DESIGN OF REGULATED VELOCITY FLOW ASSURANCE DEVICE FOR THE PETROLEUM INDUSTRY

A Thesis

by

CHAITANYA YARDI

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

MASTER OF SCIENCE

December 2004

Major Subject: Mechanical Engineering

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ABSTRACT

Design of Regulated Velocity Flow Assurance Device for the Petroleum Industry.

(December 2004)

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The petroleum industry faces problems in transportation of crude petroleum because of the deposition of paraffins, hydrates and asphaltenes on the insides of the pipeline. These are conventionally removed using either chemical inhibitors or mechanical devices, called pigs, which travel through the pipeline and mechanically scrape away the deposits. These pigs are propelled by the pipeline product itself and hence travel at the same velocity as the product. Research has indicated that cleaning would be better if the pigs are traveling at a relatively constant velocity of around 70% of the product velocity.

This research utilizes the concept of regulating the bypass flow velocity in order to maintain the pig velocity. The bypass flow is regulated by the control unit based on the feedback from the turbine flowmeter, which monitors the bypass flow. A motorized butterfly valve is used for actually controlling the bypass flow.

In addition to cleaning, the proposed pig utilizes on-board electronics like accelerometer and pressure transducers to store the data gathered during the pig run. This data can then be analyzed and the condition of the pipeline predicted.

Thus, this research addresses the problem of designing a pig to maintain a constant velocity in order to achieve better cleaning. It also helps gather elementary data that can be used to predict the internal conditions in the pipe.

To my parents

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Reza Langari for his guidance and support during my graduate studies at Texas A&M University. I will always remember his willingness to spare time to meet me to discuss the project and most importantly his looking into my welfare as well as those of his other students.

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CHAPTER I

INTRODUCTION

A. Introduction

The major part of the energy available today is through hydrocarbon reserves, mainly - oil and gas deposits. The development of offshore and onshore drilling technology has allowed these reserves to be tapped. These hydrocarbon reservoirs are produced, drained and transported over large distances through pipelines.

However there are problems in retrieving and transporting these resources from deep under the earth to refineries, hundreds of miles away. Naturally occurring hydrocarbons contain significant amounts of hydrates, asphaltenes, paraffins suspended in the oil. These crystallize and precipitate onto the inner walls of the pipeline over time, thus slowly choking the flow of the hydrocarbons itself. The problem is worsened under certain thermodynamic conditions like sudden temperature or pressure changes. The major concerns are:

1. Increased pumping costs because of reduction in internal diameter of the pipes because of deposition of wax, asphaltenes and hydrates.
2. Restriction of flow of oil or gas as a result of increase the surface roughness.
3. The blockages caused by these deposits lead to loss of production.
4. Periodic repair, maintenance and sometimes even replacement is sometimes necessary.

The journal model is *IEEE Transactions on Automatic Control*.

These problems are magnified in the offshore oil industry as the subsea temperatures are not high enough to prevent the precipitation of these waxes.

The removal of these deposits is done by a variety of means, either by injection of chemicals which help in dissolution of these deposits, or more commonly, by devices called cleaning pigs. Pigs [1] are devices which move through the pipeline and mechanically remove the deposits by scraping the inner walls of the pipeline . Pigs are used in the oil industry to clean, scrape and remove paraffin, asphaltenes and hydrate deposits from the pipelines. These pigs are propelled by the flow itself and hence travel at the flow velocity.

B. Problem Background

The oil industry has observed that cleaning is better with special bypass pigs than with ordinary pigs. The bypass pigs travel at a lower velocity than normal pigs as some of the flow which propels the pig is bypassed. It was also noted that the flow through the bypass carried away the deposits removed by the leading edge of the pig, thus prevented accumulation of these deposits and hence reduced the chances of the pig getting stuck.

An oil consortium, DeepStar, sponsored research with Dr. Cem Serica which investigated the formation and accumulation of the cutting debris field ahead of a pig. Dr. Serica described the impact of the debris field from his (simple) experiments and went on to project that bypass fluids would minimize or prevent the accumulation of the debris field by flushing the cuttings ahead of the pig in the bypass fluid.

A number of published research topics on the transportation of solids in a fluid flow have indicated that that there is a maximum solids to liquid ratio that can be transported as a slurry. If the percentage of solids to liquids in the flow exceeds about

[1] The devices are known as pigs because of the squealing noise they make while traversing the pipeline

40%, then solids start to bridge and blockages may form. Thus the annular bypass must be so designed that the ratio of the amount of deposits removed and amount of bypass fluid required, in total flow stream ahead of the pig remains around 40% with a nice safety margin.

This has been estimated to being equivalent to bypassing about 30% of the net flow in order to maintain a safe solids to liquids margin. Thus the pig velocity is reduced to around 70% of the flow velocity. There is also a need to maintain the pig velocity fairly constant as any variation in this is going to affect the flow through the bypass and hence indirectly affect the solids to liquids ratio in the flow. This would be detrimental as it would increase the possibility of the pig getting stuck. Thus it is imperative to have a fairly constant pig velocity to have better performance and reduced chances of getting stuck.

Another important point to be considered is that all pipelines require periodic inspection to monitor the internal conditions of the pipelines. Majority of inspections are carried out using inspection pigs called 'smart' pigs. These pigs use various techniques like Magnetic flux leakage (MFL) and Ultrasonic to provide information regarding pipeline condition. The basic parameters that need to be determined being corrosion, pitting and cracking. Such smart pigs provide a standard for determining pipeline condition, however they require specially designed pigs, which can be physically large and heavy.A lot of research has been done in this field, particularly by Crouch, Anglisano and Jaarah [5] or Willems and Barbian. [6].

The industry has shown interest in bridging the gap between the 'smart' inspection pigs and the 'dumb' cleaning pigs. The possibility of combining some of the smart pig capability into the cleaning pig would be extremely beneficial.

C. Problem Statement

The oil industry has estimated that the cleaning of pipelines would be more efficient at slower speeds with a constant pig velocity of around 70% of the flow velocity.Improved cleaning is possible in principle, if the velocity of the pig is regulated in real time. A constant velocity pig would translate into

1. enhanced cleaning,
2. reduced pig runs,
3. better production,
4. lower chances of the pig getting stuck in the pipeline
5. reduced slugging effects.

D. Research Objective

The intent of this research was to apply conceptual thinking rather than configuration thinking of the problem. The main goal was to understand the real need of the design task, to identify the requirements, functions, constraints and critical parameters to the problem.

The objective of this thesis is to develop a conceptual design for a pig that will meet the requirements of cleaning the pipelines and also regulate its velocity and maintain it at a certain percentage of the flow. It is also desired to keep the design simple, using standard commercially available components, so as to keep the design economically viable for extensive use.

Even though, maintaining the pig at constant velocity for better cleaning purposes remains the primary objective of this research, adding some basic sensing capabilities to make the cleaning pig a 'semi-intelligent' pig will be the secondary motive. This would enable the monitoring of the deposition of paraffins after analyzing the data gathered by the 'semi-intelligent' pig.

E. Research Scope

This research is focussed on developing a conceptual design to meet the above stated problems and objectives. A range of designs were proposed and only the optimum design which best met the requirement was further developed. The pig is designed for pipelines carrying oil only, though it could be modified to meet the requirements of a gas pipeline too, this research focusses solely on the pig traveling in oil pipelines.

Secondly, the design concentrates on the development of a mechanism to control the velocity of the pig, and not on the design of the pig parameters, as they have already been standardized. The building of a prototype of the pig and testing it in real conditions, is out of scope for this research due to lack of financial support and funding.

Lastly, the design is limited to providing the components necessary to take basic measurements for monitoring deposition conditions. The pig is designed to make full use of the components, utilized for controlling the velocity of the pig, by continuously gathering data and recording it. This data may then be used for analysis and monitoring of the pipeline. It is out of scope of the research to actually carry out analysis of the data gathered by the 'semi-intelligent' pig.

F. Conclusions

The need to improve the current form of pigging and the benefits of a velocity regulated cleaning pig is discussed in this chapter. The research scope and objective are clearly stated and they determine the direction for this research - new ways to regulate the speed of the cleaning pig.

CHAPTER II

BACKGROUND

A. Introduction

This chapter discusses the growth of the petroleum industry in the past century and the problems faced by it. The major problem being sustaining the flow through the pipelines and hence the growing importance of the term - Flow assurance. The various types of deposits that restrict flow, the problems caused by them and the means of removal are also described in this chapter. The key terms, mechanical pigs, cleaning pigs and intelligent or smart pigs are defined and discussed in detail. The research done on velocity regulated pigging is also described to give a background regarding this field.

B. Petroleum Industry and Flow Assurance

The petroleum industry boom began in the early years of the 20th century and by 1940's several hundreds of miles of pipeline were transporting natural hydrocarbons across the country. The abundance and size of oil deposits beneath the ocean floor and the development of offshore drilling technology has allowed the offhore oil production to become a very valuable resource to the industry.

There are problems, however, in the retrieval and transportation of these resources. It was well known that natural hydrocarbons had paraffin in solution, but it was only towards the 1950's that the deposits in the pipelines started posing severe problems by slowly choking the flow through them. It was important to prevent any disruption of oil services and to ensure the availability of oil to all parts of the country. In short, these oil pipelines, which carried crude and distilled products, are the lifeline of the United States of America. Since a major part of these pipelines were either subsea or underground and hence the removal of these deposits had to be done from inside the pipeline. Assuring and maintaining flow of oil through the pipelines became important and the term 'Flow Assurance' was coined.

In addition to prevention of blockages by wax and asphaltene deposits, hydrate formation, scaling and corrosion flow assurance was later expanded to include determining pipe size, layout of pipes based on the local geography, pumping capacity and where to locate the pumps, insulation needed or heating required and addressing problems due to slugging. Flow assurance is now defined as, "Flow Assurance includes all issues important to maintaining the flow of oil and gas from the reservoir to the reception facilities"

The major Flow Assurance concerns are reduction in internal diameter of the pipes because of deposition of wax, asphaltenes, hydrates etc which results in increased pumping costs. These deposits also increase the surface roughness which further restricts flow of oil or gas. The blockages caused by these deposits lead to loss of production, periodic repair and maintenance and sometimes even replacement. Deposition at the valves may result in interference in valve operation and other instrumentation.

The extent to which deposits might choke a pipeline are shown in Figure 1 and Figure 2.[1] [2]

Fig. 1. Reduction in internal diameter of pipeline [1]

Fig. 2. Deposits removed from a pipeline [2]

In short the problems caused by these deposits are stated below:

1. Reduction in internal diameter of pipeline leads to restriction of flow

2. Increase in surface roughness resulted in increase in pumping costs

3. Complete blockages cause production break which results in production losses, repair and replacement costs

4. Interference in valve operation and other instrumentation.

Prevention of these deposits is done in three ways :

1. Mechanical/Cleaning Pigs - These pigs are mechanical devices that traverse through the pipeline and mechanically scrape away the deposits that might have formed on the inner walls of the pipeline. The flow propels the pig along with it and hence no external source of energy is needed for the propulsion of the pig.

2. Heating or Insulation - The wax deposits generally form at low temperatures, hence one way of prevention is to constantly maintain the oil above the cloud point of substances that are in suspension in the oil. This could be done by constantly

heating the oil or by insulating the oil to prevent it from falling below the cloud point. Both these methods are generally too expensive to implement on a large scale.

3. Chemicals - Special chemicals that inhibit or prevent the precipitation of these deposits are injected into the pipeline along with the flow. These have been proved to be effective and economic.

There are various kinds of deposits that might occur depending on the composition of the crude oil and each has its own unique characteristic. They are listed below:

1. Wax - This blockage forms though out the entire pipeline and starts forming early in the lifetime of the pipe. It is predicted and modeled using cloud point, pour point and gel strength. It is currently prevented using pigs, insulation, heating and chemicals. Chemical generally used is Wax inhibitor which is injected at the tree or manifold at regular intervals of time.

2. Asphaltenes - These form especially at pressure drop locations like downhole, subtrees, separators etc and deposit all through the lifetime of the pipeline. Asphaltenes may be determined and modeled using colloidal instability or solvent titration or live oil depressurization. They are currently prevented using pigs or chemicals like asphaltene inhibitor/asphaltene solvent that are injected at the bottom hole and tree respectively.

3. Hydrates - Hydrates deposit through out the pipeline and form early on in life. These are modeled and predicted using the hydrate stability curve and are kept in check using pigs, heating of pipes or use of chemicals such as methanol or kinetic inhibitor which are injected upstream and downstream of safety valve.

4. Sand - Sand deposition takes place especially at the base of risers, well heads, valves or chokes. It is usually prevented using filters .

5. Scale - Scale formation starts late in life of the pipeline. This is determined using Saturation index and is generally prevented using pigs or chemicals such as scale inhibitor which are injected intermittently at the bottom hole.

C. Mechanical Pigs

The cheapest and most effective way to solve the problem was to design a device that could travel through the pipeline, removing deposits and cleaning the pipeline while traversing. This device, called a pig, is a snugly-fit plug which is propelled through the pipeline to execute activities like cleaning or inspection. The term - Pig - got associated with this device, because of the squealing noise it made, as it traversed through the pipeline - and from then on the term stuck on. It is also referred to as the Pipeline Inline Gauge (PIG) especially in context with the smart pigs.

Pigs are slightly over sized with respect to the pipeline they are supposed to traverse in, so that they form a snug fitting plug in the pipe, thus completely sealing the pipeline on both ends of the pig. They are propelled through the pipelines, usually using the pipeline product such as oil or gas, as a propellent, though in some cases a different propellent might be used for propulsion. Pigs are available in various shapes, sizes and materials - they might be bullet-shaped, spherical or composed of an array of scraper discs or propulsion cups. They also vary from simple polyurethane pigs, mandrel pigs, batching pigs to more complex inspection or 'smart' pigs.

1. Cleaning Pigs

The early cleaning pigs were simple in design and were just cylindrical bullet shaped plugs and made of poly urethane foam. Their length was usually twice their diameter for stability while traversing the pipeline so as to prevent the pig from flipping inside the pipeline. These became popular by the name "Polly Pigs". To improve performance of the pig, it was noticed that rotating pigs provided better cleaning - pigs were then designed with helical ribs, which provided a slow rotational twist to the pig as it traversed through the pipe - which resulted in improved cleaning.Figure 3 shows a polly pig.[3]

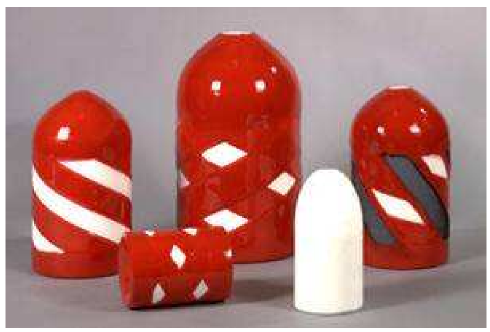

Fig. 3. Cleaning pig - polly pig [3]

As the demands of the oil industry grew, better cleaning methods were required. The pigs were modified and spring loaded brushes and scrapers were mounted onto the pig. These could scrape away even those stubborn deposits which could not be removed using the polly pigs. The base of most of these pigs was still poly urethane, hence in one cleaning run of around 30 miles, these would wear out and would be rendered useless.

The industry needed cleaning devices which could be used repeatedly for a number of runs without the need to be discarded. The new pig, with a central steel bar was developed, this had arrangement to attach scrapers, scraper discs and cups onto the base. It was called the "Steel Mandrel Pig". This pig could be used for a variety of pipeline sizes and after each run, only the scrapers and discs that had worn out needed to be replaced while the basic pig could be reused. Figure 4 shows a steel mandrel pig.[3]

Fig. 4. Cleaning pig - steel mandrel pig [3]

Today, there exist pig trains, consisting of multiple pigs to meet the demands of cleaning the pipe in as few pig runs as possible. These pig trains have several pigs joined together with universal joints, so as to enable them to navigate through the pipeline with ease.

2. Smart Pigs

The pipelines laid in the 1940s, started to develop leaks and ruptures in the mid 60s and 70s. The cost of detecting a leak over a few hundred miles was both expensive and time consuming. A major leak could lead to waste of oil/gas worth millions of dollars and also create an environmental threat. There was need to develop preventive methods rather than reactive ones. Thus the condition of the pipeline had to be monitored at a regular intervals, so as to predict faults and failure before they occurred and to take preventive steps to avoid a mishap. As most of these pipelines were either underground or subsea, there was no way of monitoring them from outside. The only way to monitor the condition of the pipeline was from inside the pipeline.

Hence, a new kind of pig was designed to meet this requirement. Instead of brushes and scrapers, it had sensors mounted on it that recorded pipeline condition as the pig traversed through the pipeline. This data was retrieved after the pig run was complete and was analyzed for faults, cracks, corrosion and pitting in the pipeline. The pig data revealed any type of anamolies in the pipeline and this helped prevent major leaks and also helped in scheduling a plan for the repair or replacement of pipelines. This kind of pig was called an Inspection pig or a Smart pig.

The smart pigs generally use either Magnetic Flux Leakage (MFL) or Ultrasonic sound technology to predict corrosion, pitting or cracks in the pipelines.

Magnetic Flux Leakage Inspection system consists of three modules - a magnetizer module, flux leakage sensors and discriminator sensors. The magnetizer module generates a magnetic flux within the pipeline by inducing a magnetic circuit into the pipeline with the help of an on-board battery. If the pipeline has defects such as corrosion or pitting, it causes localized flux leakage where corrosion or pitting exists. This change in magnetic field due to flux leakage is detected by the flux leakage sensors which indicate presence of pitting or corrosion. But it remains to be determined whether the defect is internal or external. Another set of sensors, the discriminator sensors, only measure the minimum depth at the inner surface of the pipe but cant measure external defects. Thus using a combination of the flux leakage sensors and the discriminator sensors its possible to pinpoint not only where in the pipeline the defects exist, but also whether they are internal or external defects. [7]

Figure 5 shows a smart pig which uses MFL technology to detect corrosion, pitting and cracking.[4]

The Ultrasonic Inspection system is similar to the MFL technique except that it transmits an electrical pulse into the pipeline wall to measure pipe thickness. This method requires a clean pipe for proper operation and as oil pipelines usually have some paraffin buildup even after cleaning, this inspection method is preferred for gas pipelines more than oil pipelines. [8]

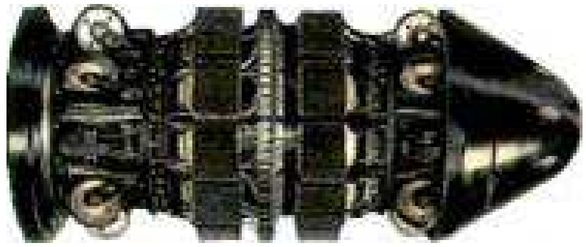

Fig. 5. Smart pig using MFL to monitor pipeline condition [4]

In order to take accurate measurments, the smart pigs need to move at a slower velocity than the flow velocity. Secondly, the velocity of the smart pigs needs to be regulated and kept relatively constant so that the data collection is uniform throughout the pipeline. The sampling rate of the sensors in the pig is constant, so if the pig velocity varies then resolution of the measurements at different velocities is different and this skews up the entire data collected. And this results in a distorted representation of the pipeline profile. Hence it is important that the velocity of the smart pig be maintained slower than the flow velocity and that it remains relatively constant throughout its run through the pipeline.

D. Past Research on Velocity Control Pigs

The smart pig needs to maintain a slower velocity as compared to the regular production flow velocity so as to take proper measurements in the pipeline. Initially, the flow velocity itself was reduced by reducing the total production of the pipeline itself. Thus, the velocity of the pig, which would still be traveling at the flow velocity, would be reduced and the measurement data obtained would be more reliable and would be a better representation of the actual condition in the pipeline.

This method worked well, but there were losses in production rate as the total output volume of oil/gas was reduced drastically and the well could not be produced at the optimum level. This resulted in large financial losses. Hence there grew a need to have a pig which could maintain a slower pig velocity despite a higher production flow.

There has been some research into this problem and a few designs have been put forward. Most of them use an annular space to by-pass some of the fluid flow. They propose to control the velocity of the pig by controlling the amount of fluid flow through the bypass.

