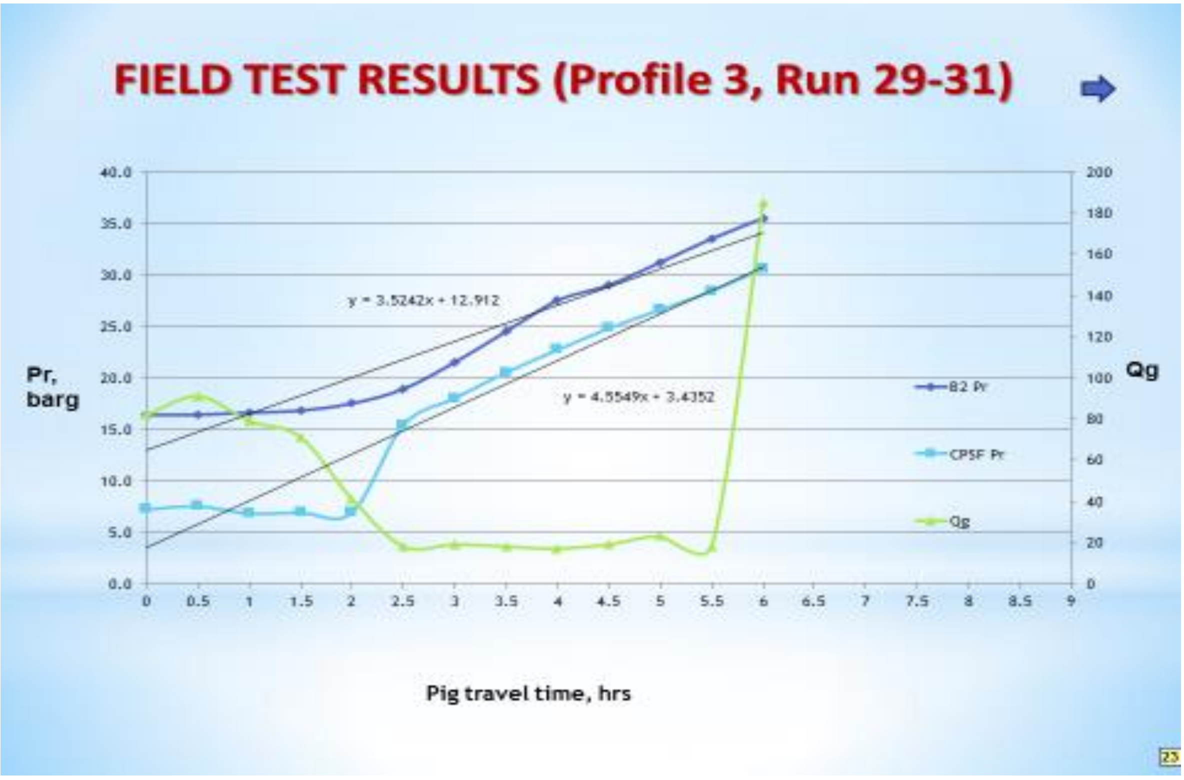


Fig 6.13: Pigging with profile 3

Summary of experimental results

Following are the main observations and conclusions of experimental results:

1. The pig travels certain distance before pressure increase in all pigging operations
2. The liquid slug observed during pigging at the receiving end is very high and is unable to be accommodated with the current design capacity
3. Conventional way of increasing the bypass hole size do not give positive results
4. The bypass gas flow rate is not increasing as per the design requirement as the bypass hole size increases
5. Conventional bypass pigging is ineffective due to less gas bypass and less differential pressure across the pig
6. The differential pressure across the pig is proportional to Drag force which in turn depends on the pig weight
7. The distance travelled before pressure rise is proportional to the liquid hold up in the pipeline.
8. The liquid hold up in the pipeline depends on the GLR maintained in the pipeline before the pigging operation
9. The multiphase fluid stream in the pipeline tends to act as a mechanical spring

Trend Analysis & Analytical Modeling

Correlations to determine the pig travel time based on the production flow during pigging, the speed reduction due to by-pass, expected slug reduction with help of bypass, back pressure conditions in the pipeline, etc. can be evolved based on a correlation developed from previously calculated results.

The liquid hold up in a long distance pipeline is a function of the Gas Liquid Ratio prevailing in the pipeline which is an indication of the production level. GLR has got an inverse relation with the liquid hold up. Based on the liquid hold up in the pipeline, the back pressure starts increasing earlier or later while pigging operation. A simple empirical correlation based on the data collected during pigging operation is proposed in this section. This empirical equation describe the flow characteristics of By-pass pigging. Slope of best fit curve was calculated. Regression fit is developed based on the data using straight line model $Y = mX + C$.

From the above tabulated results based on the linear trend fitting curve following equation is derived

- $Y = 2.9121\, X + 13.0756$ - Eqn(6.34)
- $m = 2.9121$
- $C = 13.0756$
- With this formula the back pressure at start point (Y) can be calculated during pigging at any point of time and find out what will be the maximum back pressure which can attain for calculated pig travel time

  Eg: If the Start pressure before pigging is 17 barg and the calculated maximum pig travel time is 6 hrs, the highest pressure at source while pigging can be calculated as below:

  $Y = 2.9121 \times 6 + 13.0756 =$ **30.5482 barg.**

The above developed empirical correlation shows good match with field experimental results for the conventional bypass profiles (Profile 1,2, 3) and can be used for future prediction purpose such as quick estimation of maximum expected pressure in the pipeline while pigging operation for an estimated pig travel time. This empirical equation will act as a good decision making tool enabling proactive corrective actions for a safe pigging operation. Following table shows the validation of pig travel time and back pressure in the line which are highlighted in green and yellow respectively. The table shows the results of available limited runs.

Table 6.2: Validation data for pigging time and back pressure

Profile Type	Run Nos	% Bypass area	Liquid flow rate-BLPD	Gas rate-MMSCFD	Actual pigging time-hrs	Maximum B2 Pressure-hrs	calculated pigging time at start-hrs	calculated pigging time at end-hrs	Pig travel time based on average velocity-hrs	Calculated Maximum B2 Pressure-bar g
Profile-1	19	0.8	65592	71.5	6.3	36.8	3.8	7.2	4.3	34.04
Profile-2	28	2.6	71024	53.7	7.8	38	5.1	11.0	11.6	45.11
Profile-3	29	4	70839	57.0	7.9	40.5	4.8	9.4	19.6	40.5
Profile-3	30	4	81752	61.0	6.6	36.5	4.5	7.9	15.2	36.09
Profile-3	31	4	71980	67.0	5.1	35.5	4.1	7.1	11.3	33.75

Simulation Results & Field Pigging Results _ Comparison Study

A comparison between OLGA Transient Simulation and filed results for the surge volume, pigging back pressure, pig travel time, bypass flow quantity etc. shows some deviations. The mismatch could be due to the failure of predicting a bubbly liquid surge due to the turbulence of by-pass pigging. Surge volume prediction, surge initiation timing and its duration are very complicated. Pigging Surge Models based on empirical formulations are sometimes very helpful.

