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TITLE PAGE

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Design of Contraflow Cleaning PIG for Pipeline Maintenance

By

Kresnajaya Prasetia Pancakarsa

A THESIS

SUBMITTED TO THE POSTGRADUATE STUDIES PROGRAMME

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MECHANICAL ENGINEERING

BANDAR SERI ISKANDAR,

PERAK,

MARCH, 2009

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

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Date : 16th March, 2009

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ABSTRACT

Conventional Pipeline Inspection Gauge (PIG) is a device used to remove solid deposit from the pipeline wall and driven by the fluid flow. For single offshore pipeline application, it needs to be launched from the manifold at the seabed which has drawbacks on the water depth restriction and requires intervention from the surface to launch the PIG. The current trend on the PIG design to overcome this challenge is to develop a counter flow PIG for single offshore pipeline application which is unequipped with the PIG launcher at the manifold.

Two of the commercial counter flow prototypes are contraflow tetherless mechanical crawler developed by the Astec Development Ltd. which has a drawback of poor traveling speed and Durham Pipeline Technology (DPT) crawler developed by University of Durham which has a drawback of discontinued motion. In this research, it is focused on the generation of a model of PIG with the function of wax removal. The requirement of the PIG design includes the ability to travel in both forward and reverse direction at a constant speed. In order to come out with the expected results, the scope of the research work is limited to the generation of the conceptual design of the PIG, product architecture and configuration design defined of the proposed concept and generation of Computational Aided Design (CAD) model of the proposed concept.

A systematic design based on Dieter's approach is adopted to design a PIG. It consists of conceptual and embodiment phases. In the conceptual design phase, the PIG design starts with problem definition, generating number of possible concepts using functional decomposition method and selecting the most promising concept using concept screening method. The most promising concept of PIG design consists of five modules, specifically: drive mechanism, turbine for drive mechanism, flow control, turbine for wax removal and wax removal module. Furthermore, a layout and configuration of critical components of the most promising concept is performed in the embodiment phase.

The PIG is designed with reference to the product design specification document of the pipeline operating condition of pressure of 15 MPa, fluid velocity of 1 m/s and a pressure drop across the PIG of 31 kPa. The PIG design begins with the analysis of the impeller to determine the maximum power that can be generated from the fluid flow. The turbine module has a function to provide power to drive the drive mechanism and the wax removal module. Dimension of the impeller that can generate maximum power is calculated based on the meridional and cascade flow analysis. Furthermore, to ensure the valid assumption of the design parameter that is used to determine the dimension of the impeller, a CAD model of impeller is simulated using the Fluent software.

In order to travel in a constant speed, the turbine for drive mechanism module is attached with flow control module which uses a perpetual mechanism of a poppet valve and a spring in the crawling mode and a magnetic mechanism in the return mechanism. For the drive mechanism device, a cam follower with bristle is used in the PIG design. The calculation of the cam follower mechanism follows the bristle theory that has been developed by Stutchbury. For wax removal, a cutting tool is used in the PIG design where the design of the cutting tool refers to the cutting tool standard used for machining process.

Based on the preliminary analysis, the PIG design can move in a counter flow at speed of 0.03 m/s with the time ratio between the PIG movements in forward direction and stationary condition of 4.28. The PIG design can remove wax solid deposit with a maximum shear strength of 81 kPa. The outcome of this research is an assembly drawing of the PIG design.

ABSTRAK

Pipeline Inspection Gauge (*PIG*) konvesional merupakan alat digerakkan oleh aliran cecair untuk mengasingkan sisa pepejal daripada sistem paip. Untuk aplikasi sistem paip pesisir pantai, alat ini perlu dilancarkan bermula dari *manifold* di dasar laut yang bergantung kepada kedalaman laut dan memerlukan perantaraan daripada permukaan laut untuk melancarkannya. Rekaan terkini *PIG* untuk mengatasi masalah ini ialah membangunkan aliran balas *PIG* untuk aplikasi sistem paip pesisir pantai yang tidak dilengkapi dengan pelancar *PIG* pada *manifold.*

Dua prototaip aliran balas komersial iaitu *contraflow tetherless mechanical crawler* yang dibangunkan oleh Astec Development Ltd. mempunyai kelemahan pada kelajuan rendah manakala *Durham Pipeline Technology* (*DPT*) *crawler* pula dibangunkan oleh Universiti Durham mempunyai kelemahan gerakan tidak tetap. Kajian ini memfokuskan penghasil model *PIG* dengan fungsi penyahbuangan wax. Rekaan *PIG* ini berkebolehan untuk bergerak ke depan dan mengundur dengan kelajuan sekata. Skope kajian ini dihadkan kepada penghasilan rekaan konsep *PIG*, arkitektur produk dan rekaan konfigurasi yang menekankan kepada cadangan konsep dan penghasilan model *Computer Aided Design* (*CAD*).

Rekaan *PIG* ini diadaptasi daripada pendekatan rekaan Dieter. Rekaan ini merangkumi dua fasa iaitu konsep dan implimentasi. Fasa rekaan konsep, rekaan *PIG* ini bermula dengan definisi masalah, kemudian penghasilan beberapa konsep penyelesaian masalah menggunakan kaedah *functional decomposition.* Pemilihan konsep yang paling menyerlah dilakukan menggunakan kaedah penyaringan. Konsep *PIG* ini merangkumi lima modul iaitu mekanisme pacuan, turbin untuk mekanisma pacuan, kawalan aliran, turbin untuk penyahbuangan *wax* dan sistem penyahbuangan *wax.* Susunan dan konfigurasi, komponen kritikal dalam konsep yang paling menyerlah dilakukan dalam fasa implimentasi.

PIG ini direka berdasarkan spesifikasi rekaan sistem paip yang beroperasi menggunakan tekanan 15 MPa, kelajuan aliran sebanyak 1 m/s dan tekanan turun sepanjang PIG sebanyak 31 kPa. Rekaan *PIG* ini bermula dengan analisis *impeller*

untuk menentukan kuasa terkuat yang boleh dihasilkan oleh aliran cecair. Modul turbin berfungsi untuk menyediakan kuasa untuk memacu mekanisma pacuan dan penyahbuangan *wax*. Dimensi *impeller* untuk menghasilkan kuasa terkuat dikira berdasarkan *meridional* dan *cascade* analisis cecair. Selain itu, parameter rekaan yang digunakan untuk menentukan dimensi *impeller* adalah berdasarkan pensian Fluent.

Turbin untuk mekanisme pacuan dipasang bersama kawalan aliran modul untuk memastikan kelajuan sekata yang menggunakan mekanisme perpetual injap poppet bersama *spring* di dalam modul *crawling* dan mekanisme *magnetic* dalam mekanisme pembalikan. Untuk alat mekanisme pacuan, *cam follower* dengan *bristle* digunakan untuk rekaan *PIG*. Pengiraan mekanisme *cam follower* berdasarkan teori *bristle* yang dibangunkan oleh Stutchbury. Penyahbuangan *wax*, alat pemotong digunakan berdasarkan standard yang digunakan dalam proses mesin.

Berdasarkan analysis awal, rekaan *PIG* boleh digunakan dalam aliran balas dengan kelajuan 0.03 m/s dengan nisbah masa antara pergerakan PIG ke depan dan keadaan statik sebanyak 4.28. Rekaan *PIG* juga menyahbuang sisa *wax* dengan kekuatan maximum 81 kPa. Hasil daripada kajian ini ialah lukisan penuh rekaan *PIG*.

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ABBREVIATION

ANSI	American National Standards Institute
APE	Asphaltene Precipitation Envelope
CAD	Computer Aided Design
DPT	Durham Pipeline Technology
HSS	High Speed Steel
MFL	Magnetic Flux Leakage
NACA	National Advisory Committee For Aeronautics
PDS	Product Design Specification
PIG	Pipeline Inspection Gauge or Pipeline Inspection Gadget
WAT	Wax Appearance Temperature

NOMENCLATURE

A	Pole area
A_S	Poppet valve area
b	Number of disc
B_r	Residual flux density
B_x	Residual flux density at a distance X_V
c	Impeller length chord
c_I	Distance from neutral axis to the point of interest
C_A	Axial velocity of fluid
C_{bh}	Number of bristle required on a drive mechanism housing
C_{bn}	Number of bristle required on a nut
C_D	Drag coefficient
C_L	Lift coefficient
C_{U1}	Inlet whirl velocity of fluid
C_{U2}	Outlet whirl velocity of fluid
d_w	Depth of cut
D	Maximum diameter blade
D_d	Damping coefficient for turbine and shaft
D_I	Inner diameter of pipeline
D_{ID}	Inner diameter of disc
D_n	Damping coefficient of the nut
D_m	Damping coefficient of the PIG design
D_M	Mean diameter of wax deposit
D_{OD}	Outer diameter of disc
D_s	Specific diameter of turbine
D_V	Orifice diameter
E	Modulus young
F_A	Axial force generated by the turbine
f	Feed
f_d	Friction force between the disc and pipeline wall
f_m	Friction force between the bristle and pipeline wall
f'_m	Total friction of bristle on a drive mechanism housing

f_n	Friction force of the nut against the pipe
f'_n	Total friction of bristle on nut in reverse direction
F_{AM}	Attractive force exerted by a magnet to a ferromagnetic material
F_b	Frictional force between PIG and pipeline wall
F_B	Reaction force generated by the nut
$(F_B)_P$	Reaction force on the thread
F_C	Maximum cutting force
F_P	Propulsion force generated by the thread when nut moving forward
$(F_P)_P$	Propulsion force generated by the thread when PIG moving forward
F_s	Breaking force of wax
F_S	Force acting on a poppet valve due to the pressure difference
F_t	Total force generated by the utility PIG
$(F_T)_E$	Axial force on the certain element of impeller
$F_{\Delta P}$	Propulsion force from the pressure drop across the poppet valve
F_{ws}	Frictional force between the wax plug and wax deposit surface
h	Length of bristle
H	Head
I	Moment inertia
I_d	Moment inertia of turbine and shaft
K	Mode of Euler buckling theory
K_S	Spring stiffness
l	Pitch of the screw
L	Length of screw
L_M	Magnetic length
L_S	Free length of spring
m_m	Mass of the PIG design
m_n	Mass of the nut
n_{HG}	Ratio reduction of harmonic gear
M	Bending moment
N	Number of impeller
N_d	Normal reaction force on the PIG disc
N_s	Specific speed of turbine
OD	Outside diameter of spring

P_1	Inlet pressure
P_2	Outlet pressure
P_{cr}	Critical compression length
P_T	Power generated by the turbine
Q	Volume flow rate
r	Radius from turbine axis to a certain element of impeller
r_b	Radius of bristle
r_d	Radius of shaft
r_M	Inner radius of ring shaped magnet
R_M	Outer radius of ring shaped magnet
R_H	Hub diameter of impeller
R_R	Resultant force in forward direction
R_{RF}	Ration of traction force to push bristle in reverse and forward direction
R_T	Tip diameter of impeller
R_H/R_T	Hub to tip diameter ratio
R'_A	Axial thrust in reverse direction
R'_R	Resultant force in reverse direction
t_m	Time of the PIG design to travel in one cycle motion
t_n	Time of nut travel along the entire length of double screw
T	Total torque acting on the impeller
T_B	Reaction torque generated by the nut
$(T_B)_P$	Reaction torque generated by the thread
$(T)_E$	Torque acting on the certain element of impeller
T_F	Torque required by the drive mechanism module when nut moving forward
$(T_F)_P$	Torque required by the drive mechanism module when PIG moving forward
U	Impeller speed at certain radius
U_r	Disc oversize to the pipeline diameter
V_f	Fluid velocity
v_n	Velocity of the nut
v_p	Velocity of the PIG design
W	Relative velocity of velocity

W_1	Relative velocity at the inlet
W_2	Relative velocity at the outlet
X_V	Compression length of poppet valve
β_1	Inlet fluid angle
β_2	Outlet fluid angle
β_M	Mean fluid angle
ρ	Crude oil density
η	Hydraulic efficiency
$\mu.R_N$	Friction force in forward direction
$\mu.R'_N$	Friction force in reverse direction
μ_{s1}	Sliding friction between the disc and pipeline
μ_{s2}	Friction coefficient between bristle and pipeline
φ	Friction angle perpendicular to the normal reaction force
ω	Rotational speed of turbine
ω_w	Rotational speed of wax deposit removal shaft
ω_{DM}	Rotational speed of drive mechanism when nut moving forward
$(\omega_{DM})_P$	Rotational speed of drive mechanism when PIG moving forward
ω_W	Rotational speed of wax removal tool
γ	Bristle tip angle
ΔP_T	Pressure drop across the PIG
Δz	Width of each impeller

CHAPTER ONE: INTRODUCTION

1.1 Introduction

The increasing demand of hydrocarbon in the world leads oil companies turn to the deepwater prospect. In the deepwater technology, exploration is carried out in water depth between 200 meter and 1000 meter [1]. Crude oil as a product of exploration is transported from the subsea wellhead to the platform through a manifold, a jumper, a gathering lines and a riser designed to withstand on the subsea temperature, pressure and current as shown in Figure 1-1.

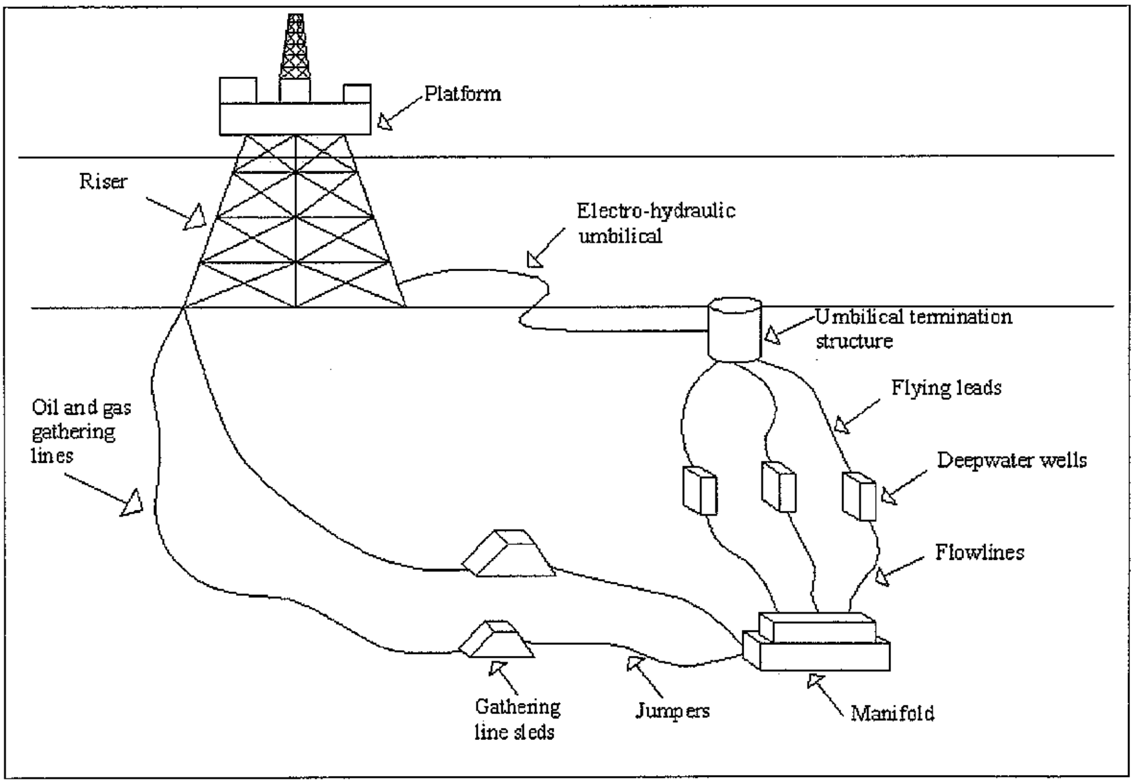


Figure 1-1: Subsea system architecture [2].

However, there is a problem in transporting crude oil from a subsea well to a platform. The change of crude oil pressure and temperature as it travels from the deepwater well to the platform can lead to the deposition of asphaltene, wax, hydrate and scale. These depositions restrict the flow of crude oil due to the reduced inner diameter of pipelines. To compensate the reduced diameter effect, the pump capacities must be increased. Thus, it yields higher operation cost [3].

There are several methods that have been developed by oil companies to limit the deposit formation, i.e. chemical treatment, pipeline insulation, and pigging. For large subsea pipelines, the use of chemical treatments such as solvent and dispersant to mitigate the solid deposit especially wax is generally not practical [4]. Solvent for solid deposit removal must be concentrated and given sufficient contact time to be effectively worked. This can be done by continuously injecting solvent to the pipeline which increases the maintenance cost. Another method is by insulating or heating the pipeline to maintain the temperature of crude oil in the range where the deposit cannot be formed. However, applying insulation or heating methods to the existing subsea pipeline requires high cost [4]. The most common way used by the oil companies to control this deposit is by running regular pigging program.

A utility or a cleaning PIG (Pipeline Inspection Gauge) is inserted into subsea pipelines by pressuring the PIG launcher. Then, fluid flow drives the PIG to travel through the entire length of the pipelines. At the end of the pipelines, there is a PIG receiver to retrieve the PIG. The utility PIG removes solid deposit by physically scraping solid deposit from the pipelines wall and pushes it to the end of the pipelines. The drawbacks of utility PIG are [3]:

a. The cleaning force used to remove solid deposit is not actively generated. Instead, it is a result of scraping effect between the pipeline inner wall and the PIG cleaning element. Therefore, the efficiency of deposit removal depends on the PIG velocity and the hardness of cleaning element. Normally, the PIG travel at speed about 1 to 5 m/s for liquid pipelines and 2 to 7 m/s for gas pipelines [5]. This requirement often can not be fulfilled by the normal operation flow from the well which results the need of a large pumping system.
b. The utility PIG is at the risk of becoming stuck due to the heavy block of accumulation wax removal. Typically, the utility PIG remove the solid deposit by pushing it and the wax removal will accumulate in front of the PIG. In case where the PIG diameter is not correct chosen or the different prediction of solid deposit thickness, the PIG may get stuck inside the pipeline. In order to retrieve it, the pipeline operation needs to be adapted or interrupted. It means that the oil companies loss their production during the pigging operation.
c. The removed deposit is accumulated in front of the PIG and being pushed out of the pipeline as the PIG moving forward.

d. The utility PIG uses the fluid flow as a main propulsion source. Typically, it is not equipped with the driving main mechanism. As a consequence, it can move only in the same direction with the fluid flow.

A pipeline is designed based on the standard to allow a utility PIG to travel through the entire length of the pipelines. To be piggable, the pipeline should be more or less constant bore, sufficiently long radius bend, and equipped with the traps to launch and receive PIG [6]. However, it is commonly found that the pipeline is unpiggable due to over or under-sized valve, repair section in a different size, a short bend or unavailable traps.

In some subsea system like in Northern Sector of North Sea Shell Expro, the pipeline that are used for transporting crude oil from a well into a platform are single lines which is not equipped with a PIG launcher at the seabed [7]. The unavailability of PIG facility makes these pipelines are unpiggable. To use a utility PIG in doing pigging to this subsea system, it creates dilemma either to create extra pipelines to make a pigging loop system or to install the PIG launcher at the seabed which requires periodic and expensive intervention from a surface supported system.

One of the challenges in the PIG development in the next 10-20 years is to develop a PIG that can be deployed from the surface and uninterrupted the production [8]. PIG companies have developed counter flow PIG types as a solution for these challenges. The counter flow PIG has a feature of drive mechanism which makes it able to travel in a counter flow direction. It operates in the pipeline without tether and generates its own power by converting fluid flow into rotational energy. The use of fluid flow as a power source to drive a drive mechanism makes the counter flow PIG able to travel through the entire length of the pipeline. If the counter flow PIG faced an obstruction or reached at the end of the pipeline, it would automatically return to the initial point of launching. The benefits of counter flow PIG are uninterrupted production during pigging operation, reducing risk of the PIG being stuck inside a pipeline, and cost saving on the PIG facilities.

Currently, there are two types of counter-flow PIG prototypes that have been developed, specifically: contraflow tetherless pipeline crawler and DPT crawler. The contraflow tetherless pipeline crawler had been developed by Astec Development Ltd., which was later acquired by the Weatherford Company in 2002, for Shell. It consists of a turbine module using an axial blade, a tractor module using an offset bearing, a wax cutting module using a cutter and a return module using a poppet valve [7]. The drawback of this prototype is poor traveling speed and inactive friction force to remove solid deposit. Hu, Appleton and Durham Pipeline Technology also have developed the DPT crawler PIG that consists of a turbine module using an axial blade, a drive mechanism using a cam follower, and a task module using a brush [9]. It has drawbacks of discontinued motion and inactive force used to remove wax deposit.

1.2 Problem Statement

Oil companies have identified that pigging operation in single offshore pipelines would be advantageous by using bidirectional PIG types. The bidirectional PIG is launched from a PIG launcher at the surface and travels in a counter flow direction against the fluid flow. It is desired that the PIG extracts the power from the fluid flow and use it to move the PIG along the pipeline against the flow. While doing cleaning, it is desired that the cleaning force is actively generated by the PIG. This cleaning force will break down the wax deposit into a small chip which is able to be carried out by the fluid flow. Since the wax removal mechanism uses an active force, the PIG needs to travels at a constant speed. In case where the PIG travels at inconstant speed but uses the constant active force, it can produce different level of wax removal. Therefore, it is desired that the PIG travels at a constant speed while doing cleaning to ensure small chip of wax removal and the same cleaning efficiency through the entire length of the pipeline. As the PIG reaches at the end of the pipeline, the PIG automatically returns to the initial point of launching.

1.3 Objective of the Study

The objective of this research work is to produce a design model of PIG for wax deposit removal from offshore pipelines. The requirement of the PIG design includes the ability to travel in both forward and reverse direction at a constant speed.

1.4 Scope of Works

The deliverables of the research are:

a. The conceptual design of the PIG.
b. The product architecture and the configuration design of the proposed concept.
c. The CAD model of the proposed PIG design.

Since the scope of contraflow PIG design is big and the test rig is expensive for verification of prototype, the work is stop at the CAD model. The work currently has main focus on generation of several model counter flow PIG and understanding of working mechanism from each concept. For the verification of the proposed PIG design model is performed by using Fluent software and CATIA.

1.5 Methodology

A systematic design approach [10] is used to design a PIG for wax deposit removal from offshore pipelines. It consists of conceptual and embodiment phase as shown in Figure 1-2.

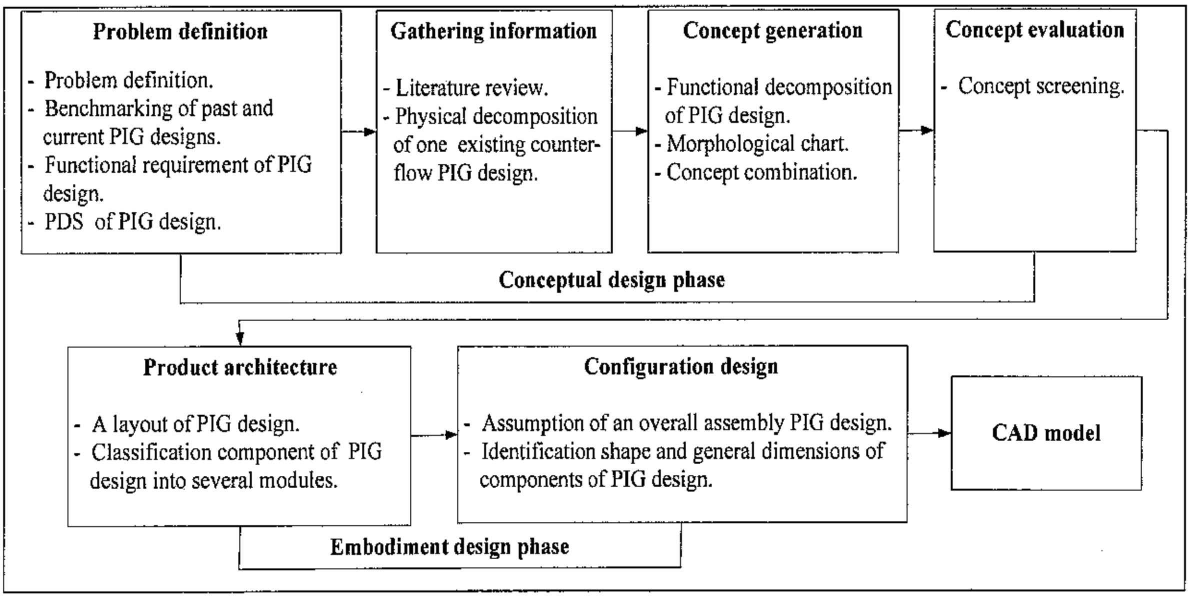


Figure 1-2: Overall methodology of PIG design [adapted from [10]].

Conceptual design phase is the phase where the PIG design is started, carried out to a point of generating a number of possible concept, and narrowed down to the most promising concept. It consists of defined problem, gather information, concept generation and concept evaluation step. The discrete activities under conceptual design phase are explained in the chapter five.

The most promising concept of PIG from conceptual design phase is transformed into a physical form in the embodiment phase. It consists of product architecture and configuration step. The detail activities in embodiment design phase are specified in the chapter five. At the end of the design process, the proposed design of PIG is represented in a CAD model.

1.6 Organization of Thesis

This thesis content consists of six chapters which are introduction, conventional PIG, counterflow PIG, methodology, result and discussion and conclusion. A systematic design approach method is adapted to meet the objective as described in the chapter one.

Chapter one describes background of this research that covers the current development in PIG design for offshore application. Furthermore, the objective and scope of this research work is defined in this chapter. The methodology that is used to design the PIG is described in this chapter.

Chapter two explains about problems in offshore pipelines and method that is used to handle these problems. In addition, a literature review of conventional PIG and also their limitation is discussed in this chapter.

Chapter three provides an extensive literature review of current PIG design for unpiggable pipeline. Furthermore, a challenge in PIG development for offshore pipeline is explained in this chapter.

Chapter four illustrates methodology that is used to design the PIG.

Chapter five describes the conceptual design and embodiment step in the PIG design. Several new of PIG concepts that can fulfill customer needs as stated in chapter three are generated. Furthermore, one of the PIG concepts is selected based on concept selection to be further developed in the embodiment step. An abstract concept of the proposed PIG design is then transformed into the physical form. In addition, the layout and general dimension of each module from the proposed PIG concept is explained. Furthermore, the final output of PIG design which is an overall assembly of the proposed PIG design is illustrated. In additional, capabilities and limitation of the proposed PIG design is discussed in this chapter.

Chapter six contains conclusion of this research and recommendations for further work.

CHAPTER TWO: CONVENTIONAL PIG

2.1 Introduction

Chapter two provides some selected literature reviews that relate to the PIG. Topics discussed in this chapter are offshore pipeline problem, method to prevent solid deposit, PIG and utility PIG.

2.2 Offshore Pipeline Problem

During transportation of crude oil from a wellhead into a platform due to the change in pressure and temperature, there will be a formation of solid deposition on a pipeline wall. To predict precipitation behavior of this solid deposit, a fluid sample is collected from the wellhead and analyzed. According to Amin et al. [11], the result from laboratories analysis of fluid sample indicates the phase boundaries of solid deposit that will precipitate from crude oil due to the change of pressure and temperature as shown in Figure 2-1.

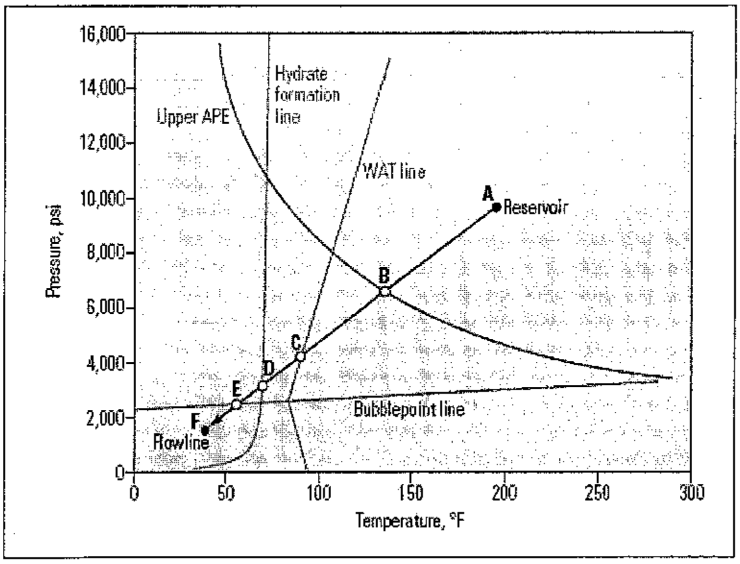


Figure 2-1: Oil phase diagram from deepwater field in Gulf of Mexico [11].

As the crude oil transported from a wellhead into a platform through an offshore pipeline, it follows a path of steadily decreasing pressure and temperature. Depending on the composition of the crude oil and operation of the production system, some or all the phase boundaries of solid deposit in the oil phase diagram may be passed. Types of solid deposit that can be formed on the pipeline wall are asphaltene, wax and hydrate. Each of them has own unique nature as explained below.

2.2.1 Wax

Paraffin is the common name for the alkane hydrocarbons with the general formula C_nH_{2n+2} [12]. Paraffin wax refers to the long chain paraffin with n=20-40 and has tendency to deposit on the pipeline wall [12]. At the reservoir pressure and temperatures condition, it remains dissolved with the produced crude oil. The solubility of paraffin wax in the crude oil decreases drastically with the decreasing temperature. Thus, it is easy for paraffin wax to precipitate out from the crude oil and deposit on the pipeline wall at the low temperature. It starts to precipitate out from the crude oil to form a solid wax phase when the crude oil temperature passes the Wax Appearance Temperature (WAT). The deposition process of wax deposit on the pipeline wall occurs slowly relative to the deposition process of hydrate [12, 13].

Yield strength of wax deposit can be varied in consistency from hard rock for the highest chain length paraffin to very soft like mayonnaises oil deposit. Factors that affect on the yield strength of wax deposit are wax contents on the deposit, cooling rate and shear stress applied to the deposit during solidification [14]. The range of yield strength of wax deposit is 300 to 2500 Pa [14].

2.2.2 Asphaltene

Asphaltene is a compound in the crude oil that is insoluble in n-pentane or n-hexane but soluble in toluene or benzene [12]. It remains soluble with the crude oil under the reservoir temperature and pressure condition. During transportation from a reservoir to a platform, asphaltene starts to precipitate when the pressure and temperature of crude oil across the Asphaltene Precipitation Envelope (APE). Compared to wax, asphaltene has a characteristic of hard and brittle [12].

2.2.3 Hydrate

Natural gas hydrate is formed when methane molecules, the primary component of natural gas, are trapped in a microscopic cage of water molecule under certain temperature and pressure [12]. As a general rule of thumb, methane hydrate will form in a natural gas system if water is available at temperature as high as 4.4°C and pressure as low as 1.17 MPa [15]. Natural gas hydrate can be formed on the pipeline wall as a solid or semi solid deposit. It has physical characteristics like ice and the range of yield stress of natural gas hydrate is 4 to 12 MPa [16].

2.3 Method to Prevent Solid Deposit

An offshore pipeline that is used to transport crude oil frequently suffers from deposition of asphaltene, wax or hydrate. As a consequence of the presence of these depositions on the pipeline wall, the operation cost is increasing as pump capacities need to be increased to compensate negative effects such as:

a. Reduction of the inner diameter of pipeline which leads to the flow restriction.
b. Increased of wall roughness.
c. Increased of oil viscosity.

Oil and gas industries have developed strategies to limit solid deposit formation and clean solid deposit of the pipeline wall. Several methods that are used to handle these deposition problems are:

a. Pipeline insulation.

   The solid deposit formation occurs when the crude oil temperature and pressure across the solid deposit boundary phase. One way to prevent the solid deposit formation is to keep the pressure and temperature of system in the region where the solid deposit is unstable by heating or insulation the pipelines. However, applying insulation or heating methods to the existing subsea pipeline requires high cost [4].

b. Chemical treatment.

   A chemical inhibition can be used to slow down the formation of solid deposit on the pipeline wall by injecting it into the pipeline. When the solid deposit already formed on the pipeline wall, a solvent is injected continuously to the solid deposit at a sufficient contact time. It makes the solid deposit dissolve with the product. However, the use of chemical treatment for subsea pipeline is costly [4].

c. Pigging

   Pigging is a standard operation performed by the oil companies to control a solid deposit formation by using a scraper device. The degree of successful of pigging operation depends on the hardness of the solid deposit. If the solid deposit is too hard, usually it will be soften first by using an solvent and then a PIG will be run to remove the solid deposit from the pipeline wall [17].

For a subsea pipeline where the hydrate is not main concern, pigging is normally the main strategy to handle wax deposition problem on the pipeline wall [12, 18]. Since the characteristic of hydrate is hard, conventional PIG is not recommended to remove hydrate due to the risk of being stuck inside the pipeline [19].

Theoretically, either chemical treatment or pigging alone should be adequate to control wax formation. In the actual pipeline operating condition neither one of these methods can guarantee a successful wax removal. This is especially true at the pipeline condition that carries crude oil with high cloud points, low flow velocities and high paraffin characteristic [5]. At this pipeline condition, the wax can be rapidly formed that make the use of chemical to disperse wax deposition is costly and the use of PIG is not enough to control the growth of deposition.

In this research, the literature review discusses more focus on the development of PIG that is used to remove wax on the offshore pipeline.

2.4 PIG

2.4.1 PIG Definition

The term of PIG was originally referred to a scraper driven by the fluid flow and attached with a rake to scrape wax off the pipeline wall. One of the tales about the origin name PIG came from the loud squealing noise that was created by the scraper while traveling through the pipeline [20]. The others say that the name is an abbreviation and stands for Pipeline Inspection Gauge or Pipeline Inspection Gadget [21]. Nowadays, pipeline operators describe the PIG as a device that travels through the pipeline for cleaning and other purposes. The process of driving the PIG through the pipeline by the fluid is called pigging.

2.4.2 PIG Classification

Although the PIG was originally developed to remove solid deposit on the pipeline wall which can restrict the flow, nowadays it is used during all phase in the life of pipeline. The type and frequency of PIG used through the each phase in the pipeline life is different. However, there are four main reasons for applying pigging which affect the selection of PIG types [5]:

a. For displacement or cleaning purposes.
b. For batching or separating dissimilar products.
c. For surveying or inspection of the pipeline.
d. For maintenance of the pipeline.

The types of PIG used to accomplish these tasks can be classified into [12]:

a. Utility PIG which is used to perform function such as cleaning, separating or dewatering.
b. Gel PIG which is used with conventional PIG to optimize pipeline dewatering, cleaning and drying task.
c. In-line inspection tool which is used to provide information about the condition of pipeline as well as area and location of the problem.

Since there is a wide variety of PIG available for a range of purpose, the literature review of PIG is focused only to utility PIG which has the function of removing wax from the pipeline.

2.5 Utility PIG

2.5.1 Utility PIG Classification

Utility PIG can be divided into two groups according to their function [12]:

a. Cleaning PIG is used to remove solid deposit from the pipeline.
b. Sealing PIG is used to provide a good seal between the PIG and pipeline either to sweep liquid from the pipeline or to separate two dissimilar products.

There are various types of utility PIG that can be used to remove wax. The most common used are foam, sphere, solid cast and mandrel as shown in Figure 2-2.

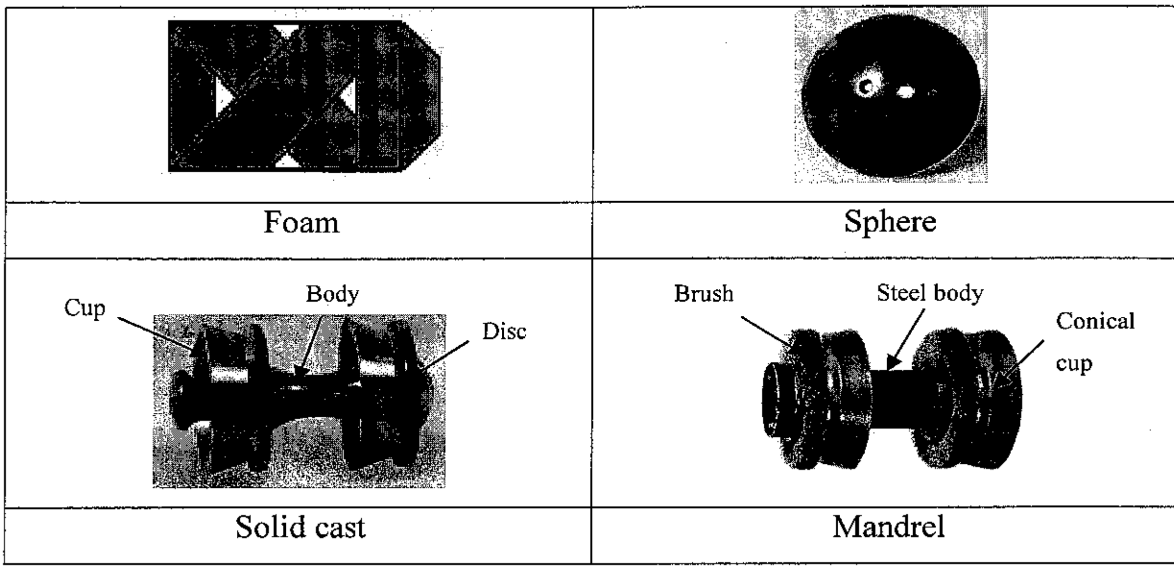


Figure 2-2: Type of utility PIG [22].

a. Foam PIG

A foam PIG is made from open cell polyurethane foams of various densities ranging from light, medium to heavy density. It is normally manufactured in a bullet shape. The foam PIG is used for light cleaning application where the condition of pipeline is uncertain [4]. The disadvantages of foam PIG are only used in one times, shorter length of run and high concentration of some acids will shorten its life [12].

b. Sphere PIG

A sphere PIG is either a solid composition or inflated sphere which is filled with water or glycol to inflate into the desired size. Typically, the sphere PIG is used for a pipeline that has not been designed to accept a standard PIG or a gas gathering system to remove liquid hydrocarbon and water [20]. However, it is inefficient to remove wax from the pipeline [12].

c. Solid cast

A solid cast PIG is usually made from polyurethane which is high-strength and abrasive resistant elastomer [20]. Typically, it is constructed as a single PIG which consists of a body and either a cup, a disc or a combination of cup and disc. It is often used for batching, displacement and cleaning purposes due to characteristic of solid cast PIG that are economical, durable and long length of run [12].

d. Mandrel PIG

A mandrel PIG is normally constructed with a central body tube that can be configured with various components for specific applications. It is used for batching, displacement and cleaning [21]. The function of cleaning is performed by the mandrel PIG due to the positive interference between a disc or a cup of the mandrel PIG and the pipeline wall which imparts a cleaning action on the pipeline wall.

Cleaning performance can be further enhanced by adding a brush, a scraper or even more aggressive tools to the mandrel PIG. For the pipeline where ferrous debris is presence, a magnet is attached to the utility PIG to pick up this ferrous debris. Figure 2-3 shows cleaning elements that is often used to enhance the cleaning performance of utility PIG.

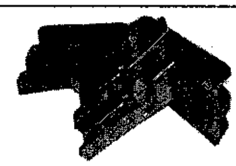
 Brush [23]	 Plough [23]
 Cutter [7]	 Magnet [24]

Figure 2-3: Cleaning element.

2.5.2 Pigging Operation Procedure

In order to be compatible with pigging operation, a pipeline must be designed with a full bore valve and equipped with a PIG launcher and receiver at the end of the pipeline [25]. The launcher and receiver consists of a quick opening closure to insert and retrieve the PIG, an oversize barrel, a reducer and a neck pipe for connection with the pipeline as shown in Figure 2-4.

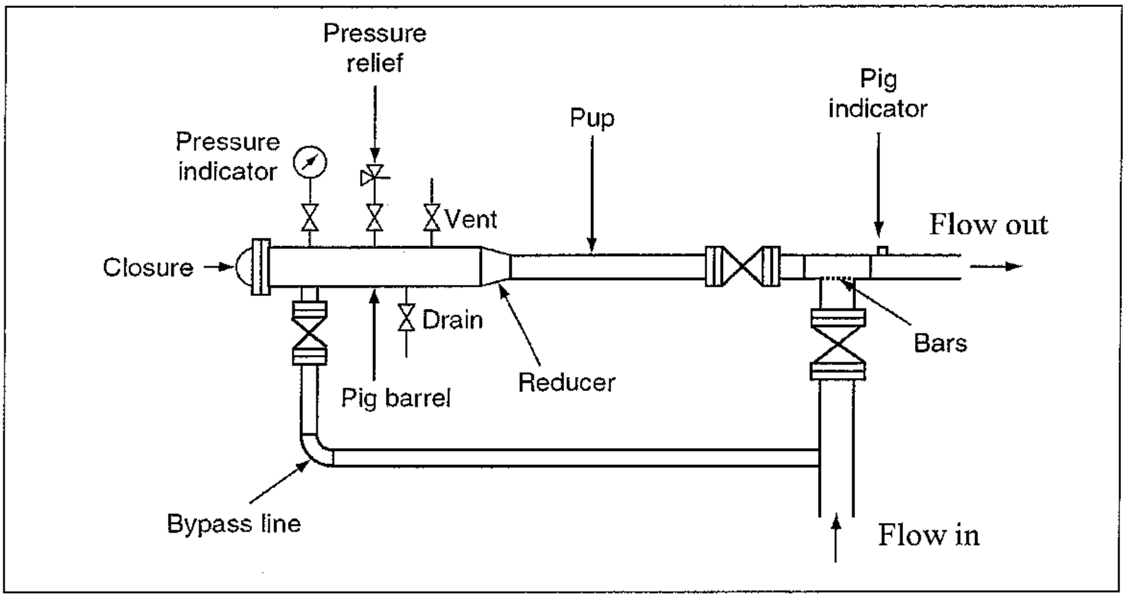


Figure 2-4: A typical configuration of a pig launcher for liquid service [12].