The designs that have been put forward to solve this problem are discussed below :

In US patent No. 5208936, Campbell described the use of two plates with openings in them in the annular by-pass of the pig at the two ends of the passageway. The rest of the annular spaces between the pipeline and the pig is sealed, thus forcing all the fluid flow to be through the annular by-pass only. One of the plates is then rotated in relation to the other, which changes the fluid connection between the passageways. The plate may be rotated with a stepper motor which is controlled by a comparator circuit that compares the desired and actual pig speeds. Varying this degree of rotation, the amount of fluid passing through the by-pass is regulated which in turn regulates the pig speed. [9]

In US patent No. 6098231, Ian Smith, et al suggested the use of an hydraulic fluid powered actuator to move a sleeve valve in order to control the flow through the annular bypass. The valve comprises of a hollow cylindrical shell open at one end and closed at the other with exit ports located circumferentially. The hydraulic actuator pushes the sleeve outward, so that the exit ports are exposed allowing the fluid to pass through. The sleeve can be retracted to close the exit ports and effectively close the bypass duct. A range of intermediate bypass flows can be achieved by controlling the actuator between these extreme positions. Thus by controlling the bypass flow, the pig velocity can be regulated.

The hydraulic actuator is controlled by a hydraulic solenoid valve and an electrically powered hydraulic pump. The actual speed of the pig is measured by odometer wheels, it is then averaged over a predetermined time period and then compared to the desired speed. The control system powers the actuator to either increase or decrease the opening of the bypass to regulate the speed of the pig. The pig would carry its own power in the form of battery pack. [10]

In US patent No. 4769598, Krieg et al. suggested the use of two hollow cylindrical carriages both about half the size of the pipe diameter and coupled together. The carriages are supported by rollers mounted on the outside and the annular passage between the cylinders and the pipeline is sealed off by sealing discs. Hence the fluids in the pipeline pass through the hollow carriages only. Two rotatable perforated discs are mounted on the first carriage and the extent to which they are aligned determines the bypass flow through the apparatus. Hence by regulating the bypass flow it is proposed to regulate the speed of the pig. [11]

E. Conclusion

The major flow assurance problem faced by the petroleum industry is the deposition of paraffins, asphaltenes, hydrates onto the inner walls of the pipelines. These are removed either by chemicals or by mechanical devices called pigs. Mechanical pigs can be of two types - simple cleaning pigs which scrape out the deposits or smart pigs which take measurements about the internal condition of the pipeline. Smart pigs basically check for corrosion or cracking.

Some research has been done in the field of velocity regulated pigs, but it is noticed that most of the mechanisms proposed are complex and require highly specialized parts. This would make the velocity regulated pig expensive and unsuitable for wide scale application in the petroleum industry.

CHAPTER III

DESIGN METHODOLOGY

A. Introduction

The design methodology for this research is described in the chapter. The problem faced, the performance desired, the design requirements and constraints are listed in the following sections. The conditions the velocity regulated pig needs to satisfy and the means to implement the requirements are noted. The various options available for implementation are compared and discussed before the best possible option is chosen for further investigation.

B. Problem Statement

Pigs are used in the oil industry to clean, scrape and remove paraffin, asphaltenes and hydrate deposits from the pipelines. These pigs travel through the pipeline at varying velocities. Improved cleaning is possible in principle, if the velocity of the pig is regulated and maintained fairly constant. Industry research has estimated that cleaning is more efficient at lower speeds with a relatively constant pig velocity of around 65-70% of the flow velocity [1]. A by-pass may be provided in the pig, to allow the by-pass flow to carry away the removed deposits to prevent them from accumulating in front of the pig and potentially immobilizing the device. A constant velocity pig would translate into enhanced cleaning, reduced pig runs, lower chances of the pig getting stuck in the pipeline and reduced slugging effects.

C. Performance Objective

The objective of this proposal is to design and develop a prototype of a pig that can regulate its velocity and maintain it at a certain percentage of the flow. It is also desired to keep the design simple and standardized, in order to avoid the use of expensive sensors, regulators and custom built parts to the extent possible. This is with the aim of keeping the design economically viable for extensive use in the petroleum industry.

D. Design Requirements

1. The designed pig has to scrape the deposits like any other normal pig.
2. In addition, it has to maintain a constant velocity at a pre-specified level (approximately 65-70% of the nominal flow velocity).
3. In the extreme case of the pig getting stuck, there should be an arrangement that allows pressure to build up behind the pig to dislodge it.
4. When stuck, if the pressure difference across the pig is too large, the design should allow for the release of some of the pressure.
5. In case it becomes necessary, the pig should accommodate back-flow pressure to dislodge the pig.

The design specifications are listed in Table I.

Table I. Design specifications

	Design Specifications	Magnitude
1.	Diameter of production line	10" ID
2.	Flow rate of product through the pipeline	3 to 5 mph
3.	Pressure in Production line	1,000 to 5,000 psi
4.	Length of Production line	30 miles
5.	Desired Pig Velocity	65-70% of flow velocity

E. Design Constraints

1. It has to operate in harsh environmental conditions present in the pipeline (solid suspensions, large variations in working temperatures, multi-phase flow nature of flow).
2. The design has to avoid bells and whistles and maintain simplicity.
3. High fluid pressure rating
4. It has to be economically viable for mass production and use.

F. Design Concept

The simple pig is propelled by the fluid in the pipeline and is not self propelled. It derives all its power for propulsion from the flow and hence moves at the same velocity as the flow velocity. But as cleaning is better at lower speeds, and a lower pig velocity is desired as compared to the flow velocity - it becomes imperative to use only a part of the propulsion energy of the flow and bypass/dissipate the rest.

An annular bypass is provided along the central axis of the pig, this bypasses some of the flow and hence only a part of the flow actually propels the pig. The size of the annular passage can be designed so that the velocity of the pig is a certain percentage of the flow velocity. Though the pig velocity is reduced, it will not maintain constant velocity as the resistance faced by it in the form of deposits changes along the pipeline. Thus in addition to having a bypass through the pig, some other means of control is needed to keep it at regulated velocity.

The advantage of using a bypass flow in addition to reducing the pig velocity is that the flow through the annular passage carries away the debris of the deposits removed by the leading edge of the pig. This prevents the accumulation of debris in front of the pig, and this reduces the chances of the pig getting stuck. This by itself results in better cleaning, more reliability and lesser number of pigs getting stuck.

Hence, it is proposed to use the concept of actively controlling the flow through the annular bypass to regulate the pig velocity.

G. Functional Requirements for Velocity Regulated Pig

There is need to regulate the velocity of the pig in order to keep it relatively constant and this needs to be done actively and not just passively by designing the annular bypass. To maintain the pig at a desired velocity, it is imperative to know the velocity at which the pig is traveling. This velocity is then compared to the desired velocity and an appropriate action is taken to get it back to the desired velocity.

The actual velocity of the pig might get lower than the desired velocity because of increased resistance from wax deposits.In such a case, the cross sectional area of the annular bypass should be reduced appropriately, so that there is a marginal increase in the pressure behind the pig. This increase in pressure would help overcome the added resistance faced by the pig. When the pig overcomes the resistance from the deposits, it might start moving at a velocity that is greater than the desired velocity, if the bypass still remains partially closed. Hence, in such circumstances the bypass must be opened to allow more fluid to bypass and reduce the pressure behind the pig. This aids in reducing the pig velocity. Thus to maintain the pig at a relatively constant velocity, it is important to actively regulate the bypass fluid flow.

In addition, in the case of the pig getting stuck, the bypass should be shut off in order to allow pressure to build behind the pig. This buildup of pressure would hopefully be able to dislodge the pig. If this doesn't work, another way of dislodging a stuck pig is to back flow pressurize it. In this, the production is stopped so that there is no flow pressure acting on the pig. A reverse pressure is then applied to the front portion of the pig by pumping fluid back into the pipeline. This aids in dislodging the pig from the accumulated deposits and moves the pig backward. The back pressure is then discontinued and production is resumed. This forward and backward pressurizing has been found to be useful in dislodging stuck pigs.

But if the pressure difference across the pig becomes too large, there is a possibility of the pig or some component of the pig (ex. scrapers) disintegrating under the high pressure. This disintegration would create debris in the pipeline which would be very difficult to clean up. Hence, though its important to buildup pressure behind the pig with the aim to dislodge the pig, too large a pressure could prove detrimental. Thus a mechanism needs to be developed which would allow the release of pressure across the pig, if the pressure difference crossed a certain threshold limit.

1. Conditions Pig Needs to Satisfy

The conditions the pig needs to satisfy are summarized below:

1. Control and regulate velocity of the pig

2. When stuck,close annular bypass

3. If difference in pressure is too large,a mechanism to release pressure
4. Allow back flow pressurizing to dislodge pig.

2. Pig Functions

The functions the pig needs to perform in order to satisfy the above requirements are listed according to conditions :

1. To control and regulate the velocity of the pig
   (a) Determine actual speed of the pig
   (b) Regulate the velocity of the pig through some mechanism
2. To close the annular bypass when stuck
   (a) Detect when the pig is stuck
   (b) Close annular bypass to allow pressure buildup behind the pig
3. To release pressure when difference pressure is extreme
   (a) Detect differences in pressure
   (b) Open annular bypass to prevent damage to the pig and creation of debris in the pipeline
4. To allow back flow pressurizing
   (a) Prevent flow in the reverse direction

H. Various Possibilities Considered

A variety of options were studied and analyzed to determine which best fit the requirement for implementation with the pig. These are discussed for all the cases in brief:

1. To determine actual speed of the pig.

   It is difficult to determine the velocity of the moving pig in the pipeline directly, hence an approach to infer the velocity of pig was adopted. If the velocity of the flow through the by-pass can be measured efficiently, then the velocity of the pig can be determined as the bypass velocity is relative to the pig velocity. When the pig is moving at the desired velocity of 70 % , the flow through the annular bypass is 30% of the flow velocity. Now consider the case of the pig moving at 100% of the flow velocity then there is no flow through the bypass as the pig itself is moving at the flow velocity, hence the bypass velocity is zero. On the other extreme if the pig gets completely stuck and the pig velocity is zero, the entire flow is through the annular bypass and the bypass velocity is 100% of the flow velocity. Thus there exists a inversely proportional relationship between the annular bypass velocity and the pig velocity. And as its easier to measure flow through a passageway, the bypass velocity will be used to determine the pig velocity.

   The ways the flow through the annular bypass could be measured are :

   (a) Differential pressure V-cone

       A differential V cone could be placed in the bypass flow and the pressure drop across the cone would indicate the flow rate through the bypass.

       Disadvantages:

       - difficult to automate and integrate into a control system
       - fear of the cone getting clogged with debris of removed wax

   (b) Ultrasonic flow measurement

       Ultrasonic flow measurement uses the 'Transit Time Principle', whereby opposite sensors are used to send and receive signals through the fluid flow. The signal travels faster when moving with the flow stream rather than against the flow stream. The difference between the two transit times is used to calculate the flow rate.

Advantages :

- no moving parts, hence less maintenance required
- can measure wide range of flow rates
- no pressure loss during measurement

Disadvantages:

- expensive as compared to conventional methods
- inefficient for multi-phase flow, as air bubbles skew readings
- difficult to adapt to harsh working environment

(c) Turbine flow meter

The turbine flow meter incorporates a bladed turbine rotor which will be installed in the annular bypass of the pig. The turbine rotor is suspended axially in the direction of flow and the momentum of the flowing fluid rotates the turbine blades on its axis. The rotation is in proportion to the rate of the liquid flow through the bypass. An electrical signal pulse is generated by 'Principle of Reluctance' in which a pickup coil wrapped around a magnet and mounted outside the annular bypass, produces a voltage pulse when each rotor blade passes the coil. This is because the rotation of the turbine blade causes a deflection in the magnetic field and hence results in a voltage fluctuation. The flow rate is measured by measuring the number of electric pulses.

Advantages :

- can operate in harsh environment, pressures up to 10,000 psi, temperature range of -450 to 1000 F

- high flow rates
- free standing, no mechanical coupling necessary to transmit rotation
- low maintenance cost

Disadvantages:

- loss of pressure

2. To regulate velocity of the pig through some mechanism

   The velocity of the pig may be regulated in basically two ways - one would be to control the flow through the annular bypass and the second would be to use some braking mechanism to reduce the speed of the pig.

   The concept of controlling by-pass flow to control pig velocity has been studied in earlier studies. The annular bypass is designed to allow 30% of the flow to pass through, this allows the pig to move at 70% of the flow velocity when it is not facing resistance from wax deposits.

   When the pig faces resistance, the bypass needs to be appropriately closed in order to increase the pressure difference across the pig so that the pig is able to overcome the resistance and yet continue with the desired velocity.

   The concept of using braking to control pig velocity is being proposed in this work. The annular bypass in this case would be designed to allow about 20% of the flow to pass through, this would increase the pig flow velocity to 80% - about 10% above the desired velocity.

   The pig would then employ necessary braking as and when appropriate to reduce the pig velocity to the desired velocity.

   The ways the velocity of the pig might be regulated are discussed below :

(a) Bellows

The bellows would be used as a braking device whenever the pig speed rose above the desired value. Normally the bellow would be deflated but when the pig speed crosses the set limit, it would be inflated either by the fluid in the pipeline itself or by other means. This inflated bellow would then be designed to push against the pipeline and increase the frictional force on the pig. This increase in friction force would lower the velocity of the pig. The bellow would be drained when the pig velocity is again within acceptable limits.

i. Passive inflation The bellow would be inflated and drained using the pressure of the fluid flow itself as and when necessary. It would be the pressure of the fluid that would push the bellow against the pipeline, thus increasing the frictional force.

ii. Active inflation In this case, the bellow would still be inflated using the fluid in the pipeline, but an active measure to compress the bellow is utilized so that it exerts a larger pressure on the pipeline walls. This would aid in higher frictional forces and better and larger control over the velocity of the pig.

Advantages :

- no power requirements
- low cost

Disadvantages:

- deflation/drainage of bellow is passive and cannot be controlled
- effectiveness, reliability not proven
- would require an operating valve to control flow into the bellow, thus needing complex mechanical linkages

(b) Braking

This is another variation of the bellow idea. The concept of braking can be applied in the literal case for reducing the pig velocity. The idea emerged from the studying the working of the mechanical shoe brake and the ball governor.

In the mechanical shoe brake, the stationary shoes are lined with braking material and expand outward into the rotating drum when activated, this increases the frictional forces and reduces the speed.

The same concept is to be used here, the only difference being instead of the drum rotating and the shoes expanding, we have a combination of rotational and linear motions for the brake pads.

The ball governor provided the concept of activating the brakes. The rotating brake pads act as weights of a Watt governor and as the rotation speed increases, they are pushed outward because of the centrifugal force. Springs may be designed to counter the centrifugal force.

The annular bypass would be so designed so as to allow only 20% of the flow velocity and hence the pig would travel at a higher velocity than desired. The shoes with braking liners would be activated as and when the pig velocity exceeds the allowable limit.

Advantages :

- no power requirements
- low cost
- effectiveness, reliability proven in a different field of application

Disadvantages:

- less control over the magnitude of braking

(c) Valves

The concept of controlling the bypass velocity to control the velocity of the pig, can be implemented using valves. The valve is placed in the annular bypass and in the path of the fluid flow and it may be opened or closed to regulate the bypass velocity. If the pig is slowing down the valve needs to close, so that sufficient pressure can be built up behind the pig which will overcome the resistance posed by the wax deposits and maintain the pig at the desired velocity.

A variety of valves may be used for this purpose like, flapper valve, gate valve and butterfly valve. The gate valve is not suitable for this type of operation due to severe space restrictions. The flapper valve too, requires high torque requirements for its operations and hence needs to be ruled out. The butterfly valve best suits the requirements amongst the valves.

Advantages :

- good throttling device
- compact, lower weight, lower cost
- standard equipment and is widely used
- effectiveness, reliability already proven
- if fail close, can act as check valve and allow back flow to help dislodge the pig
- simple to integrate and implement
- excellent rangeability from 30:1 to 100:1

Disadvantages:

- power necessary for means of activation
- increase in cost

3. To determine if the Pig is stuck

   It is important to be able to distinguish whether the pig is stuck or not, as the control system depends on this input to close the valve in the annular bypass to increase the pressure behind the pig in order to dislodge it.

   (a) Accelerometer The accelerometer can be used effectively to give an indication whether the pig is moving or stationary by monitoring the output. If the pig is going at a uniform velocity, theoretically the acclerometer should not show a reading, but in this particular case, as the pig is bouncing and scraping its way through the pipe the accelerometer will show some activity.

       When the pig is completely stuck, we might expect some chattering in the output of the accelerometer as the output might not be completely zero, because the pig may vibrate. The vibrations could be possible as the pig is facing a resistance from the wax and at the same time the fluid pressure behind the pig is trying to overcome this resistance.

       Thus a minimum threshold needs to be determined for the accelerometer output, in order to conclusively say whether the pig is stuck or not. This would be determined only after conducting a few experimental test runs.

   (b) Odometric wheels Odometeric wheels have long been used with pigs to measure distance traveled and also to get the velocity profile. They are generally spring loaded and press against the pipeline wall, the rotation of the wheels is then interpreted to measure the distance traveled by the pig. These are standard components and could be used to determine whether the pig is moving or whether its stuck.

       It might be possible to get erroneous data if the wheel stops rotating because its lost contact with the pipeline or it gets jammed because of wax deposits.

One way to overcome it would be to have input from multiple odometric wheels.

4. To close annular bypass to allow buildup of pressure

In the case the pig gets stuck, it is necessary to use 100% of the fluid power available instead of just the 70% that is utilized in the normal functioning of the pig. In order to use the other 30% of the flow which is being bypassed, it is imperative to close the annular bypass completely and allow the pressure to buildup behind the pig. The increase in pressure behind the pig should be able to overcome the additional resistance generated by the accumulation of the wax deposits.

The control logic that would be the basis of this closing of the annular bypass is illustrated in Figure 6.

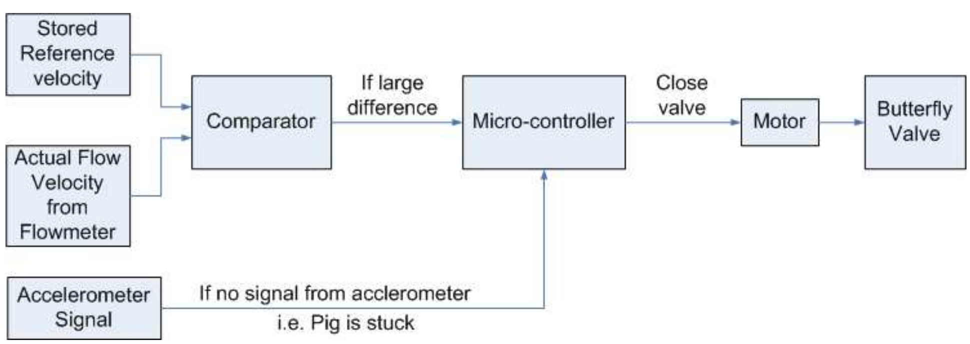

Fig. 6. Control logic when pig is stuck

5. Detect differential pressure and open valve to prevent large buildup of pressures

In the extreme case of the pig getting stuck and the buildup of pressure not being able to dislodge the pig, there exists a danger of an extremely large pressure difference across the pig. Some parts of the pig, especially the scraper discs might collapse and fall apart under this large pressure differential. Any such fragmentation or crumbling is undesirable as it creates debris in the pipeline, which may cause problems in risers and may interfere with the operation of pipeline equipment like valves, pumps etc.

In order to avoid such a situation, it is important to buildup pressure behind the pig to dislodge it, but it is more imperative to restrict the pressure differential to safe and allowable limits. Thus the differential pressure across the pig needs to be measured and kept in control.

(a) This differential pressure could be measured using a pressure transducer which could be incorporated into the pig body and if a valve is being used, it could detect the pressure across the valve. The MEMS pressure transducers are ideally suited for such applications.

    Advantages of pressure transducer

    - easy to integrate into control system
    - MEMS pressure transducers readily available
    - small size and weight

    Disadvantages of pressure transducer

    - relatively more expensive
    - would need thermal insulation against variations in temperatures

    Based on the input from the pressure transducer, the control system would open the valve in the annular bypass to release some of the pressure in order to prevent any damage to the pig. Once the pressure is drained to acceptable limits, the control system would close the valve again. This complete opening and closing of the valve would override the normal throttling operation of the valve.