The effect of increasing the by-pass area on the drag coefficient and drag force is verified. Effect of increasing the drag force by increasing the weight of the pig is proposed. Seal leakage through the disks is reviewed and discussed.

Software results are validated and differences discussed for better understanding.

Fig 6.14 to 6.16 shows different scenarios of simulation runs.

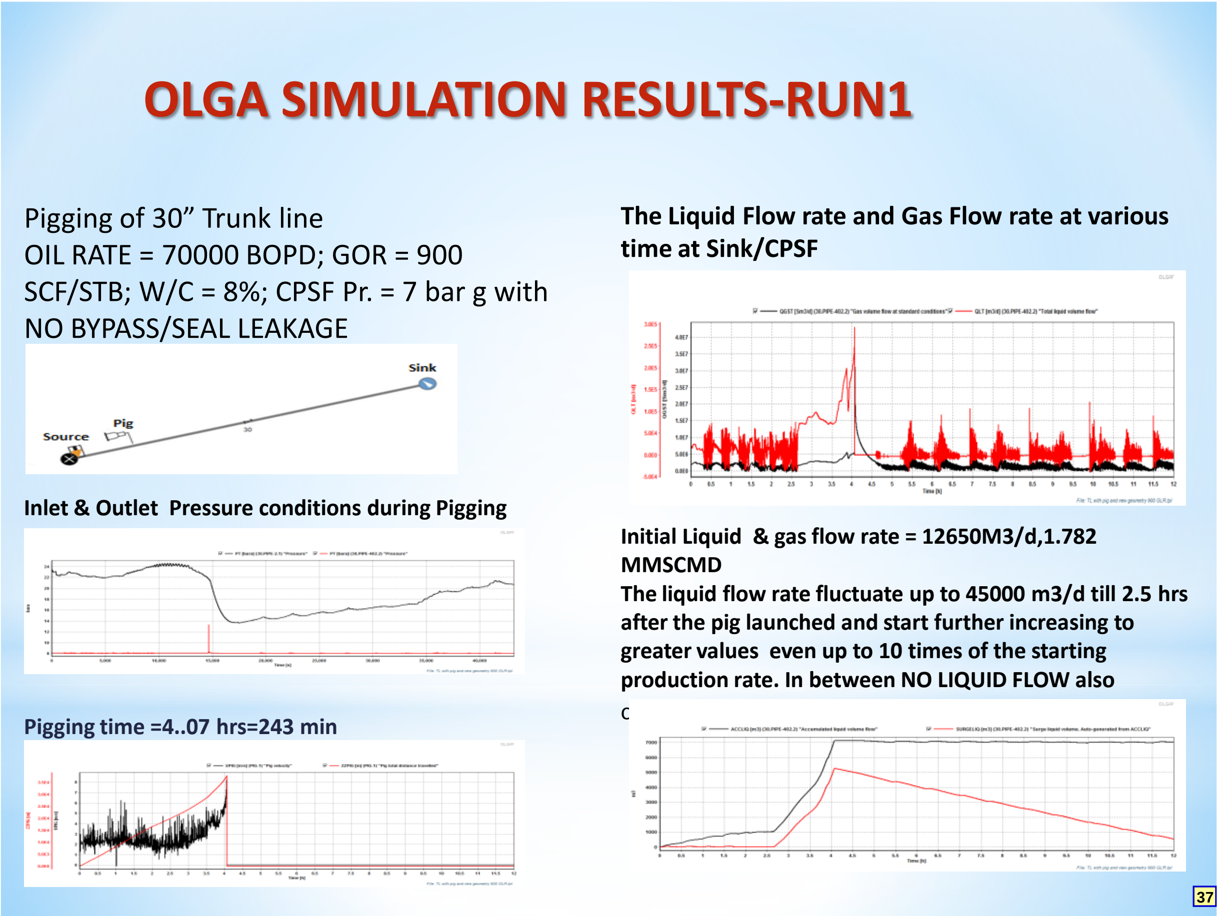


Fig 6.14: Software Simulation Run 1

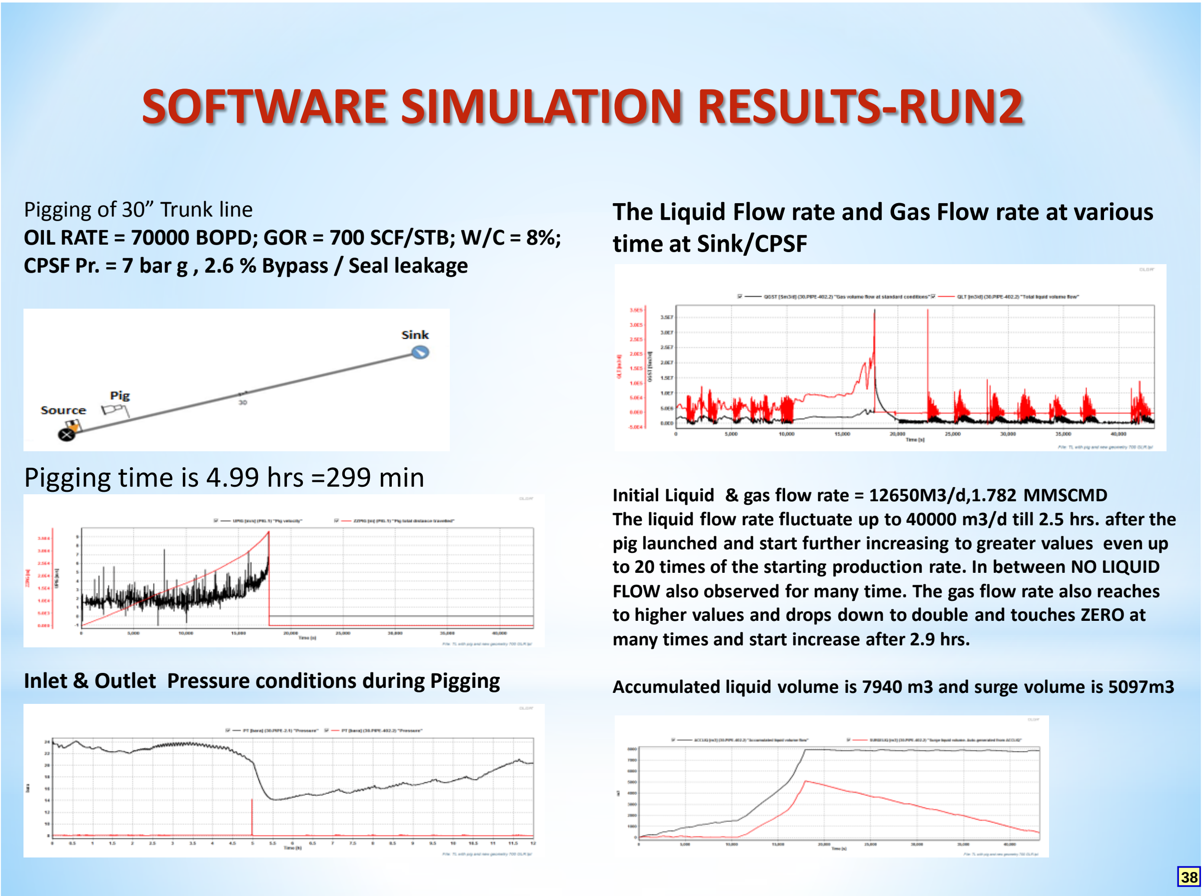


Fig 6.15: Software Simulation Run 2

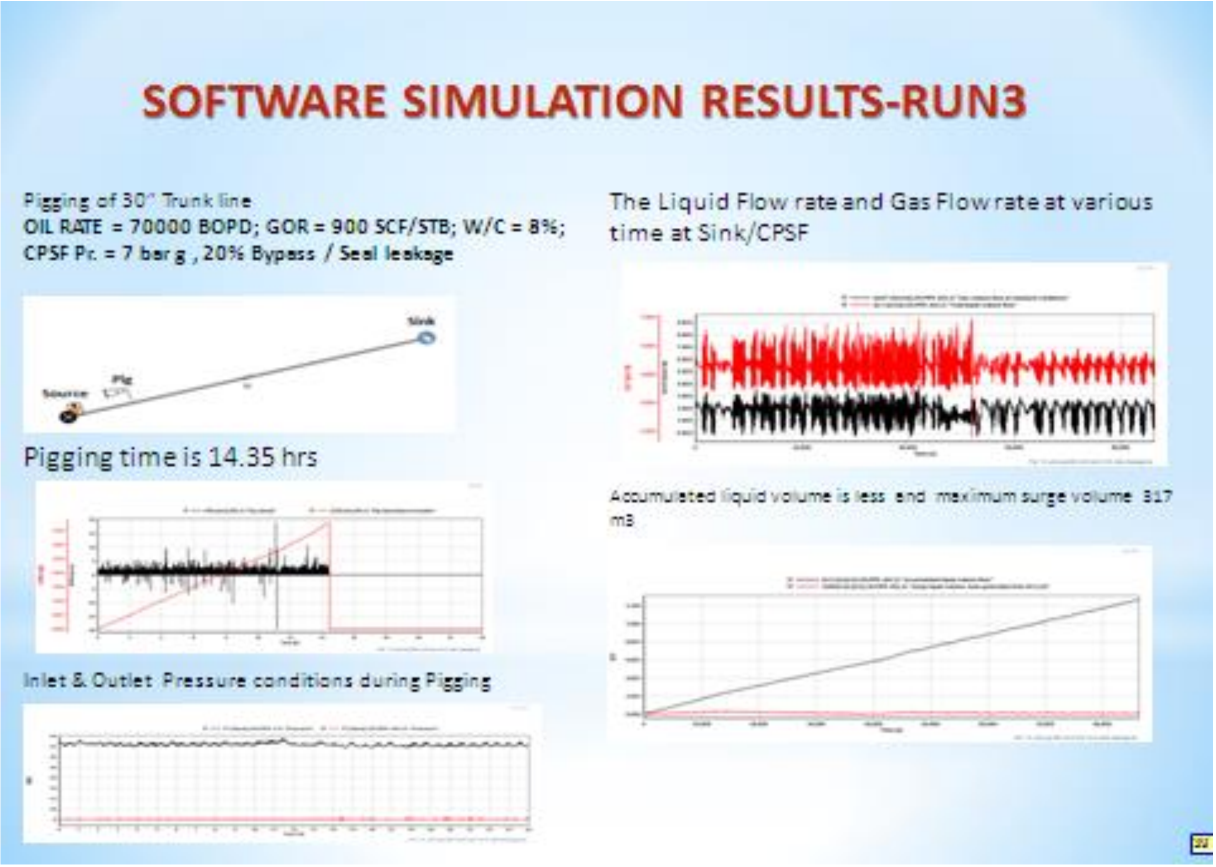


Fig 6.16: Software Simulation Run 3

Summary of Software Simulations

1. Pig travel time calculated based on simulation without bypass holes is more or less matching with actual pig travel time obtained during field pigging operation though there were some mismatches. This is evident in the smaller diameter pipeline pigging where pigging were carried out without any downstream control in liquid withdrawal rate.
2. The Pig travel time calculated based on simulation with bypass holes is NOT matching with actual pig travel time observed during field application.
3. The liquid slug is predicted to start much earlier than was observed in the field.

This time gap could be due to the failure of predicting a bubly slug flow due to turbulence of bypass pigging. More over the liquid arriving is also controlled by throttling the inlet Flow Control Valve.

4. The liquid surge volume, duration, arrival time are dependent on the normal production rate maintained in the pipeline before pigging and the pigging rate (BLPD, GLR).
5. Simulation results shows less increase in back pressure compared to actual back pressure observed during field pigging operation. This is because of the difference in the liquid withdrawal rate considered in simulation study and actual field case.
6. Bypass pigging as such can not be modeled with OLGA Software. By pass pigging has to be modeled through allocating certain % of seal leakage across the pig.
7. After allocating the calculated % of seal leakage in the simulation, the simulation is unable to complete and getting aborted.

6.5 NEW BY-PASS HOLE GEOMETRY / PROFILE

A new bypass pig geometry/profile, named as Convergent Divergent Profile is suggested in this paper followed by simplified model development. Various aspects of the proposed profile discussed and suggested field trial with selected cases.