A utility PIG is inserted to the PIG launcher. The utility PIG is designed that a sealing element always provides a positive interference with the pipeline wall. As a result, when the PIG launcher is pressurized, the utility PIG is forced to enter the pipeline. Once it is inserted into the pipeline, the utility PIG is driven by the fluid flow and moves in the same direction with the fluid flow. At the end of the pipeline, the utility PIG is retrieved at a PIG launcher. Figure 2-5 illustrates the working principles of utility PIG.

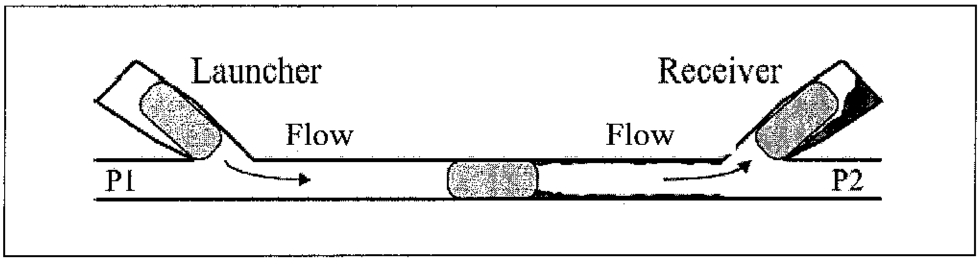


Figure 2-5: Working principle of utility PIG [21].

To clean a pipeline by pigging, it is required to gather as much as possible operational data to determine the nature and amount of solid deposit inside the pipeline. Once, the data such as temperature, pressure, flow rates, product chemistry, pipeline geometry features and pigging history had been obtained, the pigging operation can be started. Most of cleaning program can be divided into two distinct operational phase, particularly: capability pipeline being pigged with a cleaning tool and carried out pipeline pigging with this cleaning tool [17]. The first phase is performed by running a foam PIG with various foam densities. After that, the use of cleaning tool that becomes more and more aggressive is used in the second phase. The types of cleaning tool that is used in the second phase are a metal body attaching with either cups or disc. If it required, such as to remove hard wax, the metal body can be attached with scrapper blades, studs, pin or metal disc.

2.5.3 Wax Removal Mechanism

Investigation of wax removal mechanisms by a utility PIG on a pipeline wall is performed through the experiment [26]. The total forces generated by the utility PIG during wax removal process (F_t) can be divided into three components: the frictional force between the PIG and the pipeline wall (F_b), the breaking force of wax (F_s) and the frictional force between the wax plug and wax deposit surface (F_{ws}) as shown in Figure 2-6.

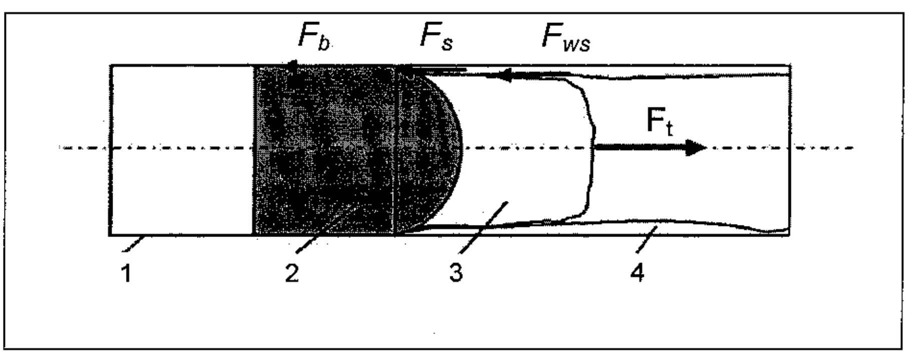
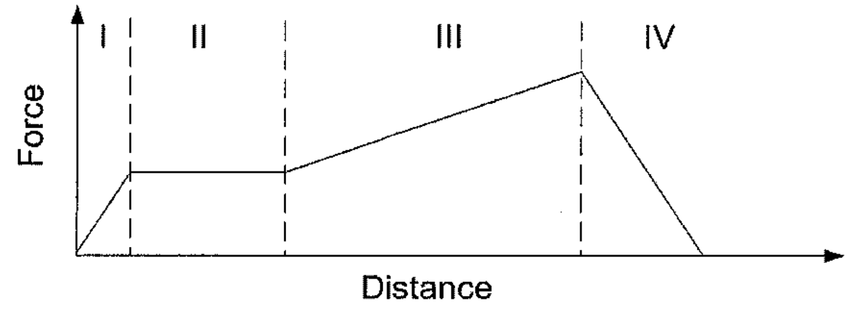


Figure 2-6: Force acting on the PIG [26].

Wax removal process by a utility PIG consists of four phase: wax breaking, plug formation, accumulation and production phases as shown in Figure 2-7 [26]. When the PIG is launched, initially, it breaks up the wax deposit on the pipeline wall as indicated by the increasing force in the build up phase. As the PIG moves forward, the broken wax starts to accumulate in front of the utility PIG and starts to form a plug as indicated by a constant force in the pre-plug phase. Once the broken wax fills up the entire cross section of the pipeline, it is considered as a condition where a wax plug is formed. The broken wax continues to accumulate in front of the PIG which results in increasing the length of wax plug as indicated by the increasing force in the build up phase. When the accumulated wax reaches the end of the pipeline, it begins to reduce as indicated by the reducing force in the production phase.



I).Build up phase, II).Pre-plug phase, III).Plug phase, IV).Production phase.

Figure 2-7: Typical force generated by utility PIG versus the distance behavior [26].

2.5.4 Drawback of Utility PIG

Eventhough a utility PIG design has been evolved over the years; the current utility PIG design has still the following drawbacks.

a. Efficiency of solid deposit removal depends on the PIG speed.

   The cleaning force used to remove solid deposit is not actively created by the utility PIG. It is a result of friction force between the cleaning element and the pipeline wall which scrapes solid deposit off from the pipelines wall. Thus, the cleaning force depends on the utility PIG velocity and the hardness and shape of cleaning element [3, 26, 27].

   The faster the utility PIG moves, the higher the cleaning force is being applied to the solid deposit but at the same time only a thin deposit layer is removed. To remove a thick deposit on the pipeline wall, several utility PIG with different diameter need to be run.

b. Risk of PIG being stuck

   Typically, broken deposit accumulates in front of the utility PIG. This deposit accumulation is pushed by the utility PIG as it moves forward. The longer pipeline or the thicker deposit, the more deposit accumulates in front of the utility PIG. In the case where the utility PIG diameter is not correctly chosen or the pipeline contains deposit thicker than predicted, the utility PIG is at risk of being stuck due to heavy block of deposit in front of it. As a consequence, several utility PIG with different diameter need to be run for safely deposit removal.

c. Interrupted production during pigging process.

   Various utility PIG work optimal when traveling at 1 to 5 m/sec for liquid pipelines and 2 to 7 m/sec for gas pipelines [5]. It can not be achieved by using normal flow production from a wellhead. As a consequence, while doing pigging process, the production flow need to be adapted in order to conduct an appropriate pigging procedure. In worst case, the pipeline operation needs to be stop to rescue a stuck PIG by reversing the fluid flow. This kind of interruption to the pipeline operation during pigging needs to be limited to a minimum level to avoid economic losses.

Until 1994, it is estimated that there are over 300 utility PIG types available in the market from at least 25 different manufacturer [27]. It has been developed from a simple form of sphere into complex shape such as a metal body attaching with the cleaning equipment. Development of this type of PIG can be considered relatively low cost and low technology devices. One of the current developments from utility PIG is Hydraulically Activated Power PIG (HAAP™) developed by HAPPP technology Ltd. The HAAP™ construction consists of three units: a brake unit, a seal unit and the cleaning head [3] as shown in Figure 2-8.

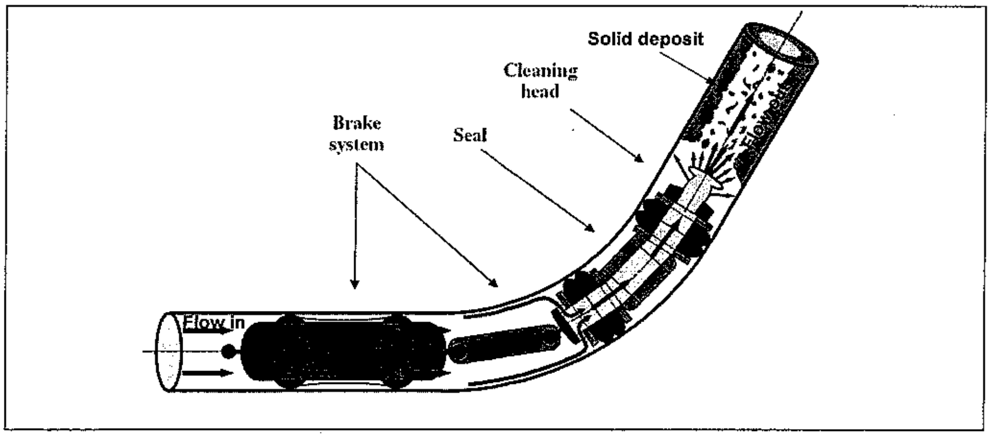


Figure 2-8. Construction HAAP™ [3].

The HAAP™ mechanism still uses fluid flow as a drive source which makes it only able to travel in the same direction with the fluid flow. All of the unit have opening which make the flow able to pass through the pipeline. The pressure drop is generated because seal and cleaning head pose a flow restriction. In a cleaning nozzle head unit, the fluid is accelerated to create a powerful liquid jet which is used to remove solid deposit on the pipeline wall. The advantages of this cleaning mechanism are to reduce wax removal accumulation in front of PIG and bigger cleaning force produced. To control the PIG speed, the HAAP™ is equipped with the brake system. It is claimed by HAPPP technology Ltd that the HAAP™ can be traveled up 60 times slower than the fluid velocity [3]. The capability to maintain the HAAP™ at a constant speed ensures that the cleaning efficiency remains the same from the beginning to the end of the pigging process.

It is suggested that the capability of PIG to travel in bidirectional can be achieved by adding an internal power source module such as a turbine or a motor and a drive mechanism module such a crawler and an incline wheel. Currently, the HAAP™ uses fluid flow as a power source to drive the PIG. Therefore, it can only travel in the same direction with the fluid flow.

As the utility PIG design becomes a matured technology, current PIG designs trend are to develop appropriate PIG for unpiggable pipeline.

2.6 Intelligent PIG

The intelligent PIG has functions for surveying a pipeline to detect a buckle and dent inside a pipeline and to measure pipeline thickness [5]. Since the intelligent PIG must capture the geometry and position data from the pipeline, the pipeline condition must be free from solid deposit on the pipeline wall before running the intelligent PIG. Therefore, the utility PIG must be run first to clean solid deposit from the pipeline. In order to get the accurate data, during intelligent PIG running, it needs to travel at a constant speed [28]. Some sensor that usually uses for surveying the pipeline are Magnetic Flux Leakage (MFL), ultrasonic, caliper survey and video camera [5].

CHAPTER THREE: CONTRAFLOW PIG

This chapter provides a review of current PIG development. An overview about some PIG design development for unpiggable are discussed. In addition, an extensive literature review of counter flow PIG development for unpiggable offshore pipeline is also discussed in this chapter.

3.1 PIG Design Development for Unpiggable Pipeline

A piggable pipeline is a pipeline that is designed to allow a standard PIG to travel through the entire length of the pipeline. Some of obstacles that can make the standard PIG would not be able to negotiate it are [29] :

a. Physical obstacles

   There are many of physical obstacles in the piping network that makes pigging become impossible such as:

   1. Bends/elbows (90°) with bend radius less than 1.0-D.
   2. Mitered joints/elbows greater than 10°.
   3. Reduced port valves.
   4. Reduction/expansion in pipe diameter greater than 50-mm (2-in).
   5. Unbarred branch connection.

b. Flow obstacles

   The pigging process depends on the availability pressure to push the PIG through the pipeline. The pressure level must be sufficiently great to overcome the pressure drop across the PIG and its association pipe friction force. Typically, it needs several hundreds PSI line pressure to drive the utility PIG. Unfortunately, not all the operation utility works at high pressure to support the pigging process.

c. Other considerations

   Some considerations that must be considered are the length of pipeline and the availability of PIG launcher and receiver. Some of pipelines are only short pipeline in the length of two miles which is not equipped with the PIG launcher and receiver.

There are two solutions that make the pipeline becomes piggable. The first option is to modify the pipeline so it becomes piggable in the end. However, this option in most case is not easy to implement. It requires interrupting pipeline operation to replace the unpiggable pipeline element which resulting in expensive cost. Another option is to develop a PIG that is able to travel in the unpiggable pipeline. Some of developments of the PIG design to overcome the unpiggable pipelines are discussed below.

a. Unpiggable due to reduced port valves.

Foster-Miller and GE Energy have developed a conceptual design of PIG that can travel through a reduced port valve as shown in Figure 3-1 [29]. It had capabilities to operate in both forward and reverse directions, as well as navigate through a smooth bend, a mitered bend and an unbarred branch connection. The Roboscan is designed to detect the corrosion in pipeline with diameter range about 12 to 24 in, pipeline velocity of 20 fps and pressure of 350 psig. The desired velocity of Roboscan for the inspection purpose is 30 ft/min.

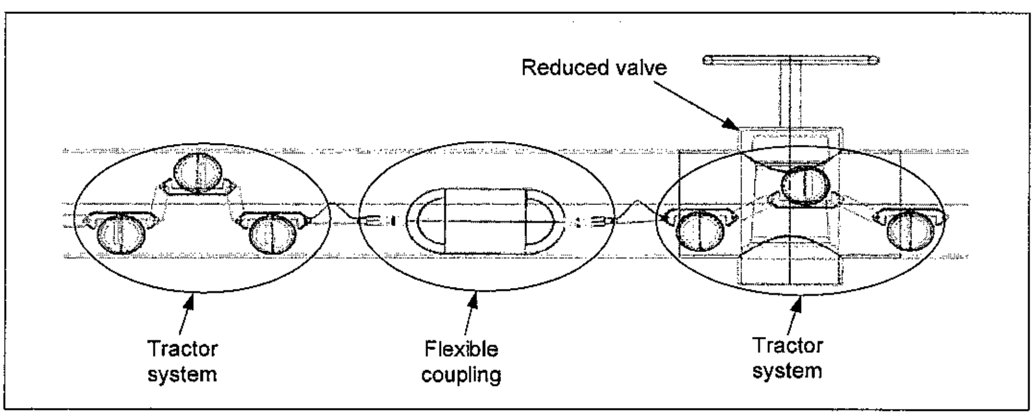
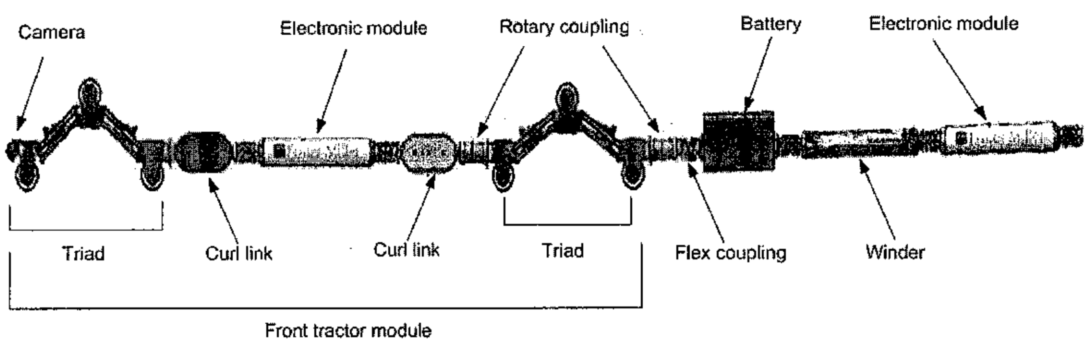


Figure 3-1: Roboscan inspection robot for unpiggable pipelines [29].

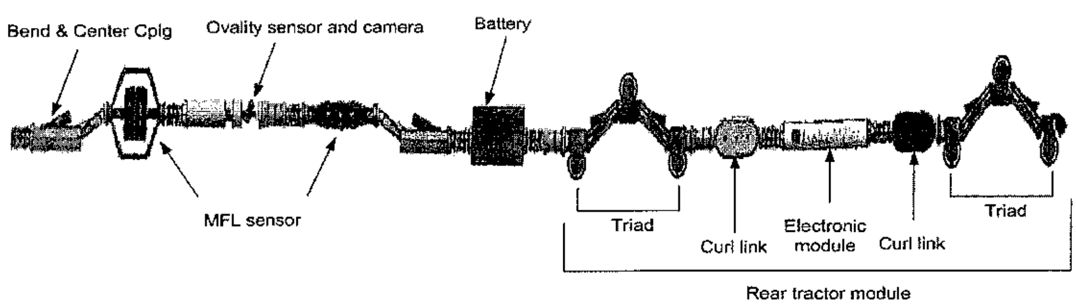
The Roboscan inspection robot consists of two tractor modules, one is at the front of PIG and the other is at the rear of PIG, two batteries modules, MFL sensor, ovality sensor and camera as shown in Figure 3-2. This Roboscan can travel through the entire length of the pipeline in both forward and reverse direction by using a bidirectional drive motor at each wheel on the four triads.

A fundamental feature of each triad is the ability to contract and extend within the pipeline wall. This triad mechanism consists of a four bar linkage which is actuated by a motor that cause each triad to independently contract or extend by shortening the triad wheelbase. The motion of the four bar linkage is controlled via a force feedback loop based on a load cells sensor located in each of the three wheels on each triad. Application of this type of PIG is for a short gas transmission pipeline where the operating pressure is low [29].

It is suspected that the Foster-Miller and GE Energy can improve by their design by adding an internal power source such as a turbine to overcome limitation of the internal battery as a power source. Currently the design uses the internal battery as a power source which makes the PIG can only travel in a certain distance. It is suggested also to use a composite material which has characteristic of light and fatigue resistance on the triad assembly. Since the component on the triad assembly always contract or extend, it can be fatigue after several times use. To overcome this problem, a composite material which are light and fatigue resistance can be used.



In front section of Roboscan



Rear section of Roboscan

Figure 3-2: Detailed of Roboscan module [29].

b. Unpiggable due to different size of diameter

Statoil has designed a dual diameter PIG in 1999 that can travel in the large diameter change as shown in Figure 3-3 [30]. This PIG has the same working principle like a utility PIG which uses fluid flow as a propulsion source to drive it in the same direction with the fluid flow. A fundamental feature that makes this PIG able to travel in the dual diameter pipeline is a driving module with mechanical spring arm mechanism. This driving mechanism consists of wheel, spring, arm and sealing component which can fold and expand depending of the diameter change.

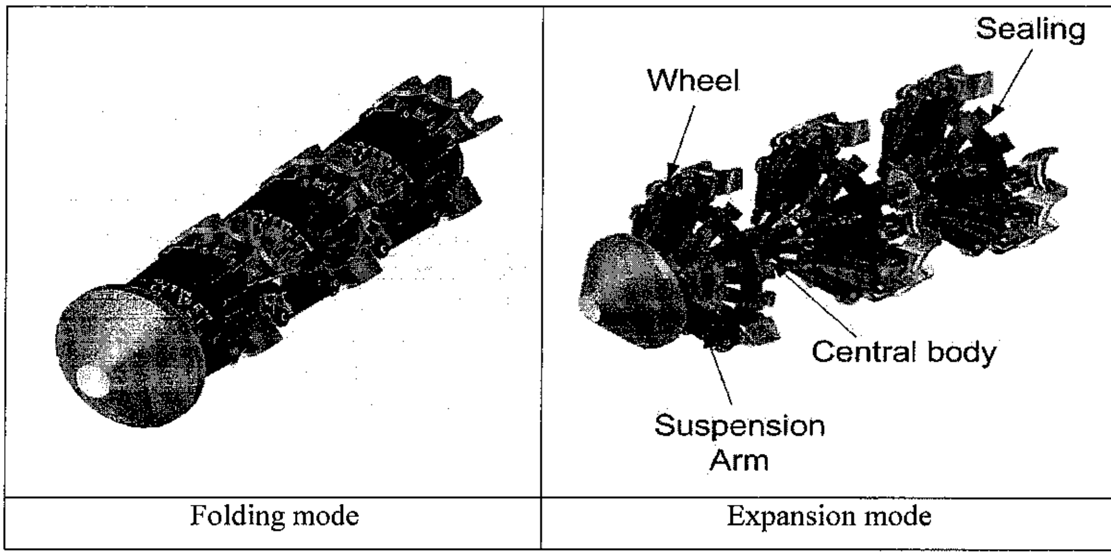


Figure 3-3: Multidiameter PIG for unpiggable pipeline [30].

Application of multidiameter PIG is for a gathering pipeline such as Asgard field which is used to transport product from several platforms to a gas processing terminal at the onshore as shown in Figure 3-4 [31]. The pipeline used to transport product of crude oil is large diameter of 42 inch. Because of the water depth, the use of conventional 42” steel riser is avoided. Therefore, production is transported by using 16” flexible riser.

Pigging operation is performed by launching a PIG at a PIG launcher near the manifold. Because of multidiameter pipeline, the PIG launcher is located at the riser near the seabed to retrieve the PIG. The use of PIG receiver of 42 inch diameter is avoided because of high risk and high cost development for subsea structure. The alternative of small diameter PIG launcher of 28 inch is then selected to overcome these problems which require a multidiameter PIG.

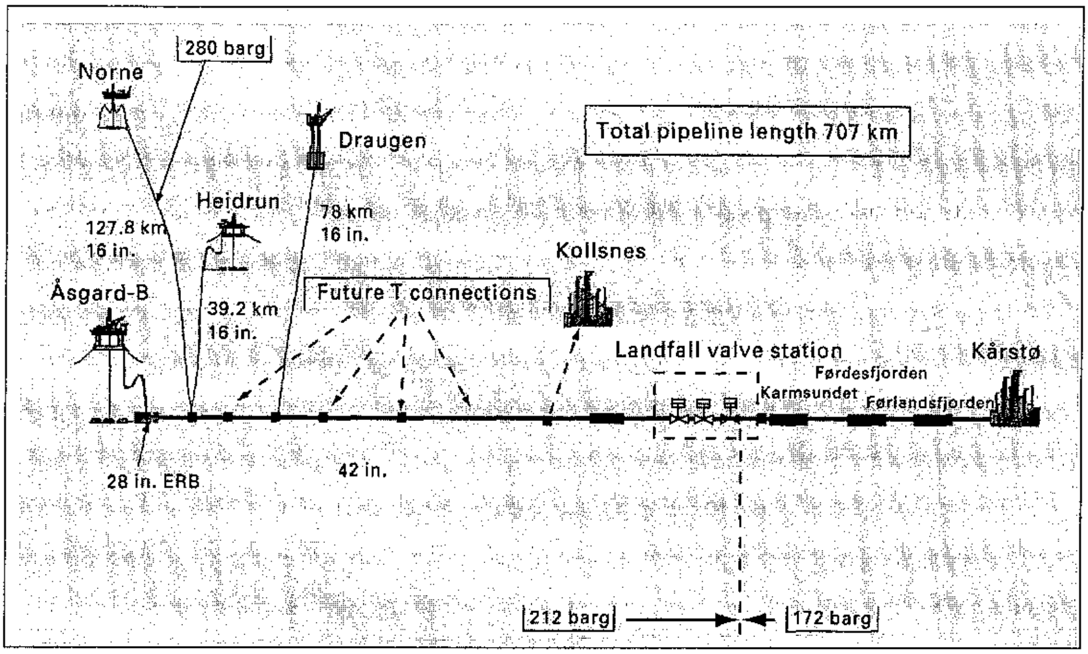


Figure 3-4: Asgard transport system [31].

Constraints that must be considered in the multidiameter PIG development are:

1. Very large hoop stress was generated when negotiating from the large pipeline size to the small size.
2. Elasticity of elastomer seal when negotiating from the small pipeline size to the large size.
3. Wear of the large diameter seal when running in the small pipeline size.
4. Space constraints of length to diameter PIG ratio when negotiating bend.

The multidiameter PIG had been tested for combination of flooding, cleaning and gauging purpose in October 1999. It can travel at velocity of about 16 m/s and received at the ERB location after 18 days [30]. The results from the pigging testing are wear on the seals with a chamfer of almost 35 mm in some places and undamaged wheels [30].

It is suggested that the PIG design capability can be improved by adding an internal power source module and a drive mechanism module to make the PIG able to travel in bidirectional. Currently the PIG design uses a fluid flow directly as a power source to push the PIG. Therefore, it can only travel in the same direction with the flow. To overcome this problem, an internal power source such as a battery or a turbine can be used. Besides that, a drive mechanism such as an incline wheel is needed for traveling in a counter flow direction. A control unit is also needed to synchronize the umbrella mechanism with the drive mechanism. In case where the PIG needs to travel in the same direction with the flow, the drive mechanism needs to be switched off and the umbrella mechanism needs to be expanding. This condition makes the fluid will push the PIG to travel in the same direction with the flow. For traveling in a counterflow direction, the drive mechanism will provide enough traction force while the force exerted to the pipeline wall by the umbrella mechanism depends on the input of the sensor such as strain gauge. Since the umbrella mechanism always expands and contracts each time it passes the different diameter, the material use must have a resistant fatigue. One of the alternative materials that can be used is composite because of light and resistance fatigue characteristic.

c. Unpiggable due to the unavailable PIG facilities

ICC's has developed a PIG in 1999 that could be deployed from a platform and then would automatically return to the platform as shown in Figure 3-5 [32]. A feature that makes the PIG able to travel in bidirectional motion is a set of inclined wheel. This set of inclined wheel is driven by the motor with batteries as an internal power source. The PIG moves in a forward direction making a spiral motion like a screw where the set of inclined wheel is driven by the motor. In order to return back to the platform, the rotational motion of motor is reversed and as a consequence the PIG moves in a backward direction. Some limitations of this prototype are incapable to negotiate tight bend of 4D radius and limited power source from the batteries [32].

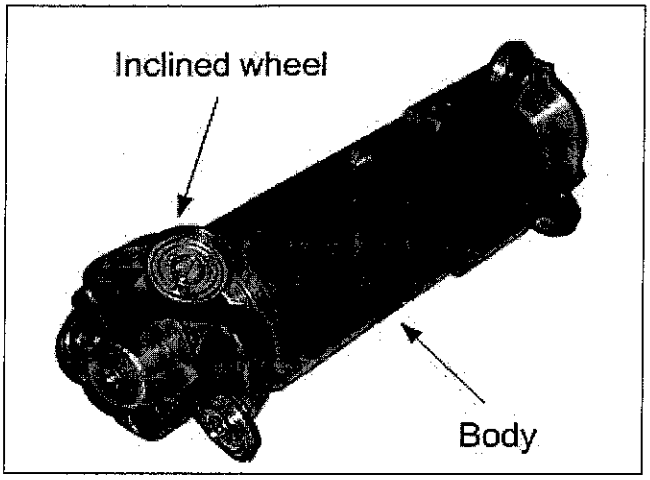


Figure 3-5: ICC Autonomous PIG for unpiggable pipeline [32].

Application of this PIG type is for a single subsea pipeline where access to the pipeline is limited only from a platform. A feature of traveling in bidirectional motion eliminates the need of PIG launcher at a seabed which can reduce capital expense of PIG facilities.

It is identified that the power limitation of an internal battery carried with the PIG can be overcome by using a turbine. The fluid flow can be converted into electrical by using a turbine and a generator. This electrical energy is further stored in a battery. With this mechanism, the PIG becomes longer where will limit the ability to travel in a bend section. To overcome this problem, the PIG module is divided into several short sections and connected by a universal joint. Another feature that can be added to this PIG is an incline wheel spring mechanism. With this mechanism, the PIG is able to travel in a different level changing of pipeline diameter.

In this research, the PIG design focuses on the generation of a PIG model that functions in removing wax from offshore pipeline. The condition of offshore pipeline used for piggging is limited only to the single pipeline where the PIG facility is not available. The unavailability of the PIG facility makes this single pipeline unpiggable. It is assumed that this pipeline is designed based on the pipeline standard where the diameter pipeline is constant through the entire length of the pipeline and the valve is full bore [25, 33]. Strategies that are used by the pipeline operator to handle this problem on the offshore pipelines are explained in the following section.

3.2 Challenges in the PIG Development for Subsea Pipeline

The oil is transported from a subsea well head to a platform through the pipeline which requires pigging operations. The ideal pigging operation is to launch the PIG through a launcher at the surface and travel with the same direction of fluid flow through the constant diameter to a receiver which is also located at the surface [34] as shown in Figure 3-6.

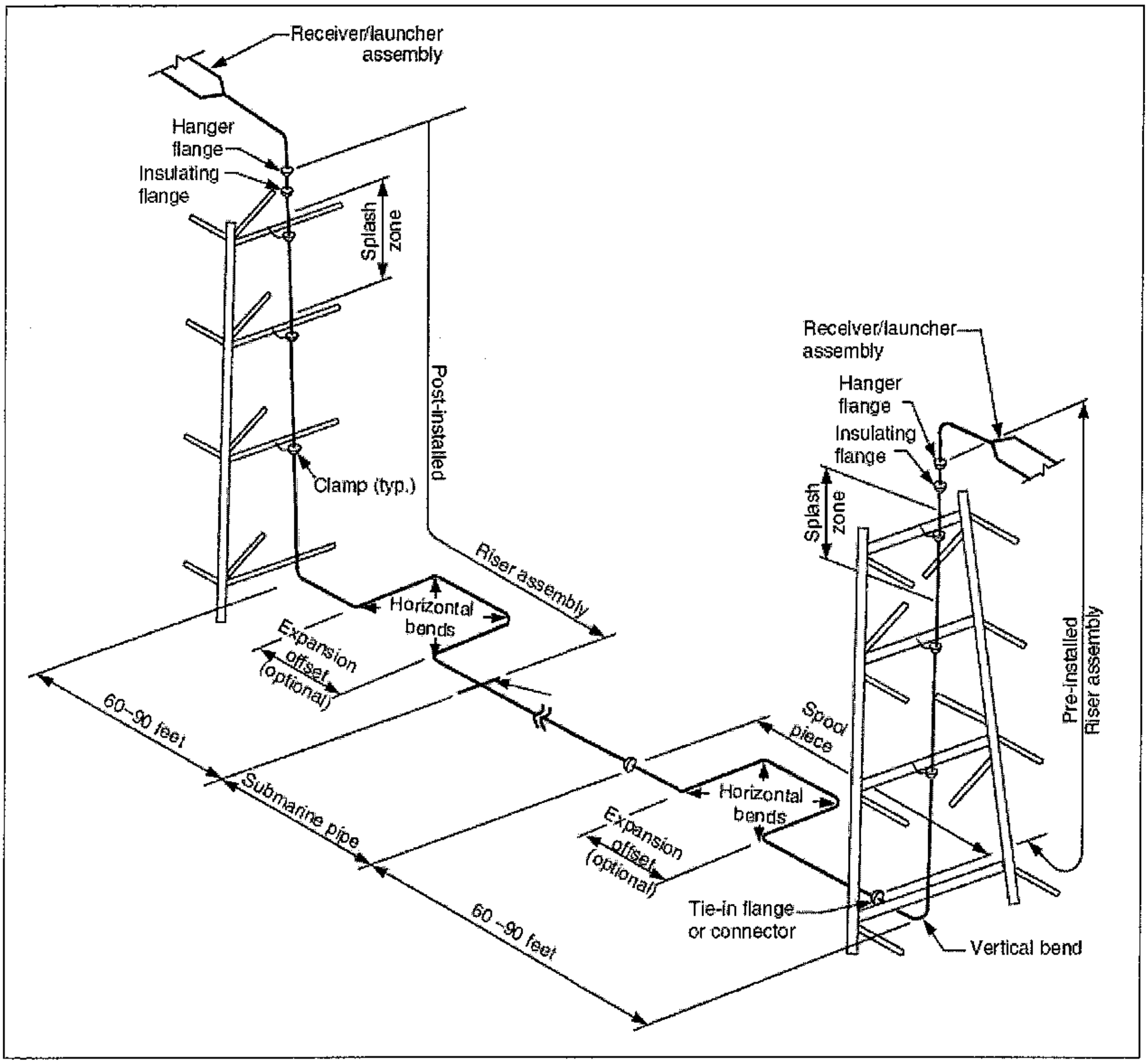


Figure 3-6: Ideal pigging operation [12].

In the real situation, pigging operation for a subsea pipeline is far from the ideal condition. Some of subsea field like in the Northern Sector of Shell Expro [7] is not equipped with a PIG launcher at the seabed. The pipeline in this subsea field is a single line which is used to transport crude oil from a manifold to a platform as illustrated in Figure 3-7.

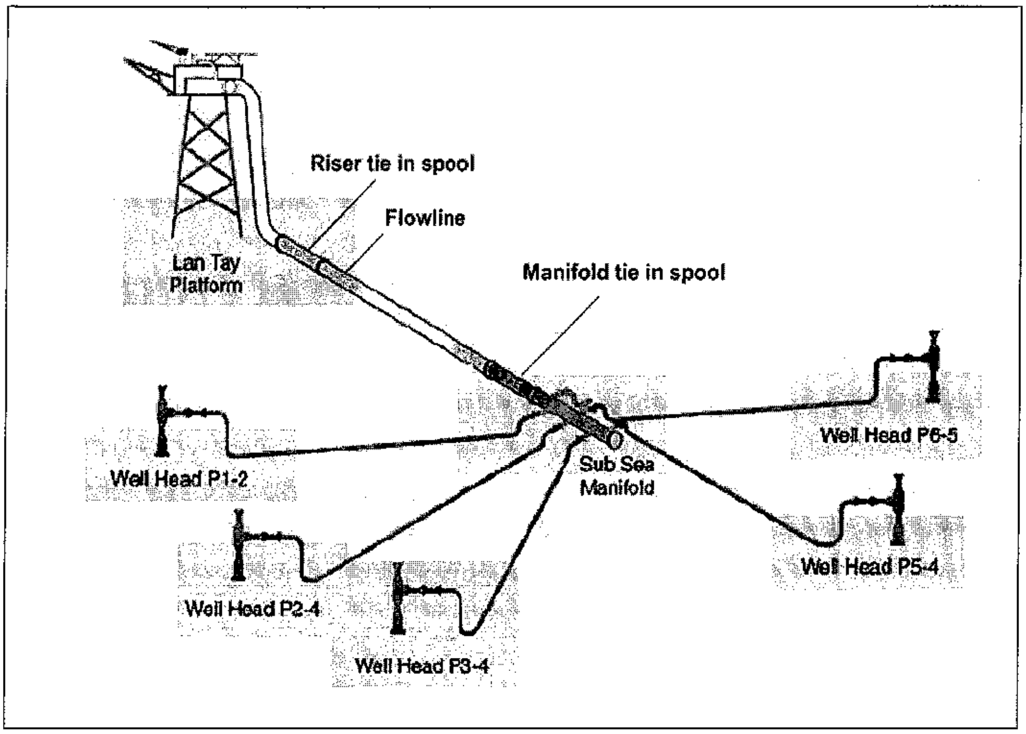


Figure 3-7: Subsea pipeline configuration [35].

To make the pipeline piggable, three different concepts can be used:

a. Pigging loop.

   The first option is to use a pigging loop which makes a utility pig able to be launched from a platform and return back to the platform. It is used for pipeline where the distances involves are not too long, the pipeline diameter is small and the pigging operation is expected to be frequently [18].

b. Launched PIG from upstream

   The second method is to deploy a utility PIG from a PIG launcher at the seabed which makes it able to travel in the same direction with the fluid flow. This method is used for long distance pigging operation and large diameter of pipeline [18]. However, this method is unpractical when the solid deposition rate is high and the pipeline requires frequent pigging operation since it needs intervention from a surface supported system [18].

c. Launched PIG from downstream.

The third method is to deploy a bidirectional PIG from a PIG launcher at the platform. The bidirectional PIG has a module of drive mechanism which makes it able to travel in a counter flow direction. It operates in the pipeline without tether and generates its own power by extracting from the fluid flow. This feature makes the bidirectional PIG able to travel through the entire length of the pipeline. If the PIG faced an obstruction or reached at the end of the pipeline, it would automatically return to an initial point of launching. This method eliminates the need of PIG launcher facility at a seabed and intervention from a surface supported system [34].

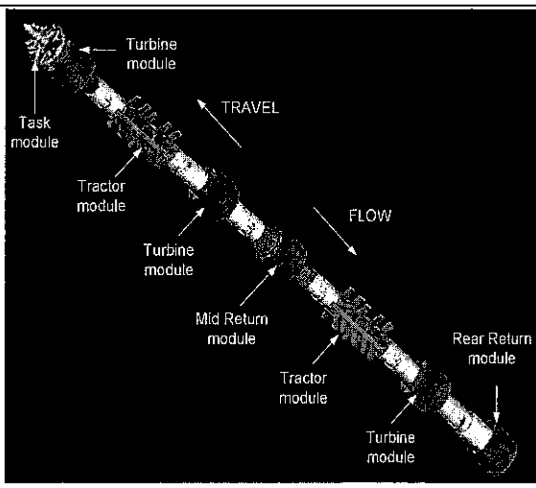
For the single offshore pipeline where it is not equipped with a PIG launcher at the seabed, there is a definite need to develop new technologies to perform pigging process. Since modification of an existing pipeline in a subsea is expensive, the option to build a pigging loop and to launch a PIG from upstream is eliminated. One of the challenges in the PIG development for subsea pipeline is to develop the PIG that can be deployed in the limited pigging facilities without interrupted production [8]. Development of counter flow PIG with fully self-powered that may crawl in the counter flow direction through the entire length of the pipeline is a solution that can solve this challenges.

3.3 State of the Art of Counter Flow PIG

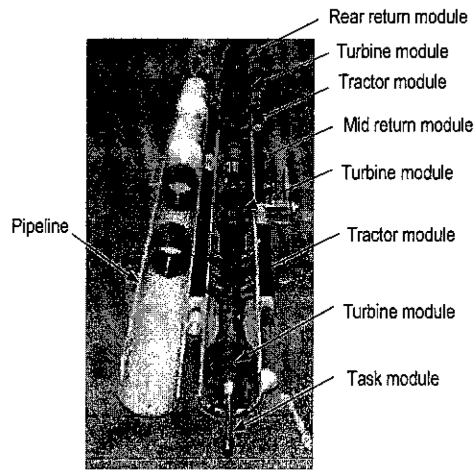
Two recent developments in counter flow PIG technologies are a contraflow tetherless pipeline crawler and a DPT crawler [36]. The contraflow tetherless pipeline crawler had been developed by Astec Development Ltd. for the Shell [7]. The DPT crawler had been developed by University of Durham researcher [9]. The counter flow PIG technologies offer the great promising of solid deposit removal from the pipeline. The solid deposit is broken down into a small chip and carried out with the fluid flow. Therefore the chips of solid deposit will not accumulate in front the PIG or block the PIG. At the end of the pipeline, there is a slug catcher which has a function to filter between the gas, oil and the wax chip [12].

3.3.1 Contraflow Tetherless Pipeline Crawler

A contraflow tetherless pipeline crawler consists of four modules: task module, tractor module, turbine module, and return module as shown in Figure 3-8. Each module is coupled with a universal joint to make a long segmented body able to negotiate at a bend section.



CAD model [37]



PIG Prototype [38]

Figure 3-8: Contraflow tetherless pipeline crawler.

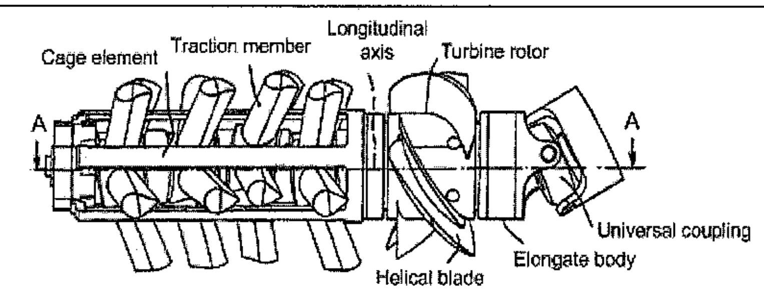
A contraflow tetherless pipeline crawler uses a turbine to generate power required from the fluid flow. There are three turbine modules in this PIG model. One is used to rotate the task module of wax removal and the others are used to drive the tractor module. The tractor module has a function to provide traction force required by the PIG to move in a counter flow direction.

Each module has either large internal or external bypass passages. It allows the fluid flow to pass through a PIG when traveling in a counter flow motion. The fluid flow through the tractor module is regulated by a return module. When the return module is closed, the fluid flow can not pass through it. As a consequence, the fluid flow will push the PIG to travel in the same direction with the fluid flow. It will act like a utility PIG and automatically return to the initial point of launching.

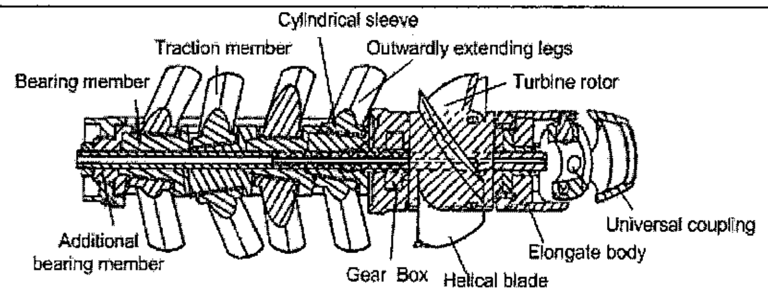
a. Working principle of contraflow tetherless mechanical crawler

   The working principles of contraflow tetherless pipeline crawler when traveling in a counter flow direction are explained below [39].

1. The fluid flow passes a turbine and rotates the shaft turbine.
2. The turbine shaft drives the tractor module shaft at a specific speed through a gear box.
3. The tractor module shaft is mounted with a series of an offset bearing as shown in Figure 3-9. A set of outwardly extending legs is mounted on the offset bearing to bridge the gap from the bearing member to the inner surface of pipelines. As the tractor module shaft rotating, the outwardly extending legs oscillate in forward, inward, rearward and outward direction.