The control system schematic for the above control logic is shown in Figure 7.

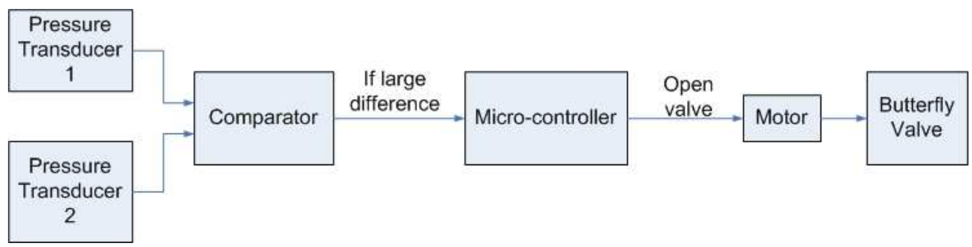

Fig. 7. Control logic if pressure difference is large

(b) Another alternative to the above problem is to design a safety valve which would control a separate bypass connecting the front and the tail end of the pig. The spring in the spring loaded safety valve would be designed such that if the pressure across the pig crossed a certain value the safety valve would open and allow the pressure to drain till the pressure differential was within limits.

Advantages of using spring loaded safety valve

- Eliminates use of expensive sensors
- Simpler control system and logic
- Proven reliability and usage

6. Allow back flow pressurizing

In the extreme case, if the pig is unable to dislodge itself even after sufficient buildup of pressure - back flow pressurizing tactic is generally used. In this, the flow behind the pig is stopped and a reverse flow or back flow is applied. This flow acts on the front end of the pig instead of the back and tries to push the pig in the reverse direction. After a while, this back flow is stopped and the normal flow resumed. This procedure is repeated with the aim of trying to dislodge the pig.

Thus is it important that the mechanism used for controlling the bypass is bubble tight shutoff in both directions. If a valve is used to control the bypass, it would offer this bi-directional shutoff.

I. Conclusion

A variety of options to meet the various functional requirements of the pig are discussed. It is proposed to use a turbine flowmeter to indirectly measure the velocity of the pig, the use of an accelerometer to determine whether the pig is completely stuck and preventing buildup of large differential pressure across the pig using a safety valve or detecting it using a MEMs pressure transducer. Two concepts for actually regulating the pig velocity were discussed - concept of controlling the bypass flow velocity and the concept of braking. Since neither had any obvious advantages over the other, it was decided to investigate the concepts further in the following chapter and then finalize on one design concept.

CHAPTER IV

CONCEPT DEVELOPMENT

A. Introduction

Now that the requirements for the pig have been properly identified and defined, it is necessary to develop different strategies to solve the problem. In this chapter three different design strategies are presented to tackle the problem of a regulated velocity cleaning pig. These different approaches are then compared and evaluated and the actual design would be based on the approach that best solves the problem.

B. Concept 1 : Governor Pig

As simplicity and cost were desired, the first approach was not to use any kind of sensors or actuators in the pig, as it would make the pig expensive. Thus, the aim was to utilize the energy of the fluid flow for all kinds of measurements and actuator mechanisms.

Instead of measuring the speed of the pig directly, it was measured indirectly and regulated by controlling the flow through the annular bypass, it was also decided to use completely mechanical means to control the bypass. The energy required for this system of mechanical links would need to be derived from the flow itself. Thus removing the need for an external source of power. A turbine flow meter is placed in the annular bypass flow stream, this generates both the power required and also gives an indication of the velocity of the pig. To control the bypass flow completely mechanically using a valve, it is necessary that the rotational motion of the turbine flow meter be converted into a linear motion to operate the gate valve.

After looking at various options, the idea of a Watt governor seemed perfect for this application. The ball governor would be located outside the annular bypass and the rotational motion of the turbine flow meter would be transferred to the governor using a set of bevel gears. As the pig starts slowing down, the flow velocity through the bypass increases and this in turn increases the rotation of the turbine flow meter. This increased rotational energy is then transferred to the governor and the centrifugal force pushes the balls outward resulting in the lifting the sleeve of the governor.

The linear motion of the governor sleeve is directly proportional to the change in rotational velocity of the turbine flow meter. And the turbine flow meter is in turn directly proportional to the flow velocity through the bypass. This linear motion of the governor sleeve is utilized for the opening and closing of the gate valve. Hence its possible to have a control system built into the mechanical system itself, which opens and closes the gate valve. This removes the need for external control logic, external power and hence is very economical.

The concept is illustrated below with the help of a simple diagram in Figure 8.

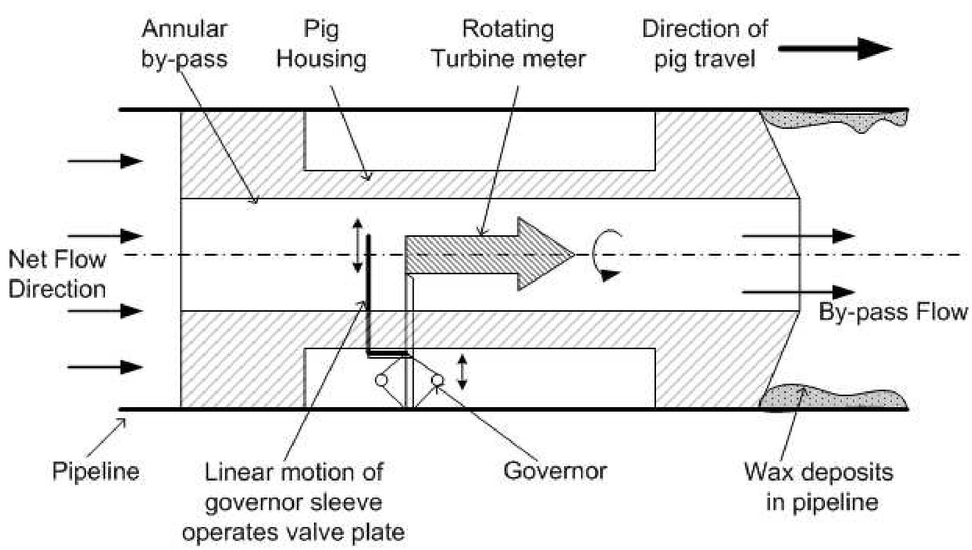

Fig. 8. Bypass control using mechanical governor

The design would be dependent on the weight of the governor balls, as they are the crux of the design. The change in rotational velocity of the turbine flow meter is figured out from the possible change in flow velocity through the bypass. The balls are designed for weight that would lift the sleeve through the desired distance using the power available through the turbine flow meter.

The governor balls need to be heavy enough so that they can lift the sleeve a specified distance in order to actuate the valve and should also be able to overcome the friction in the sleeve and the valve. But heavier the balls, the more difficult it is for the turbine flow meter to power it, as the flow meter can only provide a certain amount of rotational power that it derives from the flow through the bypass.

Again, with different flow rates in different pipelines, the rotational power supplied by the turbine flow meter to the governor would vary. Hence, the amount of sleeve movement for a set of governor balls would vary for different flow rates. Thus, a particular set of governor balls, could only be used for a certain range of bypass flow. A series of pigs with a range of governor ball weights needs to be developed to address the entire spectrum of the pipeline flows.

Another problem with the current embodiment of the design, is the severe space restrictions on the size of the governor. The annular bypass is calculated to be of 5.5-6" diameter [in a 10" diameter pipeline and for a 8" diameter pig body] in order to allow a bypass of 30-35%. Thus, there is just over an inch of space left, to try and fit in the governor.

Hence, other embodiments of the governor pig idea were discussed, one of the embodiment is shown in Figure 9.

But even this didn't give substantial advantage as the travel of the governor balls was severely restricted. Alternatives like high density materials were considered in order to give substantial weight to the governor balls and yet keep them compact. But none

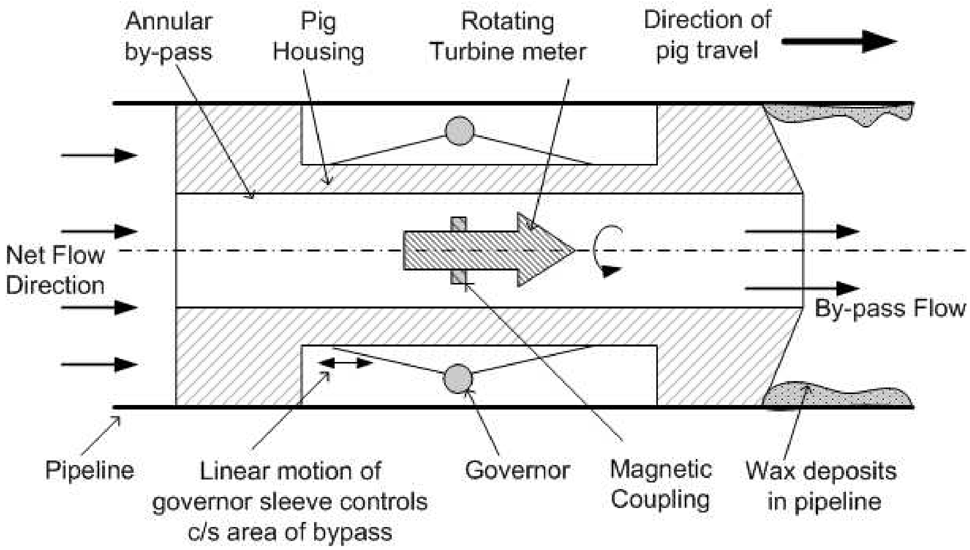

Fig. 9. Another embodiment of mechanical governor

of them proved practical in such severe space restrictions.

Hence the design was further modified to remove the restriction imposed due to lack of space. As the space was limited radially, it was decided to mount the governor along the axis of the pig, as there was less space restriction in that orientation. In order to transmit power from the propeller flow meter to the governor, the use of linkages and bevel gear mechanisms was avoided. A magnetic coupling was mounted on the rotating flow meter and this was coupled with another magnet outside the annular bypass. The governor was mechanically linked with this second magnet. The rotating motion of the flow meter was transmitted to the governor through the coupling of these two magnets. This non-contact arrangement removes the complications of mechanical linkages and gear systems in the annular bypass. Thus reducing problems of sealing, pressure drops, enclosures etc.

The actuation of the valve is similar to the earlier embodiment of the design, with the governor sleeve opening and closing the valve with change in the rotational speed of the governor. The problem of the governor being able to lift the sleeve to actuate the valve still remains uncertain.

C. Concept 2 : Pig Velocity Control Using Mechanical Braking

In the second concept, instead of using the bypass flow to control the velocity of the pig, we use the concept of braking to regulate the pig velocity. The annular bypass is sized such that the pig has a higher velocity than desired, and then the pig velocity is regulated by using mechanical brakes whenever necessary.

This design again uses the propeller type flow meter to measure the pig velocity indirectly by measuring the flow velocity through the bypass. The governor idea is further modified and the governor balls are replaced with brake pads mounted on springs. As the bypass flow increases the rotational speed of the propeller meter increases, this motion is transferred to a sleeve outside the annular bypass by the magnetic coupling. The brake pads are mounted with springs on this rotating sleeve. As the rotational speed increases, the rotating brake pads act like governor balls and move outward due to centrifugal force by overcoming the spring force. This then acts like a mechanical shoe brake, with the brake pads brushing against the inner pipe walls and thus reducing the speed. When the speed is reduced to desirable limits, the spring is designed, such that the spring force exceeds the centrifugal force and brake pads are withdrawn and lose contact with the inner pipe walls. This is illustrated in Figure 10.

The major problem with this otherwise plain and simple design is that, the brakes are activated when the flow through the bypass is high. But bypass flow velocity is high when the pig velocity is lower than the desired velocity. Hence instead of increasing the velocity of the pig, this design actually decreases it by further applying brakes.

This design basically uses the centrifugal force to overcome the spring force and

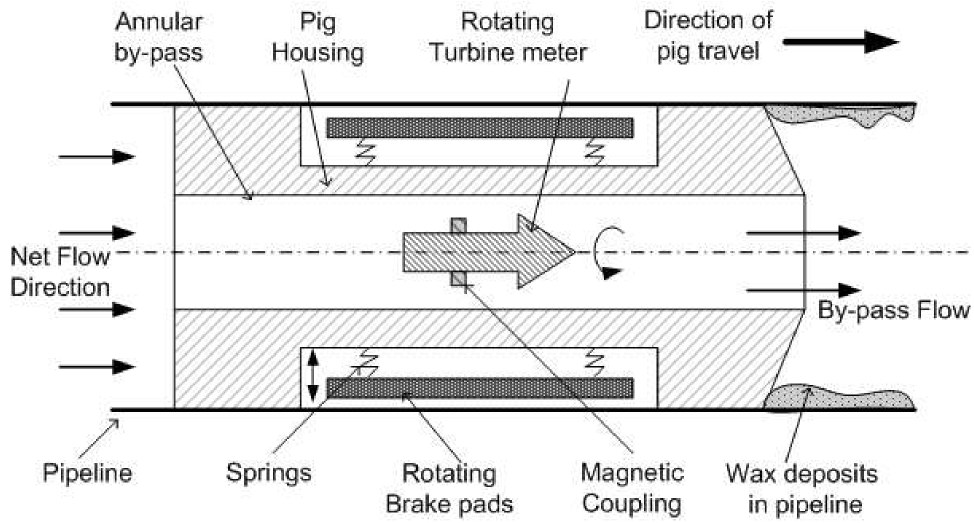

Fig. 10. Velocity control using braking

activate the brakes, and the centrifugal force is going to be maximum when the flow through by the bypass is high. While we need just the opposite, some mechanism which would pull in the brakes when the centrifugal force is high and push the brakes out with the help of the spring force.

A variety of mechanical linkages and mechanisms were analyzed in order to figure out a way to implement the above mentioned requirement. Though it is possible to implement it, the device loses its basic advantage of being a simple, inexpensive device.

D. Concept 3 : Bypass Control Using Motorized Butterfly Valve

After looking at the above mentioned concepts, it becomes evident that it is difficult to implement a device without the use of some basic actuators, sensors or power. Thus, it was decided to design a pig with standard components and some basic controls. Expensive and custom built components were to be avoided as far as possible, to keep the design simple and inexpensive.

This conceptual design also uses the flow meter to infer the velocity of the pig, instead of some expensive ultrasonic velocity measurement. The inferred pig velocity is transmitted to a control unit, which compares the inferred velocity with the desired velocity and accordingly actuates a butterfly valve in order to control the flow through the bypass. This is illustrated in Figure 11.

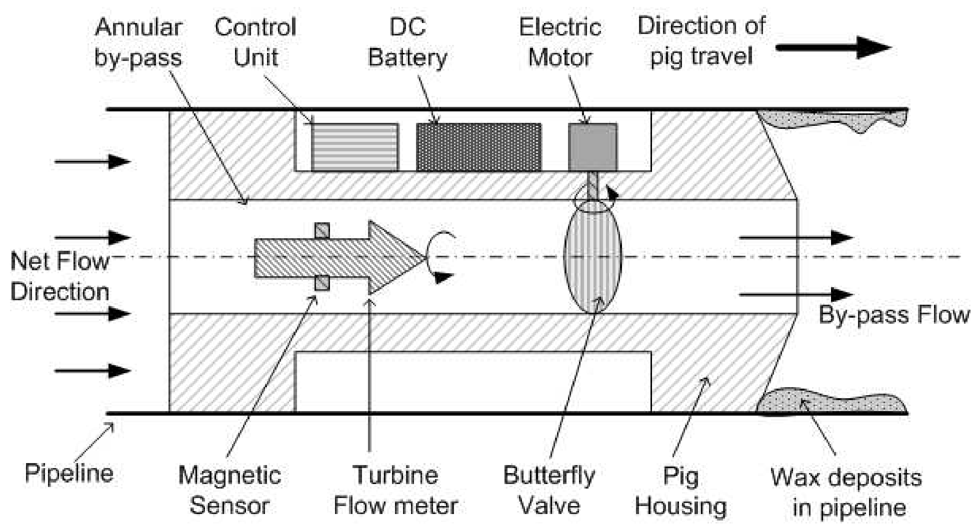

Fig. 11. Bypass control using motorized butterfly valve

1. Pig faces no resistance from wax deposits or accumulations

   In such a case, when the pig might be moving through a clean section of the pipeline, though rare and temporary, the pig velocity remains steady and is largely governed by the design of the annular bypass which is enables the pig to move with the desired velocity. The control unit doesn't do anything and just allows the pig to operate in the pre-defined bandwidth of the desired velocity. Only if the pig goes outside the bounds of these limits does the entire control mechanism come into action.

2. Pig faces resistance from wax deposits or wax accumulations

Due to the resistance caused by the wax deposits, the pig velocity falls down below the desired 65% of flow velocity. As the pig velocity reduces, the by-pass velocity increases, this results in faster rotation of the turbine flow meter which determines the velocity based on the number of rotations. This is calculated using a magnetic pickup and this signal is transmitted to the control unit. The control unit continuously monitors the flow rate through the bypass and compares it to the desired bypass flow velocity [The desired flow velocity through the bypass is calculated as being 30-35% of the pipeline flow velocity].

The control unit then closes the butterfly valve proportionally to allow a marginal buildup of pressure behind the pig. This buildup of pressure allows the pig to push its way through the wax accumulation, recover its lost velocity and resume cleaning at the desired velocity. Once the desired velocity is attained, the control unit opens the valve back to its original position, and allows the normal functioning of the pig. If it didn't do that, the velocity of the pig would keep increasing and would cross the upper bound of the desired velocity limit.

3. Pig gets completely stuck due to large wax accumulation

   In the extreme case of the pig getting stuck, it is not possible to rely only on the input of the flow meter. This is because, if the pig gets stuck, the pig velocity becomes zero, thus the by-pass velocity increases rapidly. The flow meter relays this information to the control unit, which promptly shuts off the butterfly valve completely - with the aim of building up a large pressure behind the pig in order to dislodge it. But as soon as the valve is fully shut, the by-pass velocity drops to zero and this is conveyed to the control unit by the flow meter. This information relays the fact that the pig is now moving with the 100% flow velocity (because the by-pass velocity is zero). Thus the control unit acting only on the information from the flow meter would open the valve. But the pig might still be stuck, and as the pig velocity is zero, so the by-pass velocity would rapidly rise again, again forcing the valve to be completely shut off. This would lead to a 'chattering' of the valve without the pig getting 'unstuck'!

So the problem being, the control unit doesn't realize whether the pig is stuck or not. One way to overcome this would be, to set a time for which the valve remains shut - enough for the pressure to buildup and dislodge the pig. A rough estimate may be determined regarding the amount of time needed for sufficient buildup of pressure. But the pressure needed to dislodge the pig would vary with each case and predominantly be dependent on the wax accumulation in front of the pig - and there is no way of estimating that.

The way around this problem is to have extra information for the control unit to decide whether the pig is stuck or not - and this information is provided by the accelerometer. As the pig moves in the pipe, it bumps and grinds along the pipe walls, thus the accelerometer generates electrical signals as long as it is in motion. But with the pig getting stuck, there would be no signal from the accelerometer. Thus the control unit can decide to keep the valve completely shut as long as there is no signal from the accelerometer. When the pig is dislodged and the pig begins to traverse the pipeline again, the accelerometer generates and sends out a signal to the control unit which then opens the butterfly valve.

Thus with the accelerometer, it is possible for the control unit to close the valve as long as the pig is stuck, thus allowing pressure buildup and increasing the chances of the pig getting 'unstuck'.

4. Pig is stuck and the differential pressure across the pig is too high

   In case the pig is stuck and cannot dislodge itself, despite the buildup of pressure behind the pig, there is always a danger of excessive pressure buildup which may damage the pig or the pipeline itself. In this extreme case with the differential pressure exceeding a safe limit, it is needed that some of the pressure be released.

This is achieved by having a spring loaded safety valve which controls a separate by-pass. The safety valve opens and releases pressure only when the pressure difference is too high. And after pressure has been released and the pressure behind the pig is in a safe limit, it shuts off again. This prevents buildup of excessive pressure which may cause harm to the pig or the pipeline.