Through this innovative design the critical flow is achieved at a lower pressure ratio so that a stable constant gas flow rate can be achieved through the bypass holes utilising a Convergent Divergent Profile where the gas entry is through a nozzle section, stabilizes at the throat and recover back the pressure through a diffuser section. The nozzle convert the high pressure energy into velocity energy and the diffuser regains the pressure back before its exit out of the hole. At a pre-defined inlet pressure and area of cross section of the hole, a properly designed convergent nozzle with throat section will give maximum critical flow rate at the exit by reducing the gas pressure to the critical pressure ratio. However, with help of the diffuser section, the high velocity energy is converted back into pressure energy and the line pressure is regained up to 90% of the upstream pressure.

Salient features of New Geometry

- In conventional bypassing, increase in bypass area reduce CD, delta P and hence do not increase gas flow rate correspondingly. This is evident from experiments.
- New innovative bypass hole geometry design (Convergent divergent Nozzle design at the central) maintain high gas flow rate at higher delta P
- The throat diameter is decided based on the quantity of gas bypass required.
- At the throat sonic velocity is achieved with critical gas flow rate.
- In the diffuser section the pressure energy is recovered
- In the diffuser section the pressure energy is recovered even up to 90 %
- In the nozzle and diffuser section, Isentropic expansion and compression process is anticipated
- Material selection shall be LTCS/SS to withstand low temperature

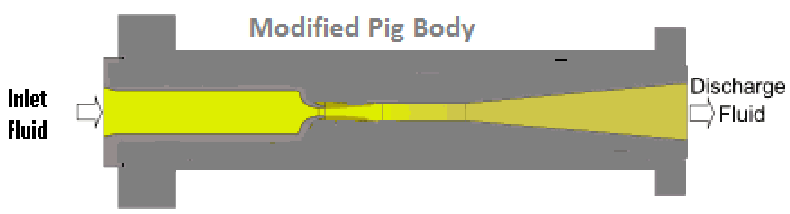


Fig 6.17: Innovative new geometry profile

Typical Design of Convergent Divergent Profile

Oil Rate = 70000 BOPD; GOR = 1300 scf/stb; W/C = 8%; Source Pressure =17 barg; Sink Pressure = 7 barg;

Total Gas at starting point = 90 MMSCFD

Critical gas flow rate @ 17 barg = 43 MMSCFD

Calculated Throat diameter = 7.5 cm

Critical Pressure at Throat = 17 x 0.53 = 9.01 barg

Considering an angle of convergence of 10 degree (total), Length of Convergent section = 149 cm with an inlet diameter of 23 cm.