Tractor module



Cross section A-A of tractor module

Figure 3-9: Tractor module of contraflow tetherless mechanical crawler [39].

The mechanism of motion of the tractor module to create a walking action is illustrated in Figure 3-10.

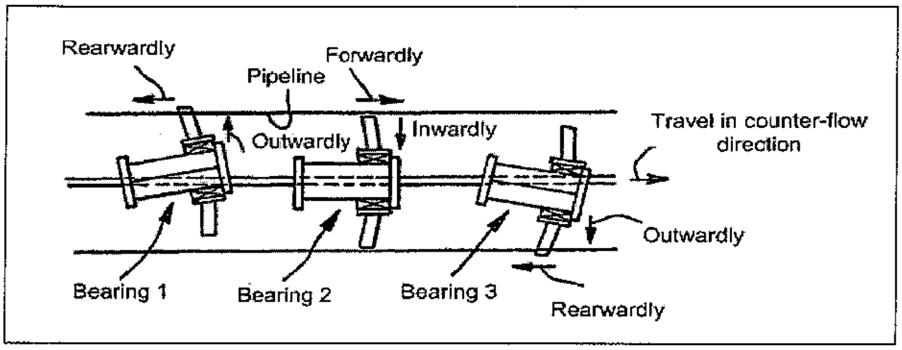


Figure 3-10: Working principle of tractor module [39].

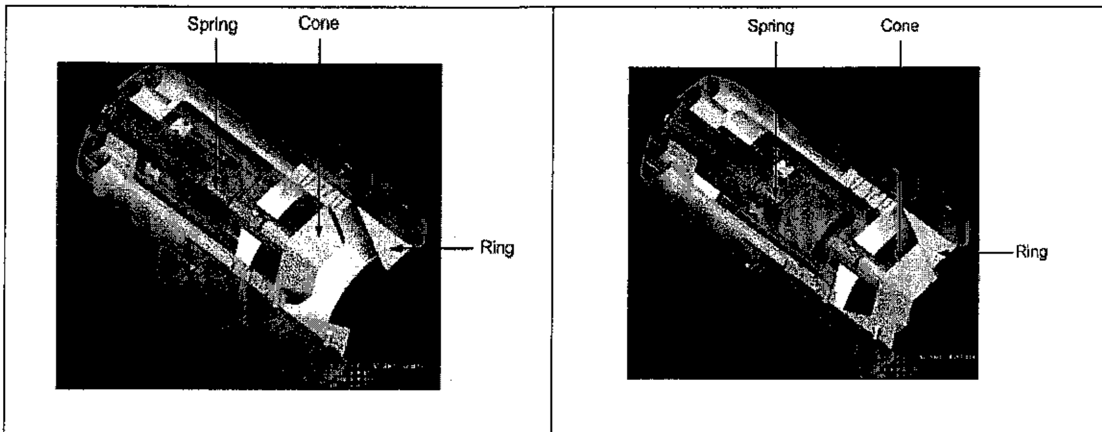
1. The outwardly extending leg at bearing 1 and 3 moves in outward and rearward direction when the axis of bearing moves outward from the centreline of the tractor module shaft. Thus it will make the outwardly extending leg to contact with the pipeline wall and remain compression until the axis of bearing passes the centreline of tractor module shaft. At this position, the outwardly extending leg creates a traction force required by the PIG to move in a counter flow direction.

2. The phase of second bearing differs by 90° with the first bearing. The outwardly extending leg at bearing 2 moves in inward and forward direction when the axis of bearing passes to centreline of the tractor module shaft. At this position, the outwardly extending leg closes to the centreline of tractor module shaft which makes it to be free from the pipeline wall.

3. The outwardly extending leg on the other side of bearing follows the same cycles at a different phase angle. Thus the oscillation of outwardly extending leg creates a walking action.

The working principles of the contraflow tetherless pipeline crawler when traveling in the same direction with the flow are explained below.

1. The return module is activated when the return mechanism is actuated. It consists of a metal cone and annular ring with a conical internal face as shown in Figure 3-11. Normally, the cone is axially separately from the ring allowing the fluid passes through the ring.



Crawl mode	Return mode

Figure 3-11: Return module [40].

2. When sensor triggers a return mechanism, a spring pushes the cone along a rod to seat in the ring and blocks the fluid flow. The pressure drop across the PIG is then enough to push the PIG at the same direction with the fluid flow. Therefore, the PIG automatically returns to the initial point of launching by using a propulsion force due to pressure drop across the PIG.

b. Limitation of contraflow tetherless mechanical crawler

The drawback of contraflow tetherless mechanical crawler prototype is the PIG speed. With the fluid flow of 0.75 m/s, the PIG prototype has capability to travel in a counter flow direction about 0.013 m/s [7, 40]. The desired speed of the PIG design is approximately 0.033 m/s [38]. According to Short, this desired speed is feasible for cleaning wax in the pipeline of length about 10 km which requires 82 hours pigging operation [38]. Another drawback is the cutting tool design became halt during wax testing removal after 1 m running because of adhesion wax in some parts [7, 40].

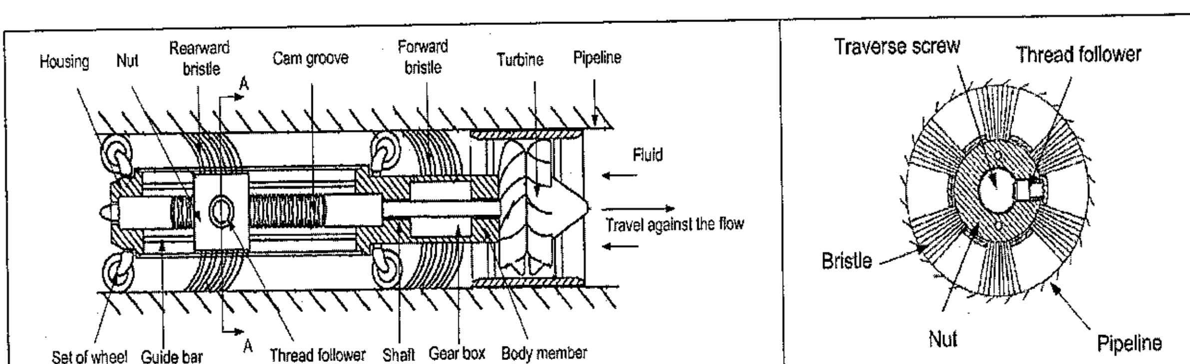
It is identified that Weatherford Ltd. can further improve their design to overcome the poor traveling speed by increasing the number of offset bearings mounted with legs. It can give more traction force which will increase the PIG speed. The constraint on the increasing of the number of offset bearing is the length of each module that can travel in the desired bend. Besides that, the power of the turbine can be increased to make the rotational shaft movement faster. It make the PIG will travel faster. To increase the power of turbine, a guide vane can be added before the impeller which will increase the fluid flow. For the wax adhesion problem, the cutting tool design can be improved by optimized element of cutting in the cutting tool. It can make the solid wax cut into smaller chip with the same power source.

c. Experiment result

The Weatherford Ltd. has successfully make prototype and running it in a test loop. The design parameter uses to design the contraflow tetherless mechanical crawler is not specified. The PIG is tested under condition of fluid flow of V_f = 0.75 m/s [40]. Based on this fluid flow input, the power that can be generated by the turbine is 250 Watt [40]. The power from the turbine is then used to drive the tractor module which can generate traction force of 1400 N per tractor module [40]. By using the two tractor modules, the PIG can travel in a counterflow at a speed of V_P = 0.0133 m/s [40]. The characteristic of wax used during testing is not mention. It just said that to remove the wax, based on the experiment, the maximum power required is 132 Watt [40].

3.3.2 DPT Crawler

A DPT crawler consists of two modules, specifically, turbine and drive mechanism module as shown in Figure 3-12. The principle of DPT crawler operation is based on the unique characteristic of the bristle which is easier to push in a forward rather than pull it in a backward direction. When two set of bristle are connected by a mechanism that generates a reciprocating motion towards and away from each other, the DPT crawler moves in a successive step.



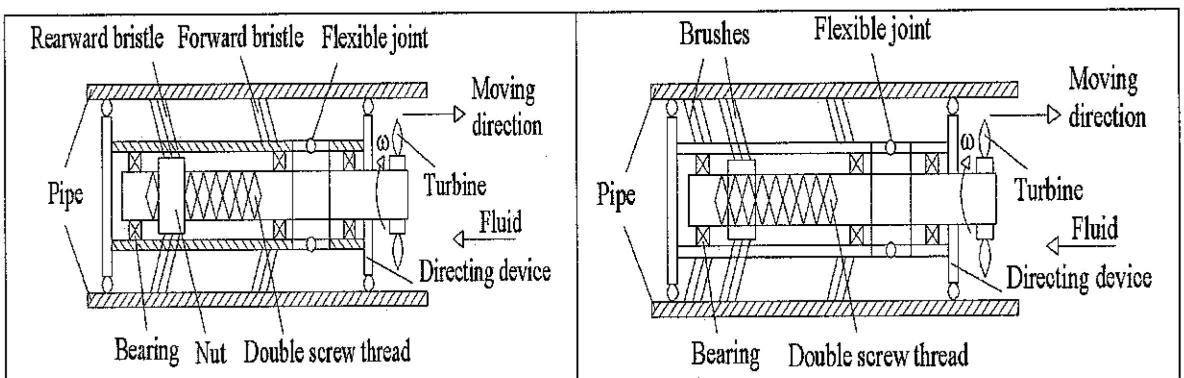
Basic structure of DPT Crawler	Cross section A-A

Figure 3-12: DPT Crawler [41].

A DPT crawler uses a turbine to generate power required from the fluid flow. A turbine shaft which is rotated by fluid flow is connected to a shaft of drive mechanism module through a gearbox. The drive mechanism module consists of two set of bristle, specifically: forward and rearward bristle. A forward bristle is mounted on the PIG bodies while a rearward bristle is mounted on the nut. The nut is attached with a thread follower which can travel in the drive mechanism shaft. The shaft in the drive mechanism is a traverse screw form that makes the rearward bristle able to travel in a forward and rearward direction.

a. Working principle of DPT crawler

The working principle of DPT crawler is shown in Figure 3-13.



Two set of bristle moves away to each other	Two set of bristle moves toward to each other

Figure 3-13: Working principle of the DPT crawler [9].

The DPT crawler movement is as a result of a series step as described as follows.

1. At the beginning of a cycle, the DPT crawler is stationary. Initially, a frontward and rearward bristles are stationary and inclined backward as shown in left Figure 3-13.
2. The fluid flow passes through a turbine and rotates the turbine shaft.
3. The turbine shaft drives a drive mechanism shaft in a specific speed through a gear box.
4. As the drive mechanism shaft rotating, the rearward bristle moves toward to the forward bristles because the resistance force generated by the forward bristle is greater than the force required to push the rearward bristle. It is illustrated in right Figure 3-13.
5. As the rearward bristle reaches the end of the traverse shaft, the cam follower on the nut is forced to engage to the other cam grove. At this position, the

resistance force generated by the rearward bristle is greater than the forward bristle. As a consequence, the forward bristle farther from the rearward bristles. It makes the DPT crawler moves forward in a specific distance.

6. The rearward bristle reaches at the end of the traverse shaft as shown in left Figure 3-13 but at difference location from the beginning of the cycle. The process is repeated to create a successive movement.

b. Limitation of DPT crawler

The drawback of DPT prototype is discontinued motion [9]. As the rearward bristle moves toward to the frontward bristle, the DPT crawler is in stationary position. The DPT crawler starts to move in a forward direction when the rearward bristle moves away to the frontward bristle. The discontinued motion time can be reduced by using pitch variation in the double screw thread. In the beginning and end of the shaft, the pitch is smaller than the middle of the shaft. With this type of pitch, the acceleration force required to move the nut from the idle position is less.

It is identified that the DPT can further improve their design by adding a cutter or a bristle powered by a turbine. It makes the wax removal is caused by an active force. The benefit of using this method is the size of wax chip can be determined before the pigging process. It will reduce the possibility the PIG gets stuck inside the pipeline. Currently, the solid deposit is removed as a result of friction force between the bristle and pipeline. Therefore, the amount of wax removal depends on the PIG speed.

c. Experiment result

The DPT has successfully run their prototype to travel in bidirectional in a test loop. The design parameter used in the prototype is shown in Table 3-1. Further, with this design parameter, the DPT prototype is tested to move in a counterflow direction with fluid flow of V_f = 1.62 m/s. The result of the test is shown in Figure 3-14. Based on the test result, the PIG able to travel in a counterflow direction with speed of V_P = 0.167 m/s at a time ratio of three between the PIG movement and stationary condition.

Table 3-1. Design parameter of DPT crawler [9].

Design parameter	Value
Radius of the shaft (r_d)	19 mm
Pitch of the screw (l)	15 mm
Mass of the nut (M_n)	2.7 kg
Length of the screw (L)	345 mm
Inertia moment of the turbine and shaft (I_d)	1.09 x 10^{-3} kg.m^2
Mass of the PIG (M_m)	25 kg
Friction force on the PIG ($(F_P)_p$)	895 N
Friction force on the nut (f_m)	200 N

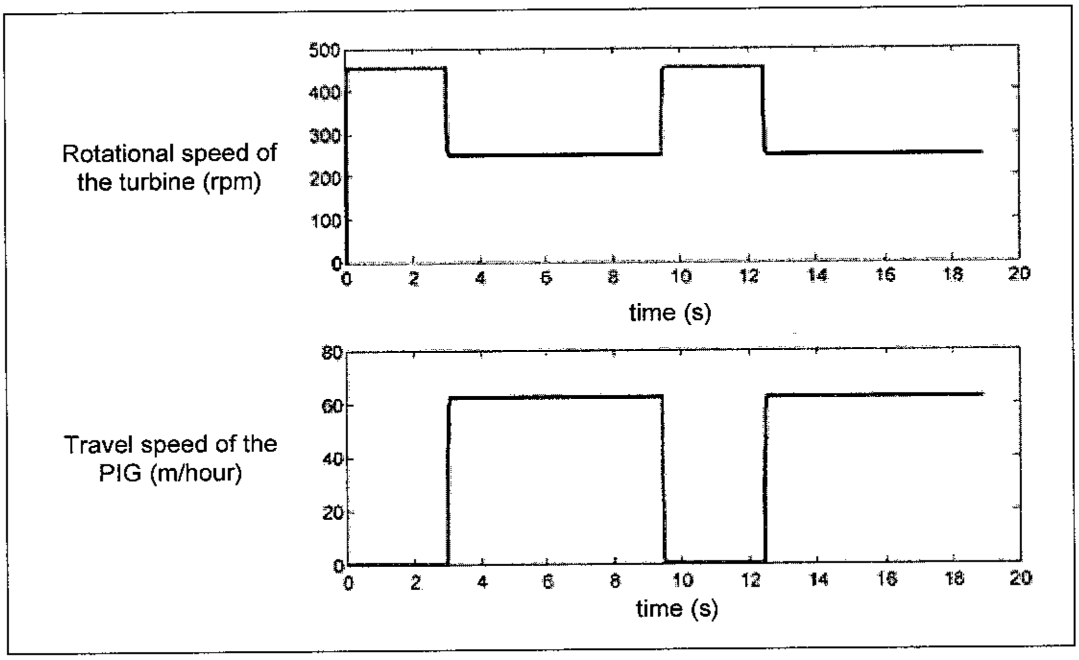


Figure 3-14: DPT crawler motion [9].

3.4 Some Others Concept Model of Contraflow PIG

There are some of concept model of contraflow that have been generated. Some of them are a pipeline PIG developed by Boe in 2007 and an autonomous robotic crawler for in-pipe inspection developed by Ghorbel in 2007. The detail of working mechanism from each of them is discussed as follows.

3.4.1 Pipeline PIG

A pipeline PIG consists of six module, particularly: a tool, a resistance, a turbine, a gear, a crawler and a control module as shown in Figure 3-15. Each of them is connected by using a universal joint to make it able to negotiate with the tight bend. The detailed of each module is shown in Figure 3-16.

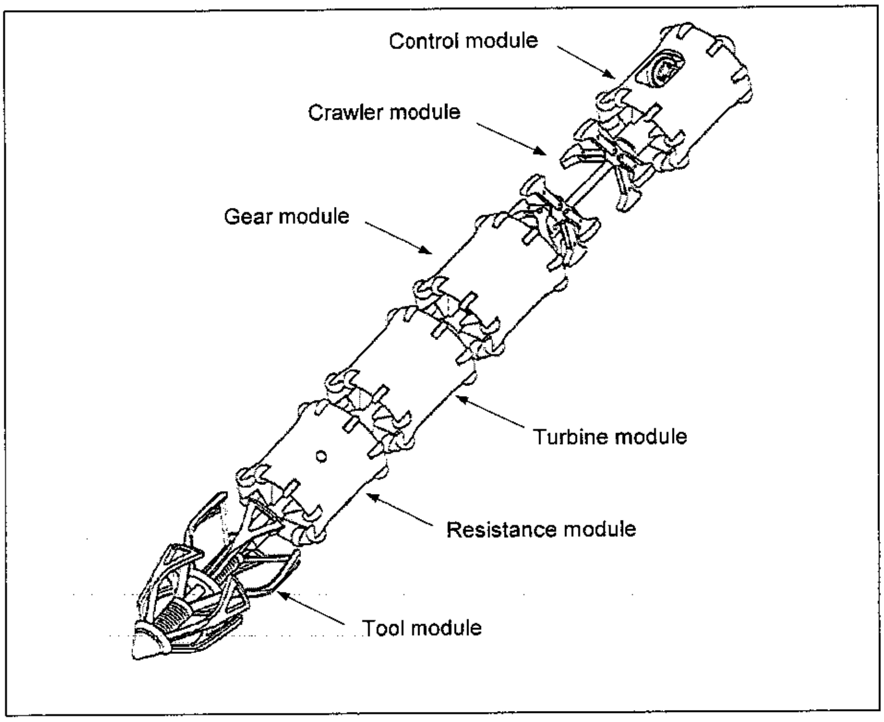


Figure 3-15: Pipeline PIG [42].

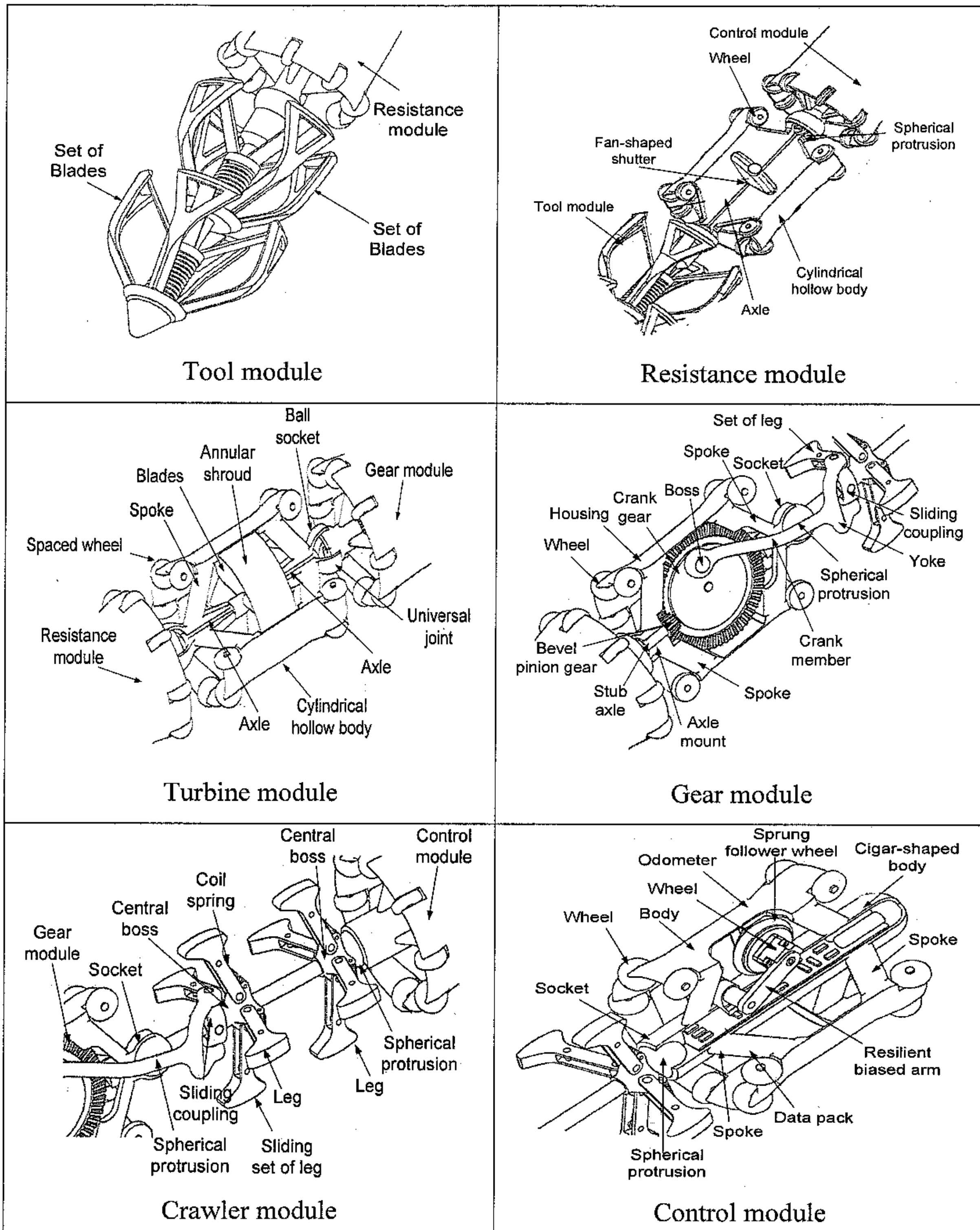


Figure 3-16: Detail each module of pipeline PIG [42].

a. Working principle of pipeline PIG

The main function of a pipeline PIG is for cleaning purpose. To do this task, a tool cutting module which consists of a set of blade is used. This tool module is a passive mechanism which uses friction force to remove solid deposit. For movement in a counter flow direction, the pipeline PIG uses fluid flow as a power source to drive the PIG. This fluid flow is converted into rotational energy by using a turbine module. In order to convert this rotational energy into translational energy, a gear module which consists of a bevel gear and a crank mechanism is used. Furthermore, this translational energy is used to move a sliding coupling mounted with a sliding set of leg in the crawler module. The sliding set of leg move toward and away to each other to create a successive motion as shown in Figure 3-17. In order to pull the rear sliding set of leg, a latch mechanism is used so the pipeline PIG can move forward. When the pipeline PIG is desired to move in the same direction with the flow, a fan-shaped shutter needs to be closed. It makes the fluid flow will push the pipeline PIG to return to the initial point of launching. At the rear, there is a control module which has function to determine whether to move in a counter flow or in the same direction with the flow. It consists of an odometer wheel which will compare the actual speed with the desired speed.

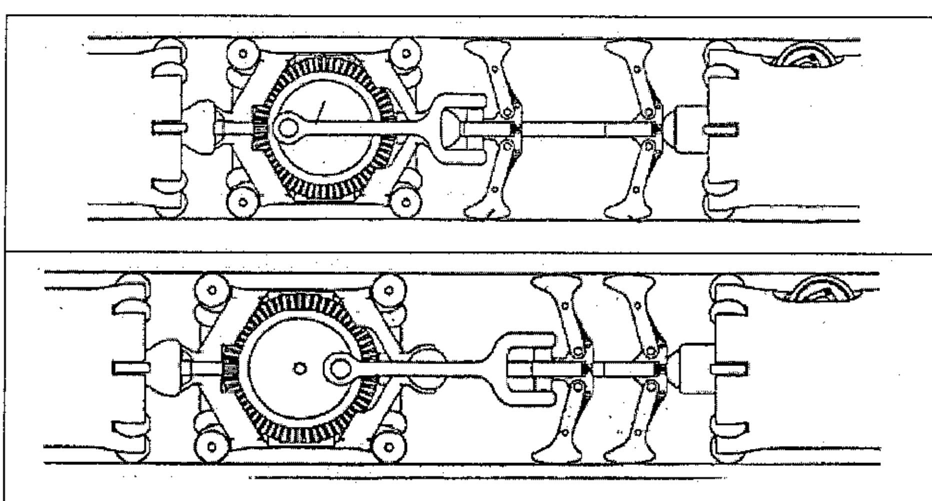


Figure 3-17: Working principle of pipeline PIG [42].

b. Limitation of pipeline PIG

Based on the critical review, it is identified that the solid deposit is removed by using set of blades as a result of friction. Therefore, the removal of solid deposit depends on the pipeline PIG speed. Compared to the DPT crawler, the efficiency of solid deposit removal is better since the pipeline PIG is equipped with the control module. A turbine module can be attached to rotate the blade so the wax removal is based on the active force rather than friction result. The benefit of this method is the size of the wax removal can be determined before the pigging process. Another drawback of the pipeline PIG is a discontinued motion since it uses a reciprocating mechanism for crawler function in a counter flow direction. This discontinued motion can be minimized by adjusting the position of the crank at the outer edge of gear but sacrificing the torque. For the part in the crawler module, the composite material which has characteristic of light and fatigue resistant can be used. The expanding and contracting mechanism makes the part in the crawler module is not resistance for the fatigue problem.

3.4.2 Autonomous Robotic Crawler for In-pipe Inspection

Autonomous robotic crawler consists of three modules, particularly: drive module, master control unit and turbine module as shown in Figure 3-18. In order to be able to travel through the entire length of the pipeline, each module is connected by using a flexible coupling.

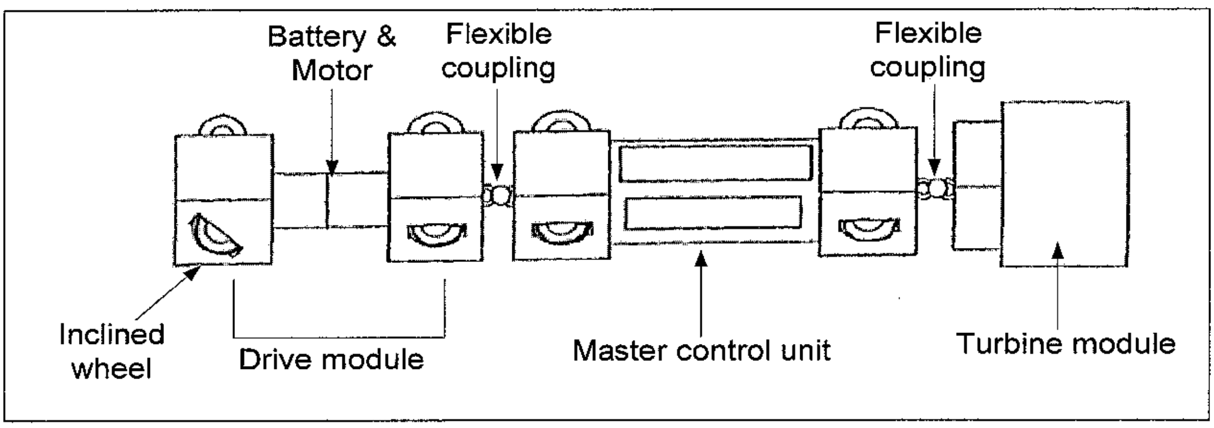


Figure 3-18: Autonomous robotic crawler [43].

a. Working principle of autonomous robotic crawler

In order to move in a counter flow direction, fluid flow energy is converted into rotational energy by using a turbine module. This rotational energy is then converted into electrical energy by using a generator. Further this electrical energy is used to power electrical equipments in a master control unit and a drive module. Motor which uses a battery as a main power source drives a set of inclined wheel. Incase the PIG is required to return to the initial point of launching, the master control unit will give signal to turn off the motor. As a consequence the fluid flow still flowing, the PIG will be pushed by the fluid flow to travel in the same direction with the flow.

b. Limitation of autonomous robotic crawler

   Based on the critical review, it is suspected the movement of autonomous robotic crawler is continues since using a wheel mechanism. Compared to the other concept such as a contraflow tetherless mechanical crawler, a DPT crawler and a pipeline PIG, the traction force generated by a drive module is smaller. To overcome this drawback, a pitch of inclined wheel needs to be reduced. As a consequence, the pipeline PIG travels slower but more traction forces generated. The PIG can be added another feature for specific function such as cleaning by adding a set of blade or a bristle or inspection by adding an ultrasonic or a MFL sensor. A spring mechanism can be attached to the inclined wheel feature to overcome problem when passing the dent.

3.5 Customer Need of PIG Design

Oil companies have identified that pigging operation in single offshore pipelines would be advantageous by using bidirectional PIG types. From literature review, the customer needs of PIG design for wax removal from pipelines are:

a. It is desired that the PIG is able to be launched from a platform and travel against the flow through the entire length of the pipeline [7-9, 32].
b. It is desired that the PIG extracts the power from the fluid flow and use it to drive the PIG to travel in a bidirectional motion [7-9, 32].
c. While doing cleaning, it is desired that the cleaning force is actively generated by the PIG [3].
d. It is desired that during the wax removal process, the PIG travels a constant speed to control amount the wax removal and to avoid wax accumulation in front of the PIG [3, 7, 8, 28].
e. When the PIG reached the end of the pipeline, it is desired that the PIG would automatically return to the initial point of launching [7-9, 32].

This research focuses on the producing a proposed CAD model of bidirectional PIG that can fulfill customer needs as described before. The benefits of development this PIG type is:

a. Reduce capital expense

   Since the PIG can be deployed from a surface at a platform, the need of PIG launcher at a seabed is eliminated. It can save a cost on the capital expense of PIG facilities.

b. No disruption to production

   PIG uses normal fluid flow as a power source. Fluid flow is converted into rotational energy which is used to drive the PIG in a counter flow direction and to rotate a cutter tool. Since the PIG uses normal fluid flow operation while doing pigging, production process is undisrupted. The amount of wax removal is also in controllable because it is removed by an active force. The risk of PIG being stuck due to wax accumulation in front of the PIG is reduced with this feature. Therefore, the possibility of production to be stop in order to retrieve the stuck PIG inside a pipeline is small.

CHAPTER FOUR: METHODOLOGY

This chapter discusses the methodology that is used to produce a CAD model of the proposed PIG. The methodology is based on Dieter's systematic design approach [10].

4.1 Overall Methodology

Design is a process to translate an idea based on customer needs into a product. In order to generate a good product that can fulfill a customer requirement within on time and efficient, it is important to follow a systematic design approach. In the systematic design approach, the required design activities are structured in a purposeful way and form a sequence of main phases and individual steps. Hence, the flow of design process can be planned and controlled.

A systematic design approached based on Dieter [10] is followed in this research work to produce a CAD model of PIG design. The overall methodology of the PIG design is depicted in Figure 4-1.

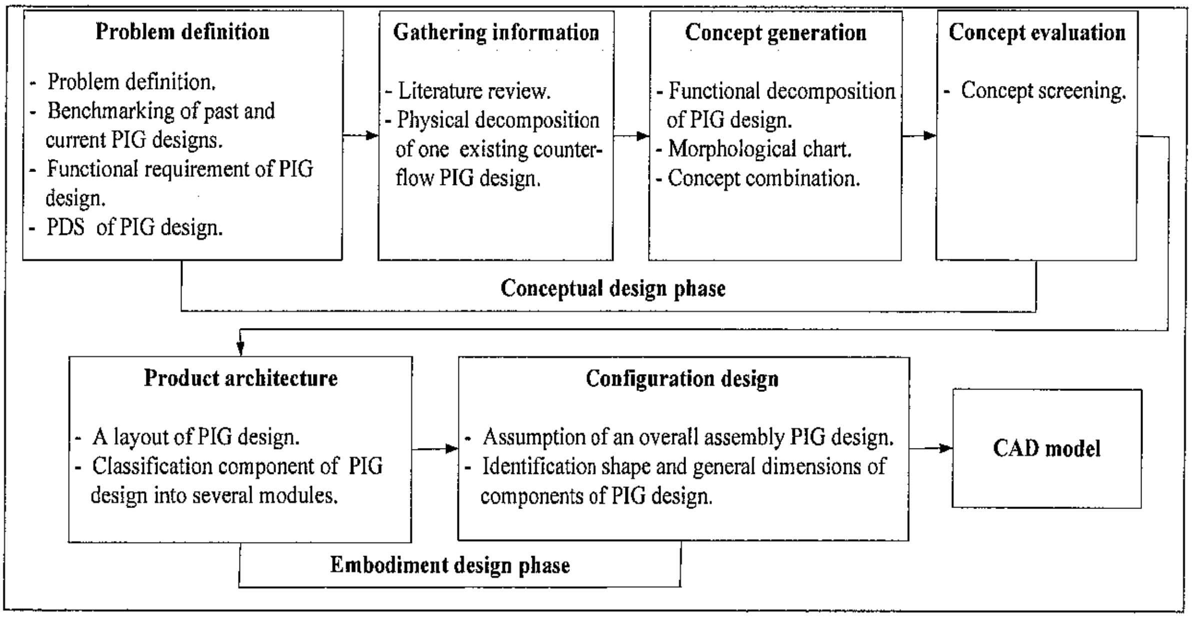


Figure 4-1: Overall methodology of PIG design.

The steps in conceptual and embodiment design phase and also activities in each steps is explained in detailed below.

4.1.1 Conceptual Design Phase

Conceptual design phase is a phase where the PIG design problem is defined, generating several potential concepts of PIG design and selecting one of the promising concept. The steps under conceptual design phase are problem definition, gathering information, concept generation and concept evaluation.

4.1.1.1 Problem Definition Step

The problem definition step consists of problem definition, benchmarking, functional requirement and Product Design Specification (PDS) of the PIG design activities.

Initially a statement about the purpose of the PIG design is created. Furthermore, benchmarking of past and current PIG design is performed to find strong points and drawbacks from the previous PIG design. A set of function requirements of PIG design are created based on benchmarking to improve the drawbacks from the previous design. Constraints that can quantify performance of PIG design for each requirement are defined in PDS.

4.1.1.2 Gathering Information Step

The gathering information step consists of literature review and physical decomposition of one existing current PIG design activities.

Study literature of the related PIG designs are explored in the gathering information step to gain understanding about working principle from previous designs. Further, one of the current PIG design is chosen as a datum for the PIG design development. Functions required to carry out the overall function from the datum design is studied through a physical decomposition. These functions will be used to assist in determining the detail function of PIG design.

4.1.1.3 Concept Generation Step

The concept generation step consists of functional decomposition, morphological chart and concept combination activities.

A working principle of PIG design is established in the concept generation step by using a functional decomposition approach. It is started by defining the overall function of PIG design. Further, the overall function of PIG design is decomposed into sub-functions. These sub-functions are then arranged in a logical order which will transform initial input into desired output in terms of energy, material and information flow.

Sub-functions that are required to accomplish the overall function of PIG design is then mapped into a morphological chart. Furthermore, solutions that can fulfill the sub-functions are explored through a literature review and brainstorming. Several alternative concepts of PIG design are generated by combining solution from each sub-function.

4.1.1.4 Concept Evaluation Step

Several alternative concepts of PIG design that are produced in the concept generation step are narrowed down into a single best concept. A method used to select the most promising concept is a concept screening. In the concept screening, relative performance from each concept is compared to a datum of one existing PIG design for particular criteria which is created based on the functional requirement of PIG design. The outcome of conceptual design phase is one of the most promising concepts of PIG design.

4.1.2 Embodiment Design Phase

In the embodiment design phase, the abstract concept of the most promising PIG design from conceptual design phase is transformed into a physical component. The steps under the embodiment design phase are product architecture and configuration design.

4.1.2.1 Product Architecture

A layout of the most promising PIG design is drawn roughly to show the arrangement of the selected component and illustrate their shape and sizes. Furthermore, a physical component that contributes to the same function is clustered into the same module.

4.1.2.2 Configuration Design

The proposed design of PIG consists of several modules where each module consists of several components. Initially, the number and dimension of some component in the overall assembly of PIG design is assumed based on the rule of thumb from previous design. Furthermore, the feature and dimension of critical components is determined through a preliminary analysis. For other standard components that are insignificant to the overall performance of PIG design and can be obtained from the manufacturer, an analysis is performed only to determine the type, size and specification of its component.

4.1.3 CAD Model

A CAD model of PIG design is produced at the end of design process. It illustrates the overall assembly of the PIG design and component required to accomplish the overall function of PIG design.

4.2 Tools

The tools used in this research work are:

1. CATIA [44]

   CATIA software is used to draw the component of PIG design. An overall assembly of the PIG design is illustrated by using assembly design module in CATIA software.

2. Fluent [45]

   The performance of a device that is used to convert hydraulic energy into rotational energy is simulated in Fluent software.

CHAPTER FIVE: RESULT AND DISCUSSION

5.1 Introduction

Conceptual and embodiment design phase of PIG design is discussed in chapter five. In the beginning, conceptual design phase is discussed first and then followed by the embodiment design phase. The final output of the design process which is a CAD model of PIG design is illustrated at the end of this chapter.

5.2 Conceptual Design

The first step in the conceptual design phase is problem definition where the PIG design problems are generated based on the customer requirements. Furthermore, the relevant information about the PIG design is performed in the gathering information step. In addition, several new concept of PIG design are generated in the concept generation. At the end, the most promising concept is selected in the concept evaluation step.

5.2.1 Problem Definition

Initially, the design process is started by defining the problem of current PIG design. Activities in a defined problem step consist of identifying customer requirement, benchmarking of past and current PIG design, functional requirement of the PIG design and PDS of the PIG design activities.

a. Identifying customer requirements

   A product is designed and developed because there is an opportunity to sell the product in a market. In order to success in the market, the product design must be developed based on the customer requirements. It can be obtained through [10, 46]:

   1. A document of customer complaint about the existing product.

2. Interview with the potential customer to get a feedback about existing product.
3. Customer survey to gain opinion about the existing product that is well understood by the public.

Understanding the customer requirements in the beginning of process design is very important. These customer requirements will determine the final design of product. As stated in chapter three, the primary customer need of PIG design is a model of PIG that can travel in bidirectional motion without disturbing the pipeline operation during pigging process. The PIG design has a main function to remove wax from the offshore pipeline.

b. Benchmarking

Customer requirement is stated in the customer language. It leaves too much margin for subjective interpretation. For this reason, a set of specification which describes the functional requirements of PIG design in measurable value is required to establish. In order to determine the functional requirement of PIG design, benchmarking of past and current PIG design is carried out through the study literature. In this benchmarking, three types of PIG design is chosen to find strong points and drawbacks of their design. A conventional PIG design is selected to represent a past PIG design and two counter-flows PIG designs, specifically: a contraflow tetherless mechanical pipeline crawler and a DPT crawler are chosen to represent a current PIG design. The result of benchmarking is shown in Table 5-1.

Table 5-1: Benchmarking of past and current PIG design.

Criterion	Conventional PIG [12]	Contraflow tetherless mechanical pipeline crawler [40]	DPT crawler [9]
Cutting force	Inactive	Active	Active
Wax removal	Accumulated in front of the PIG and pushed out from pipeline while the PIG moving forward	Unaccumulated in front of the PIG and carried out with the fluid flow	Unaccumulated in front of the PIG and carried out with the fluid flow
Production	Interrupted	Uninterrupted	Uninterrupted
Facility requirement	PIG launcher and receiver	PIG launcher	PIG launcher
Direction of PIG	Normal with the flow	Bidirectional	Bidirectional
PIG speed	PIG velocity of 0.9 to 1.52 m/s for fluid velocity of 0.9 to 1.52 m/s	PIG velocity of 0.013 m/s for fluid velocity of 1 m/s	PIG velocity of 0.03 m/s for fluid velocity of 1.5 m/s
PIG motion	Continuous	Continuous	Discontinuous

c. Functional requirement of PIG design

Based on the benchmarking of past and current PIG design, the functional requirements of PIG design are determined as follows.

1. Able to remove wax deposit with an active force.
2. Able to travel in bidirectional directions (forward and reverse direction).
3. Able to travel at a constant speed while doing wax removal process (in forward direction).

The functional requirements as described above are important in developing a new concept of PIG. The reasons that the new concept PIG must have these functional requirements are:

1. During pigging operation, the PIG design removes wax deposit on the pipeline wall by applying an active force. The use of active force during wax removal makes amount of removed wax deposit that is removed from pipeline still in a controllable value. As a consequences, the risk of wax build up in front of the PIG which may cause the PIG get stuck inside the pipeline is reduced [7].
2. The PIG is designed to be deployed from a platform at the surface and travel against the flow. When the PIG reaches at the end of the pipeline, it is desired to automatically return to the initial point of launching. It means that the PIG design has a function to travel in bidirectional motion. The PIG facility at the seabed can be eliminated with this function and results on reducing capital expense of PIG facility [40].
3. Wax removal process is performed by the PIG design when it travels against the fluid flow. It is required that the PIG design has a function to maintain the speed while doing wax removal process. The cleaning efficiency of wax deposit removal which is performed by PIG with this function is same through the entire length of the pipeline [3].

In this research work, the scope of work is limited to identify features required by the proposed PIG model and its general dimension.

d. PDS of PIG design

The functional requirements of PIG design are stated in measurable value at the PDS document. This document states the performance of the PIG design that should be achieved at the end of the process design. The PDS of the PIG design is shown in Table 5-2. It is adopted from the PDS of contraflow tetherless mechanical pipeline crawler [40].

Table 5-2: PDS of PIG design [40].

Requirements	Value
To remove wax deposit from pipelines wall - Wax deposit thickness - Yield strength of wax	 1" annular ring 300 – 2500 Pa
To travel in bidirectional motion without being affected by the fluid - Fluid velocity operation	 1-1.5 m/s
To travel in constant speed - PIG desired velocity	 0.03 m/s
To operate in offshore condition - Pressure operation - Temperature operation	 150 bar 4-90°C
Length of travel	6 km

5.2.2 Gathering Information

Once the problem definition of PIG design has been identified, the next step on the design process is to gather information about the relevant PIG design. This step will help in determining the detail function required by the PIG design to accomplish its overall function. The activities in the gathering information step are discussed in this section. It consist of literature review and physical decomposition activities.

a. Literature review

   Information about the PIG design is performed through a literature review. The main sources of literature review are published journals, patents and handbooks. Due to the abundant information about the PIG, the literature review is limited to the PIG design development for cleaning function in the offshore application. The result of literature review of PIG design is summarized concisely in chapter three.

b. Physical decomposition of an existing PIG design

   The PDS of PIG design provides useful information on functional requirement based on customer requirements. However, the specific functions that are required by the PIG design to accomplish the overall function are not specified. Therefore, physical decomposition of an existing current PIG design is performed to determine function required by the existing current PIG to accomplish the overall function. This method dismantles the existing current PIG design into their respective component to get a better understanding of the solutions selected from the previous designed.