This concept is more complete and covers all the possible conditions the pig might face. It offers better control over the velocity of the pig as the size of the bypass can be regulated to a much greater extent using a motorized butterfly valve. It also takes into consideration extreme conditions of the pig getting stuck.

The conceptual designs have been summarized in the Table II.

Table II. Comparison of various concepts

Concepts	Regulating velocity	Pig stuck		
		Building of pressure	Extreme pressure difference	Back flow pressurizing
Governor concept	Poor	Ok	Poor	Ok
Braking concept	Ok	Not possible	N/A	N/A
Motorized Bypass Valve	Excellent	Excellent	Ok	Good
Safety Valve	N/A	N/A	Excellent	N/A

E. Conclusion

After reviewing the three conceptual designs discussed above, the motorized valve design seems to be the most viable concept to develop further. This concept will be taken further and actual design would be based on this concept.

CHAPTER V

DESIGN OF PIG

A. Introduction

This chapter deals with the actual design of the pig and its components. The objective of this design is to use standard components and avoid the use of custom built instruments. Hence this design utilizes readily available commercial instruments to the extent possible. Thus, more than designing the instruments, the aim of this chapter is to identify the appropriate instruments and describe the specifications that best meet the requirements of the application.

The design of this pig includes the design and specification of :

1. Butterfly valve
2. Actuator for the valve
3. Power source for the pig
4. Gear train to connect the actuator to the valve
5. Flow meter
6. Accelerometer
7. Safety valve/MEMs pressure transducer
8. Control unit
9. Pig housing

B. Basic Design Calculations

Unfortunately, the petroleum industry hasn't gathered much information regarding wax deposition in the pipelines. Only very broad guiding parameters are available while working on the design. A lot of information however has been collected on the condition of the pipeline, mostly presence of corrosion, pitting or cracks. Information is not available on the actual amount of deposition of wax in the pipeline, the places it usually deposits and the resistance they offer to the pig. Even though these are estimated by conducting experiments in the lab, they do not represent the true picture as in the pipeline.

The data supplied by Chevron Texaco is listed in Table III, this will be the reference to all the design data used in this research work.

Table III. Design requirements

	Design Specifications	Magnitude
1.	Diameter of production line (d)	10" ID
2.	Flow velocity of product through the pipeline(V_m)	3 to 5 mph
3.	Pressure in Production line(P)	1,000 to 5,000 psi
4.	Length of Production line	30 miles
5.	Desired Pig Velocity	70% of flow velocity

The basics working parameters are worked out in the desired units using the above table as a base.

1. The net flow rate, Q_N, through the pipeline

$$Q_N = (\Pi/4) * d^2 * V_m \tag{5.1}$$

Converting miles into inches,

$$Q_N = (\Pi/4) * 10^2 * 5 * 63360/60$$

$$Q_N = 414678 in^3/min$$

Converting into gallons per min (GPM),

$$Q_N = 1795 GPM$$

Approximating, and using a higher flow rate,

$$Q_N \approx 2000 GPM$$

Hence the total flow through the pipeline is 2000 GPM, and as the flow through the bypass is to be maintained at 30% of the flow velocity, the bypass flow rate, Q_b, is

$$Q_b = 0.3 * Q_N \tag{5.2}$$

$$Q_b = 600 GPM$$

2. Pressure difference across the pig

   Each scraper disc can withstand a maximum pressure difference, ΔP_s, of up to 30 psi across it. A cleaning pig usually has around 2-4 such discs, hence the net pressure difference across the ends of the pig,ΔP_a is,

$$\Delta P_a = \Delta P_s * 4$$

$$\Delta P_a \approx 120psi$$

The safe operating differential pressure, ΔP_p for the pig would be lower, using a factor of safety of 1.25,

$$\Delta P_p = 120/1.25 \tag{5.3}$$

$$\Delta P_p = 96psi$$

$$\Delta P_p \approx 100psi$$

Thus even though the ambient pressure is high, 5000 psi, the pressure difference across the pig should not exceed 100 psi otherwise the scraper discs might burst and this would create debris in the pipeline.

Hence the butterfly valve would operate at a maximum differential pressure of 150 psi during normal operations. Even when the pig is stuck, the pressure difference will not be allowed to exceed 100 psi, as it is necessary to prevent creation of debris in the pipeline. This would be enforced using a safety valve or a MEMS pressure transducer.

The suggested pigging pressure for a 10" pipeline is around 25-50 psi.[12] The pressure drop across the Butterfly valve,ΔP_{bv}, is taken to be 10% of the pressure drop, and is given in Equation 5.4.

$$\Delta P_{bv} = 3 - 5 \tag{5.4}$$

3. Specific Gravity

   The specific gravity, S_g, for crude oil [13] is,

$$S_g = 0.85 \tag{5.5}$$

4. Cross sectional area of the annular bypass

   As it is desired to maintain the pig at a velocity of around 70% of the flow velocity, the bypass velocity should be around 30%. Thus, the cross sectional area of the annular bypass, A_b should be 30% of the cross sectional area of the pipe, A_p.

$$A_p = (\pi/4) * d^2$$

$$A_b = 0.3 * A_p$$

   Therefore,

$$(\pi/4) * (d_b)^2 = 0.3 * (\pi/4) * d^2 \tag{5.6}$$

   where d, d_b are diameters of the pipeline and annular bypass respectively.

$$d_b = \sqrt{30} = 5.4772 inches$$

$$d_b \approx 5.5 inches$$

C. Design of Butterfly Valve

The butterfly valve needs to be designed and specified. One might be tempted to use a butterfly valve of 6 inch diameter, i.e. the same diameter as the annular bypass. But by doing so, one might be seriously undersizing or over sizing it. If the valve is oversized, even though it will meet the flow constraints and regulate the flow accurately, the actuator required to power the valve is unnecessarily large. This would result in requirement of additional power, additional battery space and would lead to severe space constraints. Hence it is of utmost importance to design the butterfly valve appropriately.

1. Determining Valve Size

The flow coefficient for the butterfly valve, is defined as the flow of water at 60 F in US gal/min at a pressure drop of $1lbf/in^2$ across the valve. [14]

The flow coefficient is a convenient way to relate flow rate to the pressure drop across the valve. It is generally derived empirically for a specific type of valve and varies with construction and size of valve.

$$C_v = \frac{Q_b}{\sqrt{\Delta P_{bv} * S_g}} \tag{5.7}$$

where the values of $Q_b, \Delta Pbv, S_g$ are obtained from equations 5.2, 5.4, **??** respectively.

$$C_v = 600/\sqrt{(3 * 0.85)}$$

$$C_v = 375.73$$

Looking up the appropriate valve size for this flow coefficient in the partly reconstructed Table IV.[15]

Table IV. Flow coefficients for various valve sizes

	Valve Size (inches)	Flow Coefficient (C_v)
1.	3”	260
2.	4”	475
3.	5”	770

Thus the appropriate valve size for this application is 4” diameter valve.

If the value of $C_v/(d_{bv})^2 > 20$, then the pressure drop needs to be calculated more precisely,

Hence, checking the value of $C_v/(d_{bv})^2$,

$$\frac{C_v}{(d_{bv})^2} = 375.73/4^2 = 23.48$$

As, $C_v/(d_b)^2 > 20$, it is important to recalculate the Net pressure drop, ΔP_{Net} [16], using,

$$\Delta P_{Net} = \Delta P_{bv} - \frac{0.008986 * S_g * f * (Q_b)^2}{(d_{bv})^4} \tag{5.8}$$

where f is the friction factor.

Replacing P_{bv} using equation 5.7,

$$\Delta P_{Net} = \frac{(Q_{bv})^2}{(C_v)^2 * S_g} - \frac{0.008986 * S_g * f * (Q_b)^2}{(d_{bv})^4} \tag{5.9}$$

We know,

$$C_{vnet} = \frac{Q_b}{\sqrt{\Delta P_{Net} * S_g}}$$

as it is a similar to Eq.5.7

Thus,

$$(C_{vnet})^2 = \frac{(Q_b)^2}{\Delta(P_{net}) * S_g} \tag{5.10}$$

Replacing ΔP_{Net} in equation 5.9 with Equation 5.10

$$(C_{vnet})^2 = \frac{(Q_b)^2}{(\frac{(Q_b)^2}{(C_v)^2 * S_g} - \frac{0.008 * S_g * f * (Q_b)^2}{(d_{bv})^4}) * S_g}$$

$$(C_{vnet})^2 = \frac{(C_v)^2}{1 - (\frac{0.008 * (S_g)^2 * f * (C_v)^2}{(d_{bv})^4})} \tag{5.11}$$

First finding the friction factor, f,

To determine the friction factor, it is necessary to know $v * d_{bv}$ and ε / d_{bv},

where v is the velocity(ft/sec)and dbv is the diameter of valve(inches)

$$v * d_{bv} = 7.33 * 4 = 29.33$$

$$v * d_{bv} \approx 30$$

The average roughness factor for the annular bypass, ε is 0.00015 for commercial steel in ft

And the diameter of the valve,d_{bv} is 0.333 in ft.

Therefore,

$$\varepsilon / d = 0.00015/0.33 = 0.00045$$

Now using $v * d_{bv}$ and ε / d_{bv} to look up Moody chart to determine the friction factor.

In the Moody chart, following $\varepsilon / d_{bv} = 0.0004$ upwards till $v * d_{bv} = 30$,

$$f \approx 0.025 - 0.03$$

$$f \approx 0.027$$

Using this friction factor, f, in the Equation (5.11),

$$(C_{vnet})^2 = \frac{(C_v)^2}{1 - (\frac{0.008*(S_g)^2*f*(C_v)^2}{(d_{bv})^4})}$$

$$(C_{vnet})^2 = \frac{(375.73)^2}{1 - (\frac{0.008*(0.85)^2*0.027*(375.73)^2}{(4)^4})}$$

$$(C_{vnet})^2 = \sqrt{(}156280.22)$$

$$C_{vnet} = 395.32$$

This C_{vnet} value compare this with the table IV, and it is found that the C_{vnet} value is still within the range of the 4" valve that has been chosen.

Calculating the net pressure drop, using Equation 5.8,

$$\Delta P_{Net} = \Delta P_{bv} - \frac{0.008986 * S_g * f * (Q_b)^2}{(d_{bv})^4}$$

$$\Delta P_{Net} = 3 - \frac{0.008986 * 0.85 * 0.027 * (600)^2}{(4)^4}$$

$$\Delta P_{Net} = 2.7099$$

But, as the bypass diameter is 5.5" and the butterfly valve is just 4", there is a need to have a set of reducer and diffuser to reduce the diameter of from 5.5" to 4" and then increase it back to 5.5".

But this complicates things as the bypass flow which was earlier designed to be 30% of the flow through the 5.5" diameter is greatly reduced as the limiting diameter becomes 4".

Hence it is decided not to use a 4" valve, but a 5.5" valve.

2. Material Selection for Valve

Now that the valve size has been determined, it is important to establish criteria for selection of valve body, disc body and valve seating to be used. This would enable us to specify the butterfly valve completely.

1. Valve Body

   As the fluid flow through the valve is a mixture of hydrocarbons, brine and gases with solid suspensions like paraffins, asphaltenes, hydrates and fine sand. It is important that the valve body material be resistant to corrosion. The well being produced might be sweet or sour, but the presence of gases like CO_2, H_2S further increase chances of stress cracking. Hydrogen Sulphide gas,H_2S, tends to attack when the temperatures are below 140F. And as the operating temperatures of the pig are well below 140F, the problem of low temperature stress cracking is inevitable. Thus the body material should not be too brittle and the hardness level should be maintained below HRC 36.

   The presence of fine sand in the flow makes the fluid particularly abrasive, thus the valve needs to be made of a abrasive resistant material.

   The material should remain ductile and should not turn brittle at low temperatures. Thus DBTT (ductile to brittle transition temperature) temperature should be below the operating temperature, so that there is no transition from ductile to brittleness during the operation of the pig.

   Some of the commonly used valve body materials and their characteristics are listed below :

   (a) Carbon Steels - with varying composition of carbon and different alloys, the properties vary. But generally, they have greater strength and toughness, resistance to shock, vibration and suitable for high temperature applications. DBTT : -20F to 50F

(b) High Strength Low Alloy Steels (HSLA) - recommended for high pressures and temperatures, good strength and toughness, resistance to piping strains, shock, vibration. DBTT : around -50F

(c) Stainless Steel - should be heat treated for corrosion resistance, high strength, good wear characteristics. It is resistance to wear, galling erosion and oxidation. DBTT : No problem caused.

Stainless steel if properly heat treated, would do a good job especially because of there is no transition from ductile to brittleness. Secondly, the characteristics of to resist corrosion and abrasive wear are most pertinent for this application. And as stainless steel has them it makes it an excellent choice. Thus stainless steel is to be used for the body of the valve.

2. Disc body

As the disc of the butterfly valve is in the path of the fluid flow, hence has to be extremely resistant to abrasive wear. This is important because if the valve disc wears out on its ends, it wont be able to form a bubble tight shutoff with the valve seat. This would affect the performance of the valve.

The need to resist corrosion, in addition to wear resistance is important. This can be attained in two ways, one is to use an a good wear and corrosion resistant material like stainless steel which would make the valve expensive. And the second would be use a standard metal like HSLA (high strength low alloy steel) for the disc and then coat it with a good wear and abrasion resistant coating.

These coatings can be easily applied to the valve disc and would provide excellent wear characteristics without increasing the cost substantially. Thus the use of coatings is recommended for high abrasive and corrosive streams.

The coatings that might be applied to the valve disc are discussed below :

(a) TFE (TetraFluroEthylene) - TFE properties are nonstick characteristic, non-permeability, corrosion resistance and lubricity. It is commonly used to encapsulate butterfly and ball valves. It tends to deform under constant pressure and does not resist abrasion well.

(b) FEP (Fluorinated Ethylene-Propylene) - It is chemically inert, has low coefficient of friction, wide temperature range, high toughness and flexibility. It can be molded on discs and seats and machined to close tolerances for excellent fitting and sealing. Unfortunately, the wear characteristics of FEP are not exceptional.

(c) UHMWPE (Ultra-High-Molecular-Weight Polyethylene) It is one of the most abrasion resistant liner material (it is 6 times as abrasion resistant as carbon steel). It is corrosion resistant, easy to mold and can withstand high temperatures. It can be easily molded onto the disc body.

Coating of the valve disc with UHMWPE to resist the abrasion and corrosion of the fluid flow seems more than adequate for the purpose.

3. Valve Seat The valve seats need to be corrosion resistant and abrasion resistant like the valve body.

   The different valve seats that can be used are listed below:

   (a) Butyl - It is a rubber copolymer and has good chemical resistance. Wear characteristic is not particularly good.

(b) EPDM (Ethylene Propylene Diene Monomer) - It has excellent abrasion resistance, tear resistance and is chemically resistant to large variety of chemicals. It is recommended for use with petroleum products.

(c) Viton - It has good resistance to a variety of chemicals and has wide temperature range. It is abrasion resistant and resists acids, salts and petroleum oils.

The use of EPDM for the valve seat seems to meet all of the requirement perfectly. Thus the valve seat is specified to be made of EPDM material.

Thus the specifications of the butterfly required for this pig are:

1. 5.5 inch valve diameter
2. Body made of Stainless steel
3. Valve disc encapsulated with UHMWPE
4. EPDM used for valve seat
5. Flanged ends

D. Design of Actuator for the Valve

1. Type of Actuator

Now that the valve has been decided on, the actuation of the valve needs attention. The butterfly valve may be actuated manually, pneumatically or electrically. But as there is need to control this valve through a control system, the manual option is immediately discarded.

Since it is not possible to manually operate this valve, we are left with the option of either pneumatic actuators or electric actuators. The disadvantage of using a pneumatic actuator is that it needs a source to provide pressurized air. As the cleaning pig moves inside a pipeline, it would prove to be a hassle to provide a supply of pressurized air. Hence, using an electrical actuator seems optimal for this application.

2. Torque Requirements of the Actuator

Thus, a motor needs to be specified that will provide the necessary torque to open the valve and meet the space constraints of the pig.

Also, the power source to run the motor would be a battery as that is the only way to provide power to a moving pig. As the battery is a DC power source, hence the motor needs to be a DC motor and not an AC one. The voltage requirements of the motor should not be extremely high like 90 VDC, it needs to be reasonable because of the space restrictions on the battery size. Thus the motor should be a DC motor running on a voltage of around 24 VDC.

In order to determine the size of the motor, it is necessary to know the amount of torque it needs to supply in order to regulate the valve. The seating and unseating torques for the valve are listed below in the Table V.[17]

Table V. Seating and unseating torque requirement

	Valve Size	Differential Pressure		
	(inches)	100psi (in.lbs)	150psi (in.lbs)	200psi (in.lbs)
1.	3”	246	264	282
2.	4”	395	430	466
3.	5”	668	734	799
4.	6”	893	989	1085

The differential pressure across the pig, calculated from the number of discs on the pig, as seen from Equation 5.3 is,

$\Delta P_p \approx 150$

And as the valve size chosen is 5.5", the seating and unseating torque,T_{req}, for regulating the valve is,

$$T_{req} = 800 lbs.in$$

Using a factor of safety of 1.125 for the torque requirements,

$$T_{req} = 1.125 * 800 = 900 lbs.in$$

The actuator, i.e. the electric motor should hence be capable of producing such high torques such as 900 lbs.in. Though motors exist that easily provide the kind of torque needed, it is difficult to find a motor which meet the space constraints in addition to the torque requirement. The severe space restrictions exist because all the parts need to be housed between the two concentric cylinders.

Secondly, the motor could not be mounted on to the valve shaft directly because of severe space restrictions. The only way it could be mounted was along the axis of the pig. The butterfly valve on the other hand is mounted across the flow and hence the valve shaft is normal to the pig axis. Thus, the valve shaft and the motor shaft were perpendicular to each other.

The only way to transmit power from the motor to actuate the valve is to have some kind of mechanical coupling between the two. One way would be to use commonly available motors with high speeds, usually in the range of 1750 rpm, and then reduce the speed to around 1-5 rpm for the regulation of the butterfly valve. But such large reduction in speed would mean a complete design of a custom built gear box with a large gear reduction ratio, which would offset the price advantage of a easily available motor. Another way this could be accomplished is by using bevel gears or worm gears.

Thus it was decided to use a motor whose output speed was low and could be effectively coupled with a simple worm gear drive, so that the hassles of a gear box could be eliminated. Figure 12 illustrates how the motor, worm drive and butterfly valve are to be coupled.

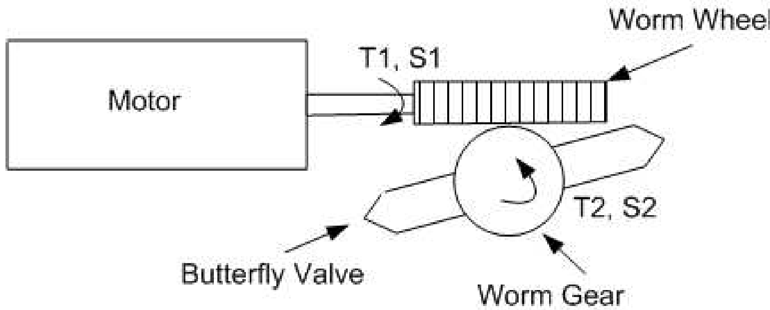

Fig. 12. Worm wheel drive to connect motor to valve

The gear reduction ratio for the worm gear is given by,

$$\frac{T_1}{T_2} = \frac{S_2}{S_1} \tag{5.12}$$

where T1,T2 are torques at the worm wheel and the worm gear respectively, while S1,S2 are speeds of the worm wheel and the worm gear respectively.

Assuming a convenient gear ratio of 10:1,

$$\frac{T_1}{T_2} = \frac{S_2}{S_1} = \frac{1}{10}$$

But T_2 is the torque needed to regulate the valve, thus $T_2 = T_{req}$

However, the efficiency of worm gears,η_{wg} needs to be taken into consideration as it quite low,

$$\eta_{wg} \approx 70\%$$

Hence,

$$T_2 = T_{req}/0.7$$

$$T_2 = 675/0.7$$

$$T_2 = 964.28 lbs.in$$

$$T_2 \approx 1000 lbs.in$$

Thus,

$$\frac{T_1}{1000} = \frac{1}{10}$$

$$T_1 \approx 100 lbs.in$$

And, $T_1 = T_{gm}$, and T_{gm} is the torque generated by the motor, hence the motor needs to provide a torque of around 100 lbs.in.