For isentropic flow at Po=17 barg, To=293 K, A*= 44.156 cm2 (Throat Diameter = 7.5 cm)

Gas density $\rho_0 = Po/RTo$ - Eqn(6.35)

$= 21.41\ Kg/M^3$

Sound Velocity at entrance, and throat, Gas velocity at entrance and throat are calculated along with density.

Diffuser diameter is calculated at M2=0.10 and M2=0.05 which is 18.1 cm and 25.5 cm respectively.

Diffuser Length (L) is calculated as below;

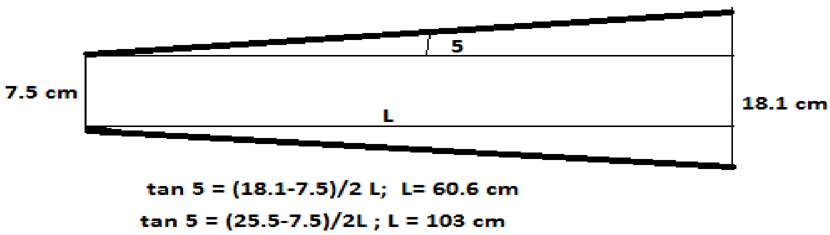


Fig 6.18: divergent section design

Profile 4: New Profile with convergent-divergent geometry. Inlet diameter of the hole is 25 cm, throat diameter of 7.5cm, exit diffuser diameter of 18.1 cm and overall length of 105 cm.

Appendix – A3 provides the details of the software design spread sheet used for sizing the nozzle and throat sizes.

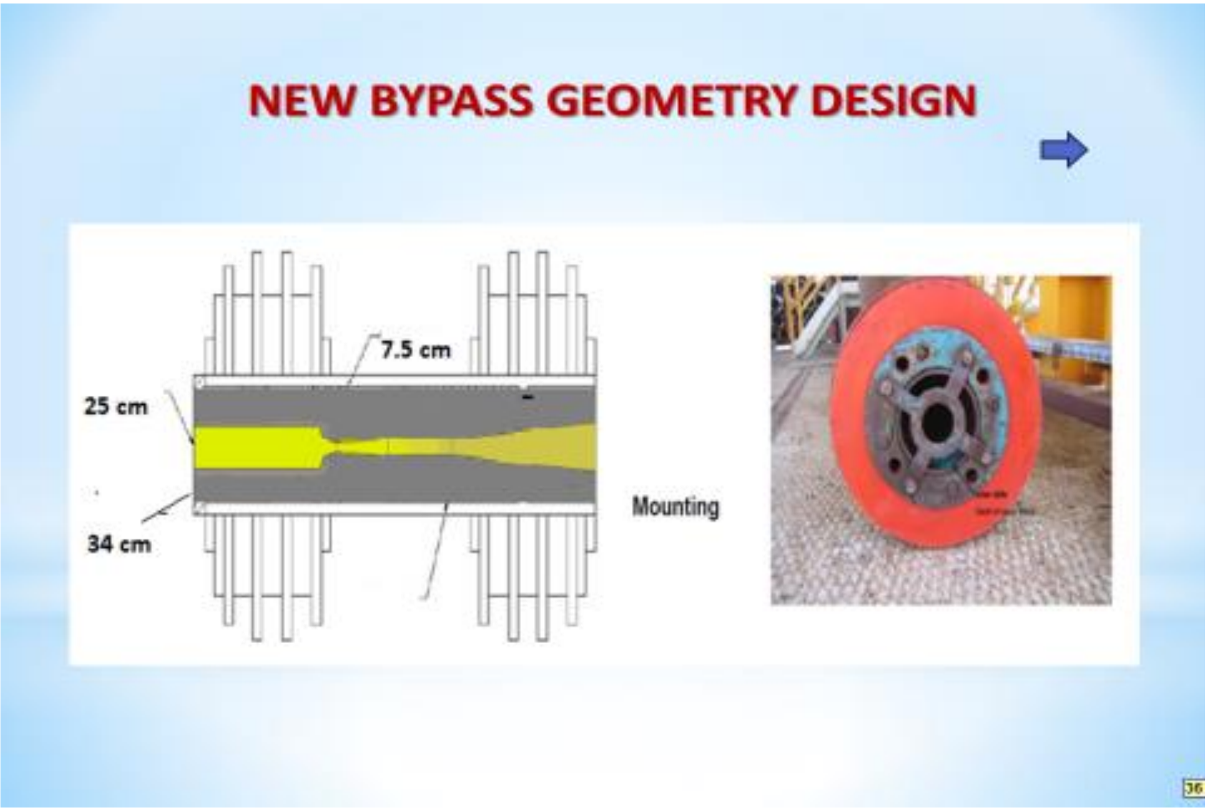


Fig 6.19: New bypass Geometry Profile 4

Additional force exerted on the diffuser wall is also calculated. This force is equal to the thrust of the flow in the backward direction which is equal to the change in the impulse function

$$T = F_2 - F_1 \qquad - \text{ Eqn(6.36)}$$

$$F_1^* = F_2^* = P_1^* A_1^* (1 + \gamma) \qquad - \text{ Eqn(6.37)}$$

From gas tables, for $M_2 = 0.1$;

$F_1 / F_1^* = 1$; $F_2 / F_2^* = 4.30$; $F_2 = 4.30 F_2^*$

$T = (4.30 – 1) F_1^* = 3.30 P_1^* A_1^*(1 + \gamma)$

$= 3.30 * 9.504 * 10^5 *3.14 *0.075*0.075*(1+1.4) = 33237$ N

The pig body shall be able to with stand this additional force acting on it due to the new profile.