A contraflow tetherless mechanical pipeline crawler is selected as a datum for development of the PIG design because it provides more information about their design. The contraflow tetherless mechanical pipeline crawler is decomposed into its physical component that is essential to accomplish the overall function by using physical decomposition. The decomposition process is stopped when basic physical components are identified. Hierarchical structure of physical component of the contraflow tetherless mechanical pipeline crawler is illustrated in Figure 5-1.

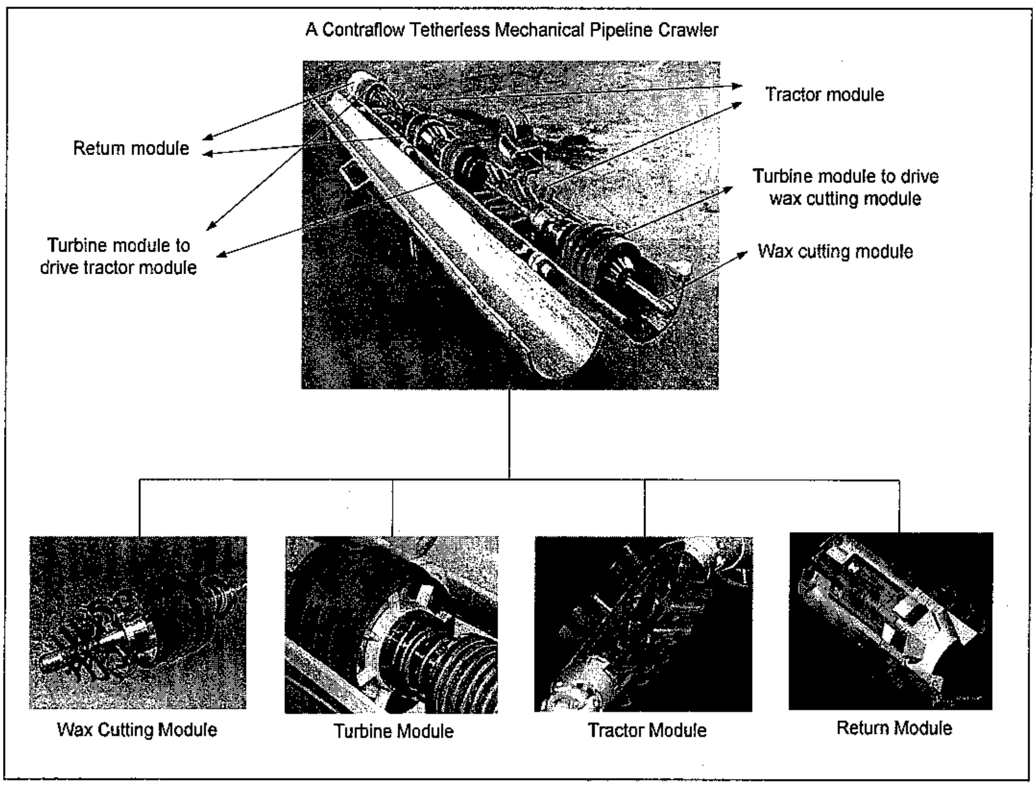


Figure 5-1: Physical decomposition of the contraflow tetherless mechanical pipeline crawler [40].

To achieve the overall function of wax removal, a contraflow tetherless mechanical pipeline crawler requires a wax cutting, a turbine, a tractor and a return module. The turbine module converts energy from fluid flow into rotational energy. This energy is used to drive the wax cutting module. Another turbine module is used to drive the tractor module. The return mechanism module is attached to a turbine module to control fluid flow that pass through the turbine. When fluid flow pass through the turbine module is reduced, the power generated by the turbine to drive the tractor module will be reduced. If the traction force from the tractor module is less than the propulsion force due to the pressure difference across the PIG bodies, then the PIG will move in the same direction with the fluid flow.

After the physical component required by the contraflow tetherless mechanical crawler to accomplish the overall function is identified, then function from each physical component is mapped as shown in Table 5-3.

Table 5-3: Function from each subassemblies of the contraflow tetherless mechanical pipeline crawler.

Sub-assemblies	Function
Wax cutting module	To remove wax
Turbine module	To convert fluid energy into rotational energy
Tractor module	To convert rotational motion into translational motion
Return module	To block the flow and to drive the PIG in return mode

5.2.3 Concept Generation

A PIG concept is generated based on the functional decomposition approach. It describes what the PIG design must do in order to accomplish the main function. This method allows flexibility to a designer to use their creativity to generate a wide variety of alternative solutions [10]. The activities in the concept generation step are discussed in this section. It consists of functional decomposition and concept combination activities.

a. Functional decomposition

In order to achieve the main function of wax deposit removal, the PIG design requires specific functions to carry out this task. Functional requirement of wax removal with an active force, traveling in bidirectional motion and traveling at a constant speed in forward direction as described in problem definition step is used as a basis to determine functional requirements of PIG design. Functional decomposition approach is used to further refine these functional requirements into specific function required to accomplish the overall function of PIG design [47].

In functional decomposition approach, the system function of a product design is described as a transformation between an initial state and a desired state in terms of either energy, material or information flow [48]. The benefit of using this technique is to force a detailed understanding of what the product design is supposed to do at the beginning of the design process.

The process of functional decomposition is started by decomposing the overall function of product design into sub-functions expressed by a verb-noun combination. The verb is used to indicate what is performed by a product design. The noun is used to indicate the object on which the verb acts [47]. The list of function verb that may help in determining the function of PIG design is shown Table 5-4. Sub-functions result from functional decomposition is further ordered to give a logical flow transformation in order to achieve the overall objective of the product design. Finally, each sub-function is examined whether the decomposition is enough or not. If not, a further decomposition of sub-subfunctions is generated. The parameter to indicate enough functional decomposition is when the function identified can be fulfilled by existing objects.

Table 5-4: Typical mechanical design function [47].

Absorb / remove	Dissipate	Release
Actuate	Drive	Rectify
Amplify	Hold or fasten	Rotate
Assemble / disassemble	Increase / decrease	Secure
Change	Interrupt	Shield
Channel or guide	Join / separate	Start / stop
Clear or guide	Lift	Steer
Collect	Limit	Store
Conduct	Locate	Supply
Control	Move	Support
Convert	Orient	Transform
Couple/interrupt	Position	Translate
Direct	Protect	Verify

The functional decomposition process of PIG design starts with a statement of the overall function of PIG design. It is stated in an action statement (verb-noun form) of wax deposit removal with the relevant input and output as shown in Figure 5-2.

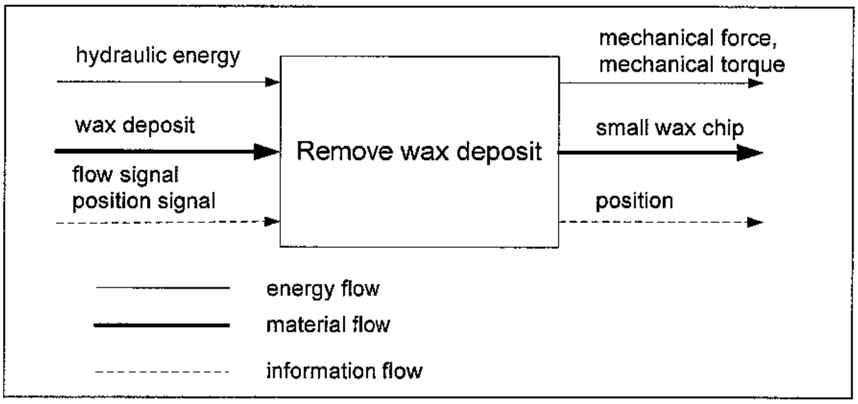


Figure 5-2: Overall function of PIG design.

Overall function of PIG design is further decomposed into sub-functions. This functional decomposition is continued until a set of function can be achieved by a physical component. According to Ullman [47], the reasons for decomposing the overall function are:

1. To get a better understanding of the design problem.
2. To control the solution searching.
3. To realize that there might be some already existing components that can fulfill the function required.

Based on the function that had been identified in the physical decomposition activities, a detail function of PIG design is created in a schematic diagram as shown in Figure 5-3. A control flow and a verify obstacle function is added in the schematic diagram in order to fulfill the requirement of traveling at a constant speed.

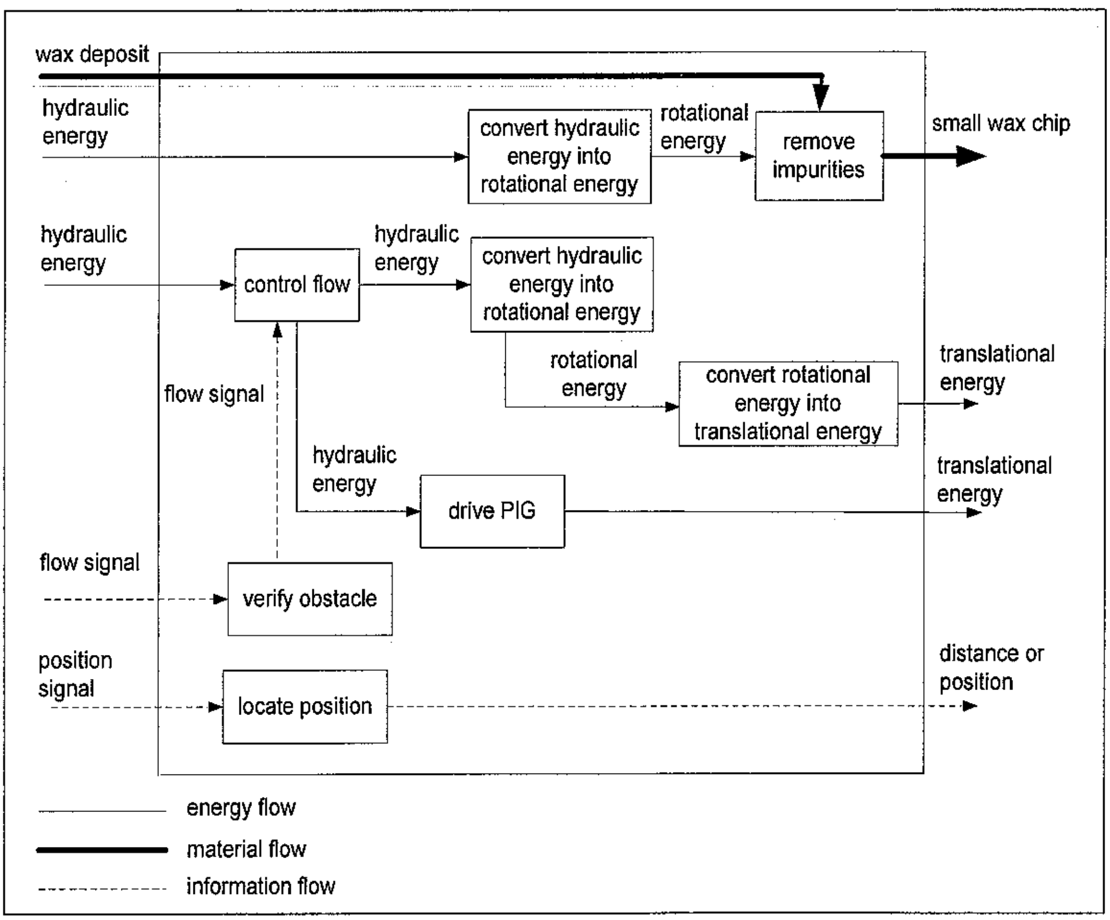


Figure 5-3: Detail function of PIG design.

Detail function of PIG design also represents the working principle of PIG design. It is explained as follows.

1. Wax deposit removal function.

   A hydraulic energy is converted into rotational energy by a device. This rotational energy will be used by another device to break down wax deposit into a small chip.

2. Traveling function

   Hydraulic energy passes a device that controls the fluid flow. In counter flow mode, hydraulic energy is converted into rotational energy by a device. This rotational energy will be converted into translational energy by another device to make the PIG design able to travel in a counter flow direction. If the PIG travels in the undesired speed, a device that can verify an obstacle will give a feedback to the control flow device. In case the PIG travels faster than the desired speed, the flow control device will reduce the amount of fluid pass over its. For the case the PIG travels very slowly and out of the range from the designed, the control flow device will be fully closed. As a consequence that hydraulic energy still flow, it will drive the PIG through a device to make it automatically return to the initial point of launching.

3. Safety function

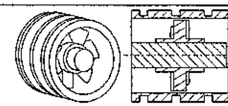
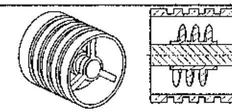
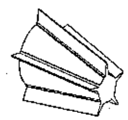
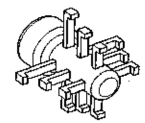
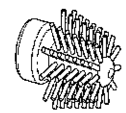
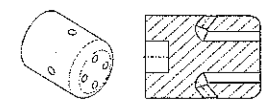
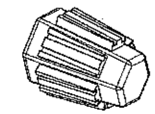
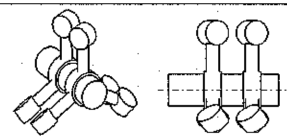
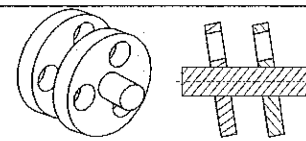
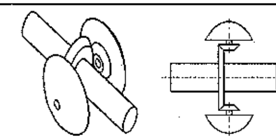
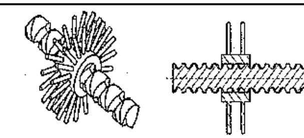
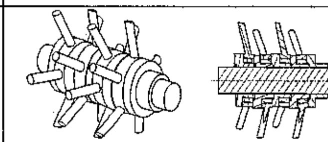
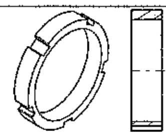
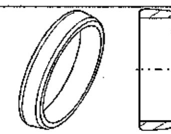
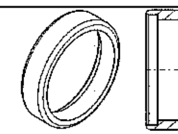
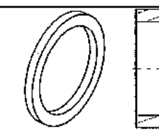
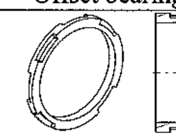
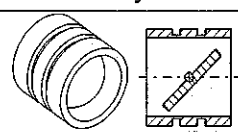
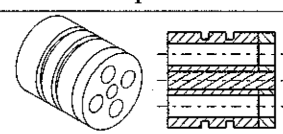
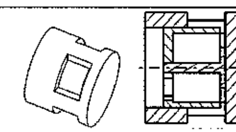
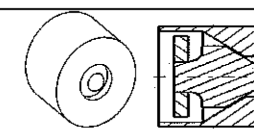
   Position of the PIG will be indicated by a device that can transmit and receive the signal.

The detail function of PIG design helps to illustrate its working principle. It provides a key step leading to the generation of large number of potential solutions that can fulfill the required function of PIG design.

b. Morphological chart

The function required to carry out the overall function that had been identified in the functional decomposition activities is put in a morphological chart. A morphological chart is a visual way to capture the required function of PIG design and to explore the solution for each required function. The solution for each function is further explored as many as possible from patents, journal, handbook and brainstorming. Once finished, the morphological chart contains a complete range of all solutions for each function required to accomplish the overall function of PIG design as shown in Table 5-5.

Table 5-5: Morphological chart of PIG design.

Solution / Function	1	2	3	4	5
Convert hydraulic energy to rotational energy	 Axial turbine	 Screw turbine			
Remove solid deposit	 Cutter I	 Cutter II	 Brush	 Nozzle	 Plough
Convert rotational energy into translational energy	 Wheel	 Offset wheel	 Tractor wheel	 Cam follower	 Offset bearing
Drive PIG	 Butterfly disc	 Cup disc	 Standard disc	 Disc	 Petal flapper
Control flow	 Butterfly valve	 Several passageway	 Sliding plate	 Poppet valve	
Verify obstacles	Optical encoder	Turbine flow meter	Gauge ring	Orifice plate	
Locate position	Electromagnetic	Magnet	Radio transmitter		

The consideration of solution selection from each function is discussed below.

1. Convert hydraulic energy to rotational energy

   A turbine extracts hydraulic energy and converts it into rotational energy. When fluid flow passes the turbine, it will impinge the blade and rotate a turbine shaft attached to it. An axial turbine is constructed by several axial blades wrapped around the axis while a screw turbine is constructed by a screw profile wrapped around the axis. The axial turbine and the screw turbine is used to generate power in operating conditions with low pressure drop and huge flow rate of fluid [49]. The axial blade profile makes the chip from the result of wax deposit removal able to pass the turbine and to be carried out in the same direction of fluid flow [40]. In the screw turbine type, the chip from the result of solid deposit removal may build up in the screw turbine due to the contour profile of screw blade.

2. Remove wax deposit

   Type of wax deposit removal tool depends on the mechanical properties of solid deposit that want to be removed. A wire brush is used to remove hard deposit while an elastomer plough and a steel scraper is used to remove soft deposit such as wax and sludge [20]. A nozzle is attached to the PIG to prevent solid deposit accumulation in front of the PIG by spraying the fluid [20].

3. Convert rotational energy into translational energy

   The drive mechanism can be classified into wheel, crawler, legged mobile and inchworm type as shown in Figure 5-4 [50]. The wheel and crawler type need a device to press the wheel to the pipeline wall to create a traction force. The benefits of this type of drive mechanism are the simplest drive mechanism compared to the others, easily to miniature and higher energy efficiency [50]. The legged mobile type provides a poor traction force and appears to be complicated for practical application [9]. The inchworm type provides a good traction force but the PIG movement is in discontinued motion [9].

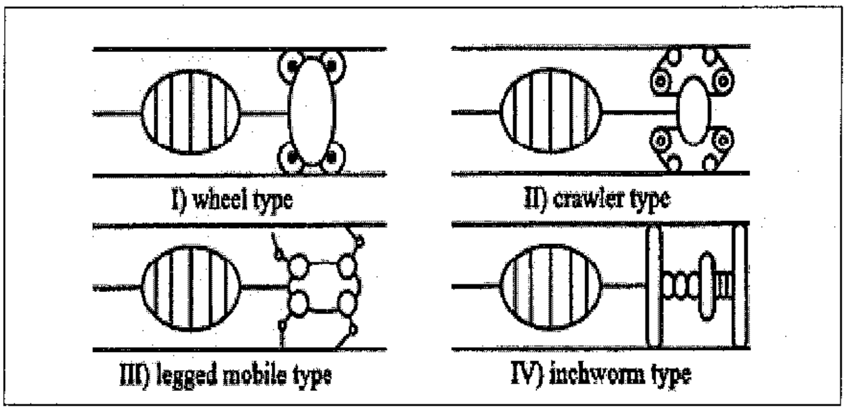


Figure 5-4: Classification of drive mechanism [50].

4. Drive PIG

A conventional PIG utilizes fluid source through the disc as a propulsion force. The pressure difference across the disc forces the PIG to move in the same direction with the fluid flow. Disc types can be classified into butterfly, cup, standard, petal flapper, and disc. The advantages and drawbacks of each disc type are discussed below.

i. Butterfly disc

The butterfly disc is made by removing some material to overcome hoop stress when it enters the smaller pipeline. The sealing performance is not satisfactory but can be improved by adding a thin membrane behind the butterfly disc [30].

ii. Cup

The cup disc provides a better sealing performance and able to pass obstruction until twenty percent of the pipeline diameter [20].

iii. Standard disc

The standard disc is known as the least expensive [20].

iv. Petal flapper

The petal flapper comprises of a set of individual disc which overlaps to form a seal. It is more efficient than the butterfly disc but still unformed an adequate sealing [30].

v. Disc

The disc is able to use in a reverse direction and very effective for sealing function [51].

5. Control flow

The PIG speed can be regulated by controlling the volume flow rate of fluid that passes through a turbine. A flow control device is attached to the turbine to make the PIG travel in a constant speed. When the PIG travels faster than the desired speed, the valve opening will be smaller than normal condition. The type of flow control device can be classified into butterfly valve, passage way, sliding plate, and poppet valve. The advantages and drawbacks of each type of flow control device are described as following.

i. Butterfly valve

A butterfly valve is used to control the volume flow rate of fluid across the PIG bodies. It is driven by an internal motor with an internal battery as a power source. The advantages of this device are simple to implement and a good throttle device [28].

ii. Several passage way

Several passage way device consists of several tubes that pass through the PIG bodies and an end plate that is moved relative to the PIG bodies [52]. The relative movement between the end plate and PIG bodies regulates the volume flow rate of fluid through the PIG bodies. An internal motor with an internal battery as a power source is used to drive the end plate that moves relative to the PIG bodies.

iii. Sliding plate

A sliding plate device consists of a sleeve valve that slides through the bypass duct to regulate the fluid flow. A hydraulic or an electrical actuator is used to drive the sleeve valve across the duct. This device is suitable for an application in huge volume flow rate of the fluid operation [53].

iv. Poppet valve

The volume flow rate of fluid across the PIG bodies can be controlled by using a poppet valve that consists of a cone valve and a spring. An opening valve is determined by the spring stiffness. This system does not depend on the internal power source [54].

6. Verify obstacles

A sensor is used to determine whether a PIG travels at constant speed or not. A controller receives a feedback from this sensor and gives an order to an actuator to regulate an opening valve. The type of device that can be used to verify obstacles are turbine flowmeter, orifice plate, optical encoder, and gauge ring. The advantages and drawbacks of each type of this sensor are discussed below.

i. Turbine flowmeter

The fluid flow that passes through a turbine can be used indirectly to indicate the PIG speed. When the fluid flow passes through the turbine flowmeter larger than a setting point, it means the PIG travels faster than the desired value. The drawback of turbine flowmeter sensor is unsuitable for application in abrasive fluid [55].

ii. Orifice plate

An orifice plate is used to measure indirectly the PIG speed by comparing the measurement value of fluid velocity to a setting point of PIG speed. It has advantage on the least expensive. The drawback of the orifice plate is limitation of the range measurement [55].

iii. Optical encoder

A rotational shaft speed of turbine can be used indirectly to indicate the PIG speed. An optical encoder is used to measure the turbine rotational shaft speed. It has advantages on simple, reliable and low cost solution [55].

iv. Gauge ring

A tactile sensor like gauge ring can be used to measure force act on the PIG. It can be used to indicate whether the PIG can pass an obstruction or not. The advantage of gauge ring is simple and compact.

7. Locate position

PIG locating is a method to determine the position of PIG in the pipeline. A transmitter device is carried by the PIG while a receiver is put along the pipeline to locate the PIG. The devices that can be used to locate the PIG position are electromagnetic, magnet and radio transmitter. The strong points and drawbacks from each device are discussed below.

i. Electromagnetic

An electromagnetic device is mounted in a PIG. This device transmits an electrical magnetic field. The electrical magnetic field will be received by a receiver located in the ship that operates near the operation pipelines. This system generally has a range area of one until three meter for the offshore application [20].

ii. Magnet

A small permanent is attached in a PIG. When the PIG passes a marker that is laid on the pipeline, the magnet field will turn on the marker. The advantage of this device is independent on an internal power source which may exhaust during the pigging process. The drawback of this device is the range of operation limited up to two meters below the ground [20].

iii. Acoustic pinger

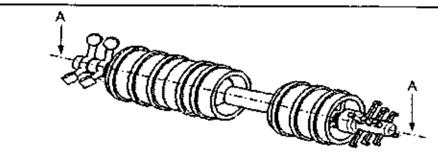
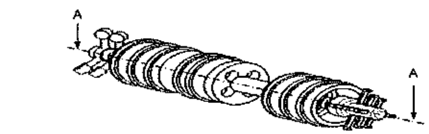
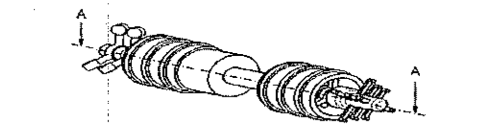
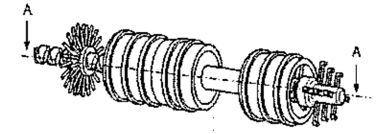
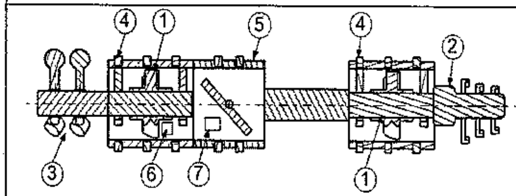
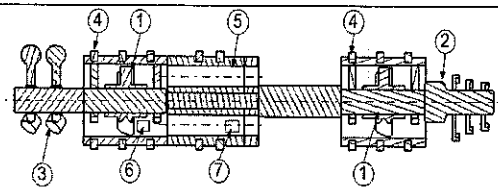
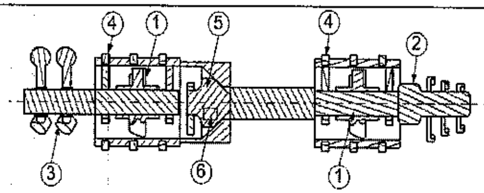
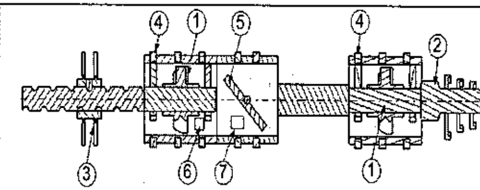
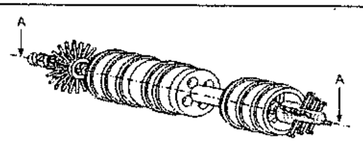
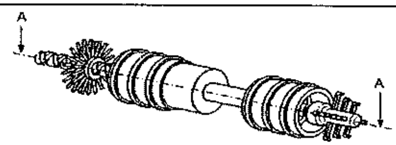
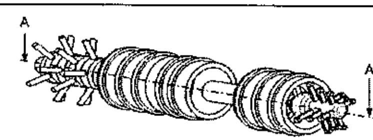
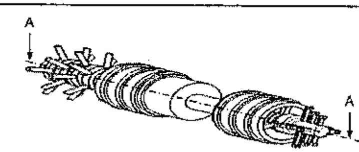
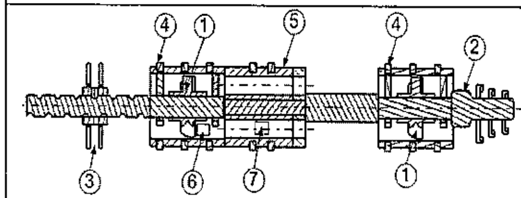
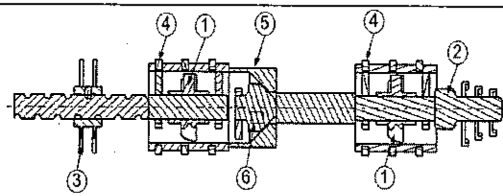
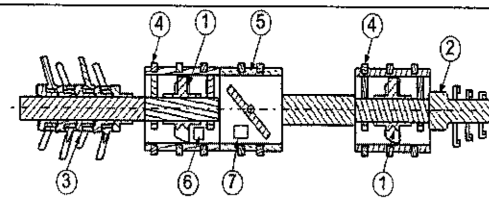
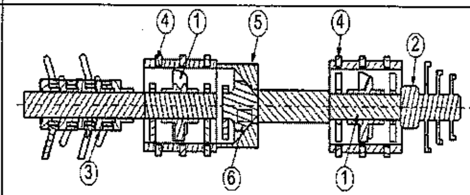
An acoustic pinger is a battery-powered acoustic beacon which emits an acoustic pulse at regular time and particular frequency. This device has a range area up to two km and accuracy in a range between five and ten meter [56]. The drawback of this device is that it is not suitable for gas pipeline and dual layer pipeline [57].

c. Concept combination

Generating conceptual design of PIG is performed by selecting solution for each function and combining them to form concepts. If all the solution from each function from the morphological chart of PIG design at Table 5-4 is combined, it will produce around 12000 concept of PIG design.

During the combination process, several criteria are considered to produce potential concepts design of PIG. The criteria used are combination of solution that would demonstrate ability to move in bidirectional motion at a constant speed, rank of the possible solution factor and compatibility factor [58]. Based on these criteria, several PIG concepts are generated. A schematic drawing of each concept design of PIG is then created to visualize each individual concept as shown in Table 5-6.

Table 5-6: Several new PIG concepts.

Concept A	Concept B	Concept C	Concept D
			
			
1. Axial turbine, 2.Cutter II, 3.Wheel, 4.Disc, 5.Butterfly valve, 6.Optical encoder, 7.Acoustic pinger.	1. Axial turbine, 2.Cutter II, 3.Wheel, 4.Disc, 5. Passage way, 6.Optical encoder, 7.Acoustic pinger.	1. Axial turbine, 2.Cutter II, 3.Wheel, 4.Disc, 5.Poppet valve, 6.Acoustic pinger.	1. Axial turbine, 2.Cutter II, 3.Cam follower, 4.Disc, 5.Butterfly valve, 6.Optical encoder, 7.Acoustic pinger.
Concept E	**Concept F**	**Concept G**	**Concept H (Datum)**
			
			
1. Axial turbine, 2.Cutter II, 3.Cam follower, 4.Disc, 5.Passage way, 6.Optical encoder, 7.Acoustic pinger.	1. Axial turbine, 2.Cutter II, 3.Cam follower, 4.Disc, 5.Poppet valve, 6.Acoustic pinger.	1. Axial turbine, 2.Cutter II, 3.Offset Bearing, 4.Disc, 5. Butterfly valve, 6.Optical encoder, 7.Acoustic pinger.	1. Axial turbine, 2.Cutter II, 3.Offset Bearing, 4.Disc, 5. Poppet valve, 6.Acoustic pinger.

The working principle for each concept is explained as follows.

1. Concept A

   Concept A consists of an axial turbine with function of converting hydraulic energy into rotational energy, a cutter with function of wax deposit removal, a butterfly valve with function of regulating the volume flow rate of fluid through the axial turbine, an offset wheel with function as a drive mechanism, an optical encoder with function of sensing the obstruction of fluid velocity change and an acoustic pinger with function of locating the PIG.

   One turbine is used to rotate a cutter tool and the other is used to drive a drive mechanism of offset wheel. The turbine for drive mechanism is attached with the butterfly valve which is driven by an internal motor with an internal battery as a power source. The optical encoder is used to measure the rotational speed of turbine shaft which represents the PIG speed. Based on this input, the butterfly valve is driven by the internal motor to open or close partially.

   The PIG can move in a counter flow direction because the wheel axis is not perpendicular to the pipeline axis. When driven by the turbine, a torque is applied to the drive mechanism shaft, the wheel moves in a forward direction and makes a spiral motion like a screw. In case drive mechanism is incapable to provide enough traction force to move in the counter flow direction, the butterfly valve will be fully closed. Since fluid flow keeps flowing, the PIG is forced to return to the initial point of launching.

2. Concept B

   Concept B is the same with concept A. The difference is a device that is used to regulate the volume flow rate of fluid through the axial turbine is a several passage way mechanism. It consists of an end plate at the front passage way mechanism which can block the fluid flow. The end plate is driven by an internal motor with an internal battery as a power source.

3. Concept C

   Concept C is the same with concept A. The difference is a device that is used to regulate the volume flow rate of fluid through the axial turbine is a poppet valve mechanism. This poppet valve mechanism is a perpetual mechanism where the volume flow rate of fluid through this valve depends on the spring stiffness.

4. Concept D

   Concept D consists of an axial turbine with function of converting hydraulic energy into rotational energy, a cutter with function of wax deposit removal, a butterfly valve with function of regulating the volume flow rate of fluid through an axial turbine, an cam follower with function as a drive mechanism, an optical encoder with function of sensing an obstruction of fluid velocity change and an acoustic pinger with function of locating the PIG.

   One turbine is used to rotate the cutter tool and the other is used to drive the drive mechanism of cam follower. The turbine for drive mechanism is attached with the butterfly valve which is driven by an internal motor with an internal battery as a power source. The optical encoder is measured the rotational speed of turbine shaft which represents the PIG speed. Based on this input, the butterfly valve is driven by the internal motor to open or close partially.

   The PIG can move in a forward direction because of the unique characteristic of the bristle which is easier to move in a forward rather than in a backward direction. As the drive mechanism shaft rotates, the bristle slides along the traverse shaft until it reaches at the end of the shaft. When the bristle reaches at the end of the shaft, it will move continuously in the backward direction. By taking the advantage of the bristle which is easier to move in the forward direction rather than in the backward direction, the bristle will grip the pipeline and the PIG will move in the forward direction. This sequential step of the drive mechanism is repeated continuously to make the PIG able to crawl in the forward direction. When the fluid flow is incapable to be converted into the traction force required to move in the counter flow direction, the butterfly valve will close and block the path of fluid flow. At this condition, the PIG will act like a conventional PIG. The fluid flow will push the PIG to return to the initial point of launching.

5. Concept E

   Concept E is the same with concept D. The difference is a device that is used to regulate the volume flow rate of fluid through the axial turbine is a several passage way mechanism. It consists of an end plate at the front of passage way mechanism which can block the volume flow rate of fluid. The end plate is driven by an internal motor with an internal battery as a power source.

6. Concept F

   Concept F is the same with concept D. The difference is a device that is used to regulate the volume flow rate of fluid through an axial turbine is a poppet valve mechanism. This poppet valve mechanism is a perpetual mechanism where the volume flow rate of fluid through this valve depends on the spring stiffness.

7. Concept G

   Concept G consists of an axial turbine with function of converting hydraulic energy into rotational energy, a cutter with function of wax deposit removal, a butterfly valve with function of regulating the volume flow rate of fluid through the axial turbine, an offset bearing with function as a drive mechanism, an optical encoder with function of sensing an obstruction of fluid velocity change and an acoustic pinger with function of locating the PIG.

   One turbine is used to rotate the cutter tool and the other is used to drive the drive mechanism of the offset bearings. The turbine for a drive mechanism is attached to a butterfly valve which is driven by an internal motor with an internal battery as a power source. The optical encoder is measured the rotational speed of turbine shaft which represents the PIG speed. Based on this input, the butterfly valve is driven by the internal motor to open or close partially.

The PIG can move in a counter flow direction because of the oscillatory motion of outward, backward, inward and forward from a set of legs. The legs are mounted to the bearing where the axis of this bearing is offset from the axis of the drive mechanism shaft. The bearing moves forward towards the centreline of the drive mechanism shaft when the shaft of the drive mechanism rotates. It makes the leg mounted on the offset bearing at a particular time to touch the pipeline wall to create a traction force. By ordering the sequence of the legs to touch the pipeline wall, the PIG will be able to travel in a counter flow direction like a human walking mechanism. In case the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the butterfly valve will close. As a consequence, the PIG will be pushed by the fluid flow to return to the initial point of launching.

8. Concept H

   Concept H is the same with concept G. The difference is a device that is used to regulate the volume flow rate of fluid through an axial turbine is a poppet valve mechanism. This poppet valve mechanism is a perpetual mechanism where the fluid flow through this valve depends on the spring stiffness.

   Concept H is almost similar with the contraflow tetherless mechanical pipeline crawler that has been produced by Astec Development Ltd. for the Shell. Therefore, in the concept evaluation step, it is chosen as a datum to represent a commercial PIG that has been produced in the market.

5.2.4 Concept Evaluation

Once the design concepts of PIG have been generated, concept evaluation is to be done to select the most promising to be further developed in the embodiment design phase. This is performed in the concept evaluation step. Each concept is compared to each other for particular criteria to find its strength and weakness. The method that is used to select the most promising concept in this design process is concept screening [46].

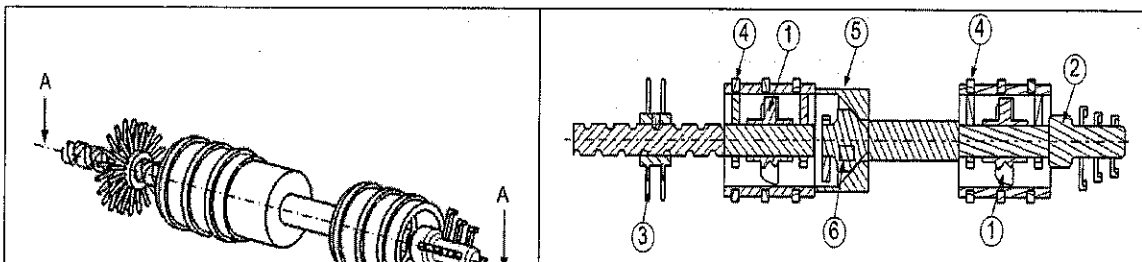
In the concept screening method, each design concept is compared to each other for particular criteria with the equal weight. The criteria that are used to select the most promising concept of PIG are: able to travel at uniform speed, ease of traveling in forward and reverse direction, reliability, ease of manufacture, duration of operation and robustness. These criteria are derived based on the PDS of PIG design and related references [47, 59]. A concept screening matrix evaluation form is further generated based on these criteria.

In order to select the most promising concept of PIG, a survey was performed to solicit feedback from peer reviewers. Initially, the survey forms were sent through the academic people in Universiti Teknologi of PETRONAS, Malaysia, pigging company and pipeline operator. The reviewers from the academic people consist of four lecturers and two PhD. students, who have a background in the mechanical design to represent feedback from education point of view. Meanwhile, the pigging companies that had been sent the survey form are Rosen Inspection Far East, Weatherford, Romstar, BJ Oilwell Service and Aker Kaverner Sdn Bhd. Pipeline operators that were sent are Petronas Penapisan Sdn Bhd, Kerteh, Trenganu and Petronas Carigali Sdn Bhd. The reviewers who send back the survey were from academic people and Petronas Penapisan Sdn Bhd. An example of survey form of concept evaluation matrix is attached in Appendix A. The ranking of each concept is based on the result of survey as shown in Table 5-7. Further, score weight factor is used to determine the most promising concept of PIG.

Table 5-7: Score–rank table of PIG selection survey.

Rank	Score	Concept						
		A	B	C	D	E	F	G
1	12	0	0	3	0	0	2	1
2	10	3	2	0	0	0	2	0
3	8	1	1	1	0	3	2	1
4	6	0	3	3	5	1	0	4
5	4	3	1	0	2	2	1	1
6	2	0	0	0	0	1	0	0
Total score = Number of response x score		50	50	62	38	40	64	48

Based on the result from the concept selection step, concept F as shown in Figure 5-5 is proposed to be developed in the embodiment design phase. The proposed PIG concept consists of two axial turbines. One is to drive a cam follower as a drive mechanism and the other is to drive a cutter as a wax deposit removal tool. Each turbine converts fluid flow into rotational energy and transfers it through the shaft. The turbine that provides power to the drive mechanism is equipped with a poppet valve. This poppet valve has a function to control the amount of volume flow rate of fluid through the turbine. By adding the feature of the poppet valve, the PIG will be able travel at a constant speed and also through the entire length of the pipeline since it is perpetual mechanism. If the PIG speed is faster than the desired speed, the poppet valve will open smaller than normal operation and vice versa. If the PIG faced an obstruction, the poppet valve would be fully closed and the fluid flow would force the PIG to travel back to an initial point of launching.



1. Axial turbine, 2.Cutter II, 3.Cam follower, 4.Disc, 5. Poppet valve, 6.Acoustic pinger.

Proposed 3D PIG model	Cross sectional (A-A) view of PIG model

Figure 5-5: The proposed PIG concept.

The advantages of concept F are:

a. It provides traction force to travel in a counter flow direction at the offshore pipeline operating condition.
b. It has a capability to negotiate with obstruction such as reducing diameter due to wax deposit.
c. It is a perpetual mechanism which makes it able to travel through the entire length of the pipeline.

5.3 Embodiment Design Phase

The proposed concept from conceptual design phase is transformed into physical component in the embodiment design phase. It consists of product architecture and configuration design step.

5.3.1 Product Architecture

The definition of product architecture is the scheme that describes the interaction of each module which composed from several product elements function [46]. The activities to define the product architecture of PIG design are:

a. Schematic design of PIG design.

   The required element functions of PIG design are classified into five main modules, specifically: flow control, wax removal, drive mechanism, turbine for solid deposit wax removal and turbine for drive mechanism module. Schematic diagram of PIG design is shown in Figure 5-6.