The opening and closing of the valve doesn't need to be very rapid as it would unnecessarily increase the load the motor which would lead to increase in motor size which has to be avoided given the space restrictions. Thus choosing the operation of the valve between 1-5 rpm,

$S_2 = 1$ to 5 rpm $S_2 \approx 3$

And,

$$\frac{S_2}{S_1} = \frac{1}{10}$$

Therefore,

$$S_1 \approx 10 * S_2$$

$$S_1 \approx 10 * 3$$

$S_1 \approx 30$rpm

And, as $S_1 = S_{gm}$,where S_{gm} is the speed of the motor. Thus the motor needs to run at a low speed of around 30 rpm. The gear reduction serves to decrease the speed of the motor and increase the torque output without increasing the motor size.

3. Type of Motor

Regular DC motors were too large in size for the torque output provided and hence could not meet the space restrictions inherently imposed by the design. Thus a smaller motor was needed that could provide a larger torque and a lower rpm.

Stepper motors were looked at to if they could be implemented in this device. The reason stepper motors were considered was the considerable ease in controlling them to throttle a valve. The control unit becomes a lot simpler as there is no need to have a position feedback on the motor shaft position and in turn the valve position. But for the size requirements of this application, the torque output of stepper motors was poor. They could provide only about 220 oz-in torque, which comes to around 13.75 lbs.in, which was way less than the 100 lb.in required. Thus the idea of using a stepper motor as an actuator was discarded.

Another kind of motor examined was the DC gear motor, it combined a DC motor with an in-built gear box. This had advantages of smaller size motor providing large torque at low speeds because of the gear reduction by the gear box. The gear reduction tends to reduce the normally high speeds of the DC motor and also tends to magnify the torque output. Thus, DC gear motors were found to meet the requirement of torque, low speed output and space restrictions. This option seemed viable and hence was chosen to see if it met the actual requirements of this application.

The standard available DC motors used in the DC gear motor are listed in Table VI.[18]

Table VI. DC gearmotor specifications

	Voltage (VDC)	Current		Speed (rpm)
		No load (amps)	Rated load (amps)	
motor 1	27	0.35	3	12,500-15,500
motor 2	27	0.35	3	9,000-11,000

And the reduction ratios of the gear boxes built into commercially available DC gear box are listed in Table VII.[18]

Table VII. DC gear motor speed reduction ratio and torque outputs

	Speed reduction ratio	Max Const Torque Rating (lbs.in)	Length (inches)
1.	306:1	77	4.010
2.	445:1	100	4.010
3.	647:1	100	4.010
4.	941:1	100	4.010
5.	1166:1	100	5

Using Table VI and selecting motor 1, with a speed of, $S_m = 15,000$ rpm. To decide on what gear reduction ratio must be used, it is necessary what the output speed of the DC gear motor should be, this is done using,

$$\frac{S_m}{X_r} \approx S_1$$

where X_r is the gear reduction ratio

$$\frac{15,000}{X_r} \approx 30$$

$$X_r \approx 500$$

Looking up table VII to find an appropriate gear reduction ratio, the most suitable one is 445:1. Using that gear ratio to calculate the actual values of S_1,

$$S_1 = \frac{S_m}{X_r}$$

$$S_1 = \frac{15,000}{445}$$

$$S_1 = 33.70rpm$$

Using Equation 5.12,

$$\frac{S_2}{S_1} = \frac{1}{10}$$

$$\frac{S_2}{33.70} = \frac{1}{10}$$

Therefore,

$$S_2 = 3.37$$

rpm

Using Equation 5.12,

$$\frac{T_1}{T_2} = \frac{1}{10}$$

$$\frac{100}{T_2} = \frac{1}{10}$$

Therefore,

$$T_2 = 1000$$

lb.in

4. Final Specifications for the Actuator

Thus the actuator, the DC gear motor, for regulating the butterfly valve is specified below:

1. Voltage - 24 VDC
2. Rated current - 3 amps
3. Motor speed - 15,000 rpm
4. Gear reduction ratio - 445:1
5. Output shaft speed - 33.70 rpm
6. Output shaft torque - 100 lbs.in

E. Design of Power Source - Battery

The power source, which in this case is an electrical DC battery, needs to supply power mainly to the motor for actuation of the butterfly valve. The other sources of power consumption are the flowmeter, the control unit, accelerometer among others - but all these are low consumers of power when compared to the electric motor. Hence the sizing of the battery will be primarily dependent on the motor rating and the duration of time it has to operate.

The motor is rated at 27 VDC and 3A current at rated load. Thus, the power requirement is,

$Power = V * I = 27 * 3 = 119$ W

$Power \approx 120$ W

The time the pig is going to be in the pipeline is determined below, Flow velocity, $v_f = 3 - 5$ mph

Pig velocity is 70% of the flow velocity,

$v_p = 0.7 * 3 = 2.1$ mph

$v_p \approx 2.5$ mph

Distance the pig has to travel = 30 miles

Hence,

$$time = 30/2.5$$

$time = 12$ hrs

The control unit is designed to monitor the pig velocity for some time duration approximately a minute, average the velocity and then use that averaged velocity to control the butterfly valve.

The valve can be operated at around 3-4 rpm, and the butterfly valve needs to be operated between +/- 30 degrees for throttling purposes. Hence, the time of operation is about 5 seconds for every minute of pig operation.

Thus for a 12 hour pig run, the valve will be operating about an hour. Hence the battery needs to power the motor for around an hour.

Thus, the minimum power required from the battery,

$$Power_{net} = 120 * 1$$

$Power_{net} = 120$ Whr

Assuming motor efficiency to be 80%,

$Power_{net} = 120/0.8 = 150$ Whr

Since it is advisable to maintain a minimum of 40% battery charge for better battery life,

$$Power_{net} = 150 * 1.4$$

$Power_{net} = 210$ Whr

$Power_{net} \approx 200$ Whr

Selecting the type of battery for this application :

The basic consideration for the battery is to have a high energy density, so that it can provide the necessary amount of power and also fit into the rather severe space restrictions.

Some of the types of batteries and their energy densities are listed in Table VIII.[19]

Table VIII. Comparison of available batteries

	Type of Battery	Energy Density (Wh/L)
1.	Ni-MH	150-250
2.	Ni-Cd	70-150
3.	Li-Ion	200-350

Thus based on the energy density, the NiMh battery is best suited to meet the requirements. The NiMh batteries have a nominal voltage of 3.6V, hence it is not possible to use it directly to power the gear motor which operates at 27V. So, the Li-ion batteries have to be suitably arranged in a battery power pack to meet the requirements of the motor.

The volume of the designed battery, V_b is calculated as,

$$V_b = P_{net}/energydensity$$

$$V_b = 200/200$$

$V_b \approx 1$ liters

Thus the specifications for the battery are:

1. NiMh Battery

2. Voltage 27 VDC

3. Rated current 3A

4. Size 200 Whr

F. Design of Worm Gear

The motor could not be mounted on to the valve shaft directly because of severe space restrictions. The only way it could be mounted was along the axis of the pig. The butterfly valve on the other hand is mounted across the flow and hence the valve shaft is normal to the pig axis. Thus, the valve shaft and the motor shaft were perpendicular to each other. The worm gear was chosen was chosen to transmit power from the motor to operate the valve.

The advantage of the worm gear is that if designed correctly, it is non reversible, i.e it transmits power only in one direction and not in the other. Usually the worm transmits power to the worm gear and the reverse is not possible as the worm gear gets locked.

This is a very important property that can be effectively utilized in this design. The butterfly valve faces a lot of dynamic loads when regulating flow, which creates an unpredictable torque on the valve disc. This leads to problems in regulating the valve, hence it is important to prevent the transmission of this torque from the valve disc to the motor shaft. The worm gear prevents the transmission of power from the worm gear to the worm wheel and hence protects the motor from unpredictable torques. Thus, the property of worm gear helps us effectively combat the menace of dynamic loads on the valve disc.

Thus it was decided to use a motor whose output speed was low and could be effectively coupled with a simple worm gear drive, so that the hassles of a gear box could be eliminated.

The gear reduction ratio, as discussed in the previous section was put at 10:1. As the power transmission speeds are not too high, there are no severe restriction on the material selection. Hence standard gear materials will be utilized. The worm wheel would be made of carbon steel while the worm gear should be a softer material and hence cast bronze is selected.

G. Design of Flowmeter

The turbine flowmeter was to be utilized for the purpose of measuring the bypass flow and hence determine the pig velocity. This is because turbine flowmeters are availble in large sizes, can measure greater range of flows, operate at high pressures (upto 10,000 psi), large temperature range (-450 to 1000 F) and most importantly for this application, they are non-contact type measurement devices.

1. Working of Turbine Flowmeter

The turbine flowmeter consists of a bladed turbine rotor suspended axially in the direction of the flow. The rotor rotates on its axis and these rotations are proportional to the quantity of fluid flow through the pipe.

When the liquid strikes the rotor, it creates a low pressure area between the upstream cone and the rotor hub. The differential pressure created across the rotor blades, causes them to move toward the low pressure area, but as they are restrained they tend to rotate on their own axis. Thus the fluid imparts an angular velocity to rotor which is proportional to the fluid velocity. The degree of the angular velocity depends upon the angle of rotor blades to the flow stream direction.

An electrical signal is generated using a pickup coil wrapped around a magnet which is mounted outside the flow stream. It uses the principle of reluctance for the generation of the output. The magnet creates a magnetic field around the pickup coil and every rotating rotor blade that passes in the proximity of this field deflects it. The change in the reluctance of the magnetic field produces a voltage pulse and each pulse represents a discrete amount of volumetric fluid flow. The K-factor is defined as the total number of pulses generated by the specific amount of liquid that has passed through the turbine flowmeter. Its units are pulses per unit volume, and it is used to determine the actual volumetric flow through the turbine flowmeter.

Volumetric flow per unit time = (Pulse rate)*(K-factor)

A fluid with low specific gravity creates a lower pressure drop across the rotor blades and hence the energy left to turn the blades is low. Thus with decrease in specific gravity the K-factor drops off. In such a case, the angle of the rotor blades is changed to compensate for lower specific gravity or low flow rates. That being a major reason for the use of turbine meter for a wide range of fluid flows.

2. Specifying Flowmeter

Turbine flowmeters are generally specified using the pipe diameter and the flow rate to be handled. In this application, the total flow through the pipeline is about 2000 GPM, and that through the bypass is 30% i.e. 600 GPM.

The flowmeter is basically only going to measure the bypass flow and hence the under normal working condition it would be handling just 600 GPM. But in the condition of the pig getting stuck, all of the pipeline flow then passes through the bypass, and the flowmeter should be designed for this large flow (2000 GPM) too. Thus the turbine flowmeter should have a flow range of 600-2000 GPM.

Secondly, as the turbine flowmeter is to be installed in the annular bypass, the flowmeter diameter has to be equal to the bypass diameter which is 5.5 inches. Thus the flowmeter diamter has to be 5.5 inches.

The operating temperatures for the cleaning pig are in the range of 40 to 150 F. As most turbine flowmeters have a much larger operating temperature range, this is an easy requirement to meet.

The other concern, is the operating pressures in the pipelines, which are in the higher range, around 5,000 psi. Hence the turbine flowmeter needs to be specified to operate at around pressures of 5,000 psi. As turbine flowmeters have already been designed for pressures as high as 10,000 psi, no custom modifications are needed for this application.

Many turbine flowmeters are designed for the petroleum industry, and thus are available in a variety of materials of construction. The material of construction should resist corrosion and should be wear resistant. Stainless steel would be a good material for the this application, and there are commercially available flowmeters made of stainless steel.

3. Final Specifications

Thus the specifications of the flowmeter required for this cleaning pig are:

1. flow range - 600 to 2000 GPM
2. Line size - 5.5" diameter
3. Temperature range - 40 to 150 F

4. Pressure range - 1,200 to 5,000 psi

5. Material of Construction - Stainless steel

The above specified requirements of the flowmeters are easily met as such flowmeters are commercially available in the market today.

H. Specification of the MEMs Accelerometer

The use of the MEMs accelerometer was for two purposes, one it provides a feedback to the control unit when the pig is stuck and secondly research has shown that accelerometer data can be used to predict the condition inside the pipeline. [20]

It is important to be able to distinguish whether the pig is stuck or not, as the control system depends on this input to close the valve in the annular bypass to increase the pressure behind the pig in order to dislodge it. The MEMs accelerometer provides this useful information to the control unit to help it make decisions.

Secondly, there exists a gap in the offshore market between the intelligent 'smart' pig technology and the simple cleaning pig technology. Smith, et al. have shown that even simple accelerometers, differential pressure transducers and temperature sensors may be used to monitor the basic condition of the pipeline [21]. The measurements of these simple instruments could be analyzed and the amount of deposits, kind of deposits and location of the deposits could be determined. This is done by analyzing the vibration profile registered by the accelerometer along with inputs from pressure sensor regarding the pressures existing along the pipeline. Thus the inclusion of these simple instruments could provide valuable data and also an insight to the deposition conditions in the pipelines. Thus the motivation to include it into the regulated velocity cleaning pig.

Hence the cleaning pig, is no longer a 'dumb' pig, but a semi-intelligent one, which gathers basic information in addition to cleaning. The basic reasons for developing this kind of a semi-intelligent cleaning pig are:

1. Reduction of costs

   Smart inspection pigs are expensive, both in terms of technical support and in preparation and deployment costs. This is so, because it includes a pre-cleaning programme, modification of the pig traps and the requirement for special handling facilities. Thus, the use of smart pigs is sanctioned only after careful consideration and only in limited number of inspection runs. A semi intelligent cleaning pig would be cheap and would require no such pre-requisites.

2. No need for specialized conventional tools

   The majority of the smart inspection pigs are aimed at weld anomalies and corrosion. The sophistication in design, technical development and data processing has yielded tools that provide specific information as required by the operator. It was felt that there was a gap between such tools and the dumb pig used for cleaning.

Smith, et al.[21] used a +/- 2g and a +/- 10g accelerometer for the tests conducted by them. The 2g accelerometer were used to measure lower intensity vibrations while the pig traversed the line while the 10g accelerometer was used to investigate the peak accelerations that the pig faced at a pipe flange or a restriction.

Thus, for this application the accelerometer would be such that it covered the entire range of possible accelerations in the pig. Hence, a 10g accelerometer is chosen. The MEMs accelerometer would be mounted in-line, along the axis of the pig. This way any change in the velocity of the pig due to resistance from the deposits is correctly measured and recorded.

The other specifications for the MEMs accelerometer are:

1. Range ±10g

2. Accuracy ± 1 %

I. MEMs Pressure Transducer

The MEMs pressure transducer has two functions, one is to prevent excessive pressures from developing across the pig and second is to record the pressure profile along the pipeline.

In the case of the pig being stuck and the bypass valve being closed, the pressure difference across the pig could rise rapidly. Even though the pig body and the valve maybe designed to withstand the extra pressure, the scraper discs cant, and hence they would be the first to fail under large pressure differences. This would create debris of the scraper discs in the pipeline, and cleaning up would be extremely expensive and also very difficult. Hence the aim is to prevent any kind of debris from being created during the pig run. The MEMs pressure transducers continuously monitor the differential pressure across the pig, and when it exceeds a set limit, usually about ΔP_p, i.e. 150 psi, the control unit opens the valve to release some of the excess pressure build up.

Secondly, Smith, et al.[21] have shown that elementary data gathered by pressure transducers, acclerometers and temperature sensors can provide a deep insight into the condition of the pipeline as discussed earlier.

The pressure transducer operates in a ambient pressures of around 5000 psi, the temperatures vary from 40 - 150 F, and the surrounding medium is corrosive, abrasive and unclean. Thus, using a factor of safety of 1.5, the maximum operating pressure for the transducer is 5000*1.5 =7500 psi. The operating temperature range for the transducer has to be more than 25 - 225 F. The supply voltage to the transducer should be lower than the voltage supplied by the designed electric battery, i.e. less than 27 volts DC. And the material of construction has to be immune to the harsh environment its going to be subject to. Thus to prevent corrosion and abrasion, stainless steel is preferred.

The pressure transducer required is specified below:

1. Pressure range : 0-7500 psi
2. Temperature range : 25-225 F
3. Material of construction : Stainless steel body

J. Control Unit

The control unit is responsible for controlling the bypass flow based on feedback from the flowmeter, accelerometer and pressure transducers. The butterfly valve is actuated using the gear motor through a set of worm gears.

The average velocity over a period of one minute is calculated by the control unit and this is compared with the desired velocity. The valve is opened or closed based on this difference. Hence the control unit doesn't operate the valve continuously, but in a more intermittent way. Continuous real time operation is avoided because of the inherent instability in the system over short durations.

The control logic is illustrated as a flow chart in Figure 13.

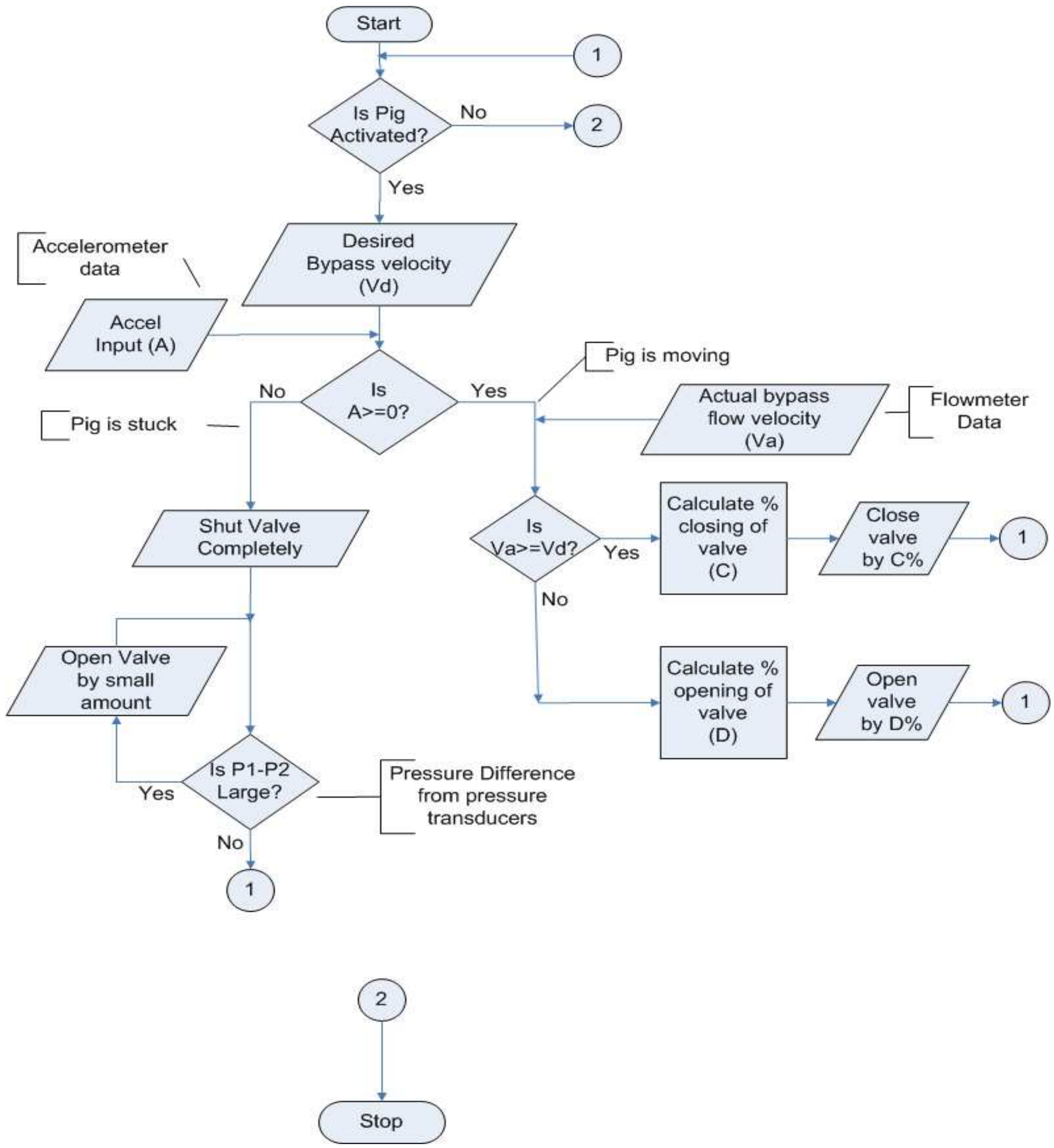

Fig. 13. Control logic flowchart

The possible conditions the pig is likely to encounter in the real oil pipelines are listed below. The desired response of the Control Unit is also detailed.