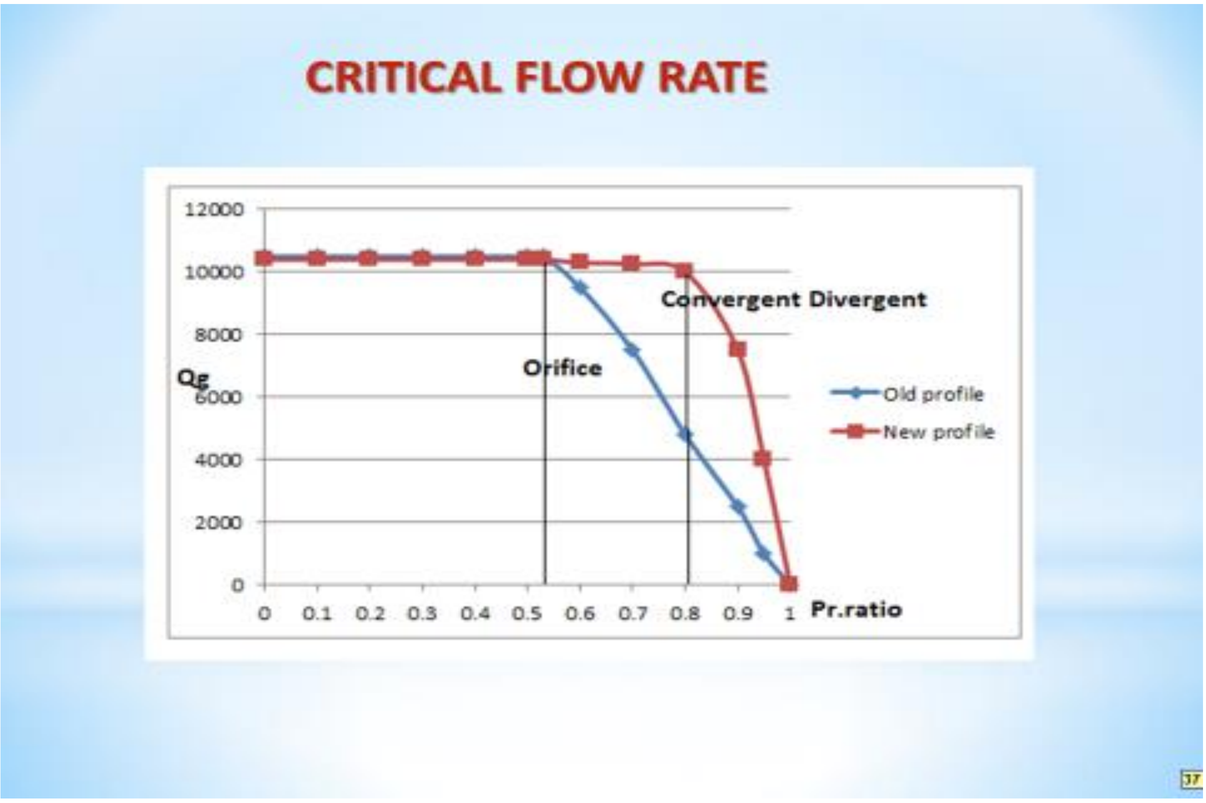


Fig 6.20: Typical expected flow profile through convergent divertent nozzle

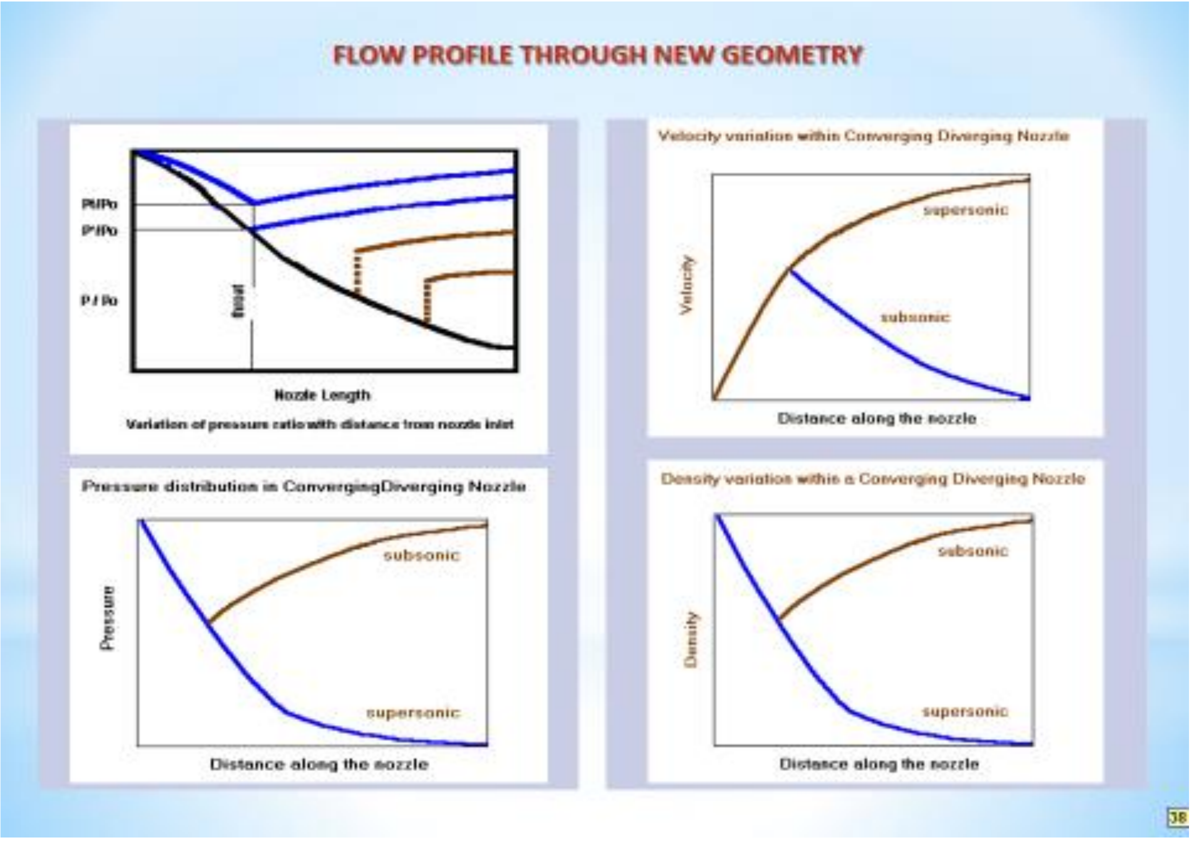


Fig 6.21: Expected fluid property profile through convergent divertent nozzle

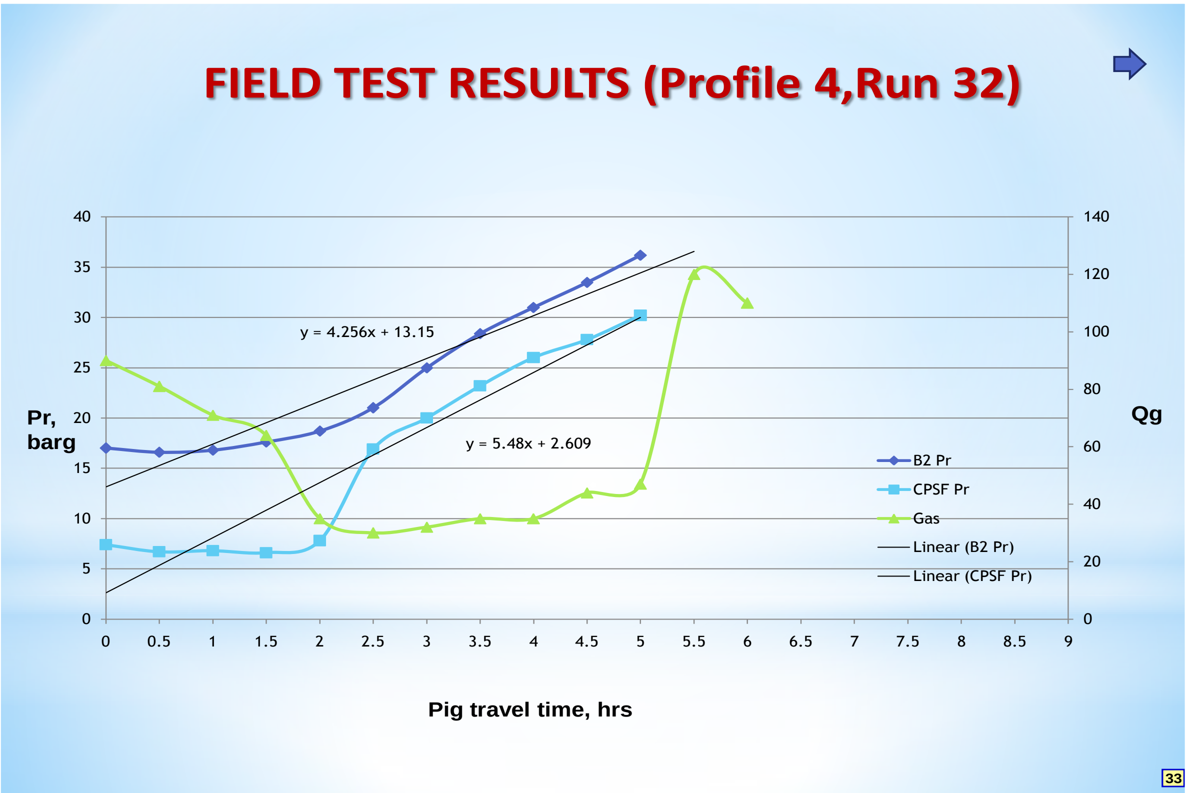


Fig 6.22: Pigging results with new geometry Profile 4

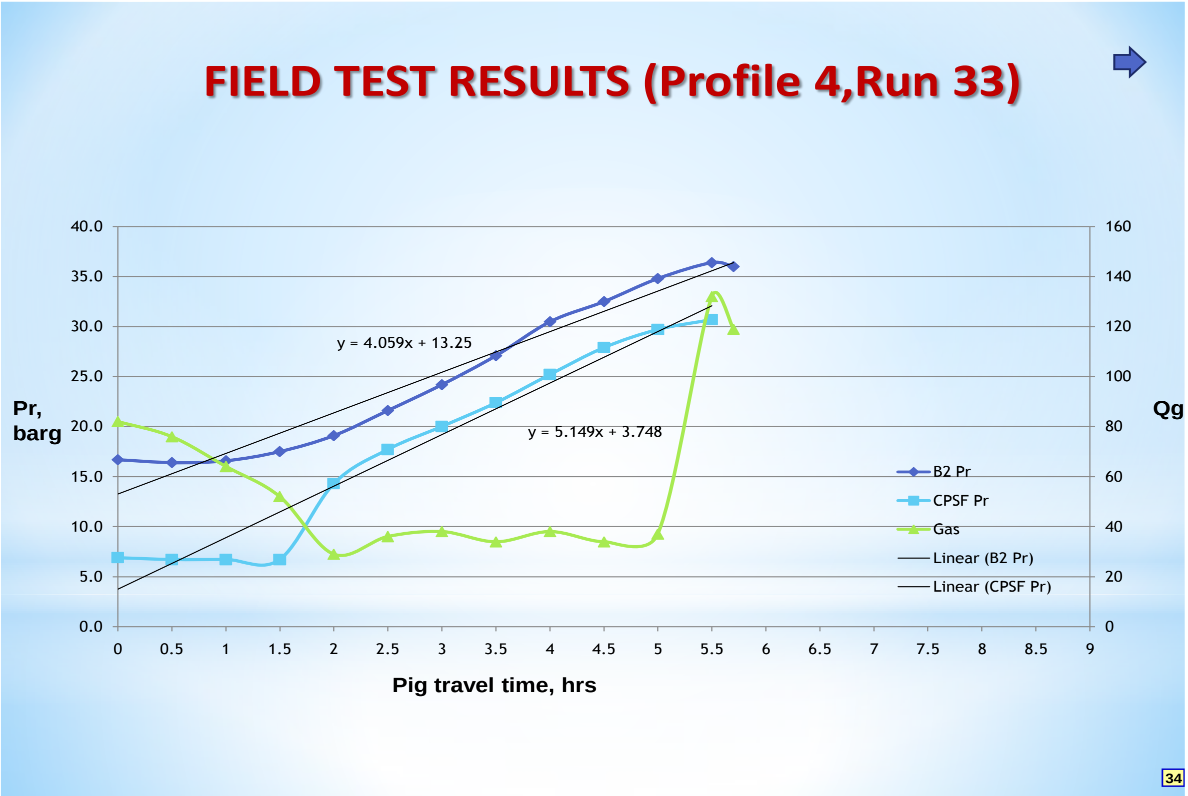


Fig 6.23: Pigging results with new geometry Profile 4

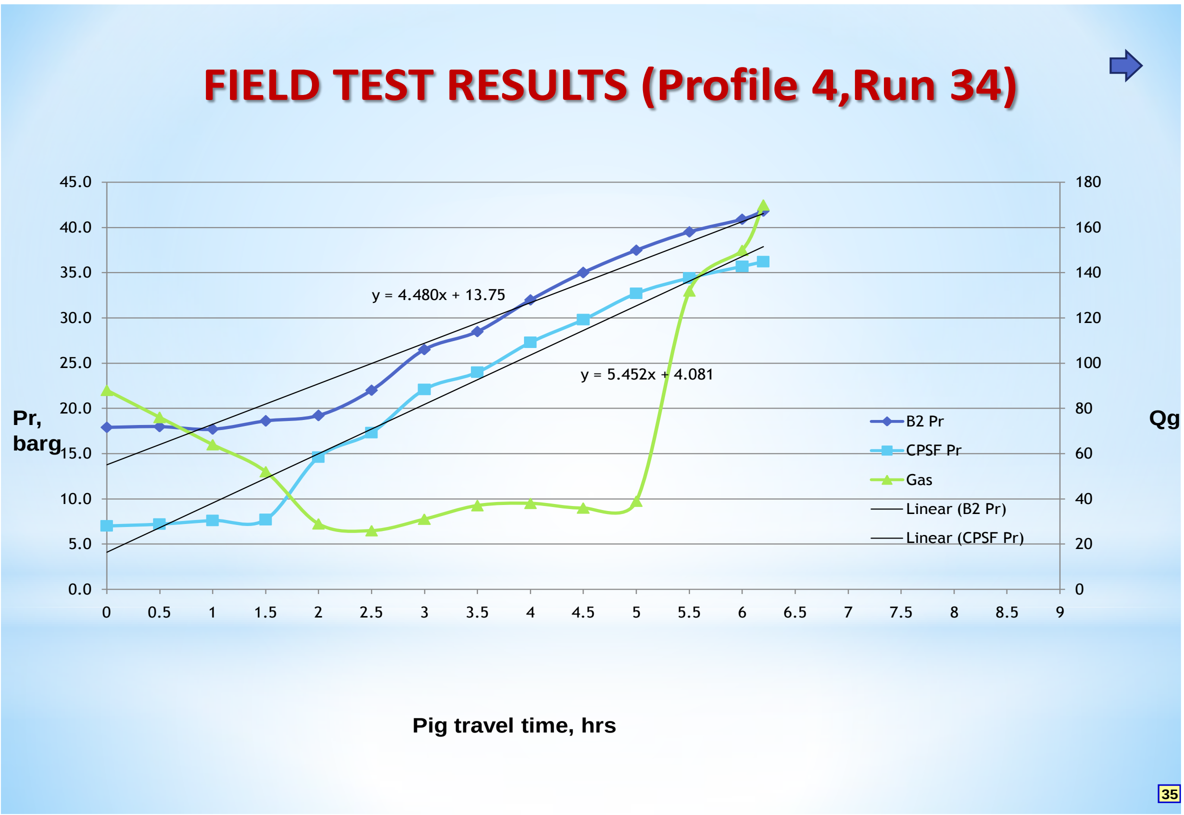


Fig 6.24: Pigging results with new geometry Profile 4

Following table shows the validation of gas bypass flow rate observed during pigging operation using new profile with the calculated bypass gas flow rate with Thorn-hil craver equation

Table 6.3: Validation data for actual and calculated gas flow rate

Profile Type	Run Nos	% Bypass	Liquid flow rate BLPD	Gas rate MMSCFD	Actual pigging time-hrs	Maximum B2 Pressure-bar g	B2 Initial Pr.-bar g	calculated pigging time at start -hrs	calculated pigging time at end -hrs	Pig travel time based on average velocity - hrs	Recorded Bypass gas rate - MMSCFD	Calculated Bypass gas rate - MMSCFD
Profile-1	19	0.8	65592	71.5	6.3	36.8	17.0	3.8	7.2	4.3	2	8.20
Profile-2	28	2.6	71024	53.7	7.8	38	17.0	5.1	11.0	11.6	15	31.00
Profile-3	29	4	70839	57.0	7.9	40.5	17.0	4.8	9.4	19.6	17	43.00
Profile-3	30	4	81752	61.0	6.6	36.5	17.0	4.5	7.9	15.2	19	43.00
Profile-3	31	4	71980	67.0	5.1	35.5	17.0	4.1	7.1	11.3	18	43.00
Profile-4	32	1.05	73807	89.8	4.1	36.2	17.0	3.0	6.3	4.6	38	43.00
Profile-4	33	1.05	79028	82.2	5.5	36.4	17.4	3.4	6.9	6.6	37	43.00
Profile-4	34	1.05	83388	88.3	6.5	42.3	18.2	3.3	7.4	5.8	39	43.00

- The Bypass gas quantity is almost matching with calculated value/design value
- In the new design the % area bypass is very low compared to conventional bypass pig
- The Bypass gas flow rate is very high due to near critical flow
- OLGA Software validate the new design assuming an equivalent high area bypass % or seal leakage
- The software simulation shows that the upstream pressure conditions and the liquid slug conditions have been changed dramatically.
- Uniform pig speed is indicated
- The software simulation shows that the accumulated liquid and surge liquid is reduced.
- The simulation shows a no pig travel status due to high seal leakage which is limitation of OLGA Software.

Experimental Results & Analysis

- With new geometry, gas quantity and the liquid quantity increased. Gas flow rate need not be curtailed unlike previous cases. High gas rate of 85-90 MMSCFD was maintained during pigging.