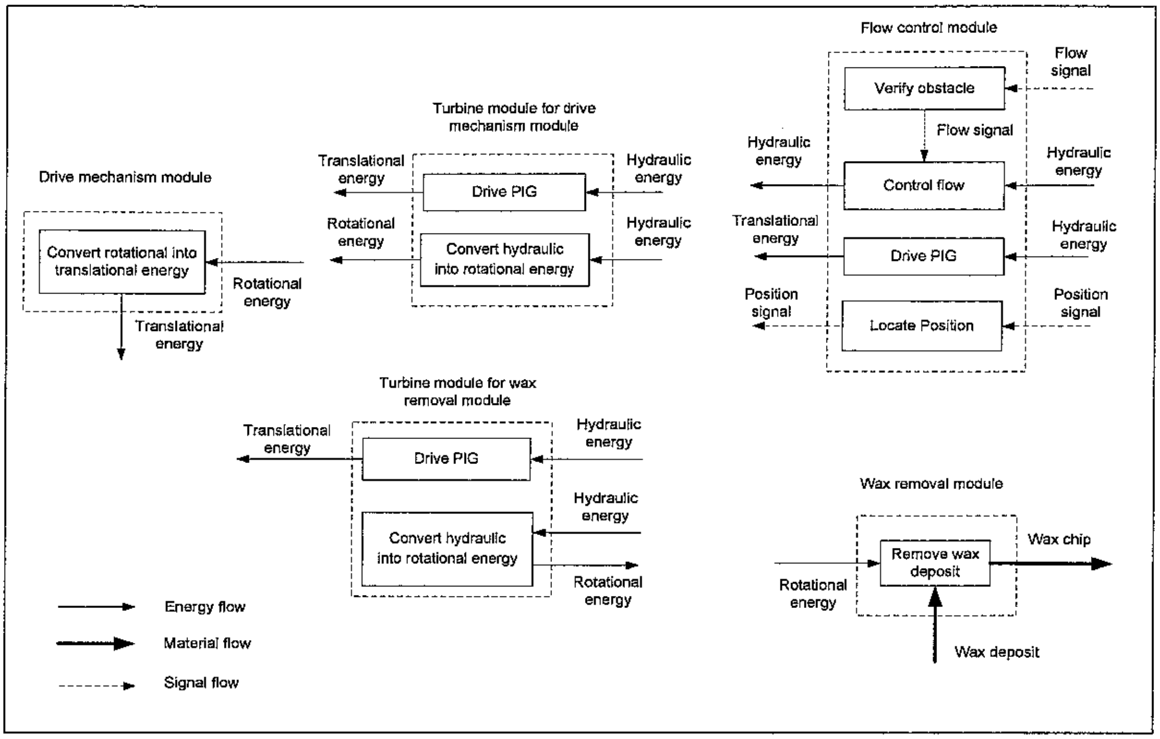


Figure 5-6 Schematic diagram of PIG design.

b. Clustering the element of PIG design

The five main modules are arranged based on the logical flow transformation. The modules arrangement determines product architecture of PIG design as shown in Figure 5-7. In this activity, the element function on each module is transformed into physical component.

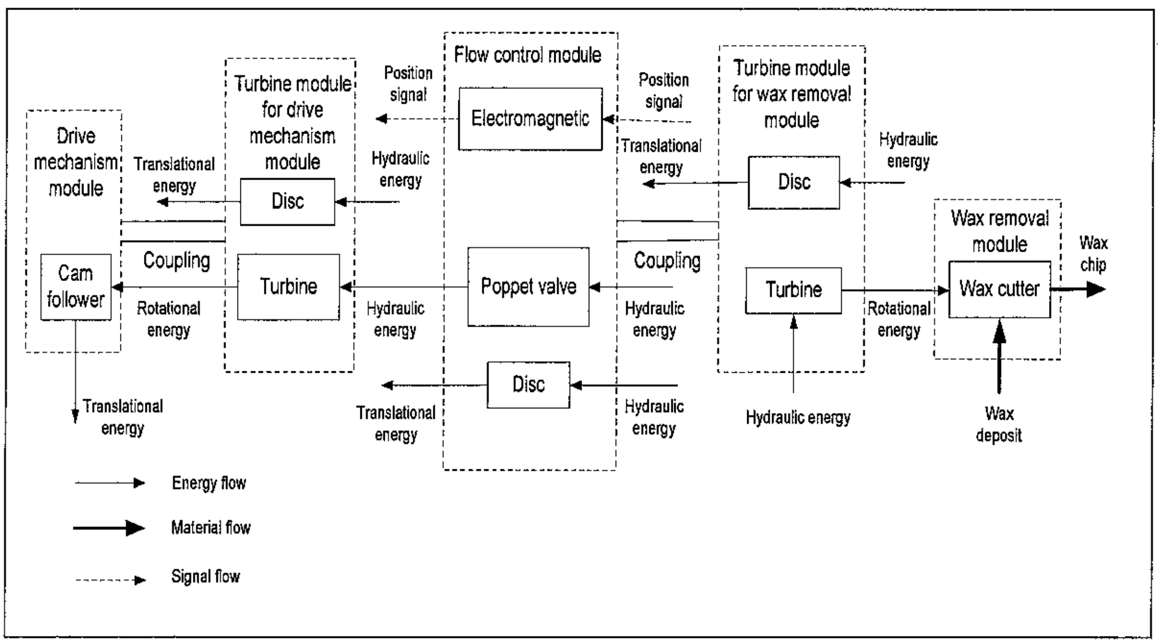


Figure 5-7: Product architecture of PIG design.

c. Rough geometry layout of PIG design.

Based on the product architecture of PIG design, a rough layout of PIG design is created. The rough layout is shown in Figure 5-8. In order to pass the pipeline bend, the PIG design is divided into three main sections:

1. Drive mechanism module,
2. Combination between turbine module and flow control module,
3. Combination between turbine module and wax removal tool module.

The connection between each section is via a universal joint.

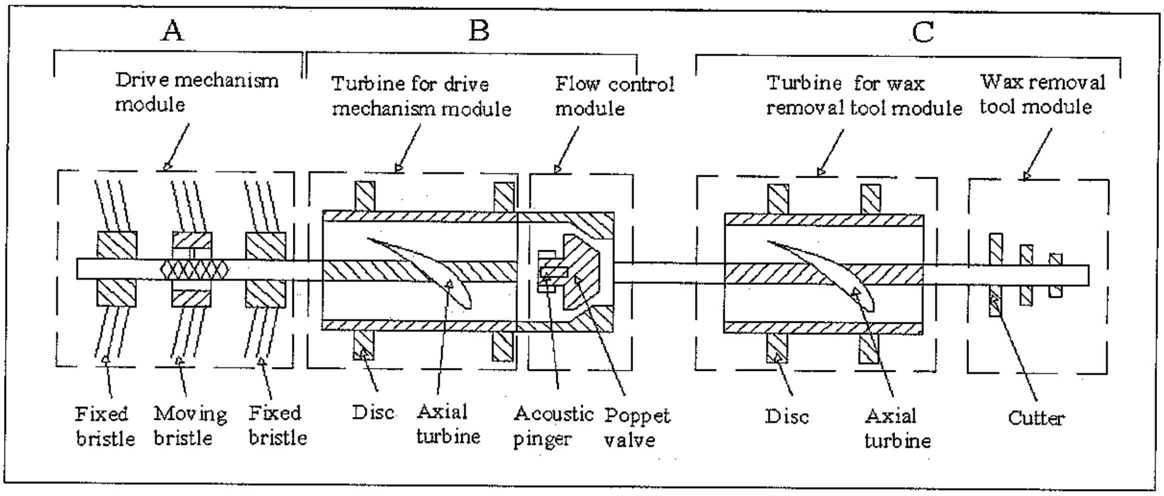


Figure 5-8: A rough layout of PIG design.

5.3.2 Configuration Design

In the configuration design step, the shape and general dimension of physical component from each module is determined based on the requirement as described in PDS document. The analysis of component from each module is limited only to component which is described in the flowchart shown in Figure 5-9.

The main requirement of PIG design is able to travel in bidirectional motion at a constant speed as stated at problem definition in section 5.2.1. The operating condition of PIG design is specified in the PDS document as stated in the section 5.2.1.4 and summarized in Table 5-8. The operating condition of PIG design will be considered as an initial starting point of the design process.

Table 5-8: PIG design operating condition.

1	Pipeline specification [7]	Value
	Nominal size	6"
	Inner diameter (D_I)	159.3 mm
	Bend section	5D
	Length of pipeline	6 km
	No PIG launcher available at the manifold	
2	Pipeline operation condition [7]	Value
	Pressure operation (P)	15 MPa
	Temperature operation (T)	4-90°C
	Fluid velocity (V_f)	1-1.5 m/s
	Pressure drop between the manifold and platform	7.44 MPa
3	PIG [7]	Value
	Desired PIG velocity (V_P)	0.033 m/s
	Pressure drop across the PIG (ΔP_T)	31 kPa
4	Crude oil properties API 40 [60]	Value
	Density	825 kg/m^3
	Kinematic viscosity	9.7 cSt
5	Wax properties [14]	Value
	Paraffin wax	C22 – C39
	Wax content in crude oil	5 %
	Cloud point of wax	28.3°C
	Yield stress	400-900 Pa
	Wax annular ring thickness	25.4 mm

5.3.2.1 Overall Flowchart Design

The overall process of PIG design is shown in Figure 5-9.

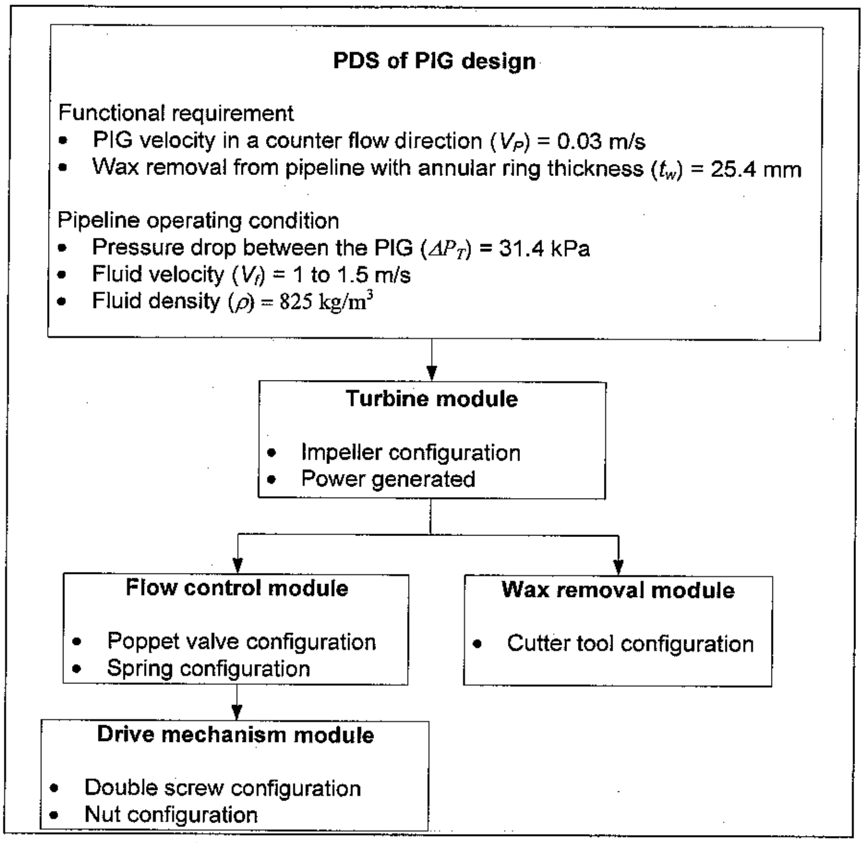


Figure 5-9: Overall flowchart of PIG design.

An input of parameter design for each module of PIG design is based on the PDS document. The PIG design is desired to travel in a counter flow direction at a constant speed of $V_P = 0.03$ m/s with the capability of wax removal in annular ring thickness of about $t_w = 25.4$ mm. In addition, the PIG design is required to operate at the pipeline with pressure drop across the PIG of $\Delta P_T = 31$ kPa, crude oil density of $\rho = 825$ kg/m^3 and fluid velocity in the range of 1 to 1.5 m/s.

The initial stage of configuration design is to configure turbine module. The analysis of the turbine module is limited to the impeller configuration which determines power generated by the turbine module.

Since the PIG design is desired to travel at a constant speed in a counter flow direction, the volume flow rate through the turbine for drive mechanism module need to be maintained at a constant value. Hence a flow control module is attached to the turbine module to fulfill this condition. The analysis of the flow control module is limited to the poppet valve and spring configuration.

In order to move in a counter flow direction, a drive mechanism module needs to generate a traction force to overcome the friction force between the PIG design and pipeline and the propulsion force due to the pressure drop across the PIG design. In this work, the analysis of drive mechanism module is limited to a double screw and nut configuration.

The wax removal process is performed through a cutter tool which is driven by a turbine module when the PIG moving in a counter flow direction. The analysis of wax removal module is limited to a cutter tool configuration.

5.3.2.2 Turbine Module

The function of turbine module is to provide power for drive mechanism and wax removal module. The fluid energy is converted into rotational energy through the impeller as the impeller is placed in the fluid flow. Figure 5-10 illustrates the working principle of this module.

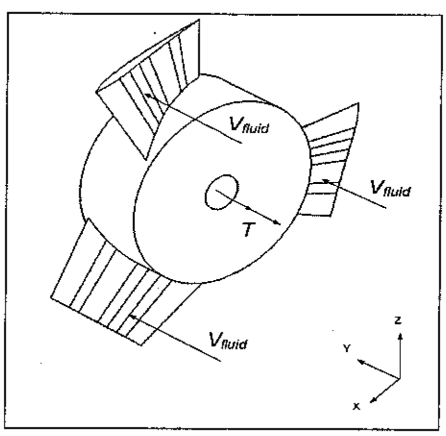


Figure 5-10: Working principle of the turbine module.

a. Design flowchart of turbine module

   The most important element that affects the turbine performance is impeller. The design procedure of turbine module can be described in the flowchart as shown in Figure 5-11.

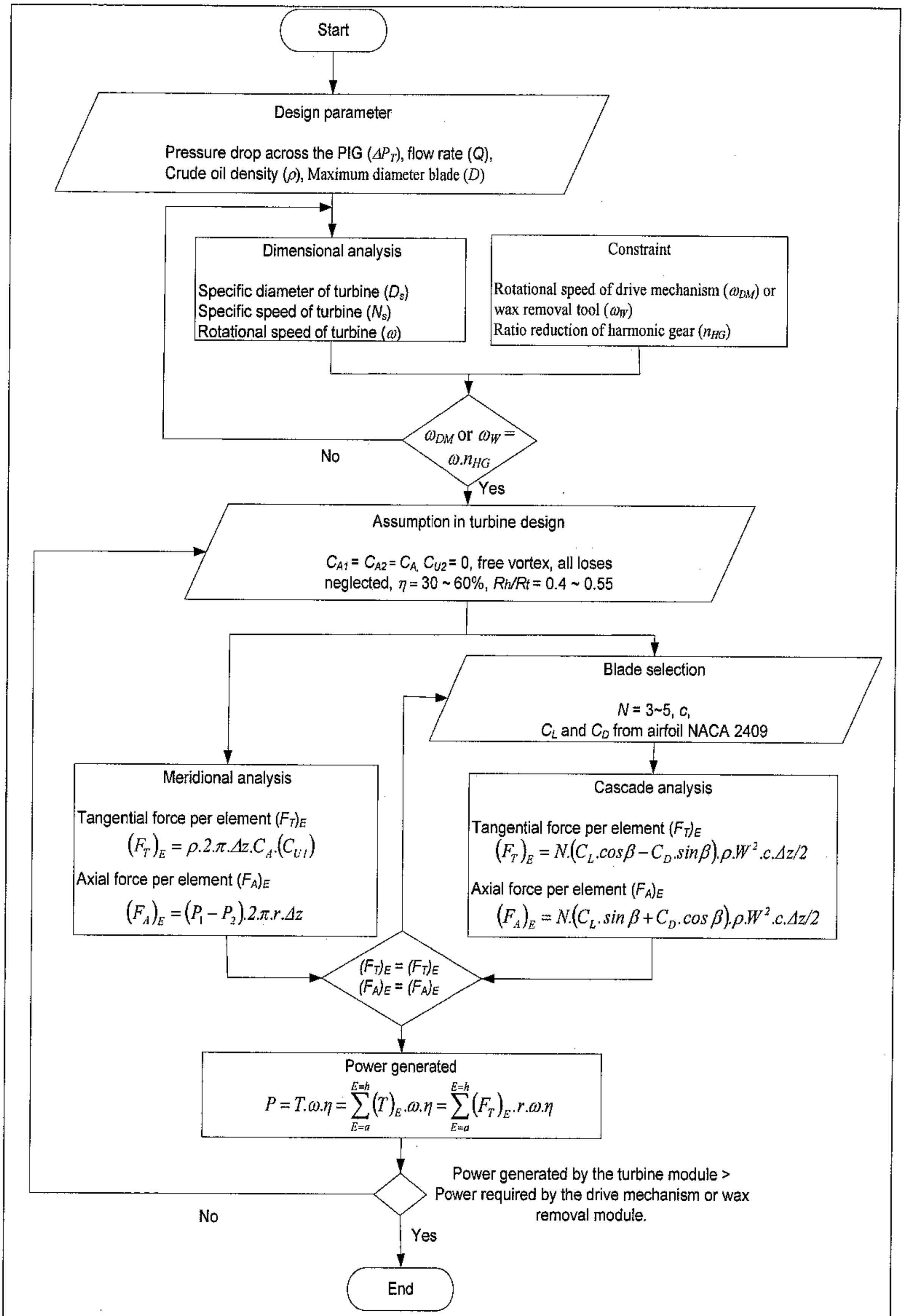


Figure 5-11: Design flowchart to determine power generated by the turbine module.

b. Power generated by the turbine module

i. Design parameter

A turbine design is started by defining the operation conditions of turbine. It is taken from the PIG design operating condition in Table 5-8 and summarized in Table 5-9.

Table 5-9: The requirement of turbine design.

Volume flow rate (Q)	0.02 m^3/s
Pressure drop (ΔP_T)	31 kPa
Fluid density (ρ)	825 kg/m^3
Head (H)	3.67 m

ii. Dimensional analysis

A dimensional analysis is performed to determine an impeller diameter (D) and turbine rotational speed (ω) with an input of turbine design requirement as defined in Table 5-9. The constraints on the selection of turbine rotational speed are gear reduction ratio (n_{HG}) and rotational speed of drive mechanism module (ω_{DM}) or rotational speed of wax removal module (ω_W).

A dimensional analysis is started from an initial selection of impeller diameter. Based on the requirement of turbine design as stated in Table 5-9, according to Wright [49], diameter specific (D_S) is estimated from:

$$D_S = \frac{D\left(\frac{\Delta P_T}{\rho}\right)^{1/4}}{Q^{1/2}} \quad (5.1)$$

The relationship between the diameter specific (D_S) and the specific speed (N_s) is given by,

$$N_s = 9.0 D_s^{-2.103}, \qquad D_s \leq 2.84$$
$$N_s = 3.25 D_s^{-1.126}, \qquad D_s \geq 2.84 \quad (5.2)$$

The turbine rotational speed (ω) is further calculated from:

$$\omega = \frac{N_s \cdot \left(\frac{\Delta P_T}{\rho} \right)^{3/4}}{Q^{1/2}} \tag{5.3}$$

A dimensional analysis of impeller diameter from 50 to 159 mm is performed to find the appropriate turbine rotational speed. The result of dimensional analysis is shown in Table 5-10.

Table 5-10: Dimensional analysis of turbine design.

D (mm)	D_S	N_S	ω (rad/s)
159	2.79	1.04	111.95
130	2.28	1.59	170.98
110	1.93	2.26	242.95
90	1.58	3.44	370.51
70	1.23	5.84	628.53
50	0.88	11.85	1275.36

Based on dimensional analysis, a turbine with diameter of D = 90 mm and turbine rotational speed of ω = 370 rad/s is proposed to be an optimum parameter. This type of turbine with specific diameter of D_S = 1.58 and specific speed of N_S = 3.44, is in the range of axial turbine ($1.25<D_S<1.65$, $3<N_S<6$) [49]. The efficiency power generated by this type of turbine is in the range of 30% to 60% [49].

iii. Assumption in turbine design

In order to simplify the analysis of power generated by an axial turbine, the complex three dimensional flows are treated as the superposition of a number of two dimensional flows. Fluid flow analysis through the turbine can be divided into two types, specifically: meridional and cascade flow [61] as shown in Figure 5-12.

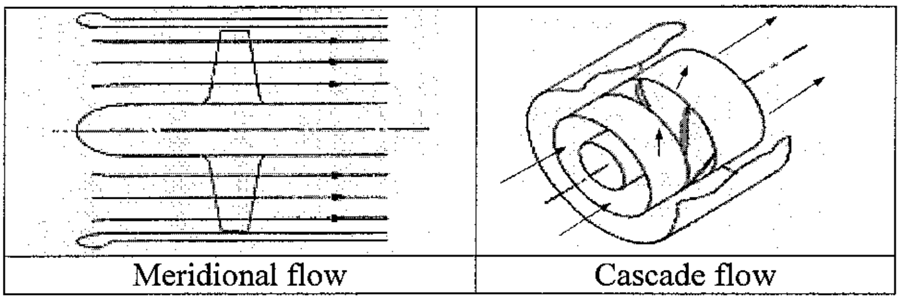


Figure 5-12: Treatment of three dimensional flows through axial turbine as superposition of meridional and cascade flow [61].

The meridional flow enters the annulus area of an axial turbine and its form still remains cylindrical as they pass through the entire length of axial turbine. Each of the meridional flow then will intersect with the impeller to form a circumferential array of impeller known as cascade. If one of the cylindrical surface at certain radius is unwrapped from its coordinates (x,r,θ) and laid out flat onto the coordinates plane (x,y) as illustrated in Figure 5-13, an infinite array of impeller stretching along the y axis is found. Therefore analysis of three dimensional flows can be modeled as a series of two dimensional cascades. The benefit of this approach is that the Euler equations can be applied to each cascade section independently to determine the inlet and outlet velocity triangle [61].

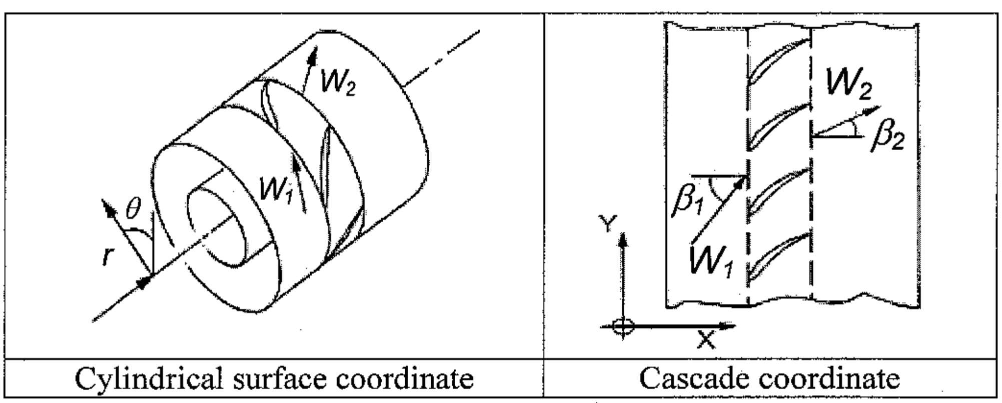


Figure 5-13: Transformation of a cylindrical cascade section into an infinite rectilinear cascade in the (x,y) plane [61].

Assumptions that are made in turbine design are [62]:

- Axial velocity of fluid is uniform at the inlet and outlet of impeller ($C_{A1} = C_{A2}$).
- Outlet whirl velocity of fluid (C_{U2}) is zero.
- Fluid motion on the impeller is free vortex.
- All losses are neglected.
- Hydraulic efficiency is 40%.

The turbine design is first analyzed by using meridional flow and then cascade flow analysis. The tangential and axial force act on the impeller from these analyses must be balanced.

iv. Meridional analysis

The resultant force acting on an impeller consists of tangential and axial force. The tangential force is developed due to a fluid momentum change in tangential direction. A power generated by the turbine depends on the tangential force acting on the impeller. Therefore it is desired to obtain maximum value of it. The axial force is developed due to a change of static pressure and momentum in the axial direction. This force does not contribute to the power generated by the turbine and will be absorbed by a bearing.

According to Round [62], the tangential force on the certain element of impeller $(F_T)_E$ is:

$$(F_T)_E = \rho.2.\pi.\Delta z.C_A.(C_{U1}) \tag{5.4}$$

where ρ is fluid density in kg/m^3, r is radius from turbine axis to a certain element of impeller in m, Δz is width of each impeller element in m, C_A is axial velocity of fluid in m/s and C_{U1} is inlet whirl velocity of fluid in m/s.

The axial force on the certain element of impeller $(F_A)_E$ is:

$$(F_A)_E = (P_1 - P_2).2.\pi.r.\Delta z \tag{5.5}$$

where P_1 is inlet pressure in Pa, P_2 is outlet pressure in Pa, r is radius from turbine axis to a certain element of impeller in m and Δz is width of each impeller element in m.

The torque acting on the certain element of impeller $(T)_E$ is:

$$(T)_E = (F_T)_E . r \qquad (5.6)$$

where F_T is tangential force on the certain element of impeller in N and r is radius from turbine axis to a certain element of impeller in m.

The total torque acting on the impeller (T) is obtained by summing total torque acting on the certain element. It can be obtained from:

$$T = \sum_{E=a}^{E=h} (T)_E \qquad (5.7)$$

where $(T)_E$ is torque acting on the certain element in N.m and E is number of element.

The power generated by the turbine (P_T) is given by:

$$P_T = T.\omega.\eta \qquad (5.8)$$

where T is total torque acting on the impeller in N.m, ω is turbine rotational speed in rad/s and η is hydraulic turbine efficiency.

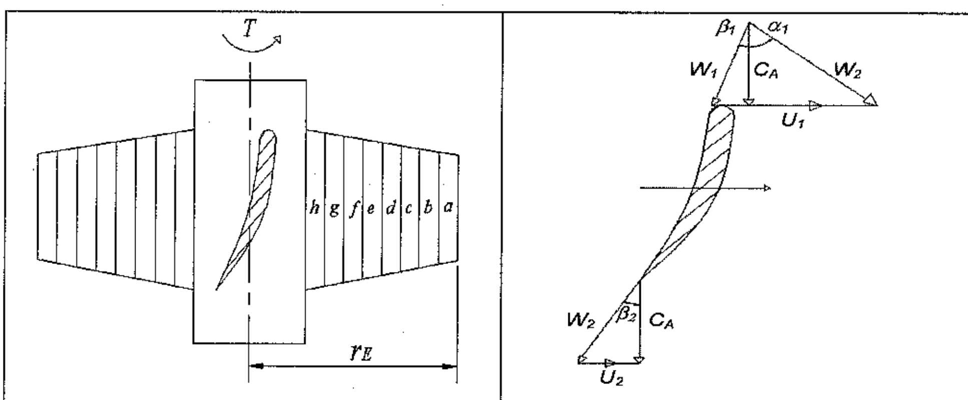
In order to calculate the force acting on the impeller, initially the hub diameter is determined by selecting an appropriate hub to tip ratio. According to Round [62], hydraulic turbine has a hub to tip ratio in the range of 0.4 to 0.55. In this design, the hub to tip ratio (R_H/R_T) is chosen as 0.55. Based on dimensional analysis, the tip diameter of impeller (R_T) is 90 mm. Thus with the selection hub to tip ratio (R_H/R_T) of 0.55, the diameter of hub (R_H) is 49.5 mm.

The annular flow area and volume flow rate can now be used to determine the axial velocity. Thus, the axial velocity of fluid (C_A) is obtained from:

$$C_A = \frac{Q}{\pi.\left(R_T^2 - R_H^2\right)} \tag{5.9}$$

where Q is volume flow rate in m^3/s, R_T is tip diameter of impeller in m and R_H is hub diameter of impeller in m. Based on the design requirement to operate at $Q = 0.02\ m^3/s$ as defined in Table 5-9 and the assumption of $(R_H/R_T) = 0.55$ as described previously, and using equation 5.9, the axial velocity of fluid is 4.53 m/s.

The annular flow area is divided into eight sections with the same width of $\Delta z = 3.01$ mm. One of the cutting planes at a certain radius is taken to show the velocity triangle at the inlet and outlet as shown in Figure 5-14.



Impeller divided into several flow element	Velocity triangle at arbitrary position

Figure 5-14: Axial turbine [62].

The inlet whirl velocity of fluid (C_{U1}) is obtained from Euler equation with assumption of no outlet whirls velocity ($C_{U2} = 0$):

$$C_{U1} = \frac{g.H}{r.\omega} \tag{5.10}$$

where H is head in m, r is radius from axis turbine to a certain element of impeller in m and ω is turbine rotational speed in rad/s. Inserting value of $H = 3.67$ m as defined in Table 5-9 and $\omega = 370$ rad/s as a result from dimensional analysis into equation 5.10, the inlet whirl velocity of fluid is $C_{U1} = (0.10/r)$ m/s.

Based on value of C_A = 4.53 m/s as calculated from equation 5.9 and C_{UI} = (0.10/r) m/s as calculated from equation 5.10, the force and torque acting on the impeller element is calculated by using equation from 5.4 to 5.7. The result of force and torque calculation is shown in Table 5-11.

Table 5-11: Force and torque acting on the impeller element based on meridional analysis.

Element	r (mm)	C_{UI} (m/s)	F_A (N)	F_T (N)	T (N.m)
a	27.5	3.70	13.40	5.97	0.16
b	30	3.39	14.61	5.97	0.18
c	32.5	3.13	15.83	5.97	0.19
d	35	2.90	17.05	5.97	0.21
e	37.5	2.71	18.27	5.97	0.22
f	40	2.54	19.49	5.97	0.24
g	42.5	2.39	20.70	5.97	0.25
h	45	2.26	21.92	5.97	0.27
		sum	141.27	47.73	1.73

In ideal condition, the total axial force acting on the impeller is 141.27 N, the total tangential force acting on the impeller is 47.73 N and the total torque acting on the impeller is 1.73 N.m. Based on an assumption of η = 40% and ω = 370 rad/s as the result from dimensional analysis, and using equation 5.8, the power generated by turbine is P_T = 256 Watt.

v. Cascade analysis

An impeller that is placed in fluid flow will result a lift and a drag force due to aerofoil shape as shown in Figure 5-15. The lift force is responsible to transfer the energy from fluid into rotational energy while the drag force is associated with the impeller losses. In order to get the maximum lift force, the impeller is set at certain angle of attack (θ) based on the cascade data.

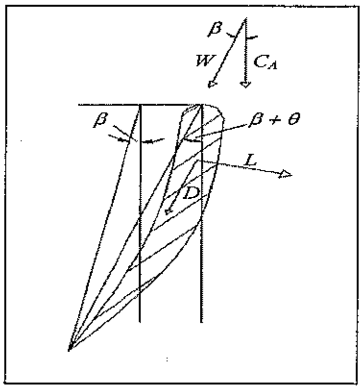


Figure 5-15: Airfoil section of axial impeller turbine [62].

The tangential force on the certain element of impeller $(F_T)_E$ is:

$$(F_T)_E = N.(C_L.\cos\beta - C_D.\sin\beta).\rho.W^2.c.\Delta z/2 \quad (5.11)$$

The axial force on the certain element of impeller $(F_A)_E$ is:

$$(F_A)_E = N.(C_L.\sin\beta + C_D.\cos\beta).\rho.W^2.c.\Delta z/2 \quad (5.12)$$

where N is number of the impeller, C_L is lift coefficient, C_D is drag coefficient, ρ is fluid density in kg/m^3, β is mean fluid angle in degree, W is relative velocity of fluid in m/s, c is impeller chord length in m and Δz is width of impeller element in m.

Before selecting the impeller profile, the fluid velocity and angle at the inlet and outlet is determined through the triangle velocity. The triangle velocity as depicted in Figure 5-16 shows the relationship between the fluid angle and fluid velocity.

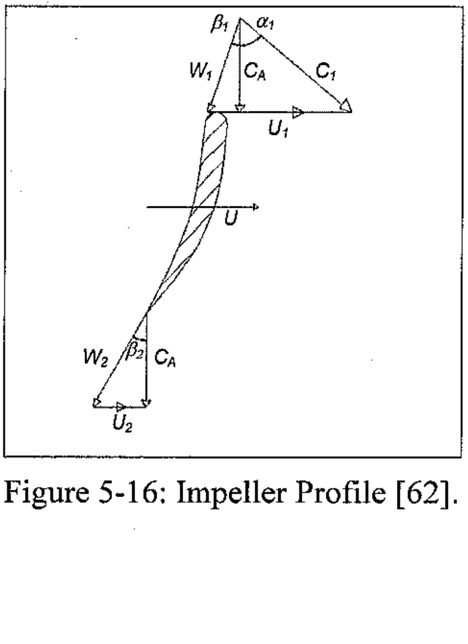


Figure 5-16: Impeller Profile [62].

The impeller speed at certain radius (U) is given by,

$$U = \omega . r \tag{5.13}$$

where ω is turbine rotational speed in rad/s and r is radius from axis turbine to a certain element of impeller in m.

Based on the known value of axial velocity of fluid (C_A) and the inlet whirl velocity of fluid (C_{U1}) from the meridional analysis, the inlet fluid angle (β_1) is calculated from:

$$\beta_1 = tan^{-1}\left(\frac{U - C_{U1}}{C_A} \right) \tag{5.14}$$

The relative velocity of fluid at the inlet (W_1) is obtained from the geometric relation:

$$W_1 = \sqrt{C_A^2 + (U - C_{U1})^2} \tag{5.15}$$

Similarly, the fluid angle at the outlet is determined by referring to the Figure 5-16. Thus the outlet fluid angle (β_2) is given by:

$$\beta_2 = tan^{-1}\left(\frac{U}{C_A} \right) \tag{5.16}$$

The relative velocity at the outlet (W_2) is obtained from the geometric relation:

$$W_2 = \sqrt{C_A^2 + (U)^2} \tag{5.17}$$

The mean fluid angle (β_M) is determined from:

$$\beta_M = \frac{\beta_1 + \beta_2}{2} \tag{5.18}$$

The mean relative velocity of fluid (W) is obtained from:

$$W_M = \frac{W_1 + W_2}{2} \tag{5.19}$$

Fluid angle (β) and the relative velocity of fluid (W) is calculated by using equation from 5.13 to 5.19 with an input value of C_A = 4.53 m/s as calculated by using equation 5.9 and C_{U1} = (0.10/r) m/s as calculated by using equation 5.10. The result of calculation of fluid angle and the relative velocity of fluid is shown in Table 5-12.

Table 5-12: Fluid angle (β) and relative velocity (W) at a particular element.

Element	r_E (mm)	U_1=U_2 (m/s)	β_1 (°)	W_1 (m/s)	β_2 (°)	W_2 (m/s)	β_M (°)	W_M (m/s)
A	27.5	10.18	55.03	7.91	65.99	11.14	60.51	9.52
B	30	11.10	59.56	8.94	67.79	11.10	63.68	10.02
C	32.5	12.03	63.01	9.98	69.35	14.44	66.18	12.21
D	35	12.95	65.72	11.02	70.71	13.19	68.22	12.10
E	37.5	13.88	67.91	12.05	71.91	13.88	69.91	12.96
F	40	14.80	69.71	13.07	72.98	14.80	71.34	13.93
G	42.5	15.73	71.23	14.08	73.92	15.73	72.58	14.90
H	45	16.65	72.52	15.09	74.77	16.65	73.65	15.87

After the mean relative velocity of fluid and the mean fluid angle are identified, the next step is to select the impeller profile. An airfoil National Advisory Committee for Aeronautics (NACA) 2409 is chosen as the impeller profile where the characteristic of this impeller is shown in Figure 5-17.

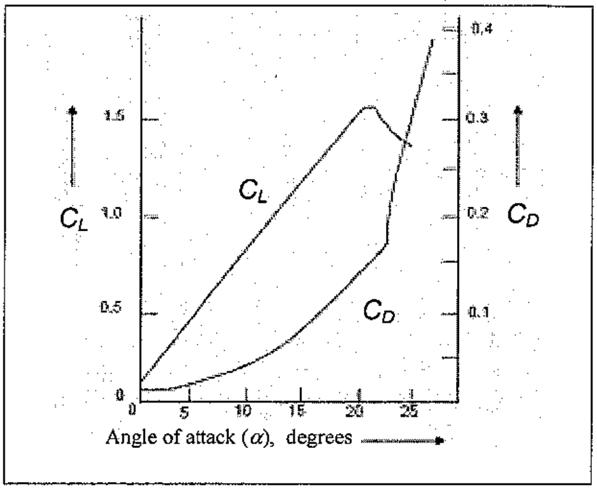


Figure 5-17: Characteristic of aerofoil NACA 2409 [63].

The assumptions that are on the impeller selection are:

- By setting the impeller at angle of attack of $\theta = 12.5°$, the lift (C_L) and drag (C_D) coefficient is 1 and 0.06 respectively.
- Number of the impeller (N) is 3.
- Impeller chord length (c) is 40 mm.

Based on the input value of β_M and W_M as defined in Table 5-12, tangential and axial forces on the certain element of impeller are estimated by using equation 5.11 and 5.12. The value of tangential and axial force on the certain element is shown in Table 5-13.

Table 5-13: Force and torque acted on elements of impeller turbine based on cascade analysis.

Element	r_E (mm)	F_A (N)	F_T(N)	T (N.m)
a	27.5	10.10	4.94	0.14
b	30	11.47	4.84	0.15
c	32.5	17.34	6.44	0.21
d	35	17.24	5.72	0.20
e	37.5	19.96	5.97	0.22
f	40	23.23	6.32	0.25
g	42.5	26.72	6.66	0.28
h	45	30.43	6.98	0.31
	sum	156.48	47.87	1.76

The total of tangential and axial forces from the meridional and cascade analysis must be balanced to ensure that the assumption on the impeller selection is correct. Total tangential force from the meridional analysis is 47.73 N as shown in Table 5-11 while from the cascade analysis is 47.87 N as shown in Table 5-13. Total axial force from the meridional analysis is 141.27 N as shown in Table 5-11 while from the cascade analysis is 156.48 N as shown in Table 5-13. It is assumed that the impeller selection is valid.

c. Fluent simulation

As comparison with the analytical calculation, a CAD model of impeller design is simulated by using Fluent. The simulation is performed in steady state condition and turbulent computation with standard k-ε model [45]. Boundary condition of turbine design simulation is shown in Figure 5-18.

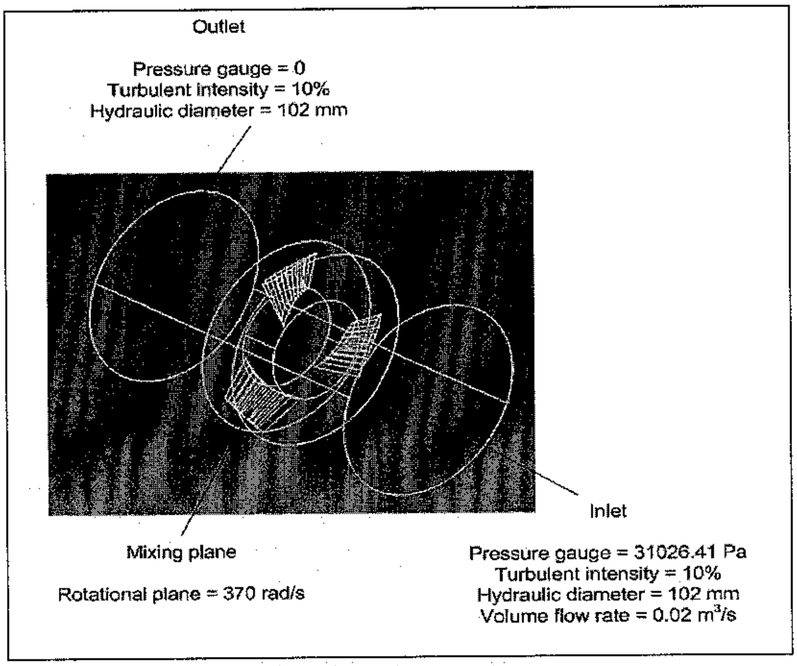
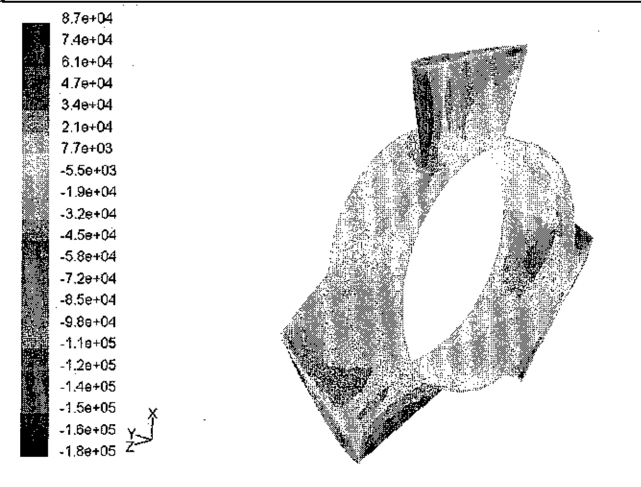


Figure 5-18 : Boundary condition of turbine design simulation.

Result from the simulation is shown in Figure 5-19. At a pressure side, the pressure act on the impeller is bigger than a suction side. This pressure difference creates the lift and drag force. The resultant force from the lift and drag force can be divided into tangential, radial and axial directions. The force in the tangential direction contributes to the power generated by the turbine. The torque acting on the impeller from the simulation result is shown in Table 5-14.



Static pressure on the impeller

Figure 5-19: Result from the simulation in Fluent.

Table 5-14: The torque act on the impeller based on simulation.

Pressure moment (N.m)		
X	Y	Z
-0.53	-0.67	0.163

The power generated by turbine is obtained by multiplying torque in y direction of $T = 0.67$ N.m as shown in Table 5-14 with turbine rotational speed of $\omega = 370$ rad/s which results 248 Watt. As comparison with analytical analysis, the power generated by the turbine is 256 Watt as calculated by using equation 5.8. The value of power generated by turbine from simulation and analytical calculation is almost same which ensures valid assumption on the impeller selection. Since the PDS used in this turbine is the same with the contraflow tetherless mechanical crawler, the result of turbine from this contraflow tetherless mechanical crawler can be used as a comparison. The field testing of contraflow tetherless mechanical crawler at flow rates of up to 1 m/s with power a pressure drop across the unit of 4.5 psi gives results of 250 Watts [7, 40]. Based on this field test, the turbine design is in the range of tolerable power that can be generated by this PDS input.

d. Characteristic of turbine design

A relationship between the fluid velocities changed with the power generated by the turbine is shown in Figure 5-20. It is obtained by changing fluid velocity input in the meridional analysis while the other design parameters are fixed. To obtain characteristic of turbine design at difference rotation speed at fixed fluid velocity, an input of turbine rotational speed is varied in the meridional analysis while the other design parameters are fixed.