Case 1: Pig is moving in a clean section of the pipeline, and faces no resistance from wax deposits or accumulations.

The by-pass is so sized that ideally the pig should maintain 70% of the flow velocity, as in this case. However if there is a local variation in the oil flow velocity, the flow meter would record this and the control unit would adjust the butterfly valve accordingly to control the by-pass flow velocity.

Case 2 : Pig faces resistance from the wax deposits or wax accumulation

Because of resistance caused by the wax deposits, the pig velocity falls down below the desired 70% of flow velocity. As the pig velocity reduces, the by-pass velocity increases. This is noted by the flow meter, and the control unit closes the butterfly valve accordingly, so as to increase the pressure behind the pig. The pressure that builds up behind the pig helps the pig to push its way through the wax, and the velocity of the pig reaches the nominal velocity(70% of flow velocity) once again. Thus the by-pass flow velocity drops and the control unit opens the butterfly valve accordingly again.

Case 3 : Pig gets completely stuck due to large wax accumulation

In the extreme case of the pig getting stuck, it is not possible to rely only on the input of the flow meter. The way around this problem is to have extra information for the control unit to decide whether the pig is stuck or not - and this information is provided by the accelerometer. As the pig moves in the pipe, it bumps and grinds along the pipe walls, thus the accelerometer generates electrical signals as long as it is in motion. But with the pig getting stuck, there would be no signal from the accelerometer. Thus the control unit can decide to keep the valve completely shut as long as there is no signal from the accelerometer.

When the pig is dislodged and the pig begins to traverse the pipeline again, the accelerometer generates and sends out a signal to the control unit which then opens the butterfly valve. Thus with the accelerometer, it is possible for the control unit to close the valve as long as the pig is stuck, thus allowing pressure buildup and hence increasing the chances of the pig getting 'unstuck'.

Case 4 : Pig is stuck and the pressure difference is too high

In case the pig is stuck and cannot dislodge itself, despite the buildup of pressure behind the pig, there is always a danger of excessive pressure buildup which might cause the scraper discs to disintegrate and create debris in the pipeline. In this extreme case if the differential pressure exceeds a safe limit, it is necessary that some of the pressure be released.

This is achieved by having two pressure transducers mounted on the ends of the pig which continually take readings, the control unit monitors the difference between these pressures. When the differential pressure exceeds a certain amount, the control unit opens the butterfly valve to allow for some release of pressure. Once the pressure is released and the pressure behind the pig is in a safe limit, it shuts off again. This prevents buildup of excessive pressure which may cause harm to the pig or the pipeline.

The control system has to be designed to control the pig for each of these specific cases. Control logic needs to be developed for each individual case and then integrated into one control unit. Control logic has already been developed for the individual cases in the previous chapters. The entire control system for the regulated velocity pig is developed and illustrated in Figure 14.

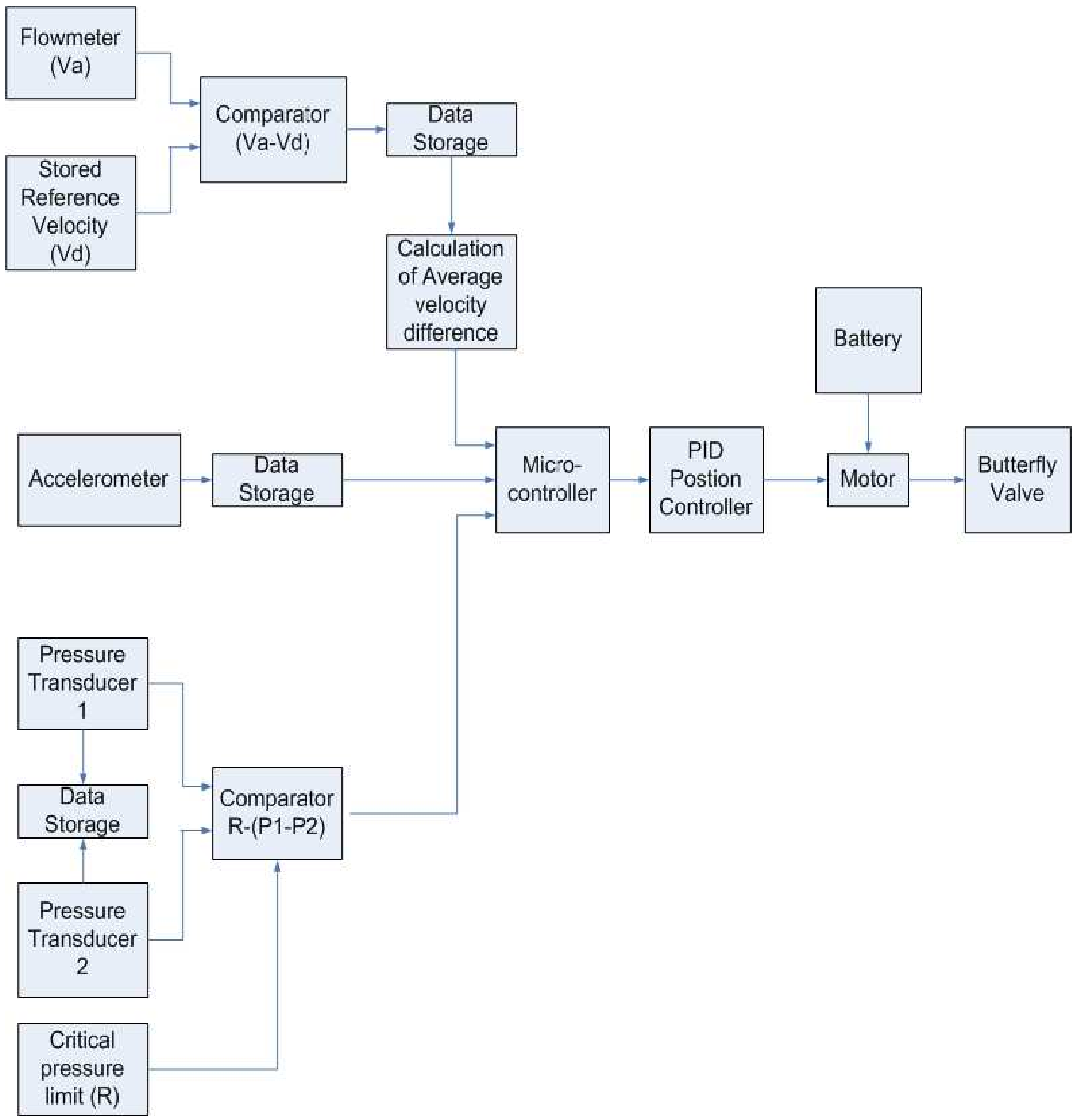

Fig. 14. Control system for the regulated velocity pig

K. Design of Pig Housing

A pressure vessel is needed that encompasses the various parts and basically forms the housing for the pig. This pig housing, is similar in structure to a cylindrical tube with an annular bypass. It consists of sealed concentric cylinders with an open bypass. The annular space between the cylinders is used to house all the components of the pig and to protect them from the harsh environment. The outer cylinder is also the base to mount the scraper discs which perform the actual cleaning action of the pig.

The flowmeter and the butterfly valve are mounted in the flow stream through the annular bypass. The magnetic pickup coil, control unit, battery, motor and gear train are all mounted between the annular space between the inner and outer cylinders.

A rough sketch of the proposed pig body is shown in Figure 15.

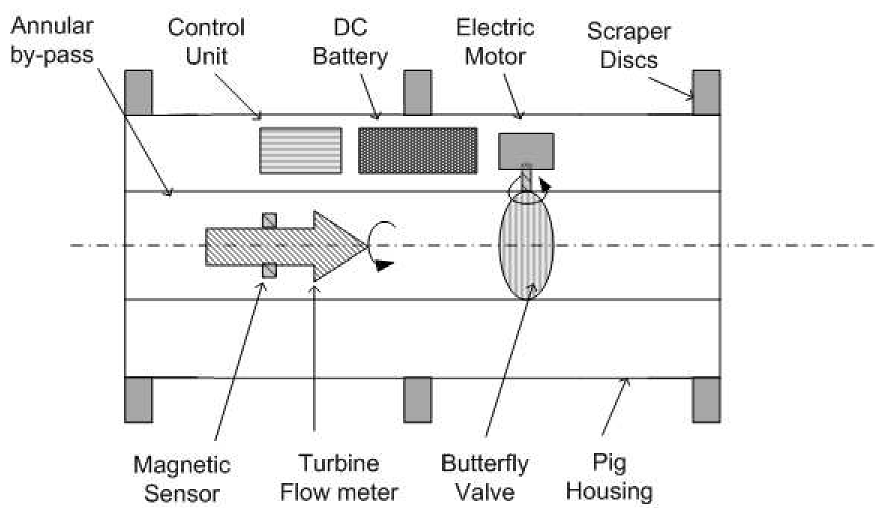

Fig. 15. Proposed pig housing

The pig body is similar to a pressure vessel with a working pressure of 1,200 to 5,000 psi. An interesting fact to note is that, unlike most pressure vessels which have either external pressure or internal pressure, the pig core faces both internal and external pressures. As the pig has an annular bypass, the inner cylindrical surface faces an internal pressure of approximately 5000 psi, while the external cylinder has a similar working pressure, but on the outside.

1. Material of Construction

The material of construction for the pig housing is compared below in Table IX.

Table IX. Material comparison

	Property	HSLA steel	Stainless steel
1.	Hardness (HRC)	27	36
2.	Ultimate Strength (psi)	125,000	180,000
3.	Yield Strength (psi)	105,000	135,000
4.	Cost/lb. ($)	2	10-12

As the body of the pig needs to withstand constant high ambient pressures in the range of 5000 psi, it is important that a material of high strength is chosen. This would enable the thickness of the pressure vessel to be small, and this is of importance in this design because of the lack of space. Thus stainless steel is chosen over HSLA steel.

Using Stainless steel as the material of construction for the pig core. The allowable stress for SS is $\sigma_y = 135,000$ psi.

Using a factor of safety of 1.25,

$$\sigma_t = \sigma_y/1.25$$

$$\sigma_t = 108,000 psi$$

$$p_i = 5000psi$$

$$d_i = 5.5inches$$

2. Calculating the Cylinder Thickness for Internal Pressure,

The pressures acting on the internal cylinder of the pig housing are shown in Figure 16 and the thickness is calculated using Equation 5.13.[22]

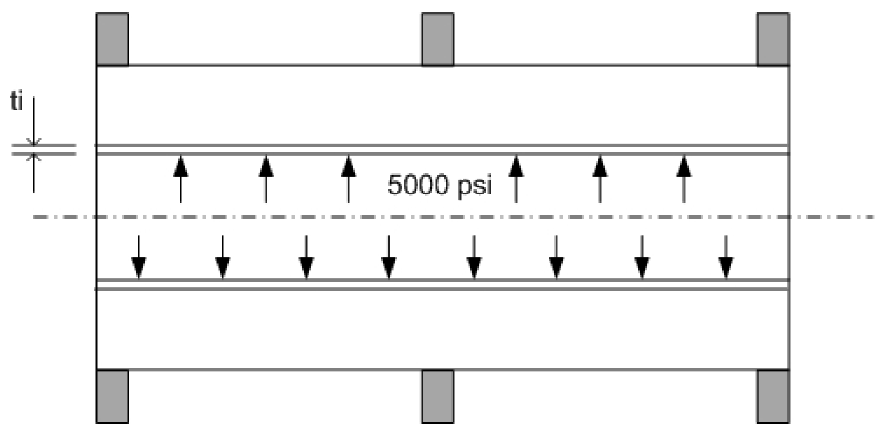

Fig. 16. Pressures acting on the internal cylinder

$$t = \frac{d_i}{2} * [\sqrt{\frac{\sigma_t}{\sigma_t - 2 * p_i}} - 1] \tag{5.13}$$

$$t = \frac{6}{2} * [\sqrt{\frac{108,000}{108,000 - 2 * 5000}} - 1]$$

$$t = 0.11$$

Using Barlows equation to verify this thickness [23],

$$\sigma_t = \frac{p_i * d_i}{2 * t} \tag{5.14}$$

$$\sigma_t = \frac{5000 * 6}{2 * 0.11}$$

$\sigma_t = 75,000$ psi

As the σ_t is lower than the allowable stresses for stainless steel, the thickness determined is correct and the design is safe.

Thus, the thickness to be used for the internal cylinder is 0.11 inches.

3. Calculating the Thickness for External Cylinder,

The pressures acting on the external cylinder of the pig housing are illustrated in Figure 17.

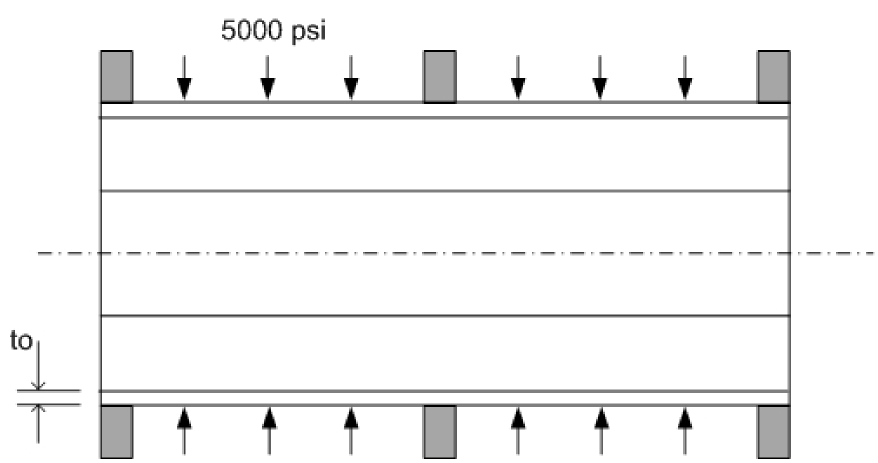

Fig. 17. Pressures acting on the external cylinder

Using the same thickness derived for the internal cylinder and checking if its suitable to be applied for the outer cylinder.

Using the formula for short thin tube under uniform external pressure [23],

$$q' = 0.807 * \frac{E * t^2}{l * r} * \sqrt[4]{(\frac{1}{1-\nu^2})^3 * \frac{t^2}{r^2}} \tag{5.15}$$

where, q'= unit external pressure at which elastic buckling occurs

E = Modulus of Elasticity,

l= length between stiffners of the pig

r= radius of outer cylinder

ν = poisson's ratio

For Stainless Steel,

E=28 Mpsi

$\nu = 0.3$

l=8 inches

r=4 inches

t=0.11 inches

Thus

$$q' = 0.807 * \frac{28 * 10^6 * 0.11^2}{8 * 4} * \sqrt[4]{(\frac{1}{1-0.3^2})^3 * \frac{0.11^2}{4^2}}$$

$q' = 4518$ psi

As $q' < 5000$ psi, the thickness needs to be increased, choosing new thickness, t=0.2 inches,

$q' = 6778$ psi

Thus with the thickness of 0.2 inches for the outer cylinder, the design is safe.

4. Calculating Head Plate for Shell

The thickness of the head plates, t_h, at the end of the cylinders needs to be determined separately as shown in the Figure 18.

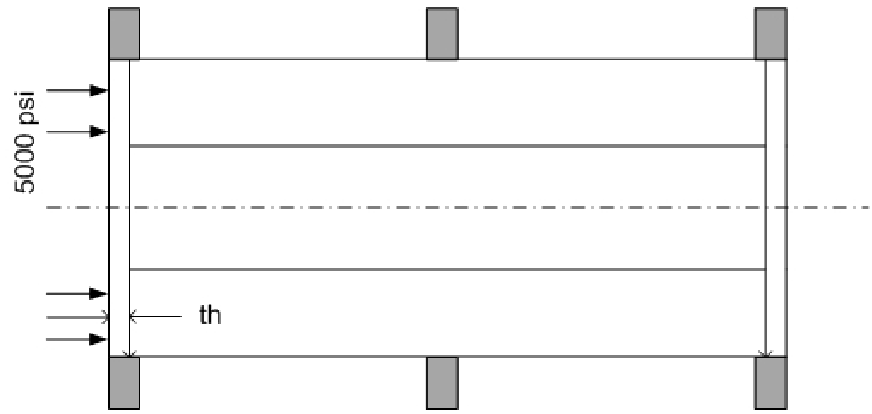

Fig. 18. Pressures acting on the head plate

The thickness of the head plates, t_h, is given by Equation 5.16.[22]

$$t_h = C * d_o * \sqrt{(\frac{P_o}{\sigma_t})} \tag{5.16}$$

where, d_o is the diameter of the outer shell and P_o is the pressure acting on the outer shell.

Value of C depends on how the head is attached to the shell - for plates welded to the end with additional fillet weld on the inside, as shown in Figure 19.

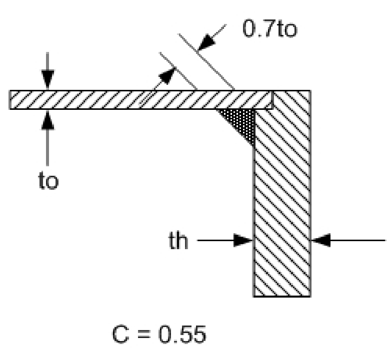

Fig. 19. Value of C for plates welded with fillet weld

C=0.55

$$t_h = 0.55 * 8 * \sqrt{(\frac{5,000}{84,000})}$$

$t_h = 1$ inches

Thus the face plates at the ends of the pig need to be of thickness 1 inches.

5. Number of Bolts required at Flange Joints

The number of bolts required is determined using an empirical relationship given below [22],

$$N = 0.024 * D + 2 \quad (5.17)$$

where, N is the number of bolts and D is the diameter of the flange.

Using this relationship to determine the number of bolts required for the outer pig case, N_o,

$$N_o = 0.024 * 8 + 2$$

$$N_o = 6.87$$

$$N_o \approx 8$$

Using this relationship to determine the number of bolts required for the inner pig case, N_i,

$$N_i = 0.024 * 6 + 2$$

$$N_i = 5.35$$

$$N_i \approx 6$$

Hence, 8 bolts need to be used for the outer case while only 6 bolts need to be used for the inner case.

6. Calculating Bolt Size needed

Calculating the bolt size for the outer flanges,

Area of outer flange, A_{fo}=20.02 sq.in

Even though the ambient pressure in the pipeline is high, around 5000 psi, the differential pressure along the length of the pig is limited to 150 psi, because of the maximum differential pressure that the scraper discs can handle.5.3

Using a factor of Safety of 2,

$$P_l = 150 * 2$$

The force trying to separate the flanges is,

$$F = P_l * A_{fo}$$

$$F = 6000lbs$$

Dividing this load by the number of bolts, in this case, 8, thus the load on each bolt is,

$$F_{bo} = 750lbs$$

Using 25 % of the yield value for calculation, i.e. 80,000/4

Diameter of bolt for outer flange, d_{bo},

$$d_{bo} = \sqrt{(}F_{bo} * 4/\pi * 20,000)$$

$$d_{bo} = 0.218"$$

Using the same design procedure for the inner flanges and calculating the diameter of the bolts. The only difference being that the number of bolts is 6 instead of 8.

$$d_{bi} = 0.25"$$

Thus, using a standard set of bolts for the entire pig with a bolt diameter of 0.25 inches.

CHAPTER VI

PIG ASSEMBLY

A. Introduction

The previous chapter discussed the design aspects of the pig, based on that solid models were developed in Solidworks 2003. The detailed solid models of all component is shown in Appendix A. This chapter deals with the assembly of the various components of the pig. It is intended to give a better idea of the construction of the pig components and the basic assembly of the pig.