- The design by pass gas quantity was 43 mmscfd. However the actual achievement was around 38 mmscfd which is inline with expectation considering many influencing parametrs.
- The back pressure rise was much lower than expected unlike conventional bypass pigging of previous cases.
- There was not much temperature reduction effect noticed during the operation
- Slug Catcher liquid withdrawal rate & level was better controlled with help of flow control valve
- The PIG generated volume was effectively controlled
- Properly designed bypass geometry can effectively minimize the liquid/solid surge by spreading the collected liquid/solid in front of the pig.

6.6 CONCLUSIONS

The new profile will ensure sufficient bypass gas quantity through the pig required for very efficient and effective pigging operation without compromising differential pressure and also avoid any pig stuck up. The availability of more bypass quantity will reduce the high amount of pig generated liquid volume and enable to deliver a uniformly mixed fluid during the pigging time. This will also avoid high slugging during pigging and eliminate the requirement large slug catching facilityarrangement.This will enable ease of compressor operation during the pigging time by minimizing the gas quantity fluctuation. Following are major conclusion of this study:

- The existing normal square edged hole operate in the sub critical region in the pipeline. The present bypass hole configuration induces variable gas flow rate through the pig which can cause pressure fluctuations in the pipeline, leading to instability in flow.
- Modified convergent divergent type by pass geometry profiles were designed based on continuity equation so as to achieve critical flow at lesser pressure differential across the pig.
- The experiments carried out on modified profiles indicated that critical flow rate through convergent divergent nozzles achieved at downstream to upstream pressure ratio of 87 % to 82 % for smaller hole sizes of 3/16 ", 1/4 " and 5/16" sizes vis-à-vis 53 % in existing square edged bypass holes.
- The results indicate that the increase in area ratio of exit to throat section beyond a limit did not result higher pressure recovery
- The most ideal total angle of convergence as indicated from test results is around 10 to 12 degrees.