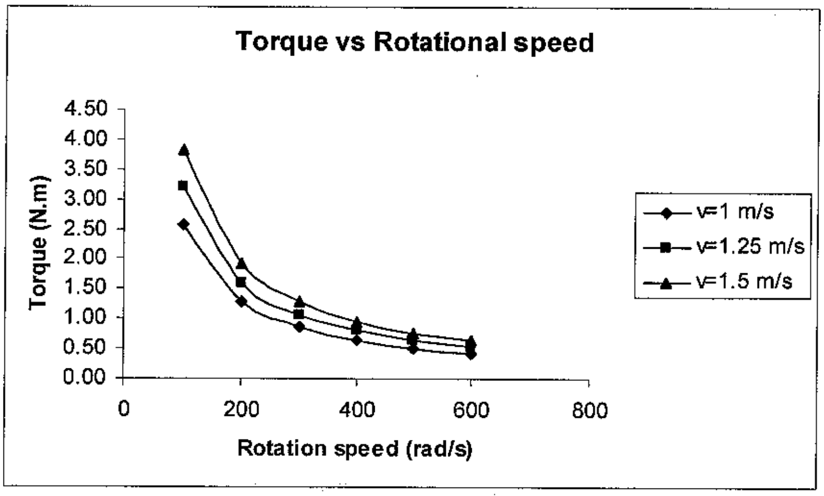


Figure 5-20: Characteristic of turbine design

5.3.2.3 Flow Control Module

In order to move in a counter flow direction, the PIG design requires a traction force which is generated by a drive mechanism module. A constant movement of PIG design in the counter flow direction is desired because it will determine the wax chip dimension during wax removal process. Therefore a flow control module is attached at the turbine for drive mechanism module to maintain the volume flow rate through it. It has also another function to block the fluid flow when the PIG design has reached at the end of the pipeline. Since the flow control module is in a closed position, the fluid flow will push the PIG design to travel with normal direction of the fluid flow to an initial point of launching.

a. Design flowchart of flow control module

A flow control module consists of poppet valve and spring component as shown in Figure 5-21. The poppet valve inside the housing is moved by the fluid flow that pushes the poppet valve off its seat to allow a flow path. The moving of poppet valve is controlled by the spring stiffness.

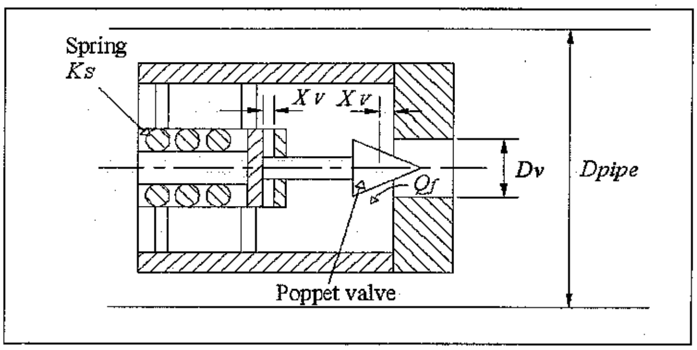


Figure 5-21: Schematic of a flow control module.

The design procedure of the flow control module is described in Figure 5-22.

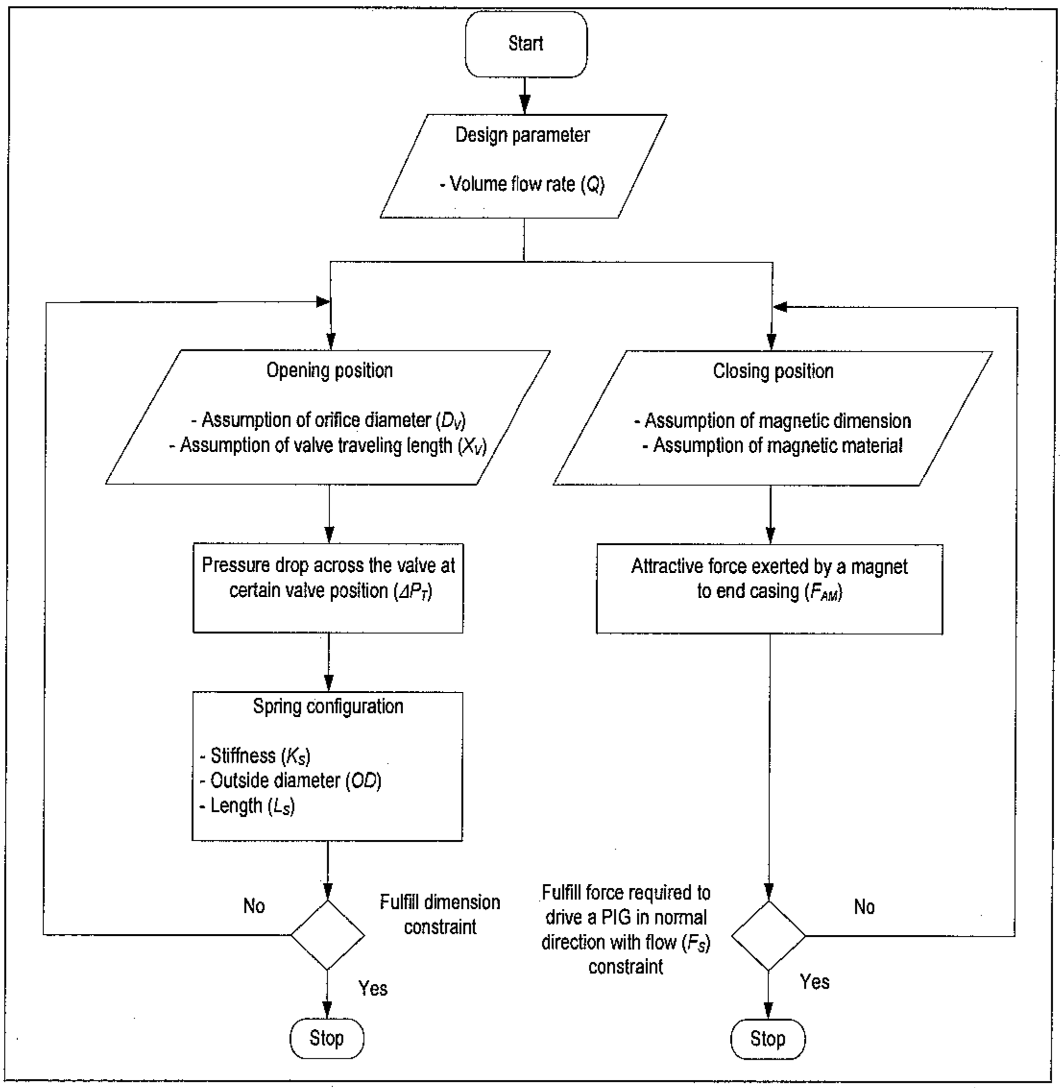


Figure 5-22: Design flowchart of the flow control module.

b. Design parameter

A flow control module is designed to provide the volume flow rate to the turbine at constant value in the range of 0.02-0.03 m^3/s as specified in the PDS at Table 5-8. In this flow control module, it is designed to operate at the fluid velocity of 1 m/s in normal operation. If the fluid velocity is 1.5 m/s, the poppet valve will move to a fully opening position. The maximum length that the poppet valve can be compressed is assumed to be 15 mm.

c. Opening position

Referring to the schematic of flow control module in Figure 5-21 and according to Liu [64], a relationship between the design parameter of fluid velocity and orifice diameter with the pressure drop across the flow control module is described as follows:

$$\Delta P_T = \rho.\left(\left(\frac{D_I}{D_s}\right)^2 - 1\right)^2 .\frac{V_f^2}{2} \qquad (5.20)$$

where ΔP_T is pressure drop across the flow control module in Pa, D_I is inner diameter pipeline in m, D_S is orifice diameter in m, V_f is fluid velocity in m/s and ρ is fluid density in kg/m^3.

A pressure drop across the flow control module creates a force that will tend to push the poppet valve in the same direction with the fluid flow. It is obtained from:

$$F_S = \Delta P_T .A_S \qquad (5.21)$$

where F_S is force acting on a poppet valve due to the pressure difference across the flow control module in N, ΔP_T is the pressure drop across the flow control module in Pa and A_s is poppet valve area in m^2.

Force acting on a poppet valve due to the pressure difference across the flow control module is balanced with the spring force. A spring stiffness required to balance this force is obtained from:

$$K_S = \frac{F_S}{X_V} \qquad (5.22)$$

where K_S is spring stiffness in N/mm, F_S is force acting on the poppet valve due to the pressure difference across the flow control module in N and X_V is compression length of poppet valve in mm.

Poppet valve and spring configuration

Assumption of design parameter of poppet valve with orifice diameter of D_S = 51 mm and maximum compression length of poppet valve of X_V = 15 mm, pressure drop across the flow control module and force acting on the poppet valve is calculated by using equation from 5.20 to 5.21 and shown in Table 5-15.

Table 5-15: Pressure drop across the flow control module and force acting on the poppet valve.

	Position X_V (mm)	Fluid velocity V_f (m/s)	Pressure drop ΔP_T (kPa)	Force acting on the poppet valve F_S (N)
Closed	0			
	7	1	31.63	64.58
	11	1.25	49.42	100.9
Fully	15	1.5	71.16	145.3

The spring stiffness required to balance the force acting on the poppet valve due to the pressure difference across the flow control module is calculated by using equation 5.21 with design parameter of spring length compression and force acting on the poppet valve as tabulated in Table 5-15. Hence, K_S = 9.68 N/mm. It is proposed that a spring type D13940 with free length of L_S =130 mm and outside diameter of OD = 55 mm [65] is used.

d. Close position

As the PIG design reaches the end of the pipeline, the flow control module needs to be closed. In order to trigger the poppet valve to be fully closed, an external magnet is attached to the end of the pipeline. Since the end rod of poppet valve attached with the magnet, when the PIG design reached at the end of the pipeline, the external magnet on the pipeline will attract the end rod of poppet valve. Figure 5-23 illustrates the magnetic mechanism that trigger the poppet valve to be fully closed.

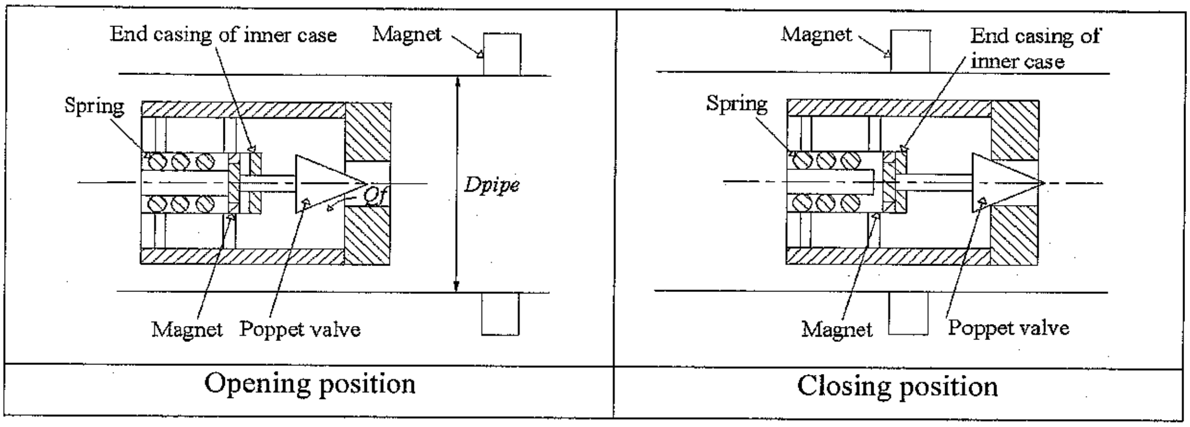


Figure 5-23: Schematic of flow control module during return mode.

The attractive force exerted by a magnet to a ferromagnetic material is obtained from [65]:

$$F_{AM} = 0.58.B_r^{\ 2}.L_M.\sqrt{A} \tag{5.23}$$

where F_{AM} is attractive force in pounds, B_r is residual flux density of magnet in Kilogauss, L_M is magnetic length in inch and A is pole area in square inches.

For the ring shaped magnet as shown in Figure 5-24, the residual flux density at a distance X_V from the pole surface on the magnet centreline under a variety of conditions can be determined. It is obtained from the relationship [65]:

$$B_x = \frac{B_r}{2}\left(\left(\left(\frac{L_M+X_V}{\sqrt{R^2+(L_M+X_V)^2}}\right)-\left(\frac{L_M+X_V}{\sqrt{r^2+(L_M+X_V)^2}}\right)\right)-\left(\left(\frac{X_V}{\sqrt{R^2+X_V^{\ 2}}}\right)-\left(\frac{X_V}{\sqrt{r^2+X_V^{\ 2}}}\right)\right)\right) \tag{5.24}$$

where B_r is residual flux density of magnet, L_M is magnetic length, R is outer radius of ring shaped magnet, r is inner radius of ring shaped magnet and X_V is distance from the ring shaped magnet to a position where the residual flux density want to be measured.

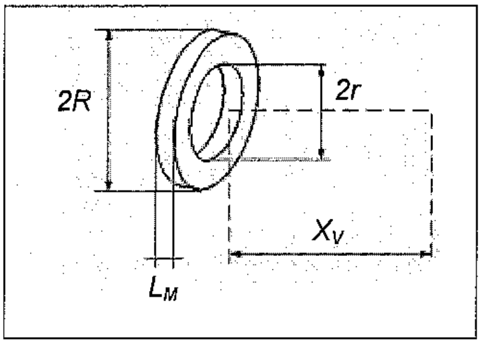


Figure 5-24: Ring shaped magnet [65].

The poppet valve is designed to open in normal operating condition when the fluid velocity of V_f = 1 m/s. The valve position is at distance of X_V = 7 mm at this condition as shown in Table 5-15. The attractive force exerted magnet to the end inner case at this position (F_{AM}) must be lower than the force due to the pressure drop across the poppet valve (F_{AP}) to make the poppet valve still open. In other condition, when the poppet valve is at the fully closed position, the attractive force exerted magnet to the end inner case must be higher than the force due to the pressure across the poppet valve to make the poppet valve always close.

Magnet configuration

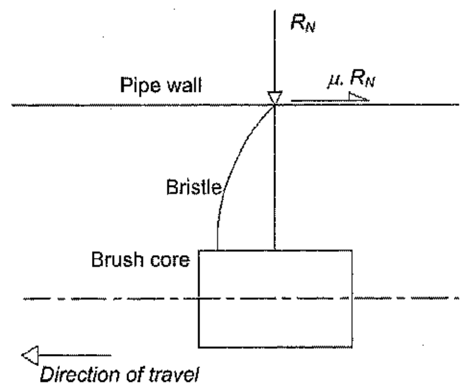
Assumption that are made on design parameter of magnet are: outer diameter of $2R$ = 35 mm, inner diameter of $2r$ = 33 mm, magnet length of L_M = 5mm, residual flux density flexible magnet of B_r = 1600 Gauss [65]. Based on this value, the attractive force exerted magnet to the end inner case at opening position and close position of X_V = 7 and X_V = 0 mm respectively is calculated by using equation 5.24 and tabulated in Table 5-16.

Table 5-16: The attractive force exerted to the end inner case by magnet.

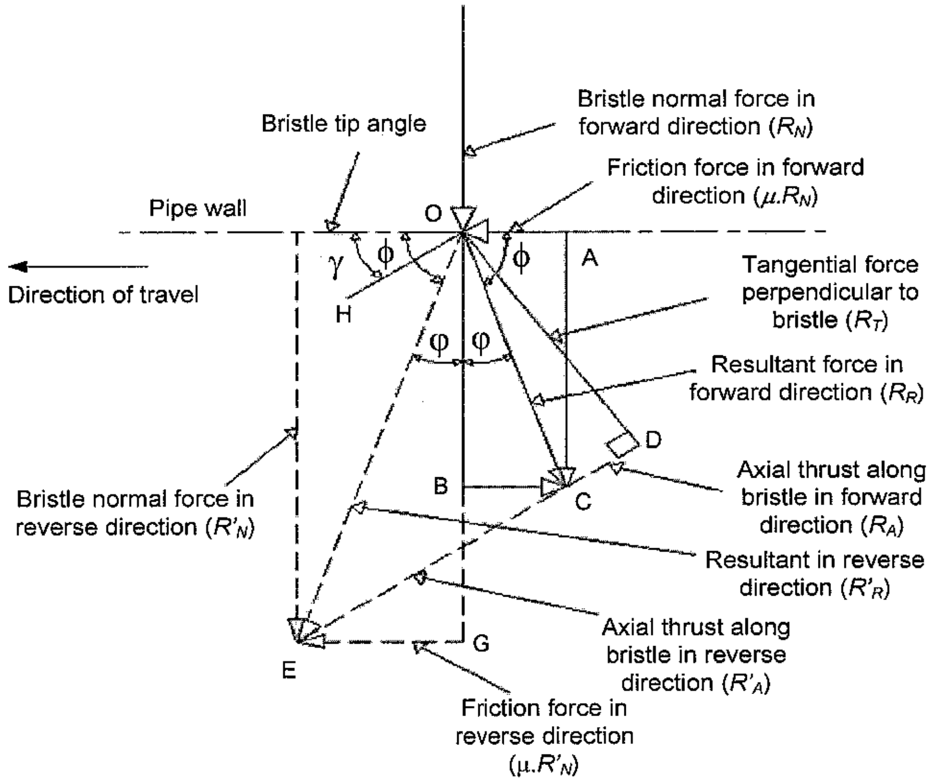
Position X_V (mm)	Attractive force exerted to the end inner case by magnet F_{AM} (N)
0	528882
7	4.68

5.3.2.4 Drive Mechanism Module

The function of a drive mechanism module is to drive the PIG in a counter flow direction. To be able to move in the counter flow direction, the drive mechanism module uses a unique characteristic of the bristle which is easier to push in a forward direction rather than to pull in a backward direction. Figure 5-25 illustrates the unique characteristic of bristle while moving in the pipeline wall.



The forces present at the bristle tip to pipe wall interface



Forces acting on the bristle at the bristle tip

Figure 5-25: A unique characteristic of the bristle [66].

a. Bristle theory

Based on references [66, 67], an explanation of the unique characteristic of the bristle shown in Figure 5-25 is described as follows.

1. Bristle forward theory

The bristle makes an angle of γ when it is inserted into the pipeline wall. A bristle normal reaction (R_N) holds the bristle to the pipeline wall when it is in a static condition. If the bristle is pushed forward along the pipeline wall (to the left as shown in Figure 5-25), a frictional force ($\mu.R_N$) is generated. This force resists the forward motion. Summation of the bristle normal reaction (R_N) and the frictional force ($\mu.R_N$) results the resultant force (R_R) acting on the bristle at friction angle (ϕ). This resultant force (R_R) can be divided into two components, one perpendicular to the bristle (R_T) and the other a thrust along the bristle (R_A). If the bristle is relatively straight and the thrust along the bristle (R_A) is not sufficient to cause buckling, then the bending bristle is assumed to be caused by the bending force acting perpendicular to the bristle (R_T).

2. Bristle reverse theory

When a bristle is pulled in the backward direction, the force acting on the bristle is reversed. At this condition, the friction force is in the opposite direction as depicted in Figure 5-25 and the bristle will grip the pipeline. Assuming that the value of friction coefficient (μ) is same in both directions, then the resultant force in reverse direction (R'_R) act on the bristle at friction angle (ϕ). Although the direction of resultant force in reverse direction is defined, but the magnitude of resultant force in reverse direction (R'_R) is not defined. In the bristle forward theory, the bending bristle is assumed to be caused by the bending force acting perpendicular to the bristle (R_T). If it is further assumed that the bristle shape remains same in both directions, only value of the axial thrust in reverse direction along the bristle (R'_A) is increasing. To determine magnitude of the resultant force in reverse direction (R'_R), the line of axial thrust in the reverse direction (R'_A) is extended and it will intersect with the friction force in the reverse direction ($\mu.R'_N$). This resultant force can be resolved in two parts, as a summation of the friction force in the reverse direction ($\mu.R'_N$) with the bristle normal force in the reverse direction (R'_N) or the axial thrust in the reverse direction along the bristle (R'_A) with the bending force acting perpendicular to the bristle (R_T).

3. Ratio of traction force required to push bristle in forward and reverse direction

   Maximum axial thrust in reverse direction (R'_A) that can be received by the bristle depends on the buckling load. The bristle can be assumed as a strut which is long compared to its cross sectional area. If an axial compression force is given to this strut, it will be fail due to the buckling before reaching the yield stress point [68] as illustrated in Figure 5-26.

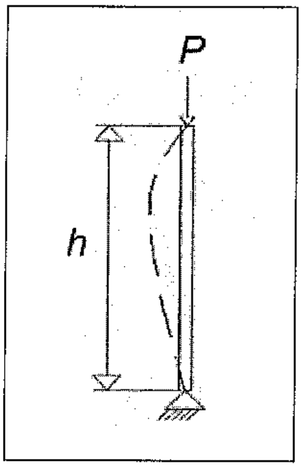


Figure 5-26: Buckling of an Euler column [68].

The critical axial compression load that can cause a column fail due to buckling is obtained from [68]:

$$P_{cr} = \frac{K.\pi^2.E.I}{h^2} \tag{5.25}$$

where K is mode of Euler buckling theory, E is modulus young, I is moment inertia, h is length of bristle.

As discussed before, the force required to push the bristle in the forward and reverse direction is different due to the unique characteristic of the bristle. A ratio of traction force required to push bristle in the forward and reverse direction can be determined through a mathematical relationship. The following equations are obtained from geometry of Figure 5-25 [67].

$$\angle HOE = 90 - \varphi - \gamma \tag{5.26}$$

$$\angle DOC = 90 - 2\varphi - \angle HOE = \gamma - \varphi \tag{5.27}$$

$$\angle EOD = 2\varphi + \angle DOC = \gamma + \varphi \tag{5.28}$$

If the axial thrust in reverse direction (R'_A or ED) can be determined through the buckling analysis, thus the resultant force in the reverse direction (R'_R or OE) and the friction force in the reverse direction ($\mu R'_N$ or EG) can be obtained from the following equations:

$$OE = \frac{ED}{sin\angle EOD} \tag{5.29}$$

$$EG = OE.sin\varphi \tag{5.30}$$

In addition, to determine the friction force in the forward direction (μR_N or BC), the tangential force (R_T or OD) and the resultant force in the forward direction (R_R or OC) must be known first. It can be acquired through the following relationships:

$$OD = ED.tan\angle EOD \tag{5.31}$$

$$OC = \frac{OD}{cos\angle DOC} \tag{5.32}$$

$$BC = OC.sin\ \varphi \tag{5.33}$$

A ratio of traction force required to push the bristle in the reverse and forward directions is obtained from:

$$R_{RF} = \frac{EG}{BC} = \frac{cos(\gamma - \varphi)}{sin(\gamma + \varphi).tan(\gamma + \varphi)} \tag{5.34}$$

b. Stages in PIG movement in a counter flow direction

The forces acting on the PIG design when traveling in a counter flow direction consist of the friction force between the disc and the pipeline wall (f_d), the propulsion force due to the pressure drop across the poppet valve ($F_{\Delta P}$), the axial force generated by the turbine (F_A) and the friction force between the bristle and the pipeline wall (f_m). A free body diagram that shows the force acting on the PIG when moving in the counter flow direction is illustrated in Figure 5-27.

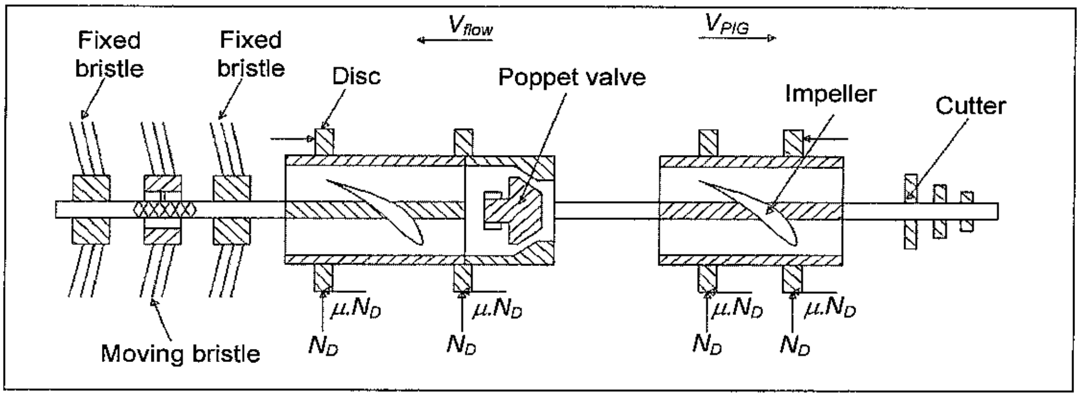


Figure 5-27: The forces acted on the PIG design.

The relationship between parameter of the PIG operating condition in a PDS document with assumption of design parameter on the drive mechanism is described as follows.

The frictional force between the PIG disc and the pipeline wall is obtained from:

$$f_d = b.\mu_{sl}.N_d \tag{5.35}$$

where b is number of disc, μ_{sl} is sliding friction between the disc and pipeline, and N_d denotes the normal reaction force on the PIG disc.

To determine the normal reaction force on the disc, it can be acquired from [69]:

$$N_d = \frac{\Delta P.\left(\frac{D_I}{2} - u_r\right)}{2.\mu_{sl}} \tag{5.36}$$

where D_I is inner diameter pipeline, u_r is the disc oversize and ΔP is pressure difference across each disc which is equal to total pressure difference across the poppet valve (ΔP_T) divided by number of disc (b).

The propulsion force due to the pressure drop across the poppet valve ($F_{\Delta P}$) is:

$$F_{\Delta P} = \Delta P_T.A_d \tag{5.37}$$

where ΔP_T is pressure drop between the PIG bodies and A_d is disc area.

The drive mechanism that consists of a nut traveling on the double screw as shown in Figure 5-28 uses a unique characteristic of the bristle as described in the bristle forward and reverse theory section.

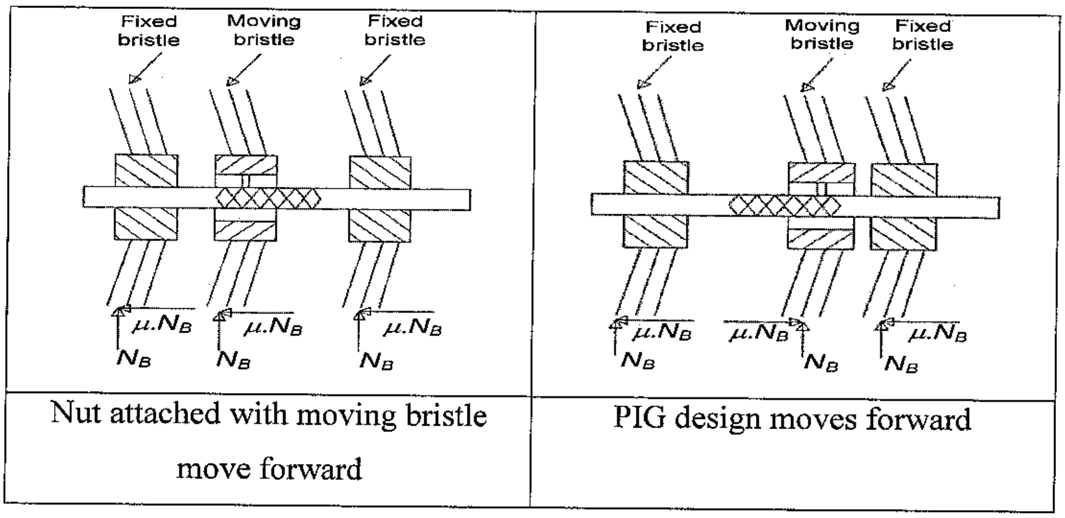


Figure 5-28: Free body diagram of a drive mechanism [9].

In order to move in the counter flow direction, the PIG design uses a turbine module as a power source to drive the drive mechanism module. The torque generated by the turbine is converted into a propulsion force by using a double screw thread as shown in Figure 5-29.

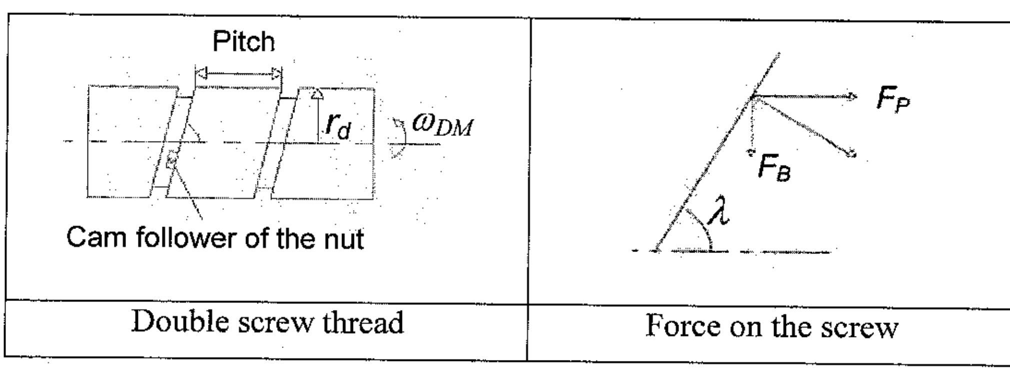


Figure 5-29: Forces acting on the double screw thread [9].

As illustrated in Figure 5-28, to move in the counter flow direction, there are two stages in one motion cycle, specifically: nut moving and PIG design moving. Detailed analysis of these motions is described as following.

1. Nut moving forward

When the propulsion force F_P is greater than the total resistance force, mainly the bristle friction force, the nut begins to move and accelerate. After a short transient time, the motion reaches a steady state where the propulsion force balance with the resistant force. The torque and force balance equation on the nut is shown as follows.

i. Torque balance equation of the drive mechanism module [9].

$$T_F = I_d.\dot{\omega}_{DM} + D_d.r_d^2.\omega_{DM} + T_B \qquad (5.38)$$
$$T_B = F_B.r_d$$

where T_F is torque required by the drive mechanism module, I_d is moment inertia of turbine and shaft, r_d is radius of shaft, D_d is damping coefficient for the turbine and shaft, ω_{DM} is rotational speed of drive mechanism, T_B is reaction torque generated by the nut and F_B is reaction force generated by the nut.

ii. Force balance equation on the nut [9].

$$F_B = ctg(\lambda).F_P = \frac{l}{2\pi.r_d}.F_P \qquad (5.39)$$

$$F_P = f_n + \dot{v}_n.m_n + (v_n - v_f).D_n$$

$$v_n = \omega_{DM}.\frac{l}{2.\pi}$$

where F_B is reaction force generated by the nut, l is pitch of the screw, r_d is radius of shaft, F_P is propulsion force generated by the thread, f_n is friction force of the nut against the pipe, v_n is velocity of the nut, m_n is mass of the nut, D_n is damping coefficient of the nut and ω_{DM} is rotational speed of drive mechanism.

2. PIG design move forward.

After the nut reaches the end of the double screw thread, the PIG design starts to move forward. At this position, the resistance force of bristle on the nut is greater than the propulsion force required to move in a forward direction. Analysis of motion characteristic of PIG moving is same like nut moving. The major differences is it needs to overcome the friction force between the bristle on a drive mechanism housing and pipeline wall (f_m), the friction force between the disc and pipeline wall (f_d), the axial force generated by the turbine (F_A) and the propulsion force due to the pressure difference across the poppet valve ($F_{\Delta P}$).

i. Torque balance equation of the drive mechanism module [9].

$$(T_F)_P = I_d.\left(\dot{\omega}_{DM}\right)_P + D_d.r_d^2.(\omega_{DM})_P + (T_B)_P \quad (5.40)$$

$$(T_B)_P = (F_B)_P.r_d$$

where $(T_F)_p$ is torque required by drive mechanism module, I_d is moment inertia of turbine and shaft, D_d is damping coefficient for the turbine and shaft, r_d is radius of shaft, $(\omega_{DM})_p$ is rotational speed of drive mechanism, $(T_B)_p$ is reaction torque generated by the thread and $(F_B)_p$ is reaction force on the thread.

ii. Force balance equation on the drive mechanism module [9].

$$(F_B)_p = ctg(\lambda).(F_P)_p = \frac{l}{2\pi\pi._d}.(F_P)_p \quad (5.41)$$

$$(F_P)_p = f_m + f_d + \dot{v}_P.m_P + (v_P - v_f).D_m + F_A + F_{\Delta P}$$

$$v_p = (\omega_{DM})_p.\frac{l}{2.\pi}$$

where $(F_B)_p$ is reaction force on the thread, l is pitch of the screw, r_d is radius of shaft, $(F_P)_p$ is propulsion force generated by the thread, f_m is friction force between the bristle on a drive mechanism housing with the pipe wall, m_m is mass of the PIG design, v_p is velocity of the PIG design, v_f is fluid velocity, D_m is damping coefficient of the PIG design, F_A is axial force generated by the turbine module and $F_{\Delta P}$ is propulsion force due to the pressure difference across the poppet valve.

c. Design flowchart of drive mechanism module

The design procedure of a drive mechanism module is described in Figure 5-30.

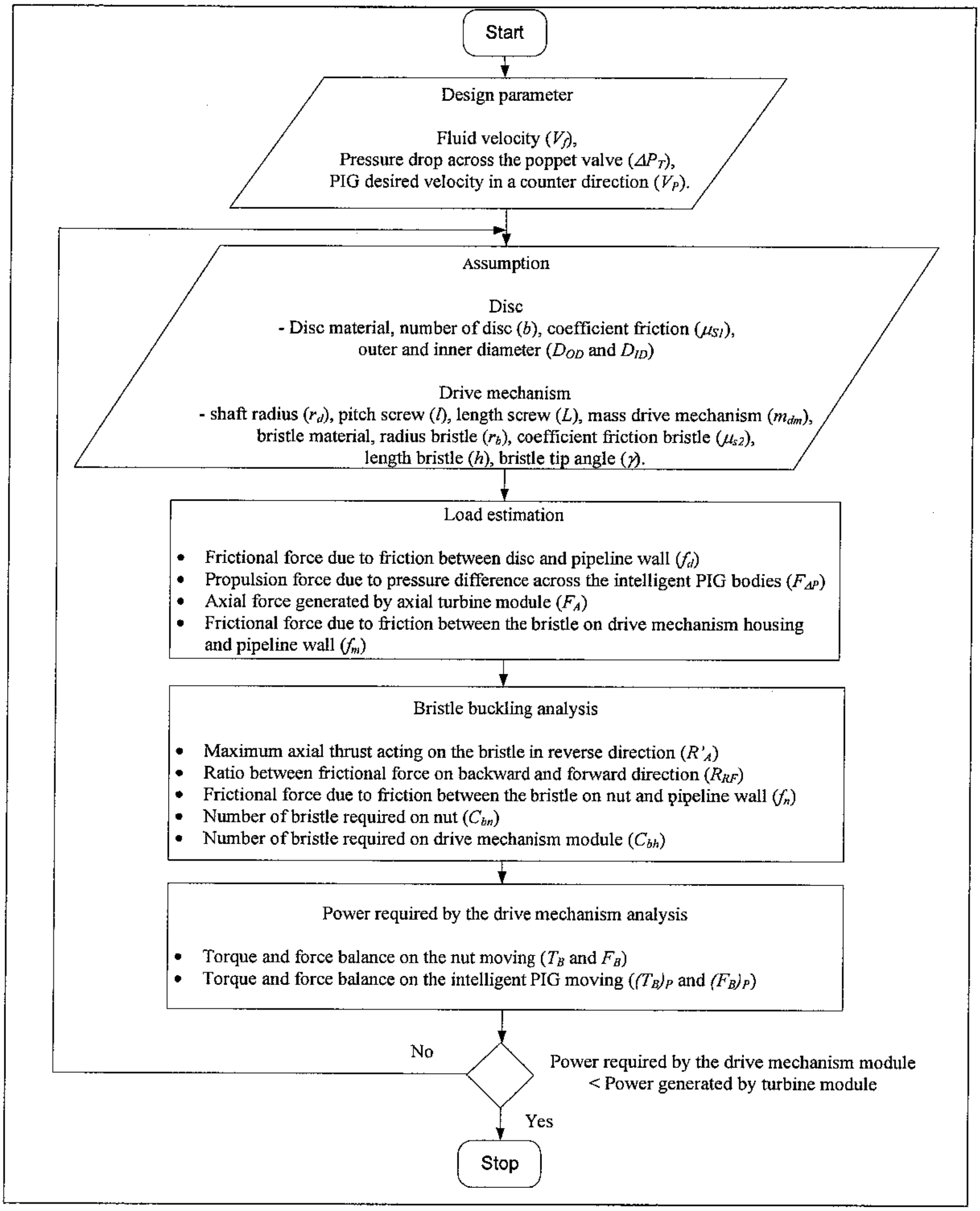


Figure 5-30: Flow chart of drive mechanism module.

1. Design parameter

   For the PIG design moving in the counter flow direction, the assumptions of design parameters for drive mechanism module is taken as shown in Table 5-17. The design parameter of drive mechanism from the PIG design follows the design parameter of the DPT crawler as described in Chapter 3 section 3.3.2. The other parameters are taken based on the related references.

Table 5-17: Assumption of design parameter for drive mechanism module.

Design parameter	Symbol	Value
Pressure drop total across the PIG bodies	ΔP_T	823252 Pa
Polyurethane disc		
Outer diameter of disc	D_{OD}	167.27 mm
Inner diameter of disc	D_{ID}	90 mm
Disc oversize to the pipeline diameter	U_r	5% [20]
Coefficient of sliding friction between disc and pipeline	μ_{s1}	0.4 [69]
Number of disc	b	4
Drive mechanism		
Radius of shaft	r_d	10 mm
Pitch of screw	l	10 mm
Length of screw	L	150 mm
Mass of drive mechanism	m_{DM}	5.5 kg
Ferrous Bristle (SAE 110)		
Length of bristle	h	40 mm
Yield strength	σ_y	300 MPa [70]
Modulus young	G	66 GPa [70]
Radius of bristle	r_b	1 mm
Friction coefficient between bristle and pipeline	μ_{s2}	0.74 [71]
Bristle tip angle	γ	40° [67]
Modus buckling fail	K	0.25 [67]

2. Load estimation when PIG design moving in a counter flow direction

   The force acting on the PIG design when moving in a counter flow direction (f'_n) is estimated with referring to assumption of design parameters as described in Table 5-17. It consists of:

   i. Disc frictional force (f_d) which is estimated by using equation 5.35.

   ii. Propulsion force due to the pressure difference across the PIG bodies ($F_{\Delta P}$) which is calculated by using equation 5.37.

iii. Axial force generated by a turbine module (F_A) which is obtained from cascade analysis in turbine design module on section 5.3.2.2.

iv. Friction force of the bristle on drive mechanism housing against the pipe (f_m) which is equal to total normal reaction bristle on the drive mechanism housing (N_B) multiply with coefficient friction between bristle and pipeline (μ_{s2}). Total normal reaction bristle on the drive mechanism is assumed equal to weight of drive mechanism (W_{DM}) as shown in Figure 5-31.

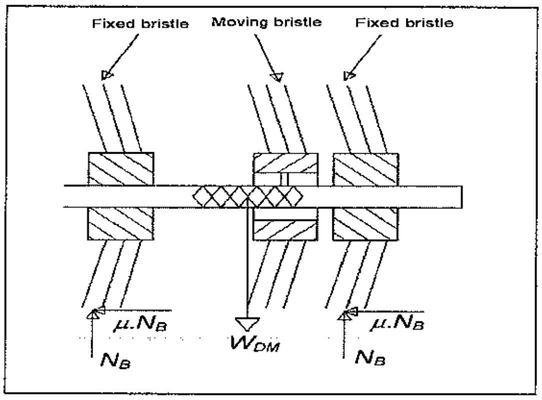


Figure 5-31: Free body diagram of drive mechanism when the PIG design is in a stationary stage.

The calculation result of force acting on the PIG design when moving in the counter flow direction is tabulated in Table 5-18.

Table 5-18: Force acting on the PIG design when moving in the counter flow direction.

Forces acting on the PIG design	Symbol	Value
Disc frictional force	f_d	1196.63 N
Propulsion force due to pressure difference between the PIG bodies	F_{AP}	565.48 N
Axial force generated by a turbine module	F_A	312.96 N
Friction force of the bristle on drive mechanism housing against the pipe	f_m	39.89 N
Total force acting on the PIG when moving in the counter flow direction	$(F_P)_p$	2114.95 N

3. Bristle force analysis

i. Maximum axial force acts on a bristle (R'_A)

A bristle used in a drive mechanism module is considered as a strut which is given by a compression load. Referring to design parameter of bristle as defined in Table 5-17 and using safety factor of $SF = 3$, maximum axial thrust force received by one bristle is estimated by using equation 5.25 which gives $P_{cr} = 17.03$ N. This value of maximum of axial thrust force (P_{cr}) is equal to the axial thrust force working on the bristle when the bristle is push in reverse direction (R'_A).

ii. Ratio between bristle frictional force on reverse and forward direction (R_{RF})

A bristle has a unique characteristic which is easier to push in forward direction rather than in reverse direction. Based on the design of design parameter of bristle in Table 5-17, and using equation 5.34, the ratio between bristle frictional force on reverse and forward direction (R_{RF}) is estimated to be 4.28.

iii. Frictional force due to friction between the bristle on nut and pipeline wall (f_n)

A drive mechanism in the PIG design uses a unique characteristic of the bristle which is easier to push in forward rather than in reverse direction. A set of bristle is mounted on the nut which travels along a double screw mechanism. To move in a counter flow direction, the total friction force of bristle on nut with pipeline in reverse direction (f'_n) must be equal to the forces acting on the PIG when moving in a counter flow direction $(Fp)_p$.