B. Assembly of the Regulated Velocity Semi-Intelligent Pig

The turbine flowmeter along with a rubber gasket is fit into 'pig body 1'. The magnetic pickup coil of the flowmeter needs to be aligned with the slot provided in the pig body 1. This is illustrated in the Figure 20.

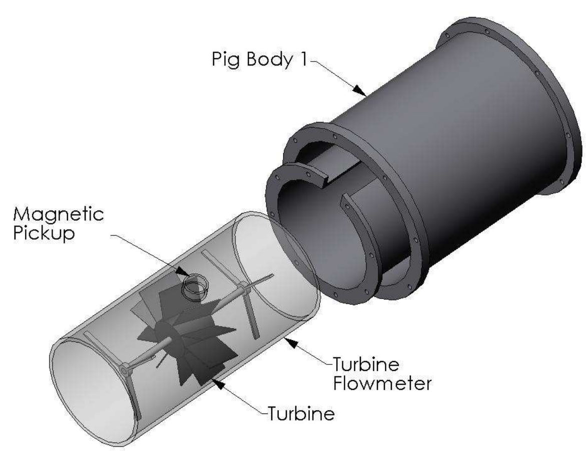

Fig. 20. Assembly of flowmeter and pig body 1

The butterfly valve and pig body 3 are bolted together to form the annular bypass as shown in Figure 21.

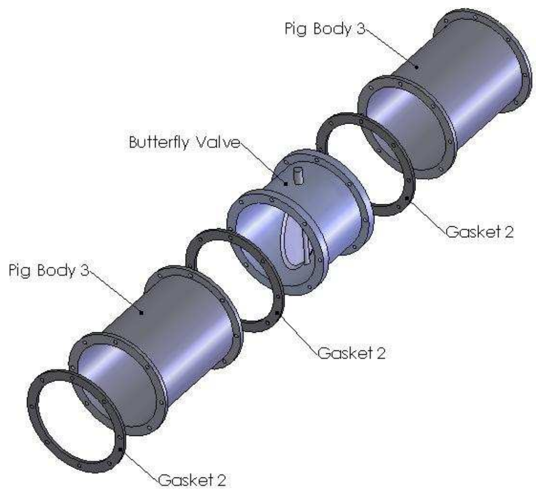

Fig. 21. Assembly of annular bypass

The gear train to transmit power from the motor to the valve shaft consists of a worm wheel and worm gear. A gear box has been designed which houses a bearing to support the free end of the worm wheel. This gives the gear drive the much needed support and stability. This is illustrated in the Figure 22.

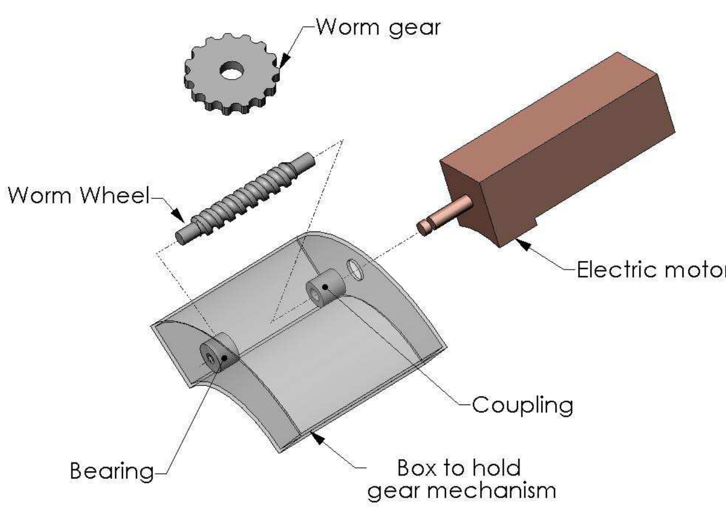

Fig. 22. Sub-assembly of gear train and motor

The completed sub-assembly is show in Figure 23.

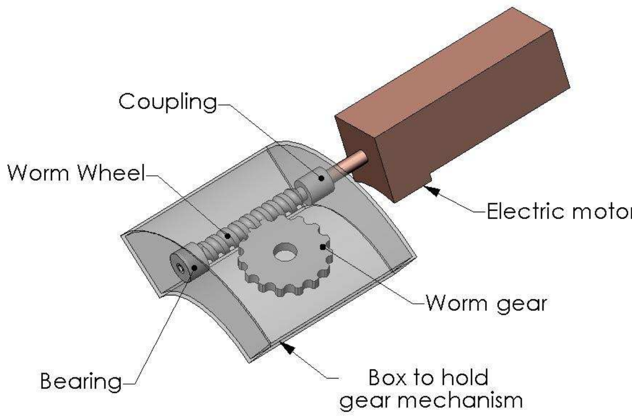

Fig. 23. Complete sub-assembly of gear train and motor

The gear sub-assembly, control unit and the battery to power the motor are mounted on to the bypass as shown in Figure 24.

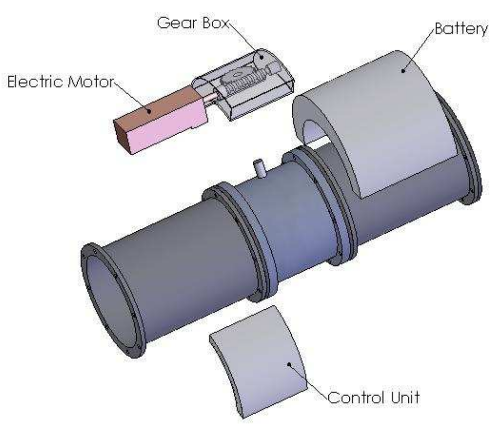

Fig. 24. Assembly of battery, control unit and gear train sub-assembly

Figure 25 shows the overall bypass assembly with all the components mounted onto the inner flange of pig body 1.

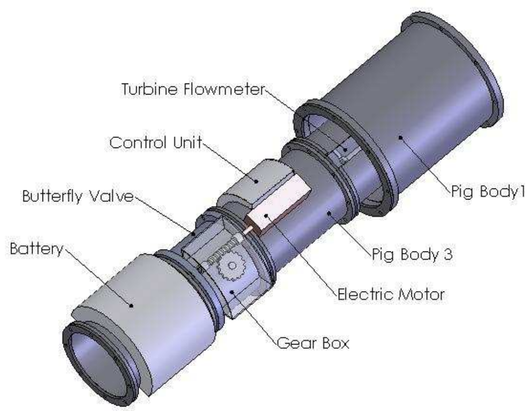

Fig. 25. Entire bypass assembly

The other end of the pig housing, pig body 2, is then mounted onto this assembly along with a rubber gasket. Two pressure sensors are also mounted on the ends of the pigs to measure the differentially pressure across the pig. The pig body 1 and pig body 2 are then bolted to each other as shown in Figure 26.

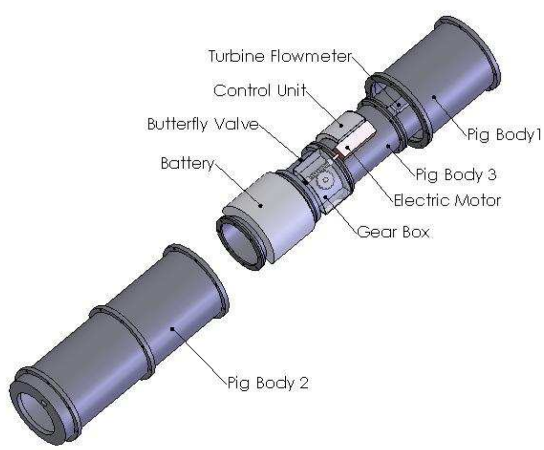

Fig. 26. Mounting of pig body 2 onto basic assembly

The components enclosed within are sized such that the pig body 2 exerts a pressure on the entire inner assembly and keeps it in place. This is shown in Figure 27.

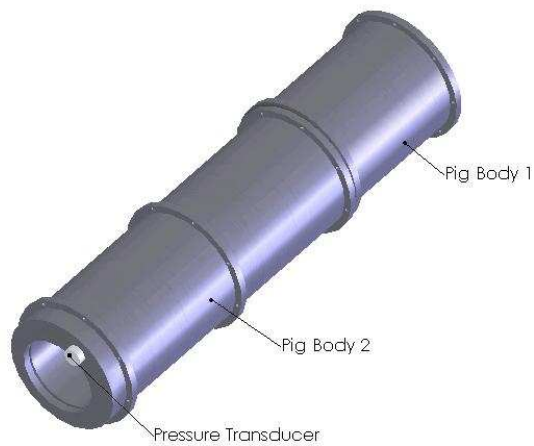

Fig. 27. Complete pig housing

The entire assembly of the pig with varying degrees of transparency is shown in Figure 28 for a better understanding of the positioning and assembly of the pig.

Fig. 28. Pig assembly with transparent components

The components of the pigs and their placement in the pig housing is described in Figure 29.

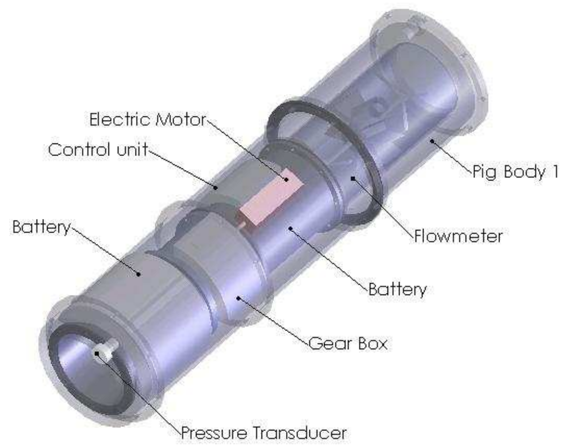

Fig. 29. Various components of the pig

The scraper discs to carry out the actual cleaning operation are mounted on this completely enclosed pig housing as illustrated in Figure 30.

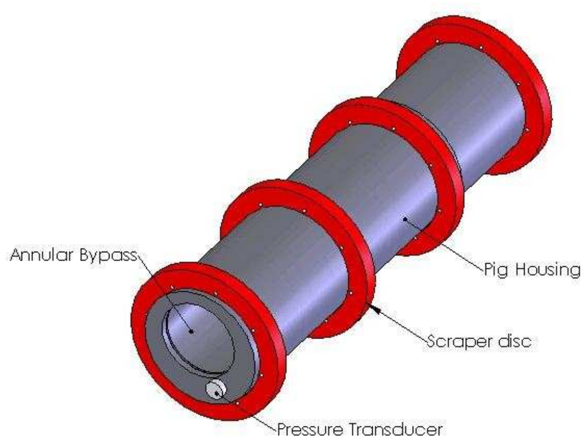

Fig. 30. Pig with scraper discs for cleaning

C. Conclusion

The assembly of the pig has been described in this chapter. It details the basic components, and how they fit into the pig housing. This should provide a better insight into understanding the functioning of the pig.

CHAPTER VII

PROOF OF CONCEPT AND PROPOSED TESTING

A. Introduction

The chapter discusses the proof of concept, an experimental setup which will demonstrate the functional capabilities of controlling the pig velocity by maintaining the bypass flow. This is a basic analogy, to verify that the concept used for designing the regulated by-pass velocity pig actually works. The second stage would be an actual test using a prototype pig in conditions similar to the ones that exist in the pipelines. It was not possible to conduct any of these tests, because of the lack of funding. But once these two tests are successful demonstrated, it would be possible to actually implement the regulated-velocity pig for cleaning purposes in the oil pipelines.

B. Experimental Setup - Proof of Concept

The test setup is to demonstrate the capabilities and also the functionality of the proposed pig in simulated conditions that resemble the actual operating conditions. The setup focuses its attention only on the by-pass flow control system, which is fundamental in the pig maintaining regulated velocity and needs to be tested. The test doesn't concentrate on the pig scraping capabilities or the ability of pigs to traverse through tight bends - as they have already been proven by the industry.

Thus, this setup aims at only proving that the assumption - the pig velocity can be regulated by controlling the by-pass velocity through the pig. The lack of sufficient funds prevented the actual building of a full scale prototype and testing it in commercial pig testing setups.

The aim is to simulate these conditions without actually having to create a prototype of the pig and send it through a pig test setup. Hence, just the core of the 'regulated velocity pig' is to be tested and examined to see if it meets the actual requirements.

Figure 31 demonstrates the proposed method to test this 'regulated velocity pig'.

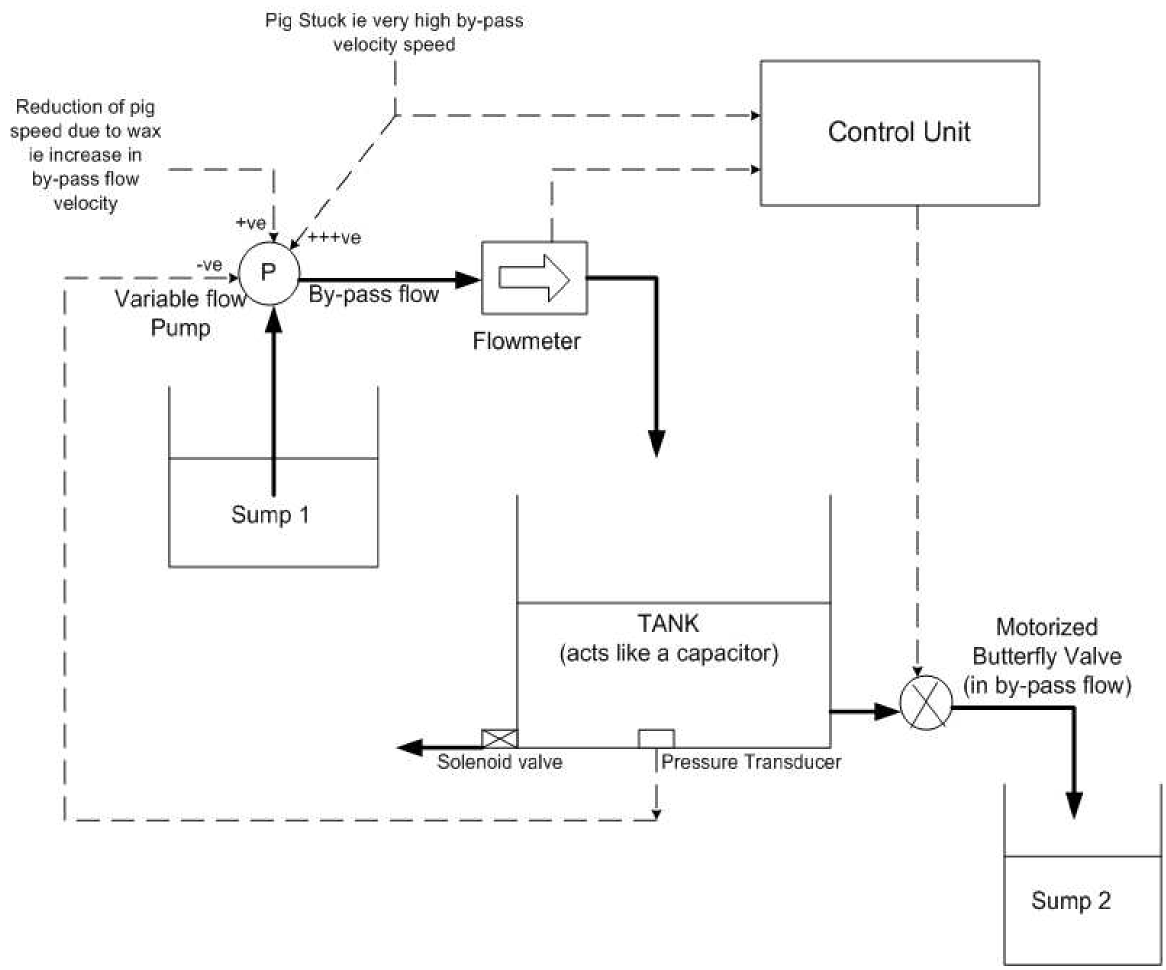

Fig. 31. Experimental test setup for proof of concept

Brief description of the setup :

A variable flow pump is used to generate the by-pass flow through the pig (not the net flow in the pipeline), this flow passes through the flow meter which measures the flow and relays this information to the Control Unit. The fluid is collected in a tank, which acts like a capacitor. At the bottom of the tank is a pressure transducer, and an outlet to Sump 2 through a motor operated butterfly valve. This motor operated butterfly valve is controlled by the control unit and is responsible for regulating the by-pass flow.

To simulate the actual conditions, two randomly generated inputs are necessary - one which simulates the pig encountering wax deposition and slowing down i.e. the by-pass velocity increases - which is simulated by increasing the pump flow. Secondly, the case of the pig getting stuck is also a random input (which represents the function of the accelerometer) - this relays information not only to the control unit but also to the pump to increase the pump flow rate by a large margin (because when the pig is stuck, all the flow goes through the by-pass and the by-pass velocity is very high)

A pressure transducer is provided in the tank to sense the pressure in the tank (which effectively represents the pressure behind the pig), it is essential for the working of the setup. If the pig is slowing down due to wax deposits, the butterfly valve is partially closed and the pressure behind the pig starts increasing, and this increased pressure helps the pig to dislodge and regain its velocity. The pressure transducer simulates the pig dislodging and regaining velocity by sending signal to the pump to reduce flow i.e. increase pig velocity, when a certain pressure is reached.

The pressure transducers also informs the control unit to open the bypass when the pressure difference exceeds the safe limit in the actual pig.

Now, analyzing how the setup operates in the aforementioned four cases :

Case 1: Pig is moving in a clean section of the pipeline, and faces no resistance from wax deposits or accumulations.

The pump is configured for a certain flow rate, which represents only the by-pass flow and not the total flow. This is supposed to represent 30% of the total flow. The flow meter relays this information to the control unit which regulates the butterfly valve, such that flow out of butterfly valve is equal to the flow from the pump. Thus the fluid level in the tank remains steady, and this symbolizes the constant pressure behind the pig, which would help it maintain constant velocity.

Case 2 : Pig faces resistance from the wax deposits or wax accumulation.

As, it is difficult to predict when the pig might encounter resistance from wad, to simulate the condition of the pig encountering wax resistance and slowing down, a randomly generated input is necessary. This input sends signal to the pump to increase the flow rate. This increase in flow rate i.e. by-pass flow rate represents the decrease in pig speed. The flow rate increase is conveyed by the flow meter to the control unit. The control unit then closes the valve accordingly to increase the pressure behind the pig. The level of fluid in the tank rises, symbolizing increase in pressure behind the pig. Since it is difficult to estimate at what pressures the pig would dislodge the wax, it is randomly estimated. When this pressure is reached, the pressure transducer basically signals the pump to reduce the flow rate and the by-pass flow rate decreases, signifying the increase in velocity of the pig. The level of fluid in the tank starts falling and finally reaches a steady value, suggesting the pressure propelling the pig reduces after the pig and soon reaches a steady value. The pressure transducer basically simulates the operation of the pig dislodging, breaking loose and regaining its velocity.

Note - this random generation of inputs does not exist in the actual 'regulated velocity pig', but is an integral part in the setup to simulate the conditions and the behavior of the pig.

Case 3 : Pig gets completely stuck due to large wax accumulation

To simulate the pig getting stuck, another randomly generated input is required which signals the pump to increase the flow by a large amount and also sends a signal to the control unit. When the pig is stuck, the pig velocity is zero and hence the by-pass velocity is very large, which is shown by the large flow rate of the pump.

Secondly, the signal sent to the control unit, represents the signal by the accelerometer to the control unit, indicating that the pig is stuck. The control unit, upon getting information from the flow meter and the accelerometer (in the set up it is just one source - the random input) it completely shuts off the valve and allows pressure to build up in the tank. Thus the level of fluid in the tank rises rapidly, indicating quick pressure buildup of pressure behind the pig. As it is difficult to simulate how and when a pig might get 'unstuck', the pressure at which it might get unstuck is randomly generated.

This signal would be indicated by the accelerometer and not the flow meter as there is no by-pass flow. And the control unit starts opening the valve when it gets a signal from the accelerometer thus resuming the by-pass flow. This leads to the fluid level in the tank falling till it reaches a steady level.

Case 4 : Pig is stuck and the pressure difference is too high

In this case, the solenoid valve which opens only when the pressure in the tank i.e. the fluid level in the tank, reaches critical limit. The solenoid valve in the setup is controlled based on the pressure readings by the pressure transducer. This simulates the opening of the butterfly valve by the control unit based on the difference in pressure across the pig as provided by the pressure transducers.