- Care shall be taken during material selection of the pig body in view of the anticipated temperature drop across the nozzle. Additional care shall also be taken in design to account the additional force exerted on the diffuser wall of the pig geometry.
- Effectiveness of wax removal/disintegration with bypass pig of new geometry shall be better
- Effective slug control/process operation/back pressure reduction achieved with help of new geometry

- New Geometry Bypass pigging is used to reduce the pigging risks like separator trip caused by surge in liquid/solids, potential for lost production due to stuck pig,
- Only limited success in predicting slug size, slug duration, back pressure rise etc. has been reported in bypass pigging with help of software simulation
- Field data and model prediction results will enable to develop liquid surge prediction practices for pipelines
- Results based on new geometry will help designers to accurately estimate the required surge capacity at process complex and reduce the CAPEX for surface slug handling facility.
- The new empirical equation and geometry proposed in the study may be very useful in safe and economical pigging application in the field.

6.7 SUMMARY

Multiphase flow through oil& gas pipeline is very complicated due to different flow regimes, terrain induced slugging, pipeline profile, gas oil ratios, presence of sand, wax and other solid particles etc. Static, steady state, and transient flowing conditions are entirely different and needs extensive simulation and flow modeling to predict such behavior accurately. There few commercial software codes such as OLGA, PHOENICS, FLUENT, CFX5 etc. in the market.

In Multiphase flow modeling, a general framework is adopted for the modeling of turbulent dispersion in Eulerian Multi-Phase Flows. The approach is based on a double averaging procedure of the local instant equations. First start with the ensemble averaged equations of Eulerian multi-phase flow, then perform a second time average of these, in order to form equations which may be used to model turbulent multi-phase flows. These are conveniently expressed in terms of Favre or Mass averaged variables.

Two Fluid Model and Drift Flux Model/Diffusion are analyzed in detail. Based on the Model 32 numbers of field tests were carried out and data collected. A new empirical correlation developed and validated. In general the results indicate a good agreement between the real case data and the prediction given by the empirical correlation. This correlation is very helpful in predicting the pigging uncertainties.