The friction force of bristle on the nut with pipeline in reverse direction (f'_n) based on the estimation of load analysis, as shown in Table 5-18, is 2114.95 N. Since a bristle has a unique characteristic which is easier to move in forward rather than backward direction, the friction force of bristle on the nut with pipeline in forward direction (f_n) is obtained by dividing the friction force of bristle on nut with pipeline in reverse direction (f'_n) with ratio between the bristle frictional force on reverse and forward direction (R_{RF}). Hence, f_n = 494.6 N.

iv. Number of bristle required on a nut and drive mechanism housing

To find the number of bristle required on a nut and drive mechanism housing, maximum axial thrust (R'_A) that can be received by a bristle need to be converted into the friction force of bristle in reverse direction ($\mu.R'_N$). Referring to Figure 5-25, the relationship between the maximum axial thrust (R'_A) acting on a bristle with the friction force of bristle in reverse direction ($\mu.R'_N$) is

$$\mu.R'_N = \frac{R'_A}{sin\angle EOD}.sin\alpha = \frac{R'_A}{sin(\gamma+\varphi)}.sin\varphi \tag{5.42}$$

Based on design parameters in Table 5-17 of bristle tip angle of γ = 40°, friction angle perpendicular to the normal reaction force (R_N) of φ = atan^{-1} (μ_{s2}) = 36.5 and the maximum axial thrust that can be received by a bristle of R'_A = 17.03 as calculated by using equation 5.25, the friction force acts on a bristle in reverse direction ($\mu.R'_N$) is calculated by using equation 5.42. Hence, $\mu.R'_N$ = 10.42 N.

The number of bristle required on a nut (C_{bn}) is obtained by dividing the total friction of bristle on nut in reverse direction (f'_n) with the friction force acting on one bristle in reverse direction ($\mu.R'_N$). It can be stated in the following relationship:

$$C_{bn} = \frac{f'_n}{\mu.R'_N} \tag{5.43}$$

Inserting value of f'_n = 2114.95 as defined in Table 5-18 and $\mu.R'_N$ = 10.42 as calculated by using equation 5.42, the number of bristle required on a nut is estimated by using equation 5.43. Thus, C_{bn} is approximately 204.

The number of bristle required on a drive mechanism housing (C_{bh}) is obtained by dividing the total friction of bristle on a drive mechanism housing in reverse direction (f'_m) with the friction force acting on one bristle in reverse direction ($\mu.R'_N$). It can be stated in the following relationship:

$$C_{bh} = \frac{f'_m}{\mu.R'_N} \tag{5.44}$$

The value of f'_m is obtained by multiplying total friction of bristle on a drive mechanism housing with pipeline in forward direction of f_m = 39.89 as tabulated in Table 5-18 with ratio between the bristle frictional force on reverse and forward direction of R_{RF} = 4.28 as estimated by using equation 5.34. Hence, f'_m = 170.73. Using this value and $\mu.R'_N$ = 10.42 N as calculated by using equation 5.42, and using equation 5.44, the number of bristle required on the drive mechanism housing is estimated to be 18.

v. Summary of bristle force analysis

A result of bristle force analysis is summarized and tabulated in Table 5-19.

Table 5-19: Bristle force analysis on drive mechanism module.

Forces act on bristle	Symbol	Value
Maximum axial force acts on a bristle	P_{cr} or R'_A	17.03 N
Ratio between bristle frictional force on reverse and forward direction	R_{RF}	4.28
Total friction force of bristle on nut with pipeline in reverse direction	f'_n	2114.95 N
Total friction force of bristle on nut with pipeline in forward direction	f_n	494.6 N
Number of bristles on a drive mechanism housing	C_{bh}	18
Number of bristles on a nut	C_{bn}	204

4. Power required by the drive mechanism

Characteristic of a drive mechanism module that consists of a nut and double screw is intermittent motion. A nut needs to be travel to the end of the double screw first and then the PIG design will start moving. A torque required to drive a nut to travel to the end of the double screw and to drive the PIG to move in a counter flow direction is different. Therefore analysis of PIG motion is divided into two stages: nut moving and PIG design moving.

i. PIG design moving

To move in a counter flow direction, a drive mechanism must provide a propulsion force $(F_P)_P$ which is equal to summation of force acting on the PIG design. Referring to a free body diagram of PIG design in Figure 5-27, forces acting on the PIG design consist of disc frictional force (f_d), propulsion force due to pressure difference between the PIG bodies ($F_{\Delta P}$), axial force generated by a turbine module (F_A), friction force of the bristle on drive mechanism housing against the pipeline wall (f_m), acceleration force of PIG ($\dot{v}_P.m_P$) and viscous damping due to the PIG moves through a liquid ($(v_P-v_f).D_P$). In analyzing of force balance when PIG design moving, acceleration force of PIG ($\dot{v}_P.m_P$) and viscous damping due to the PIG moves through a liquid ($(v_P-v_f).D_P$) is neglected due to small value compared to others force [9]. Based on this assumption, force balance equation when the PIG moving in the equation 5.41 can be stated as:

$$(F_B)_p = ctg(\lambda).(F_P)_p = \frac{l}{2\pi.r_d}.(F_P)_p \qquad (5.45)$$

$$(F_P)_p = f_m + f_d + F_A + F_{\Delta P}$$

$$v_p = (\omega_{DM})_p . \frac{l}{2.\pi}$$

where $(F_B)_p$ is reaction force on the thread, l is pitch of the screw, r_d is radius of shaft, $(F_P)_p$ is propulsion force generated by the thread, f_m is friction force of the bristle on drive mechanism housing against the pipe, F_A is axial force generated by the turbine module, $F_{\Delta P}$ is propulsion force due to pressure difference across the poppet valve, v_p is PIG velocity moving in a counter flow direction and $(\omega_{DM})_p$ is rotational speed of drive mechanism.

Using input of $v_P = 0.033$ m/s as defined in Table 5-8, l = 10mm, r_d = 10 mm and L = 150 mm as assumed in Table 5-17 and f_m = 39.89 N, f_d = 1196.63 N, F_A = 312.96 N, and $F_{\Delta P}$ = 565.48 N as tabulated in Table 5-18, $(F_P)_p$, $(F_B)_p$ and $(\omega_{DM})_p$ is calculated by using equation 5.45. The calculation result of force balance equation when PIG moving in the counter flow direction is summarized in Table 5-20.

Table 5-20: Calculation result of force balance equation when PIG moving in the counter flow direction.

Parameter	Symbol	Value
Propulsion force generated by the thread	$(F_P)_p$	2114.95 N
Reaction force on the thread	$(F_B)_p$	336.78 N
Rotational speed of drive mechanism	$(\omega_{DM})_p$	21 rad/s

To estimate power required by a drive mechanism module, total torque required by a drive mechanism (T_F) which consists of torque due to acceleration of PIG ($I_d.(\dot{\omega}_{DM})_p$), torque due to viscous damping ($D_d.r_d^2.(\omega_{DM})_p$) and torque due to reaction force on the thread ($(T_B)_p$) must be determined first. In analyzing of torque balance when PIG moving, torque due to acceleration of PIG and torque due to viscous damping is neglected because of small value compared to torque due to reaction force on the thread [9]. Based on this assumption, torque balance equation when the PIG moving in the equation 5.40 can be stated as:

$$(T_F)_p = (T_B)_p \qquad (5.46)$$

$$(T_B)_p = (F_B)_p . r_d$$

where $(T_F)_p$ is torque required by drive mechanism module, $(T_B)_p$ is torque due to reaction force on the thread and $(F_B)_p$ is reaction force on the thread and r_d is radius of shaft. Inserting value of $(F_B)_p = 336.78$ N as stated in Table 5-20 and $r_d = 10$ mm as assumed in Table 5-17 into equation 5.46, the torque required by drive mechanism module is 3.37 N.m.

Power required by the drive mechanism to provide a propulsion force required by the PIG design is obtained from:

$$P_{DM} = (T_F)_p.(\omega_{DM})_p \qquad (5.47)$$

where $(T_F)_p$ is torque required by drive mechanism module and $(\omega_{DM})_p$ is rotational speed of drive mechanism. Plugging value of $(T_F)_p = 3.37$ N.m. as calculated by using equation 5.46 and $(\omega_{DM})_p = 21$ rad/s as described in Table 5-20 into equation 5.47, power required by the drive mechanism is 71 Watt.

ii. Nut moving

To move in a counter flow direction, a nut on drive mechanism must travel to the end of the double screw first. Propulsion forces required to push a nut (F_P) must be equal to summation of friction force of bristle on nut (f_n), acceleration force of nut moving ($\dot{v}_n.m_n$) and viscous damping due to nut moving through a liquid ($(v_n\text{-}v_f).D_n$). In analyzing of force balance when PIG moving, acceleration force of nut ($\dot{v}_n.m_n$) and viscous damping due to the PIG moves through liquid ($(v_n\text{-}v_f).D_n$) is neglected due to small value comparing to friction force of bristle on nut (f_n) [9]. Based on this assumption, force balance equation when the nut moving in the equation 5.39 can be stated as:

$$F_B = ctg\,(\lambda).F_P = \frac{l}{2\pi.r_d}.F_P \qquad (5.48)$$

$$F_P = f_n$$

$$v_n = \omega_{DM}.\frac{l}{2.\pi}$$

where F_B is reaction force generated by the nut, l is pitch of the screw, r_d is radius of shaft, F_P is propulsion force generated by the thread, f_n is total friction force on nut with pipeline in forward direction, v_n is velocity of the nut and ω_{DM} is rotational speed of drive mechanism. Inserting l = 10 mm, r_d = 10 mm, L = 150 mm as assumed in Table 5-17 and f_n = 494.6 N as tabulated in Table 5-19, F_P and F_B is calculated by using equation 5.48. The calculation result of force balance equation when nut moving is summarized in Table 5-21.

Table 5-21: Calculation result of force balance equation when nut moving.

Parameter	Symbol	Value
Reaction force generated by the nut	F_B	78.76 N
Propulsion force generated by the thread	F_P	494.60 N

To estimate power required by a drive mechanism module, total torque required by a drive mechanism (T_F) which consists of torque due to moment inertia of turbine and shaft ($I_d.\dot{\omega}_{DM}$), torque due to viscous damping ($D_d.r_d^2.\omega_{DM}$) and torque due to reaction force on the thread (T_B) is estimated first. In analyzing of torque balance when nut moving, torque due to moment inertia of turbine and shaft ($I_d.\dot{\omega}_{DM}$) and torque due to viscous damping ($D_d.r_d^2.\omega_{DM}$) is neglected due to small value compared to torque due to reaction force on the thread (T_B) [9]. Based on this assumption, torque balance equation when nut moving in the equation 5.38 can be stated as:

$$T_F = T_B \tag{5.49}$$
$$T_B = F_B.r_d$$

where T_F is torque required by drive mechanism module, T_B is reaction torque generated by the nut, F_B is reaction force on the thread and r_d is radius of shaft. Based on value of F_B = 78.76 N as stated in Table 5-21 and r_d = 10 mm as assumed in Table 5-17, and using equation 5.49, T_F is 0.79 N.m.

The power supplied to a drive mechanism module by a turbine module is assumed constant. Based on this assumption, rotational speed of drive mechanism while nut moving forward can be estimated from:

$$\omega_{DM} = \frac{P_{DM}}{T_F} \tag{5.50}$$

where ω_{DM} is rotational speed of drive mechanism, P_{DM} is power required by the drive mechanism module and T_F is torque required by drive mechanism module. Based on the input value of $P_{DM} = 71$ Watt as calculated by using equation 5.47 and $T_F = 0.79$ N.m as calculated by using equation 5.48, and using equation 5.49, ω_{DM} is 89.51 rad/s.

5. PIG design traveling speed

   A drive mechanism that consists of nut travel along the double screw has a characteristic of intermittent stage. A nut needs to be travel to the end of the double screw first and then the PIG design starts moving. Since the required force to push bristles on nut in a forward direction is smaller than the required force to push the PIG design in a forward direction, the nut speed is faster compared to the PIG design speed to travel along the double screw.

   Time of the nut to travel along the entire length of double screw in one cycle motion is:

$$t_n = \frac{L}{v_n} = \frac{L.2.\pi}{\omega_{DM}.l} \tag{5.51}$$

   where t_n is time of nut to travel along the entire length of double screw in one cycle motion, L is length of double screw, ω_{DM} is rotational speed of drive mechanism and l is pitch of screw. Based on the value of $L = 150$ mm, $l = 10$ mm as specified in Table 5-17 and $\omega_{DM} = 89.51$ rad/s as calculated by using equation 5.50, and using equation 5.51, t_n is 1.052 s.

   Time of the PIG design to travel forward in one cycle motion is:

$$t_m = \frac{L}{v_m} = \frac{L.2.\pi}{(\omega_{DM})_P.l} \tag{5.52}$$

where t_m is time of the PIG design to travel forward in one cycle motion, L is length of double screw, is $(\omega_{DM})_P$ rotational speed of drive mechanism and l is pitch of screw. Based on the value of L = 150 mm, l = 10 mm as specified in Table 5-17 and $(\omega_{DM})_P$ = 21 rad/s as tabulated in Table 5-20, and using equation 5.52, t_m is 4.5 s.

Overall PIG design movement in a counter flow direction through a time is illustrated in Figure 5-32. In one cycle of the PIG design movement, a nut speed travel faster than the PIG design speed because the torque required to push a nut in a forward direction is smaller than torque required to push the PIG design in the forward direction. Therefore a rotational speed of drive mechanism is increasing when a nut moving in the forward direction compared to the PIG design moving as illustrated in Figure 5-33.

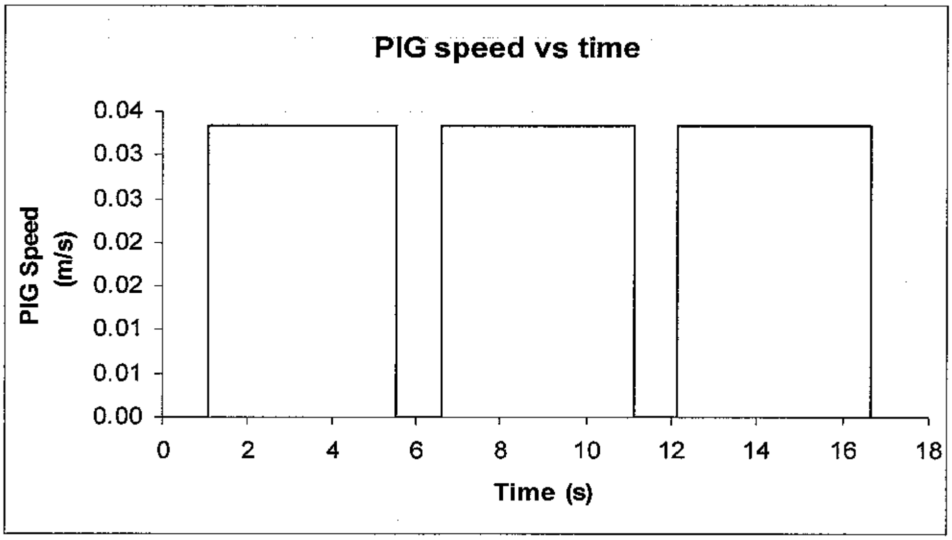


Figure 5-32: Overall PIG design speed through the time.

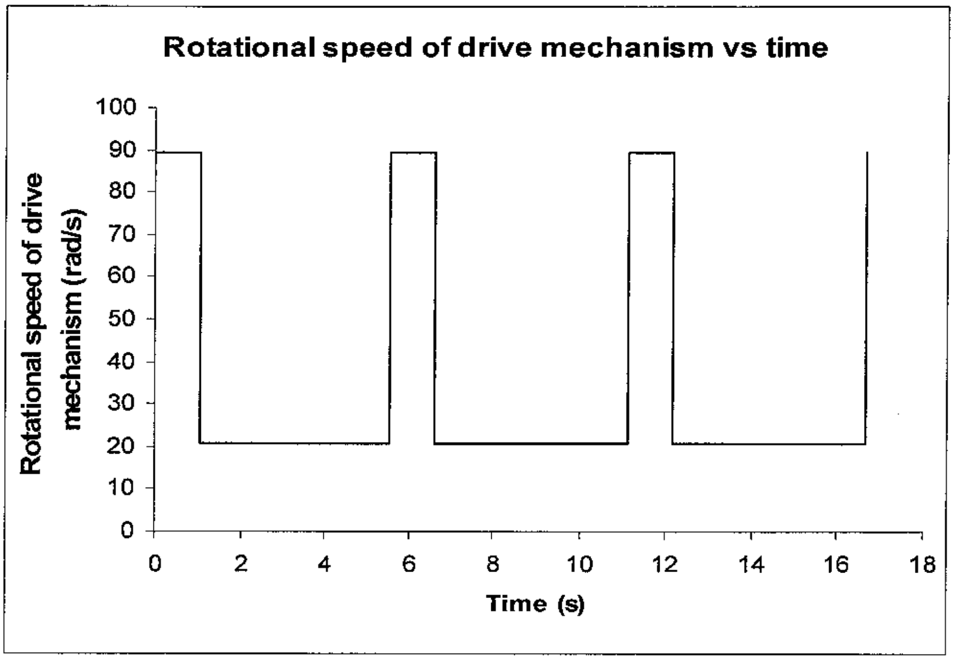


Figure 5-33: Rotational speed of drive mechanism through the time.

d. Comparison of PIG design speed with contraflow tetherless mechanical pipeline crawler.

To move in a counterflow direction, a contraflow tetherless mechanical pipeline crawler with the same PDS parameter used in the PIG design as shown in Table 5-8 can generate a traction about 2800 N [7, 40]. Meanwhile, the PIG design uses a cam follower mechanism requires traction about 2114.95 N as shown in Table 5-18. The contraflow tetherless mechanical pipeline crawler can travel at a speed about 0.0133 m/s with traction force generated by a tractor module about 2800 N [7, 40]. The PIG design with force generated by the drive mechanism module about 2114.95 N can be able to travel at a speed about 0.03 m/s as shown in Figure 5-32. Although the desired speed is achieved, the PIG design motion is intermittent since it uses a reciprocating mechanism to move the moving and fixed bristle. The time ratio between the PIG design travel and stationary condition is 4.28 as shown in Figure 5-32.

5.3.2.5 Wax Removal Tool Module

Wax deposit on the pipeline wall is cut into a small chip, allowing it to be carried by the fluid flow. Wax deposit removal mechanism is performed by turning the cutter into the wax deposit as illustrated in Figure 5-34.

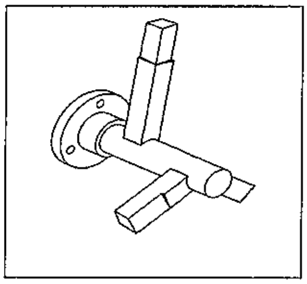


Figure 5-34: Wax removal mechanism.

a. Design flowchart of wax removal module

A flow chart of the wax removal tool design is shown in Figure 5-35.

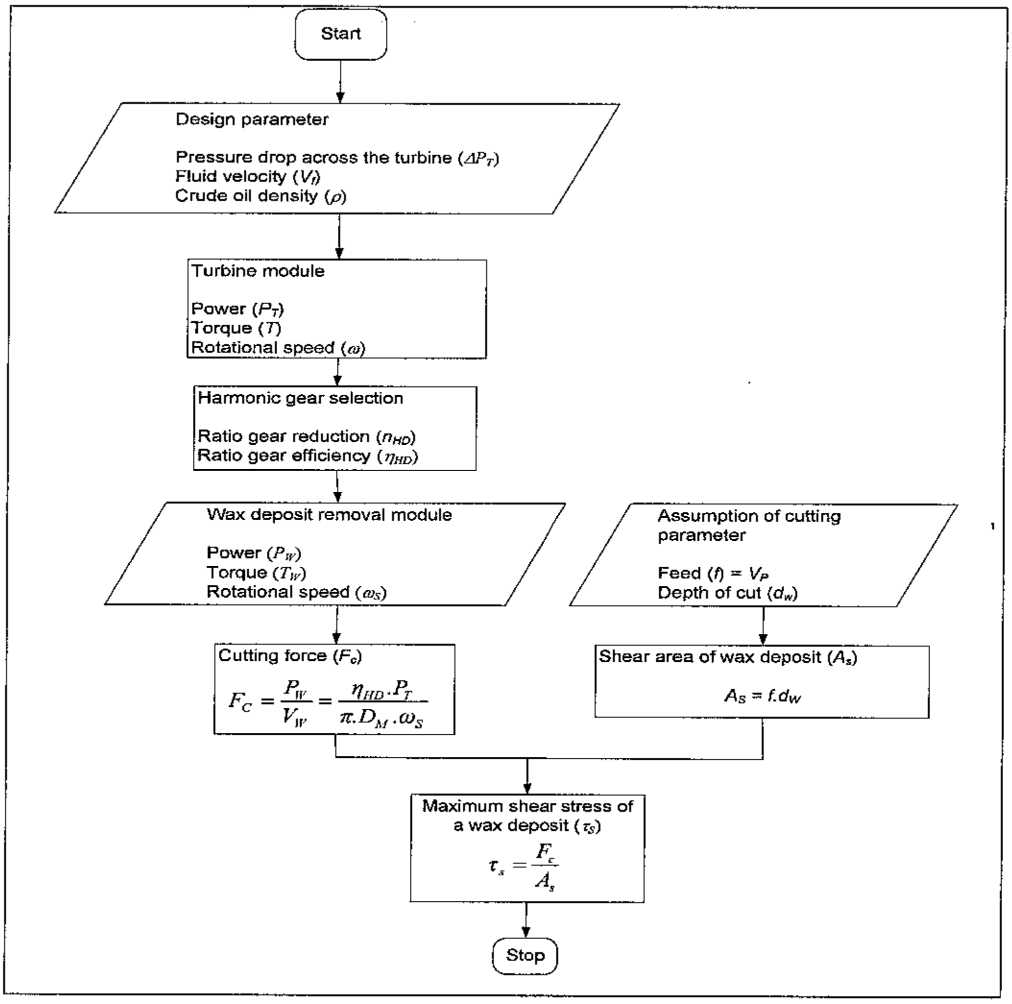


Figure 5-35: Design flowchart of a solid deposit removal tool.

b. Maximum shear strength of wax deposit

A turbine module used to drive the wax deposit removal tool is same with a turbine module used to drive a drive mechanism module as discussed in the section 5.3.2.2. To remove wax deposit, the wax removal tool needs to be operating at a low speed to obtain high torque. A harmonic gear is used to reduce a turbine rotational speed in order to get the high output torque. The specification of the turbine module is shown in Table 5-22.

Table 5-22: Specification of the turbine module.

Power generated by the turbine (P_T)	256 Watt
Turbine rotational speed (ω)	370 rad/s
Harmonic gear efficiency (η_{HD})	50 %
Harmonic gear ratio reduction (n_{HD})	100
Rotational speed of wax deposit removal shaft (ω_w)	3.7 rad/s

To simplify the analysis, the wax removal tool is assumed as a rectangular bar as shown in Figure 5-36.

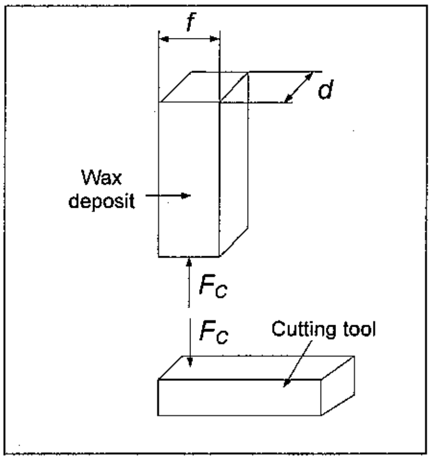


Figure 5-36: Force acted on the cutting tool and wax deposit.

The maximum cutting force (F_C) is obtained from [72]:

$$F_C = \frac{P_w}{V_w} = \frac{\eta_{HD}.P_T}{\pi.D_M.\omega_w} \tag{5.53}$$

where P_w is the power required to drive the wax removal module, V_w is the cutting speed, η_{HD} is the harmonic gear efficiency, P_T is the power generated by the turbine, D_M is the mean diameter of wax deposit and ω_W is the rotational speed of wax removal shaft. Based on the input value of $\eta_{HD} = 50\%$, $P_T = 256$ Watt as specified in Table 5-22 and $D_M = 159.3$ mm as defined in Table 5-8, and using equation 5.53, F_C is 69 N.

The shear area of the wax deposit (A_w) is obtained from:

$$A_w = f.d_w \qquad (5.54)$$

where f is the feed and d_w is the depth of cut. Based on assumption of $f = 0.033$ m/s as taken same with the PIG design speed and $d_S = 25.4$ mm as stated in Table 5-8, and using equation 5.54, A_S is 838 mm^2.

The maximum shear stress of the wax deposit (τ_S) that can be removed is calculated from:

$$\tau_S = \frac{F_C}{A_S} \qquad (5.55)$$

where F_C is the cutting force and A_S is the shear area of the solid deposit. Inserting value of $F_C = 69$ N as calculated by using equation 5.53 and $A_S = 838$ mm^2 as calculated by using equation 5.54, and using equation 5.55, τ_S is 81 kPa.

c. Configuration of wax cutter tool

A static analysis is performed to determine the cutting tool dimension. The cutting tool in this design consists of three tools. Since the maximum bending force occurs in the longest length of cutting tool, a static analysis is performed in this cutting tool. A free body diagram of the cutting tool is shown in Figure 5-37.

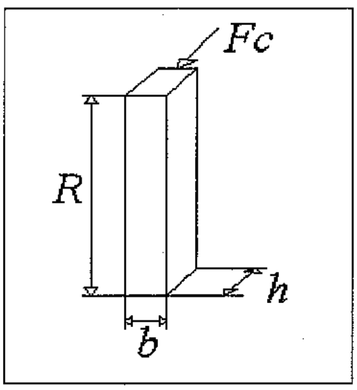


Figure 5-37: Free body diagram of the cutting tool.

To determine the general dimension of wax removal tool, the value of length (b) and width (h) is assumed same. Material of cutting tool is selected as a stainless steel type AISI 305 with yield strength of σ_{sy} = 170 MPa [70].

Maximum stress (σ) due to the bending force is obtained from:

$$\sigma = \frac{M.c_I}{I} \tag{5.56}$$

where M is the bending moment, c_I is distance from the neutral axis to the point of interest and I is moment inertia which is equal to $1/12\ b.h^3$ for a rectangular bar. The bending moment is obtained by multiply cutting force of F_C = 69 N as calculated by using equation 5.53 with maximum distance from the shaft axis to the cutting force of R = 70 mm which gives M = 5.39 N.m. Based on value of M = 5.39 N.m, safety factor of 2 and σ_{sy} = 170 MPa, b and h is calculated by using equation 5.56. Hence, b and h is 7 mm.

The shape of cutting tool is a wedge form for effective penetration into the wax deposit to reduce the cutting force. To determine the angle in the cutting tool, wax material must be represented with common material use in machining process. Referring to hardness of material as shown in Table 5-23, the nearest material that can represent wax is brass.

Table 5-23: Hardness of material [72]

Material	Hardness (BHN)
Steel	125
Cast iron	150
Leaded brass	35
Copper	40

Element of the cutting tool signature is standardized by the American National Standards Institute (ANSI) as shown in Figure 5-38 [70]. Based on the assumption of cutting tool material of High Speed Steel (HSS) and solid deposit material of brass, element of the cutting tool is obtain from the ANSI standard. The element of cutting that is used in this design is shown in Table 5-24.

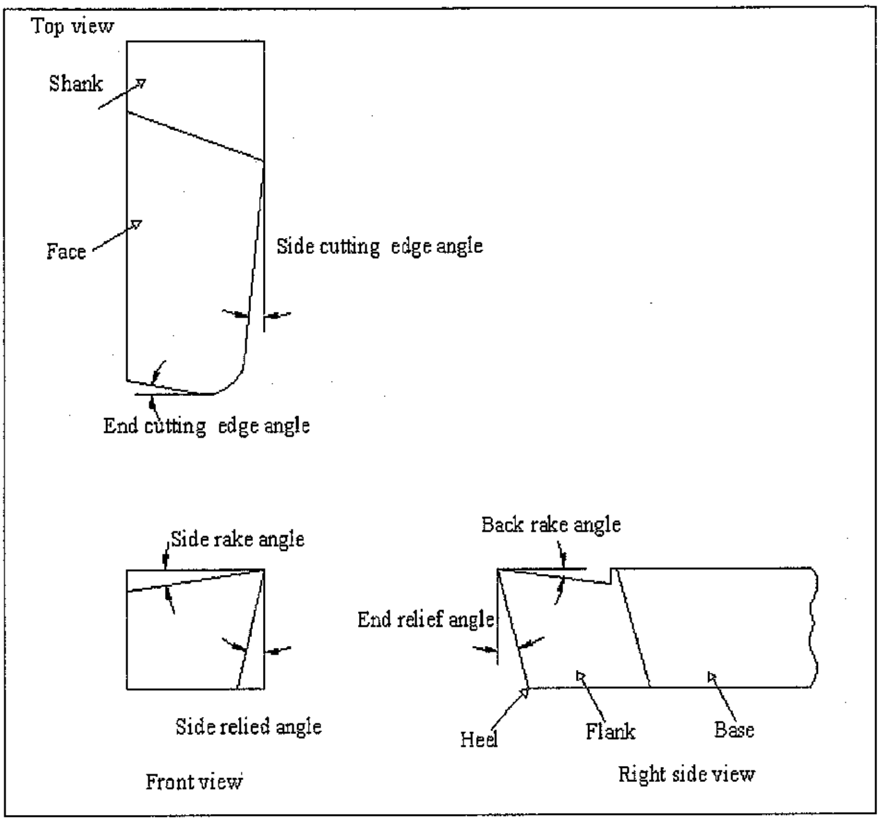


Figure 5-38: Element of the cutting tool [70].

Table 5-24: Element of the cutting tool of HSS for cutting brass [70].

Element	Angles
Back rake angle (deg)	0
Side rake angle (deg)	+8 to 10
End relief angle (deg)	1 to 3
Side relief angle (deg)	10 to 12

5.3.3 Assembly of the PIG Design

The overall assembly of PIG design consists of five modules as shown in Figure 5-39. Starting from the front, the PIG design consists of a wax deposit removal module, a turbine for wax removal module, a flow control module, a turbine for drive mechanism module and a drive mechanism module.

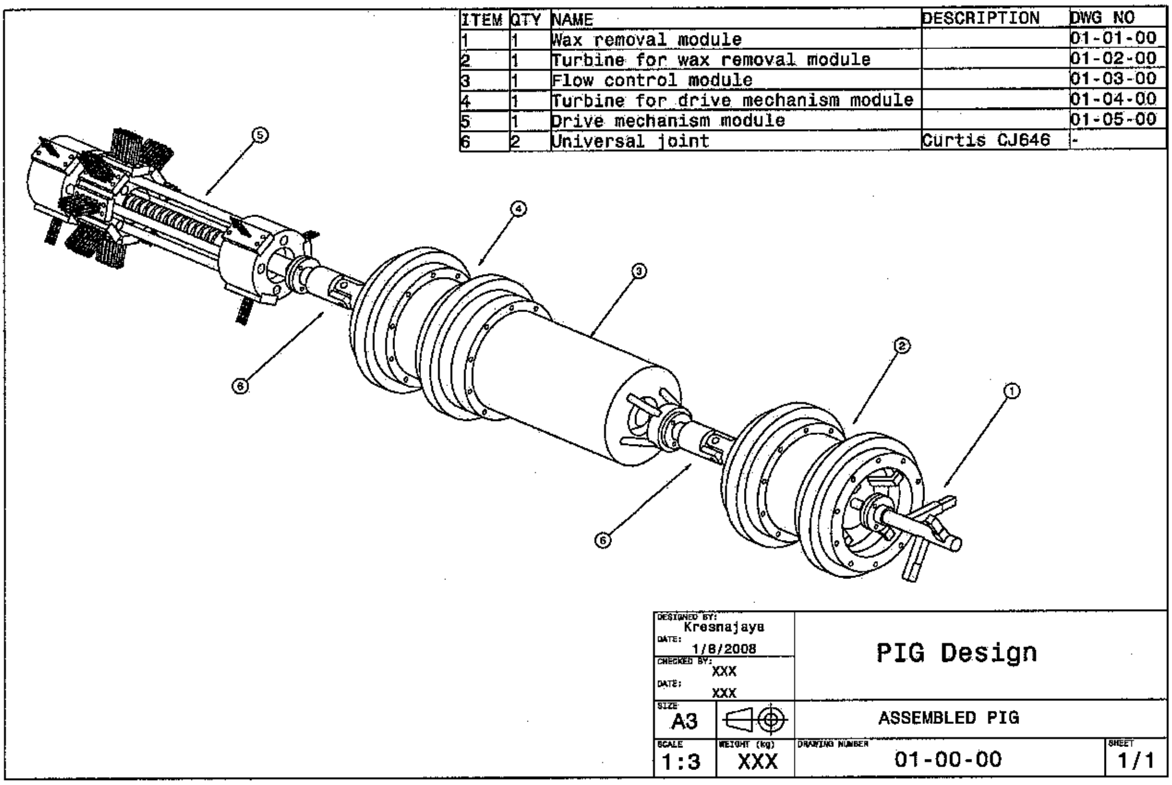


Figure 5-39: Assembly drawing of the PIG design.

The detail component that assembles of each module is described as following.

a. Wax removal module

A wax removal tool module has a main function to break a wax deposit into a small chip of wax. It consists of several components as shown in Figure 5-40. The cutting tool is attached to the shaft which is rotated by a turbine module. The connection between the wax removal tool module and the turbine module is performed through a coupling. The use of coupling makes this wax removal tool module ease to disassemble for maintenance purpose.

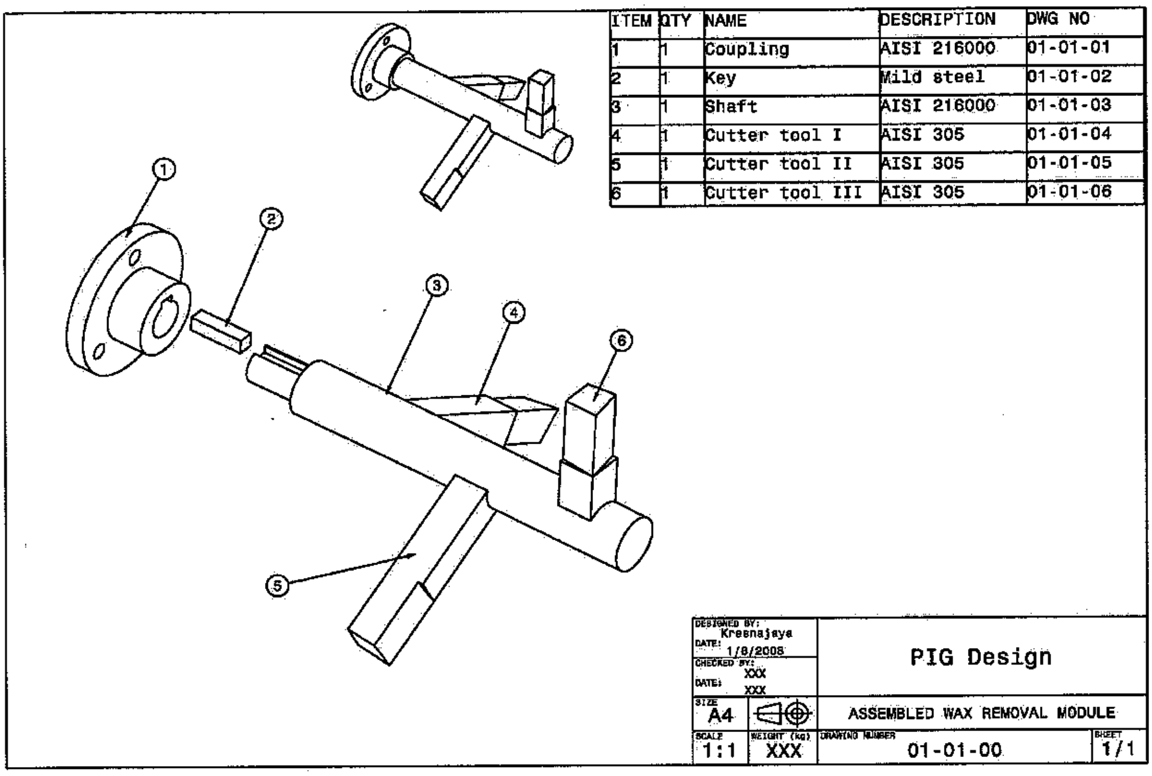


Figure 5-40: Assembly drawing of the wax removal module.

b. Turbine for wax removal module

A turbine module has a main function to provide a power required to drive a wax removal tool module. It consists of several components as shown in Figure 5-41. An axial impeller is attached to a shaft. Since the characteristic the axial turbine are working on high rotational speed, a harmonic gear is attached to the shaft in order to get a high torque by reducing rotational speed of shaft turbine. Besides producing tangential force, this turbine also generates axial force which needs to be absorbed. A roller bearing is mounted to the end of the shaft to absorb this axial force. Both of the roller bearing and harmonic gear is hold by turbine housing. This turbine housing is attached with a disc which is fastened by the flange cover. The disc has a function to reduce friction during PIG movement and also as a sealing where the pressure difference across the PIG will push the PIG in return mode.

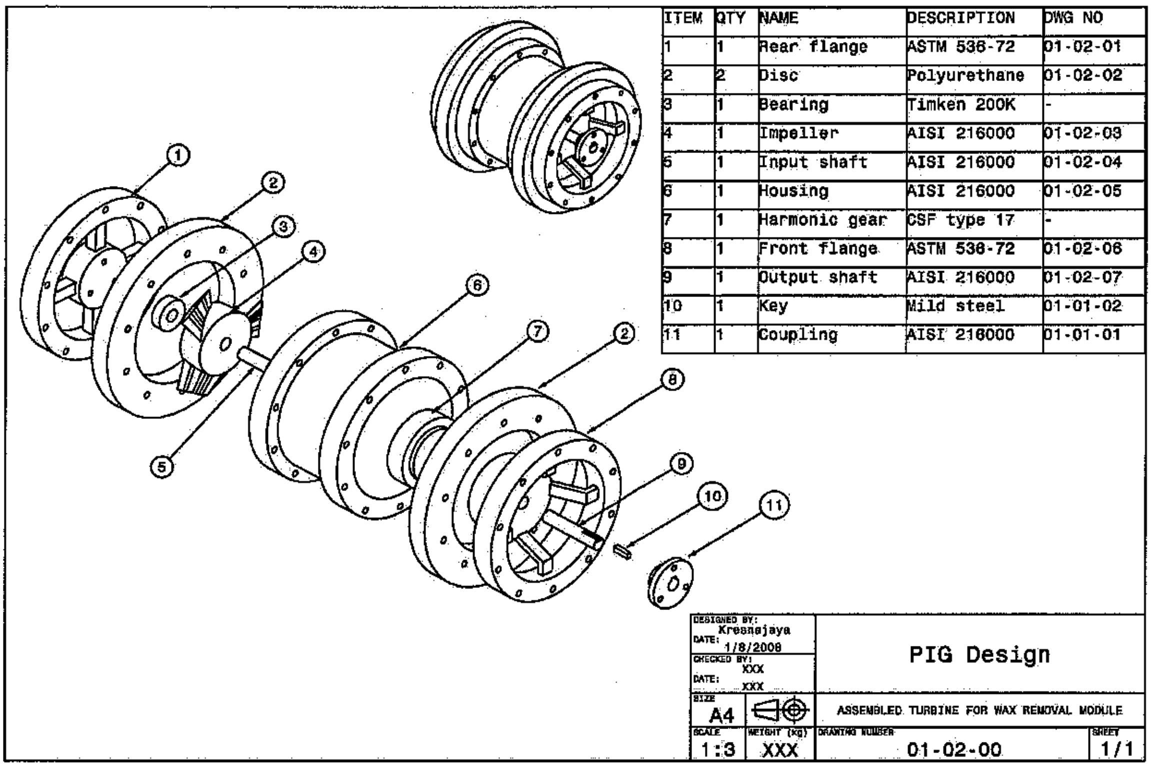
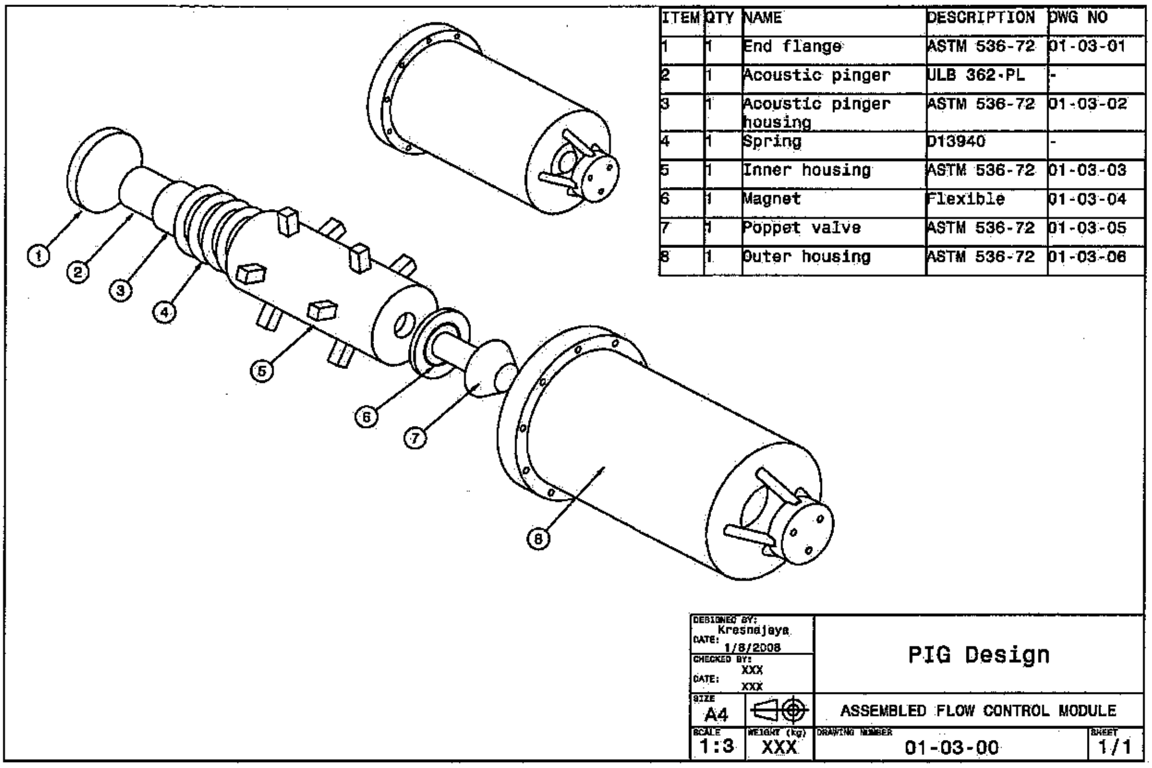


Figure 5-41: Assembly drawing of the turbine for wax removal module.

c. Flow control module

A flow control module has a main function to maintain the volume flow rate to a turbine for drive mechanism module at a constant value. It consists of several components as shown in Figure 5-42. The flow control module is characterized by having a moveable element or poppet that is used to maintain the volume flow rate. The poppet inside the housing is moved via a fluid flow that pushes the poppet off its seat allowing a flow path. The moving of poppet valve is controlled by the spring stiffness. In case the PIG design reaches at the end of the pipeline, the flow control valve will be in fully close position because of magnet force.