Note - the solenoid valve does not exist in the actual pig, it is an integral part of the setup to symbolize the spring loaded safety valve.

This experimental setup test would help us identify some of the problems that might arise in the actual scenario. It would also help us refine the control system being used for the regulation of the by-pass flow. Once this experimental setup has been successfully demonstrated, then a prototype of the pig may be built and tested before the actual production and implementation of the regulated velocity pig can begin.

C. Actual Test Using Pig Prototype

After, the pig prototype has been built, it is still risky to implement it into the oil fields right away. Some testing to check the standard of its performance is necessary. Smith, et al, developed a test setup for RST Projects Ltd, to test their SAAM (Smart Acquisitions Analysis Module)[21]. A similar test setup could be used to test the regulated velocity pig. The test setup is described in detail in the following paragraphs.

An adequate sized pipe was considered, so as to accommodate the pig. The test line consisted of two straight sections, which allowed the pig to reach the steady state velocity of 70% of the flow velocity. The Figure 32 illustrates the proposed test section.

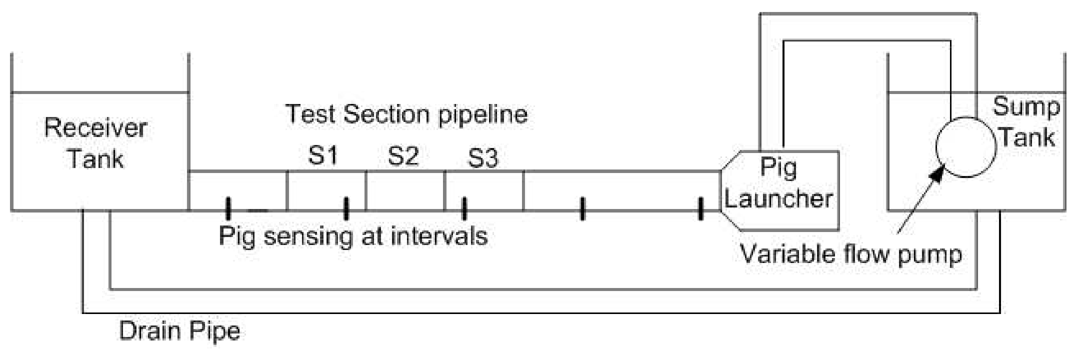

Fig. 32. Test setup for testing regulated velocity pig prototype

The entire test section was made from three, shorter pipe lengths which were approximately 0.8m in length. This was done in order to allow different internal conditions to be simulated if required. These sections were internally coated with hard wax, soft wax or were left clean.

Pure paraffin wax was used to produce the hard wax coating, while petroleum jelly was used to simulate a soft internal coating. The amount of wax to produce a given thickness over the inner surface of the pipe was calculated. This amount of wax was heated in a crucible to above its melting point to get it into molten state. The pipe was sealed from the other end using a stopper and the molten wax was poured inside. The other end was also closed and the pipe was set on a rolling machine and rolled till the wax had solidified. The coatings obtained were found to be of uniform thickness.

The different pipe lengths were then joined together to form the entire testing section. Arrangements were made to monitor the velocity of the pig inside the pipe by installing sensors in the test section. A variable flow pump was used, to enable the simulation of actual conditions of varying flow rates.

The setup described above could be used to put the velocity regulated pig that has been proposed through some rigorous tests. These test would determine the pig performance under conditions almost similar to the actual conditions and would provide an opportunity to improve and modify the pig.

D. Conclusion

Even though these tests have not been carried out because of the lack of financial support, the aim of describing the tests is to discuss a way to actually test the proposed concept in two different stages. These tests would act as a check at each stage, so that the proposed concept is verified, strengthened and if needed modified before proceeding to the next stage. The tests described above would provide a reality check for the proposed design before the regulated velocity pig is put into use.

CHAPTER VIII

CONCLUSION

The objective of this research was to design a cleaning pig that would maintain a certain velocity while cleaning. It was imperative to keep the design simple by using standard commercially available components for the pig parts.

A secondary objective of the research was to provide certain basic features that would enable elementary data collection. The aim of the data collection was to analyze it in order to determine the actual condition in the pipeline.

This thesis, clearly identifies the problem and the need to maintain the pig at 70% of the flow velocity. It also lists the basic requirements that are needed of the cleaning pig in order to maintain constant speed. Various concepts are then developed to solve the problem in different ways, they are then discussed and the best possible concept is further developed.

The concept of using a motorized butterfly valve to control the bypass flow in order to regulate the pig velocity was the best option and hence has been described in detail. The step by step procedure for the design of such a pig is also detailed in this thesis. The pig components are then modeled using Solidworks and the assembly procedure is explained.

The thesis also describes two test setups that might be used to confirm and verify the proposed design concept at different stages of development.

A. Conclusion

The initial objective of avoiding the use of any sensor, electrical equipment for regulating the velocity of the pig was found to be unpractical. The concepts developed with this in mind, reveal that though some elementary control might be possible using just mechanical means - it is not robust and reliable.

The final proposed concept of a regulated velocity pig using a motorized butterfly valve is more robust, more reliable and has better control over the by-pass flow. It would improve flow assurance and aid the petroleum industry in the following ways:

1. enhanced cleaning,
2. reduced pig runs,
3. better production,
4. lower chances of the pig getting stuck in the pipeline
5. reduced slugging effects.

These factors add up to lot of monetary savings for the oil industry in the long run.

In addition to the regulation of the pig velocity, the design also proposes to utilize the onboard electronics like the accelerometer and the pressure transducers to gather and store data onboard. It has been shown that even the elementary data gathered by sensors like accelerometer and the pressure transducers may be used to correlate the data to the conditions inside the pipe. This feature would transfer the 'dumb' cleaning pig into a 'semi-intelligent' pig.

Thus, the combination of having regulated velocity and gathering of basic pipeline data make the proposed concept a very attractive package for the oil industry.

B. Recommendations

This thesis involved the design of a regulated velocity cleaning pig, the concept needs to be proved using the experimental test setup described in chapter 7. This would bring out the faults and reliability issues especially in the control unit.

Though the details of the pig have been worked out in this thesis, the aforementioned pig was not developed. There is need to take this research one step ahead and actually build a prototype of the pig. The process of building the prototype would require further work on this project using this thesis as a base. It might also reveal better and more efficient ways of manufacturing the pig.

The developed prototype would then need to be tested in a specially built testing rig as discussed in Chapter 7 in order to iron out the minor problems in the pig.

REFERENCES

[1] Baker Hughes, "Deepwater production - flow assurance," [Online]. Available : http://www.bakerhughes.com, Accessed October 2004.

[2] Baker Hughes, "Oil and gas production - paraffin and asphaltene controllers," [Online]. Available : http://www.bakerhughes.com, Accessed October 2004.

[3] Girard Industries, "Polly pig cleaning pigs by girard industries," [Online]. Available : http://www.girardind.com, Accessed September 2004.

[4] Pipetronix Incorporation, "Magnescanhr smart pig," [Online]. Available: http://www.new-technologies.org, Accessed September 2004.

[5] R. Anglisano A. Crouch and M. Jaarah, "Quantitative field evaluation of magnetic flux leakage and ultrasonic in-line inspection," *Pipes and Pipeline Engineering*, vol. 1, pp. 23–32, Jul-Aug 1996.

[6] H. Willems and O.A. Barbian, "Ultrasonic crack detection in pipelines by advanced intelligent pigging," *Pipeline Technology*, vol. 1, pp. 223–234, Jul-Aug 1995.

[7] Baker Hughes, "Baker hughes pipeline management group," [Online]. Available : http://www.bakerhughes.com, Accessed on August 2004.

[8] Association of Oil Pipe Lines, "Pipeline integrity final," [Online]. Available : http://www.aopl.org, Accessed on August 2004.

[9] Campbell Douglas, "Variable speed pigs for pipelines," *US Patent No 5,208,936*, May 11 1993.

[10] K. Campbell I. Smith, P.A. Couchman, "Pipeline pigs," *US Patent No 6,098,231*, September 6 1988.

[11] H. Goedecke G. Krieg, "Apparatus for electromagnetically testing the walls of pipelines," *US Patent No 4,769,598*, August 8 2000.

[12] Girard Industries, "Suggested pipe and pipeline pigging pressures and flows," [Online]. Available : http://www.girardind.com, Accessed on October 2004.

[13] J.W.Hutchinson, *ISA Handbook of Control Valves*, Pittsburgh, Pennsylvania, Instrument Society of America, 1971.

[14] T. Christopher Dickenson, *Valves, Piping and Pipelines Handbook*, vol. 1, Oxford, U.K., Elsevier Advanced Technology, 3rd edition, 1999.

[15] Engineering Toolbox, "Butterfly valves, typical flow coefficients," [Online]. Available : http://www.engineeringtoolbox.com, Accessed on September 2004.

[16] William J. Rahmeyer, "Application of butterfly valves for free discharge, minimum pressure drop, and for choking cavitation," [Online]. Available : http://www.engineering.usu.edu, Accessed on September 2004.

[17] Honeywell/Tyco valves and control, "Resilient seat and high performance 2 and 3-way butterfly valves," [Online]. Available : http://hbctechlit.honeywell.com, Accessed on August 2004.

[18] Globe Motors, "Brushless dc gearmotors," [Online]. Available : http://www.globe-motors.com, Accessed on August 2004.

[19] Panasonic, "Meeting the needs of portable electronic devices : Lithium ion battery," [Online]. Available : http://www.panasonic.com, Accessed on September 2004.

[20] G. Smith B. Snodgrass, "Low-cost pipeline inspection by the measurement and analysis of pig dynamics," *Pipes and Pipelines International*, pp. 35–43, 2001.

[21] D. Russell E.H. Owens G.H. Smith, G. Short, "Testing of low cost instruments for the identification of wax in a hydrocarbon pipeline," in *International Society of Offshore and Polar Engineers*, 2000.

[22] K. Balaveera Reddy K. Mahadevan, *Design Data Handbook*, New Delhi, India, CBS Publishers and Distributors, third edition, 2000.

[23] Richard G. Budynas Warren C. Young, *Roark's Formulas for Stress and Strain*, New York, McGraw Hill Publishers, seventh edition, 2002.

APPENDIX A

SOLID MODELS OF PIG COMPONENTS

This shows the detailed drawings of the pig parts along with their dimensions.

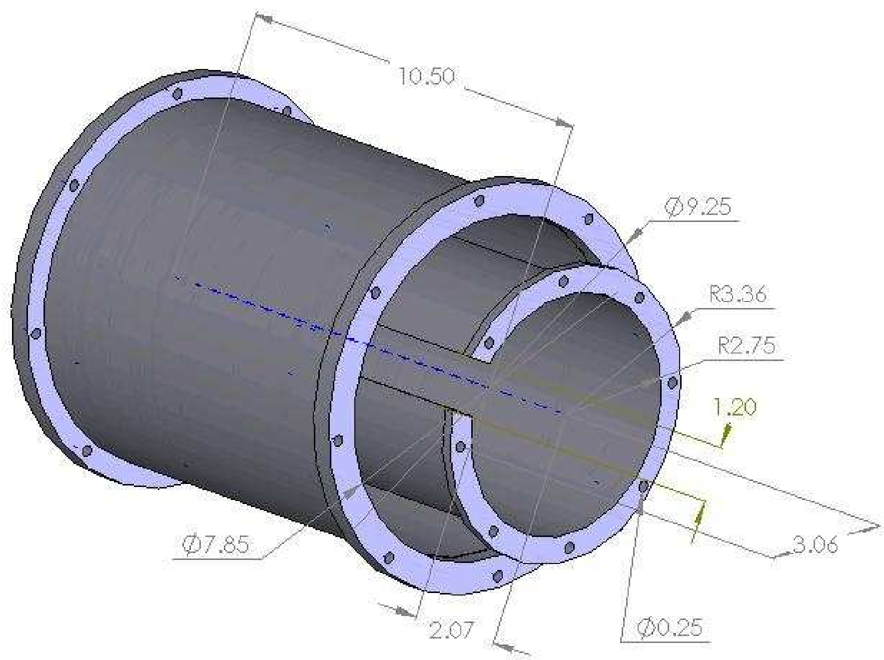

Fig. 33. Pig housing - pig body 1

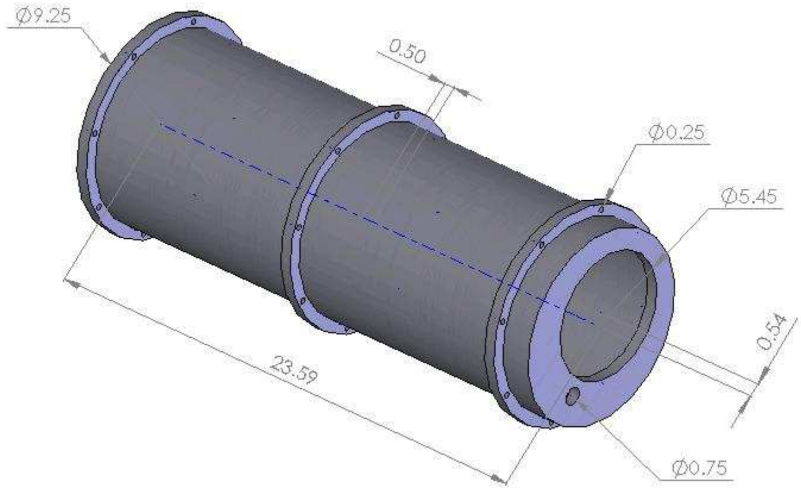

Fig. 34. Pig housing - pig body 2

Fig. 35. Pig housing - pig body 3

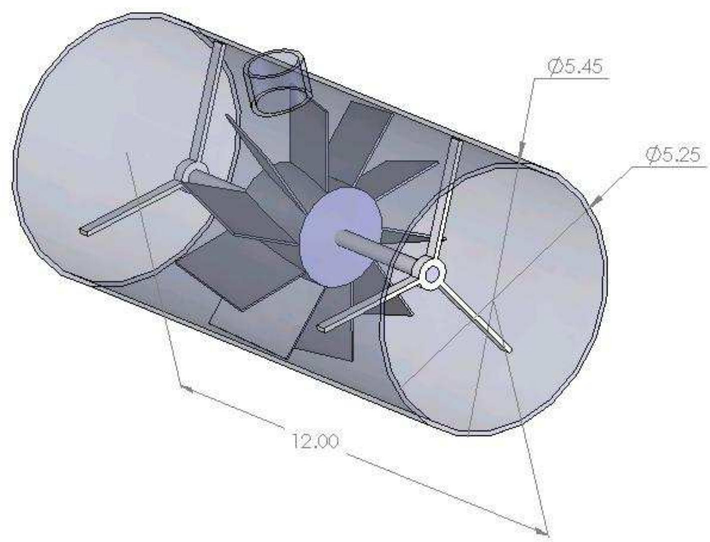

Fig. 36. Turbine flowmeter

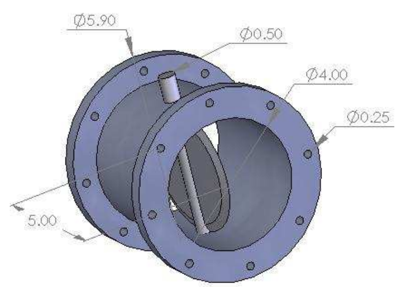

Fig. 37. 4" Butterfly valve

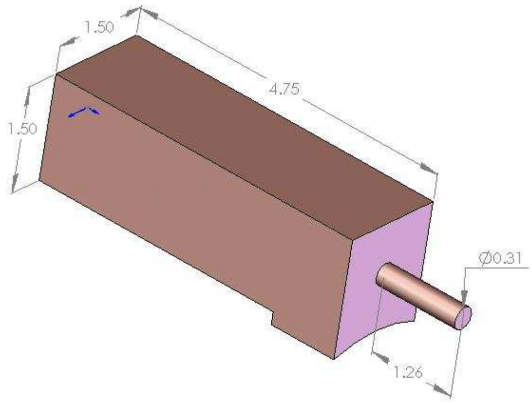

Fig. 38. DC gear motor

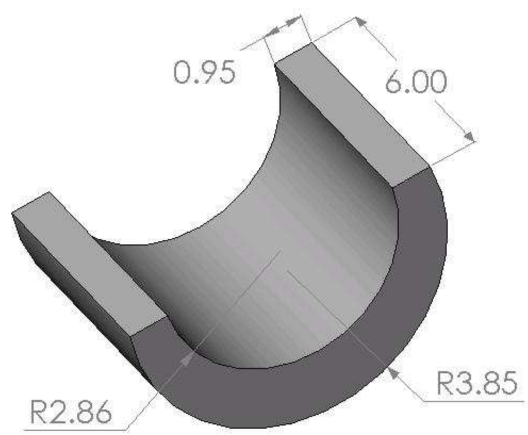

Fig. 39. Electric battery pack

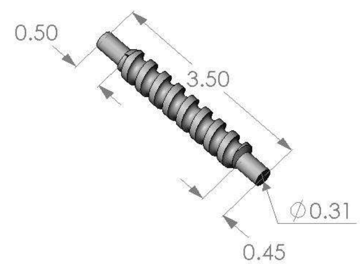

Fig. 40. Worm wheel

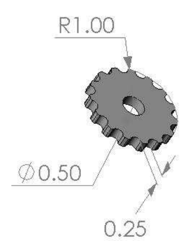

Fig. 41. Worm gear

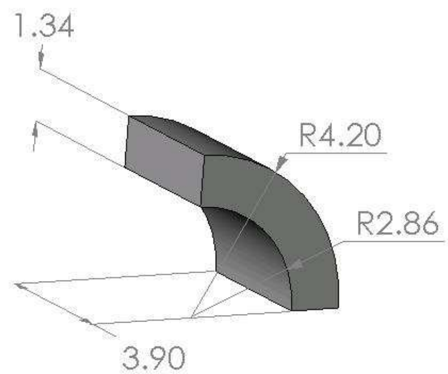

Fig. 42. Gear box to house worm wheel and worm gear

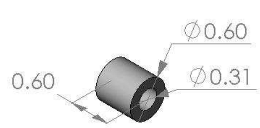

Fig. 43. Coupling to couple motor shaft and worm wheel

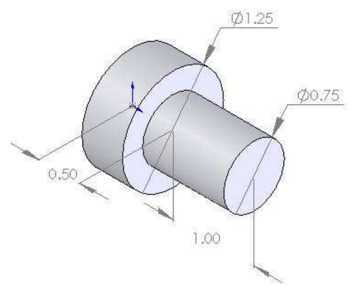

Fig. 44. Pressure transducer

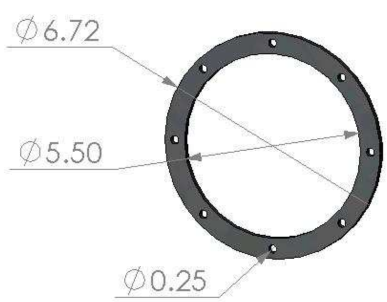

Fig. 45. Gasket for pig body 3

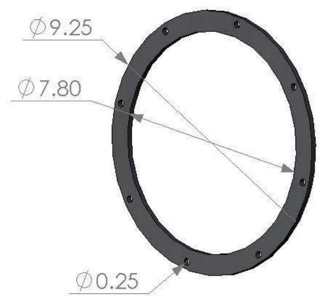

Fig. 46. Gasket for pig body 1,2

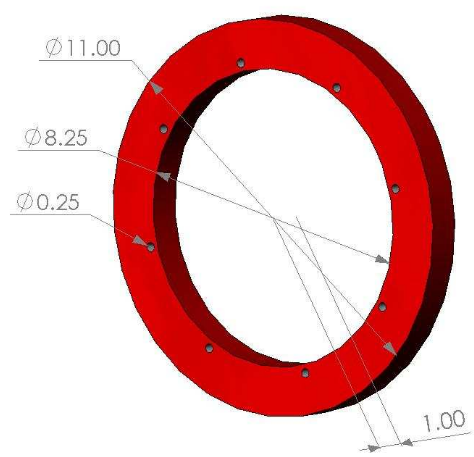

Fig. 47. Scraper discs

VITA

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