In regards to the new by-pass pig geometry and models to calculate the by-pass flow quantity and the liquid slug production and the substantial improvement in the process control operations it is expected some variation in the results, that revealed directly in the pig velocity. Depending on the model the pig velocity could be overestimated or underestimated.

The new profile will ensure sufficient bypass gas quantity through the pig required for very efficient and effective pigging operation without compromising differential pressure and also avoid any pig stuck up. The availability of more bypass quantity will reduce the high amount of pig generated liquid volume and enable to deliver a uniformly mixed fluid during the pigging time. This will also avoid high slugging during pigging and eliminate the requirement large slug catching facilityarrangement.This will enable ease of compressor operation during the pigging time by minimizing the gas quantity fluctuation.

CHAPTER - 7

CONCLUSION AND FUTURE RESEARCH

7.1 INTRODUCTION

The characteristic equations of multiphase flow such as the equation of mass conservation, momentum, energy and Pig dynamics may be solved numerically by a variety of methods. The more are the details taken into account in the model the more are the difficulties to achieve the solution to the resulting system of equations. Thus the intent of this work was to propose a simplified model to estimate the pipeline back pressure during pigging operation, to approximate the pig velocity and get an idea of the flow regime while pigging operation. The newly proposed innovative by-pass pig geometry shall be described through a complicated two fluid model with help of energy conservation equation but simplified to a Tw fluid model. This new geometry bypass pig utilizing the Convergent-Divergent profile will allow a near critical mass flow rate at minimum differential pressure across the by-pass port. This will ease out the high liquid slug to the pig receiving station/slug catcher.

7.2 SUMMARY OF RESEARCH FINDINGS

The new profile will ensure sufficient bypass gas quantity through the pig required for very efficient and effective pigging operation without compromising differential pressure and also avoid any pig stuck up. The availability of more bypass quantity will reduce the high amount of pig generated liquid volume and enable to deliver a uniformly mixed fluid during the pigging time. This will also avoid high slugging during pigging and eliminate the requirement large slug catching facilityarrangement.This will enable ease of compressor operation during the pigging time by minimizing the gas quantity fluctuation. Following are major conclusion of this study:

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- Modified convergent divergent type by pass geometry profiles were designed based on continuity equation so as to achieve critical flow at lesser pressure differential across the pig.
- The experiments carried out on modified profiles indicated that critical flow rate through convergent divergent nozzles achieved at downstream to upstream pressure ratio of 87 % to 82 % for smaller hole sizes of 3/16 ", 1/4 " and 5/16" sizes vis-à-vis 53 % in existing square edged bypass holes.
- The results indicate that the increase in area ratio of exit to throat section beyond a limit did not result higher pressure recovery
- The most ideal total angle of convergence as indicated from test results is around 10 to 12 degrees.
- Care shall be taken during material selection of the pig body in view of the anticipated temperature drop across the nozzle. Additional care shall also be taken in design to account the additional force exerted on the diffuser wall of the pig geometry.
- Effectiveness of wax removal/disintegration with bypass pig of new geometry shall be better
- Effective slug control/process operation/back pressure reduction achieved with help of new geometry

- New Geometry Bypass pigging is used to reduce the pigging risks like separator trip caused by surge in liquid/solids, potential for lost production due to stuck pig,
- Only limited success in predicting slug size, slug duration, back pressure rise etc. has been reported in bypass pigging with help of software simulation

7.3 CONTRIBUTIONS OF THIS RESEARCH

Theoretical contributions

The fully developed 2 fluid model is capable to explain the steady state and transient for compressible, incompressible flow. During pigging of multiphase flow during the initial stage we can assume a steady state situation at the upstream and downstream of the pig for certain time till liquid in front of the pig is collected completely and the liquid hold up in the downstream of the pig gradually increase due to liquid accumulation. During this period the it is still a compressible flow situation as the associated gas in the stream still forms a stratified layer above the liquid bottom layer. The gas phase moves little faster compared to the liquid phase. But the pig upstream down stream flow regime could be entirely different as a function of time for a solid pig without proper by-pass.

But as time goes the flow regime changes as the pig downstream liquid hold up increases and the mixture becomes highly incompressible, whereas the upstream is highly compressible, portion in between the front and the rear cups of the pig is still compressible. Here, a Lagrangian grid system shall be more appropriate during pigging operation. The flow regime is entirely different in the upstream and downstream of the control volume.

In the model the initial portion of the pigging operation shall be represented by a transient compressible flow regime system in a by-pass pig, whereas the latter half becomes more incompressible in nature. In this situation a Eulerian grid system to predict the liquid movement can also be utilized to simplify the situation. Where as in the case of the by- pass pig motion Lagrangian grid is more applicable.

In case of particles of wax, sand of very small size across any bypass opening will be leading to deposition based on the Brownian motion. They will tend to move away from the centre core and get deposited on the outer layer and also lead to conglomeration. The Vortex phenomenon at high Reynold's number also shall be addressed across the bypass holes. There is a clear chance of wax blockage if the particle velocity is reduced due to its smaller weight.

In the Time Vs. Pressure graph the slope variation indicates the Change in nature of the fluid flow regime during pigging operation. This slope change is an indication of the fact that the partial differential equation is applicable and can be solved. The nature of the slope change will give a very good indication about the shift of compressible flow to incompressible flow and the reduction of gas in the system and increase of liquid hold up in the pipeline. The slope change also indicate the flow regime change in the upstream and downstream of the pig and how fast the change is happening

The partial differential equation application of single order or double order can be clearly visualized. The slope curve and the liquid withdrawal graph correlation are very important in this case.

Practical Implications

- Field data and model prediction results will enable to develop liquid surge prediction practices for pipelines

- Results based on new geometry will help designers to accurately estimate the required surge capacity at process complex and reduce the CAPEX for surface slug handling facility.
- The new empirical equation and geometry proposed in the study may be very useful in safe and economical pigging application in the field.

7.4 LIMITATION AND FUTURE RESEARCH

A moving grid system is highly recommended in pig movement analysis especially in the case of by-pass pig as the system is transient. The by-pass pig as such is to be represented as a Lagrangian control volume for better accuracy overcoming the complicacy.

In the case of the new profile there is also energy transfer across the system due to temperature changes. The assumption of isothermal process is not valid in this gas by-pass process through the convergent divergent nozzle. Hence the TWO FLUID MODEL OR DRIFT FLUX MODEL may not be applicable here and shall be solved with help of Equation of Energy Conservation. Brownian motion, D'Alembert and White head Paradox are also applicable in the by-pass pig hole blockage due to fine sand/wax particle deposition. This needs elaborate study and further modeling.

An expression for the frictional force between the pig and the pipe wall shall be further explored. The equation should be tested against real experiments to check the reasonability of the expression.

CHAPTER - 8

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APPENDICES

APPENDIX – A1

Graphical representation of Liquid withdrawal rate during pigging

APPENDIX – A2

Exploratory Data Analysis of Pigging Operations

APPENDIX – A3

Software programme forbBy-pass gas flow rate & Design code for New by-pass pig geometry