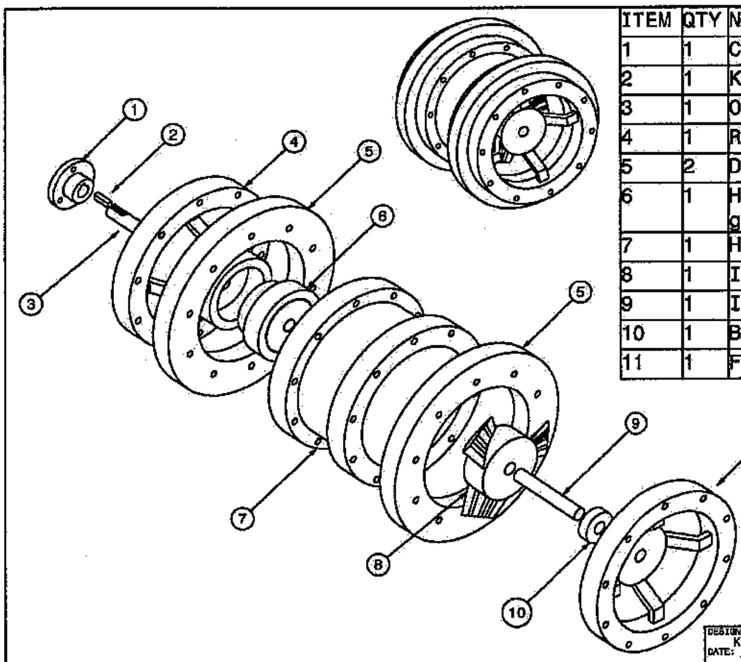


ITEM	QTY	NAME	DESCRIPTION	DWG NO
1	1	End flange	ASTM 536-72	01-03-01
2	1	Acoustic pinger	ULB 362-PL	-
3	1	Acoustic pinger housing	ASTM 536-72	01-03-02
4	1	Spring	D13940	-
5	1	Inner housing	ASTM 536-72	01-03-03
6	1	Magnet	Flexible	01-03-04
7	1	Poppet valve	ASTM 536-72	01-03-05
8	1	Outer housing	ASTM 536-72	01-03-06

Figure 5-42: Assembly drawing of the flow control module.

d. Turbine for drive mechanism module

A turbine module used to drive a drive mechanism module is similar like a turbine module used to drive a wax removal module. The only difference is the position of the harmonic gear. Since the position of the drive mechanism module is in the behind of the turbine module, the harmonic gear is attached at the back of turbine module. This harmonic gear is required in order to reduce the rotational speed of turbine shaft and to increase the torque generated by the turbine. Components that assemble turbine module are shown in Figure 5-43.



ITEM	QTY	NAME	DESCRIPTION	DWG NO
1	1	Coupling	AISI 216000	01-01-01
2	1	Key	Mild Steel	01-01-02
3	1	Output shaft	AISI 216000	01-04-01
4	1	Rear flange	ASTM 536-72	01-04-02
5	2	Disc	Polyurethane	01-02-02
6	1	Harmonic gear	HPG 14A	-
7	1	Housing	ASTM 536-72	01-04-03
8	1	Impeller	AISI 216000	01-02-03
9	1	Input shaft	AISI 216000	01-04-04
10	1	Bearing	Timken 200K	-
11	1	Front flange	ASTM 536-72	01-04-05

DESIGNED BY: Kresnajaya DATE: 1/8/2008
CHECKED BY: XXX DATE: XXX
PIG Design
SIZE A4
ASSEMBLED TURBINE FOR DRIVE MECHANISM MODULE
SCALE 1:3 | WEIGHT (kg) XXX | DRAWING NUMBER 01-04-00 | SHEET 1/1

Figure 5-43: Assembly drawing of the turbine for drive mechanism module.

e. Drive mechanism module

A drive mechanism module is used to provide traction force when the PIG design moves in a counter flow direction. It consists of several components as shown in Figure 5-44. The drive mechanism module is characterized by moving element of nut on the double screw. The double screw is held on the housing through a bearing which make it able to rotate. To be able to move in the counter flow, a bristle which has a unique characteristic easier to move in a forward direction rather than a backward direction is mounted on the nut and housing. By applying torque generated by the turbine module to the drive mechanism module through a coupling, a nut will travel in both directions through a double screw. It can move in the double screw because a cam follower is attached to the nut. As the shaft rotating, this cam follower will follow groove on the double screw. Initially, the nut will move forward until reached at the end of the double screw. At this condition, the friction force of bristle on the nut is higher than then propulsion force required to move the PIG design in the counter flow direction.

As the shaft still rotating, the cam follower on the nut is forced to move to another groove. As a consequence, the nut will be on the fixed position while the PIG design will move forward.

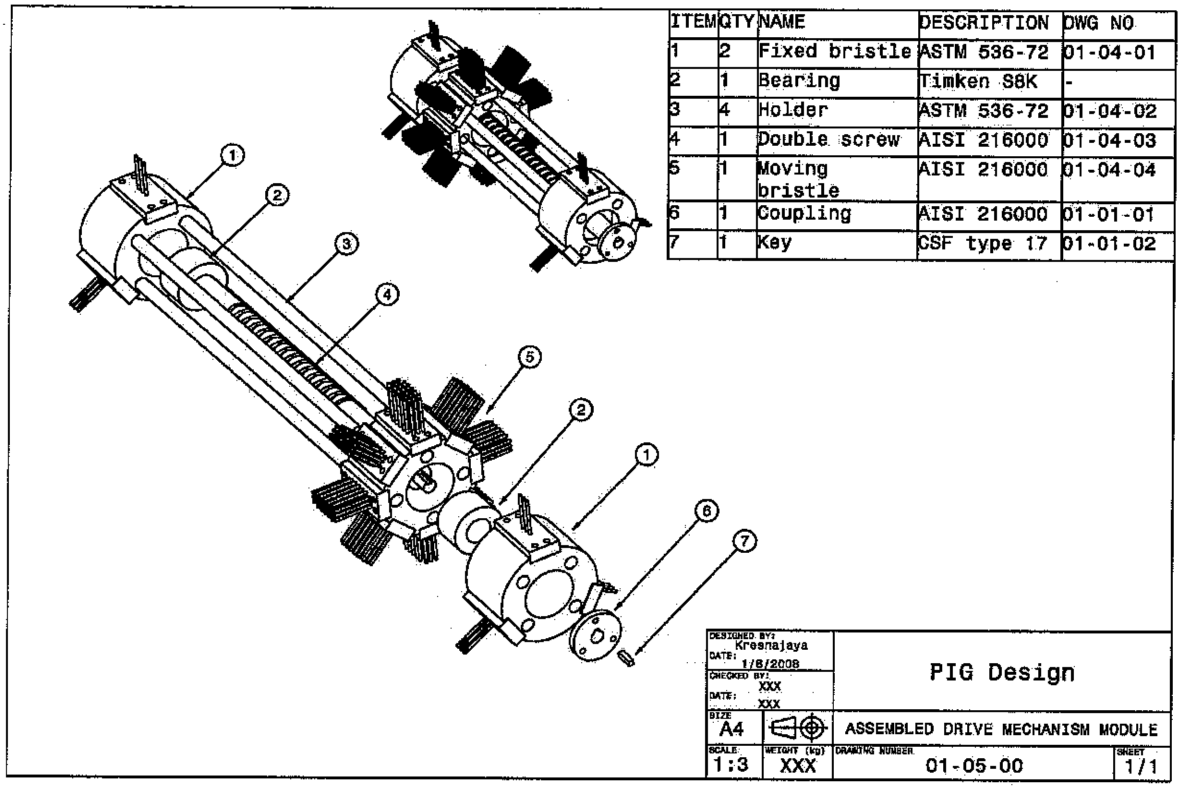


Figure 5-44: Assembly drawing of the drive mechanism module.

5.3.4 Capabilities

Based on the preliminary design as described in section 5.3.3.2, 5.3.3.3, 5.3.3.4, 5.3.3.5, with the pipeline operating condition of pressure of 15 MPa, fluid velocity of 1 m/s, pressure drop across the PIG of 31026.41 Pa the capabilities of the PIG design is summarized below.

a. To travel in a counter flow direction at speed of 0.033 m/s, the PIG requires a traction force of 2114.95 N.
b. It can travel in a counter flow direction with a discrete motion. A ratio time between the PIG design movements in a forward direction with an idle condition is 4.28.
c. The maximum shear strength of wax deposit material that can be removed is 81 kPa.

5.3.5 Limitation

The PIG design has still limitation on its design and it is summarized below.

a. The PIG design is currently design based on the data from literature review. A prototype of the proposed PIG design needs to be manufactured and test to validate the calculation.
b. The PIG design only can be respond with fluid flow variation since it is designed based on perpetual mechanism. If the pipeline consists of obstruction like a reduced valve such as gate and butterfly, the PIG design is in the risk to get stuck inside a pipeline.

5.3.6 The Difference with Contraflow Tetherless Mechanical Pipeline Crawler DPT Crawler

The PIG design consists of combination from the contraflow tetherless mechanical pipeline crawler and the DPT crawler. Since the main requirement is to be able to travel at a desired speed of 0.033 m/s, a cam follower mounted with bristle is the most promising one. Eventhough this mechanism creates an intermittent motion by sacrificing the secondary requirement to travel at a continuous motion, the traveling speed generated by this driving mechanism is better than an offset bearing mechanism as discussed in the section 5.3.3.4. For the wax removal mechanism, the PIG design uses the cutting tool module as used in the contraflow tetherless mechanical pipeline crawler. This cutting tool module uses an active force which is generated by a turbine module. It makes the wax deposit is cut into a small chip of wax which is able to be carried by the fluid flow. Comparing to the DPT crawler, it uses a scraping mechanism by pushing the bristle through the wax solid deposit. As a consequence, some of wax chip removal will accumulate in front of the DPT. In order to move at a constant speed for increasing the wax cleaning efficiency, the PIG design is equipped with the flow control module which consists of a poppet valve and a spring mechanism. This mechanism is almost same which is used in the contraflow tetherless mechanical pipeline crawler. The difference is to trigger in the close position, the flow control module in the PIG uses a magnet mechanism. The benefits of using this mechanism is a perpetual mechanism which ensures the capability of the PIG design to travel through the entire length of the pipeline.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

Chapter six is organized into two sections. The first section provides conclusion of the result in this research. The second section describes some recommendations for the future work.

6.2 Conclusion

The research work has produced a CAD model of contraflow PIG which has function to clean wax from pipeline. The proposed PIG concept consists of an axial turbine as a power source, a cutter tool as a wax removal tool, a poppet valve as a flow control, a cam follower as a drive mechanism and an acoustic pinger as PIG locating is proposed to be further developed in the embodiment phase.

Further, the physical element of each functions are classified into five modules which determines the product architecture of PIG design. It consists of turbine module to drive a drive mechanism module, a drive mechanism module, a flow control module, a turbine to drive wax removal module, and a wax removal module. Based on the preliminary analysis, with the pipeline operating condition of pressure of 15 MPa, fluid velocity of 1 m/s, pressure drop across the PIG of 31 kPa the capabilities of PIG design is summarized below.

a. To travel in a counter flow direction at a specified speed of 0.033 m/s, the PIG requires a traction force of 2114.95 N.
b. It can travel in a counter flow direction with a discrete motion at a time ratio of 4.28 between the PIG design movements in forward direction and the stationary condition.
c. It can remove wax deposit on the offshore pipeline with maximum shear strength of 81 kPa.

6.3 Recommendations

This project consists of several phases to develop a PIG design for offshore pipeline maintenance into functional prototypes. The preliminary results obtained at the end of this project relates to the configuration design phase. A preliminary calculation of PIG design has been done with reference to the PDS document, but future work would certainly lead to an improvement to this design.

First, as described previously, because of time constraint, lot of assumptions were made in order to achieve the objectives of the research work. The accuracy of the result could be improved by checking those assumptions. The most important assumptions that should be checked are friction force generated by the bristle with pipeline, friction force generated between the disc and the pipeline wall, and shear stress of wax. Further study on this subject could bring more accurate result on the PIG design performance.

For future work, it could be interesting to investigate the effect on cutting tool angle with machining parameter used to break wax deposit into a small chip of wax. It may be thought that the cutting tool angle would have been different from the one used here and the resulting design would be able to remove wax with higher shear stress by using the same power input from turbine design.

Furthermore, the prototype of the proposed PIG design should be manufactured and tested. To check the accuracy with preliminary design as comparison, it is recommended that every module should be fabricated and tested separately at first. Then, if there is a large different in the result with the preliminary design and prototype testing is found, a redesign analysis of module should be performed before doing the prototype testing again. Finally, the complete assembly of PIG prototype is to be tested and verified against the desired accuracy of the preliminary design.

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APPENDIX A: EXAMPLE OF CONCEPTUAL EVALUATION FORM OF CONTRAFLOW PIG DESIGN FOR PIPELINE MAINTENANCE

I. Personal Information

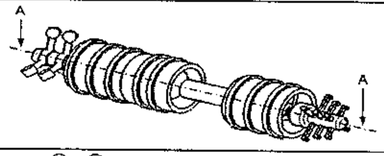
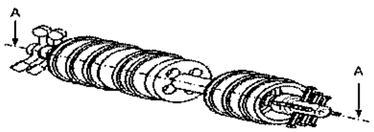
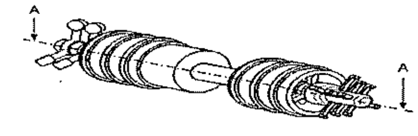
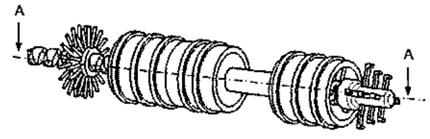
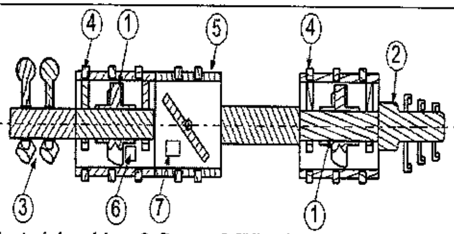
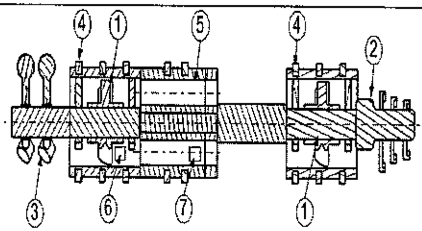
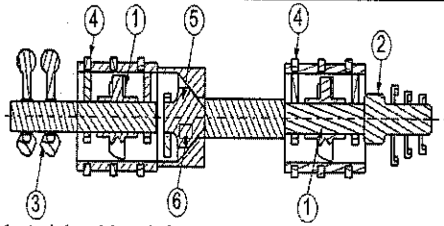
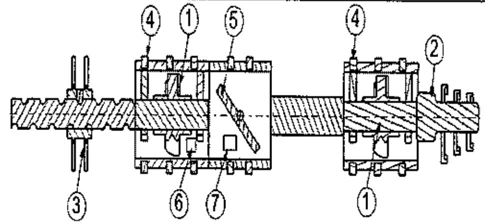
Name:______________________________ Position:______________

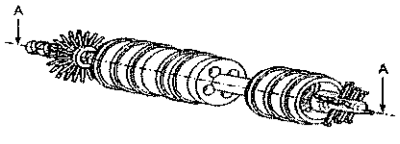
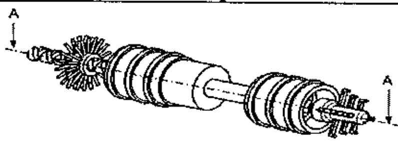
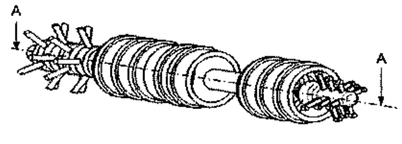
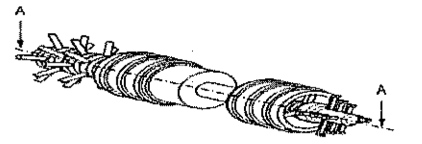
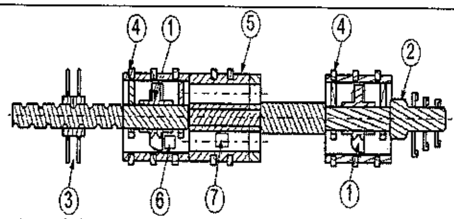
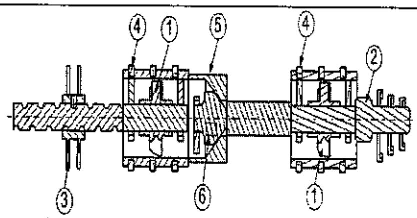
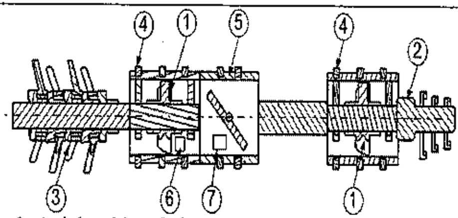
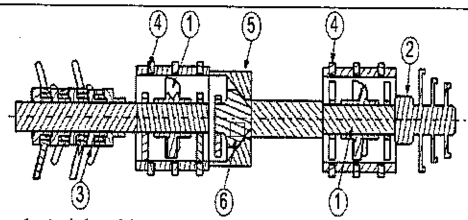
University/Company name:______________________________ Date:____/_____/____

II. Purpose of Survey

The MSc. project is entitled Design of Contraflow Cleaning PIG for Pipeline Maintenance. The method that is used to develop a model of PIG is based on the systematic design approach. One of the steps in the systematic design is concept selection. The method that is used in the concept selection is concept screening. In the concept screening, the concept is compared relative to each other for each particular criterion to determine the most promising concept. Currently, there are eight concepts of PIG that have been generated. The objective of this survey is to solicit feedback from peer reviewers in selecting the most appropriate concept. The working principle and sketch of PIG concept is attached. Your survey respond is really appreciated.

III. Several PIG Concepts

Concept A	Concept B	Concept C	Concept D
			
 1. Axial turbine, 2.Cutter, 3.Wheel, 4.Disc, 5.Butterfly valve, 6.Optical encoder, 7.Acoustic pinger.	 1. Axial turbine, 2.Cutter, 3.Wheel, 4.Disc, 5. Passage way, 6.Optical encoder, 7.Acoustic pinger.	 1. Axial turbine, 2.Cutter, 3.Wheel, 4.Disc, 5.Poppet valve, 6.Acoustic pinger.	 1. Axial turbine, 2.Cutter, 3.Cam follower, 4.Disc, 5.Butterfly valve, 6.Optical encoder, 7.Acoustic pinger.

Concept E	Concept F	Concept G	Concept H
			
 1. Axial turbine, 2.Cutter, 3.Cam follower, 4.Disc, 5.Passage way, 6.Optical encoder, 7.Acoustic pinger.	 1. Axial turbine, 2.Cutter, 3.Cam follower, 4.Disc, 5. Poppet valve, 6.Acoustic pinger.	 1. Axial turbine, 2.Cutter, 3.Offset Bearing, 4.Disc, 5. Butterfly valve, 6.Optical encoder, 7.Acoustic pinger.	 1. Axial turbine, 2.Cutter, 3.Offset Bearing, 4.Disc, 5. Poppet Valve, 6. Acoustic pinger.

IV. Working Principle

Concept A

Fluid energy is converted into rotational energy by using an axial turbine. In front of the PIG, a cutter which has a function to remove solid deposit is attached. It is driven by the axial turbine. To move in a counter flow direction, a drive mechanism of offset wheel is attached at the behind the PIG. It is driven by another turbine where the fluid flow through this turbine is regulated by a butterfly valve. The offset wheel axis is not perpendicular to the axis of the pipeline. When driven by the turbine, a rotational torque is applied to a drive mechanism shaft, the wheel move forward making a spiral motion like a screw which rotates and moves along a groove. To determine an obstruction of flow changed, an optical encoder is used to measure the rotational speed of the shaft turbine. Based on the input of this optical encoder, the butterfly will be driven by an internal motor where the power source is supplied by an internal battery. When the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the butterfly valve will close. The PIG will act like a conventional PIG where the fluid flow will push the PIG to return to the initial point of launching. It is also equipped with an acoustic pinger device which has a function to locate the PIG position in the pipeline.

Concept B

At the front of the PIG, a cutter which has a function to remove solid is attached. It is driven by an axial turbine which has a function to convert fluid energy into rotational energy. A drive mechanism of offset wheel which has a function to provide the traction force to move in a counter flow direction is attached at the behind of the PIG. It is driven by another turbine where the fluid flow through this turbine is regulated by a several passage way mechanism. The offset wheel is mounted to a drive mechanism shaft with slightly inclined angle. When driven by the turbine, a rotational torque is applied to the drive mechanism shaft. The wheel rotates and moves in circumferential direction and simultaneously moves in the axial direction because of inclined angle of wheel. In the several passage way mechanism, there is a plate that can control the flow through passage way. It is driven by an internal motor where the power source is supplied by an internal battery. In case there is an obstruction of fluid flow changing, based on the measurement rotational speed of axial turbine shaft by an optical encoder, the plate will partially open or close to regulate the fluid flow through the turbine. In case the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the plate in the several passage way mechanisms will close the path of fluid. As a consequence, the PIG will be pushed by the fluid flow to return to the initial point of launching. To locate the position of the PIG during the operation, the PIG is equipped with an acoustic pinger device.

Concept C
There are two axial turbines in the concept which has a function to convert hydraulic energy into translational energy. At the front of the PIG, the turbine is used to drive a cutter which has a function to remove solid deposit. At the behind of the PIG, the turbine is used to drive a drive mechanism of offset wheel. The offset wheel axis is not perpendicular to the axis of the pipeline. When driven by the turbine, a rotational torque is applied to the drive mechanism shaft. The wheel rotates and moves in circumferential and simultaneously moves in axial direction because of inclined angle of wheel. This turbine is equipped with a poppet valve which has a function to regulate the fluid flow through the turbine. It is perpetual mechanisms where the fluid flow through this valve depends on stiffness of the spring. When the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the poppet valve will close. As a consequence the fluid keep flowing, the PIG will be pushed by the fluid flow to return to the initial point of launching. It is also equipped with an acoustic pinger device which has function to locate the PIG position in the pipeline.

Concept D
Fluid energy is converted into rotational energy by using an axial turbine. In front of the PIG, a cutter which has a function to remove solid deposit is attached. It is driven by the axial turbine. To move in a counter flow direction, a drive mechanism of cam follower is attached at the behind of the PIG. It is driven by another turbine where the fluid flow through this turbine is regulated by a butterfly valve. The drive mechanism of cam follower consists of traverse reverse screw which a nut mounted with bristles can travel along this screw. When driven by the turbine, a rotational torque is applied to the drive mechanism shaft. This rotational torque is converted into the translational propulsion force for the PIG movement and reciprocating movement of nut in the traverse reverse screw. Initially, the nut travel moves forward until it reaches the end of the traverse reverse shaft. Due to the unique characteristic of the bristle which is easier to move forward rather than backward, the PIG will move forward until the nut reaches at the end of the traverse reverse shaft in the opposite direction. This sequential step of the drive mechanism is repeated continuously to make the PIG able to crawl in forward direction. To determine an obstruction of flow changing, an optical encoder is used to measure the rotational speed of the turbine shaft. Based on the input of this optical encoder, the butterfly will be actuated by an internal motor where the power source is supplied by an internal battery. In case the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the butterfly valve will close the path of fluid. The PIG will act like a conventional PIG where the fluid flow will push the PIG to return to the initial point of launching. It is also equipped with an acoustic pinger device which has function to locate the PIG position in the pipeline.

Concept E
At the front of the PIG, a cutter which has a function to remove solid is attached. It is driven by an axial turbine which has function to convert fluid energy into rotational energy. A drive mechanism of cam follower which has a function to provide the traction force to move in counter flow direction is attached at the behind of the PIG. It is driven by another turbine where the fluid flow through this turbine is regulated by a

several passage way mechanism. The drive mechanism of cam follower consists of traverse reverse screw which a nut mounted with the bristle can scroll along this screw. A rotational torque driven by the axial turbine is applied to the traverse reverse screw. The nut mounted with the bristle is forced to move forward until reached the end of the traverse reverse screw while the PIG is still in idle position. As the nut reached at the end of the traverse reverse screw, it will move continuously in a backward direction. As a consequence the traverse reverse screw still rotating, the bristle on the nut will grip the pipeline and the PIG will move in a forward direction. This sequential step of the drive mechanism is repeated continuously to make the PIG able to crawl in the counter flow direction. In the several passage way mechanism, there is a plate that can control the flow through the passage way. It is driven by an internal motor where the power source is supplied by an internal battery. In case there is an obstruction of flow changing, based on the measurement rotational speed of axial turbine shaft by an optical encoder, the plate will partially open or close to regulate the fluid flow through the turbine. When the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the plate in the several passage way mechanisms will block the path of fluid. As a consequence the fluid keep flowing, the PIG will be pushed by the fluid flow to return to the initial point of launching. To locate the position of the PIG during the operation, the PIG is equipped with an acoustic pinger device.

Concept F

There are two axial turbines in the concept which has a function to convert hydraulic energy into translational energy. At the front of the PIG, the turbine is used to drive a cutter which has a function to remove solid deposit. At the behind of the PIG, the turbine is used to drive a drive mechanism of cam follower. This turbine is equipped with a poppet valve which has a function to regulate the fluid flow through the turbine. It is a perpetual mechanism where the fluid flow through this valve depends on stiffness of the spring. The drive mechanism of cam follower consists of a traverse reverse screw which a nut mounted with bristle can travel along this screw. When driven by the turbine, a rotational torque is applied to the drive mechanism shaft. This rotational torque is converted into translational propulsion force for the PIG movement and reciprocating movement of the nut along the reverse traverse screw. Initially, the nut travel moves forward until it reaches the end of the traverse reverse shaft. Due to the unique characteristic of the bristle which is easier to move in a forward direction rather than in a backward direction, the PIG will move forward until the nut reaches at the end of the traverse reverse shaft in the opposite direction. This sequential step of the drive mechanism is repeated continuously to make the PIG able to crawl in the forward direction. If the fluid flow can not be converted into the traction force required to drive the PIG in the counter flow direction, the poppet valve will close. With the fluid flow still keep flowing, the PIG will be pushed by this fluid to return to the initial point of launching. An acoustic pinger device is attached to the PIG to locate the PIG position in pipeline during operation.

Concept G

Fluid energy is converted into rotational energy by using an axial turbine. In front of the PIG, a cutter which has a function to remove solid deposit is attached. It is driven by the axial turbine. To move in a counter flow direction, a drive mechanism of offset bearing is attached at the behind of the PIG. It is driven by another turbine where the fluid flow through this turbine is regulated by a butterfly valve. The drive mechanism of offset bearing consists of bearing mounted with a set of leg. Since the centreline of bearing is offset from the centreline of the drive mechanism shaft, the set of leg create an oscillate motion of outward, backward, inward and forward as the shaft of drive mechanism rotating. When the offset bearing moves forward from the centreline of the drive mechanism shaft, the leg contacts the pipeline and creates traction force. In the opposite direction, when the offset bearing moves toward to the centreline of the drive mechanism shaft, the leg does not contact with the pipeline. Leg in the other side of the offset bearing follows the same cycle at a different phase. This sequential step of the drive mechanism is repeated continuously to make the PIG able to move in the forward direction in a walking action. To determine an obstruction of flow changed, an optical encoder is used to measure the rotational speed of the turbine. Based on the input of this optical encoder, the butterfly will be actuated by an internal motor where the power source is supplied by an internal battery. In case the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the butterfly valve will close. As a consequence, the PIG will be pushed by the fluid flow to return to the initial point of launching. To locate the position of the PIG during the operation, the PIG is equipped with an acoustic pinger device.

Concept H

There are two axial turbines in the concept which has a function to convert hydraulic energy into translational energy. At the front of the PIG, the turbine is used to drive a cutter which has a function to remove solid deposit. At the behind of the PIG, the turbine is used to drive a drive mechanism of offset bearing. This turbine is equipped with a poppet valve which has a function to regulate the fluid flow through the turbine. It is a perpetual mechanism where the fluid flow through this valve depends on stiffness of the spring. The drive mechanism of offset bearing consists of bearing mounted with a set of leg. Since the centreline of bearing is offset from the centreline of the drive mechanism shaft, the set of leg create an oscillate motion of outward, backward, inward and forward as the shaft of drive mechanism rotating. When the offset bearing moves forward from the centreline of the drive mechanism shaft, the leg contact the pipeline and create a traction force. In the opposite direction, when the offset bearing moves toward to the centreline of the drive mechanism shaft, the leg does not contact with the pipeline. Leg in the other side of the offset bearing follows the same cycle at a different phase. This sequential step of the drive mechanism is repeated continuously to make the PIG able to move in the forward direction in a walking action. When the fluid flow is incapable to be converted into the traction force required to drive the PIG in the counter flow direction, the poppet valve will close. As a consequence the fluid keep flowing, the PIG will be pushed by the fluid flow to return to the initial point of launching. It is also equipped with an acoustic pinger device which has a function to locate the PIG position in the pipeline.

V. Concept Scoring

Within a particular criterion, please give relative performance for each concept in comparison with the datum in Table 1. The relative performance is scaled by using (+) to indicate better than a datum, (-) to indicate worse than a datum or (S) to indicate the same as a datum. Please use the following factor in your selection.

Table 1. The concept screening matrix

Selection criteria	Concept							
	A	B	C	D	E	F	G	H (Datum)
1. Able to travel at uniform speed								
2. Ease of traveling in both direction								
3. Reliability								
4. Ease of manufacture								
5. Duration of operation								
6. Robustness								
Total score								
Rank								

Description of the Selection Criteria

Below is the description of selection criteria that may help you to rate the relative performance for each concept comparing to the datum.

1. Able to travel at uniform speed

The PIG speed needs to be maintained at a uniform speed when traveling in a counter flow direction to ensure the solid deposit removal by pigging operation is same through the entire length of the pipeline. Reflecting on certain features on each concept, which one do you think will be able to travel at a uniform speed?

2. Ease of traveling in both directions

The PIG needs to be able to travel in a counter flow direction while doing pigging and to return to the initial point of launching when reaches at the end of the pipeline or faced an obstruction like valve, reducing diameter and etc. Reflecting on the effect of the frontal area and surface contact with the pipeline inner wall, which concept do you think will be ease to travel in both directions?

3. Reliability

Reliability is a measurement of the capacity of a PIG to operate without failure in the offshore pipeline operation condition. Reflecting on certain features on each concept, which one do you think will demonstrate the fail safe mechanism that will automatically return the PIG to the initial point of launching?

4. Ease of manufacture

The overall PIG design is assembled from the several components. Reflecting in the complexity of components and number of components, which concept do you think will be easier to manufacture?

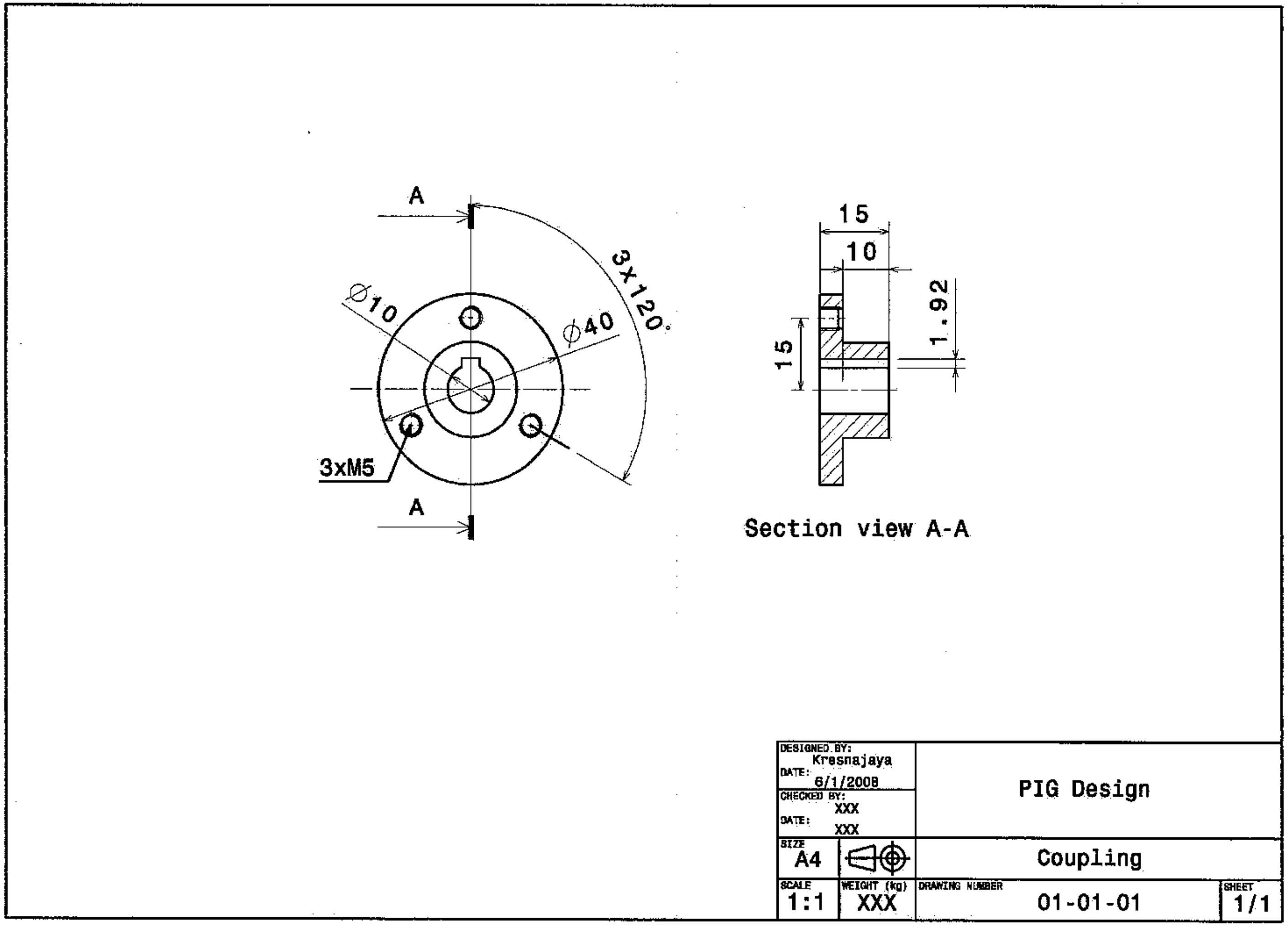
5. Duration of operation

The PIG is designed to operate in the offshore pipelines. Reflecting on certain features on each concept, which one do you think has a level confidence to complete the pigging process?

6. Robustness

Robustness is the quality of being able to withstand with the variation of the offshore pipeline operating condition. Reflecting on certain features on each concept, which one do you think will loss functionally when there is variation in its operating condition?

APPENDIX B: TECHNICAL DRAWING OF PIG DESIGN



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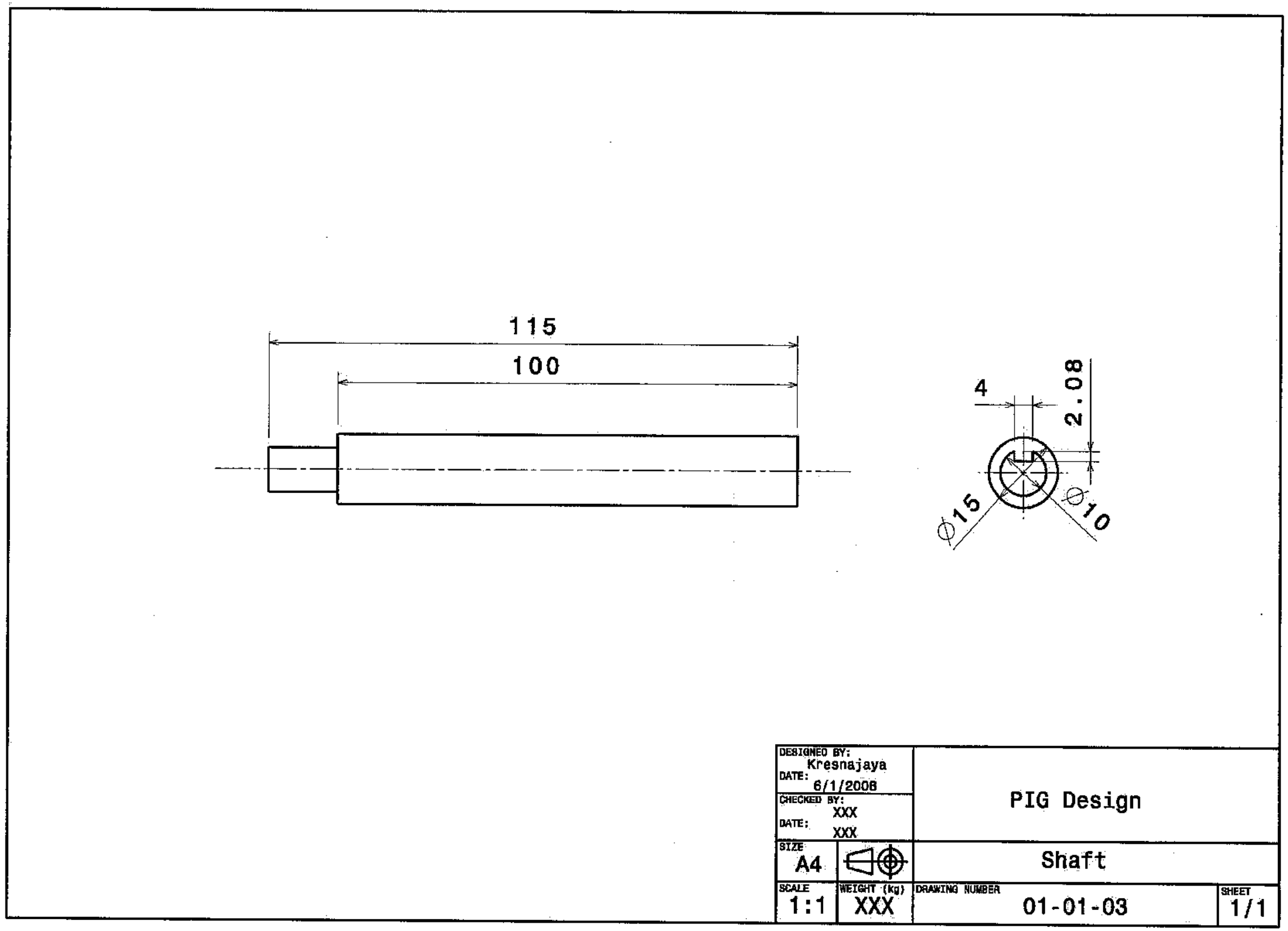
SCALE 1:1	WEIGHT (kg) XXX	DRAWING NUMBER 01-01-02	SHEET 1/1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2.08
⌀15
⌀10
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Kresnajaya
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6/1/2008
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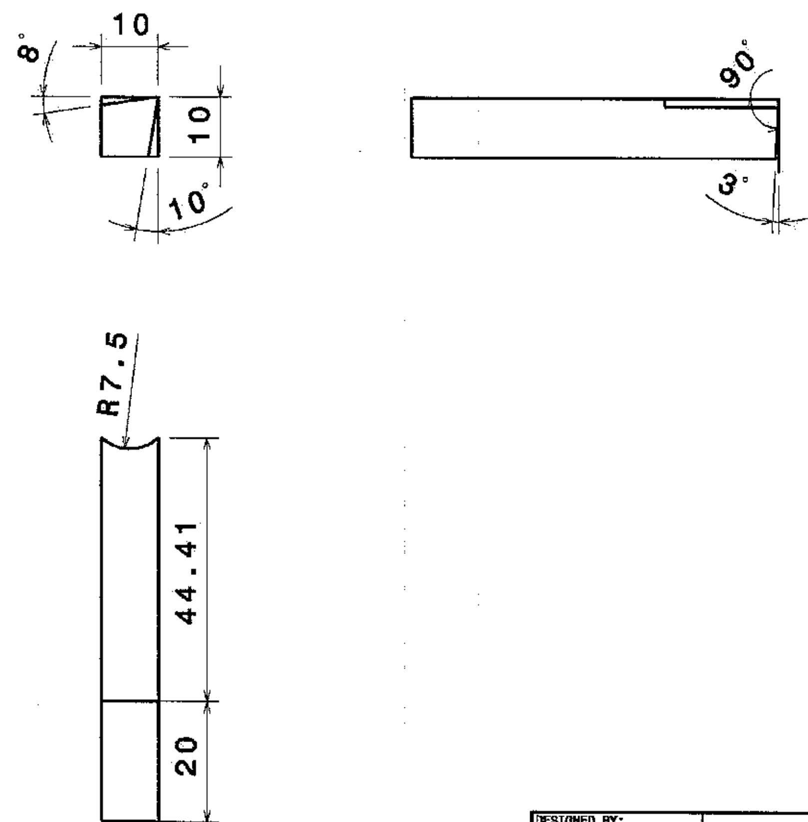
DATE:
XXX
SIZE
A4
SCALE
1:1
WEIGHT (kg)
XXX
PIG Design
Shaft
DRAWING NUMBER
01-01-03
SHEET
1/1



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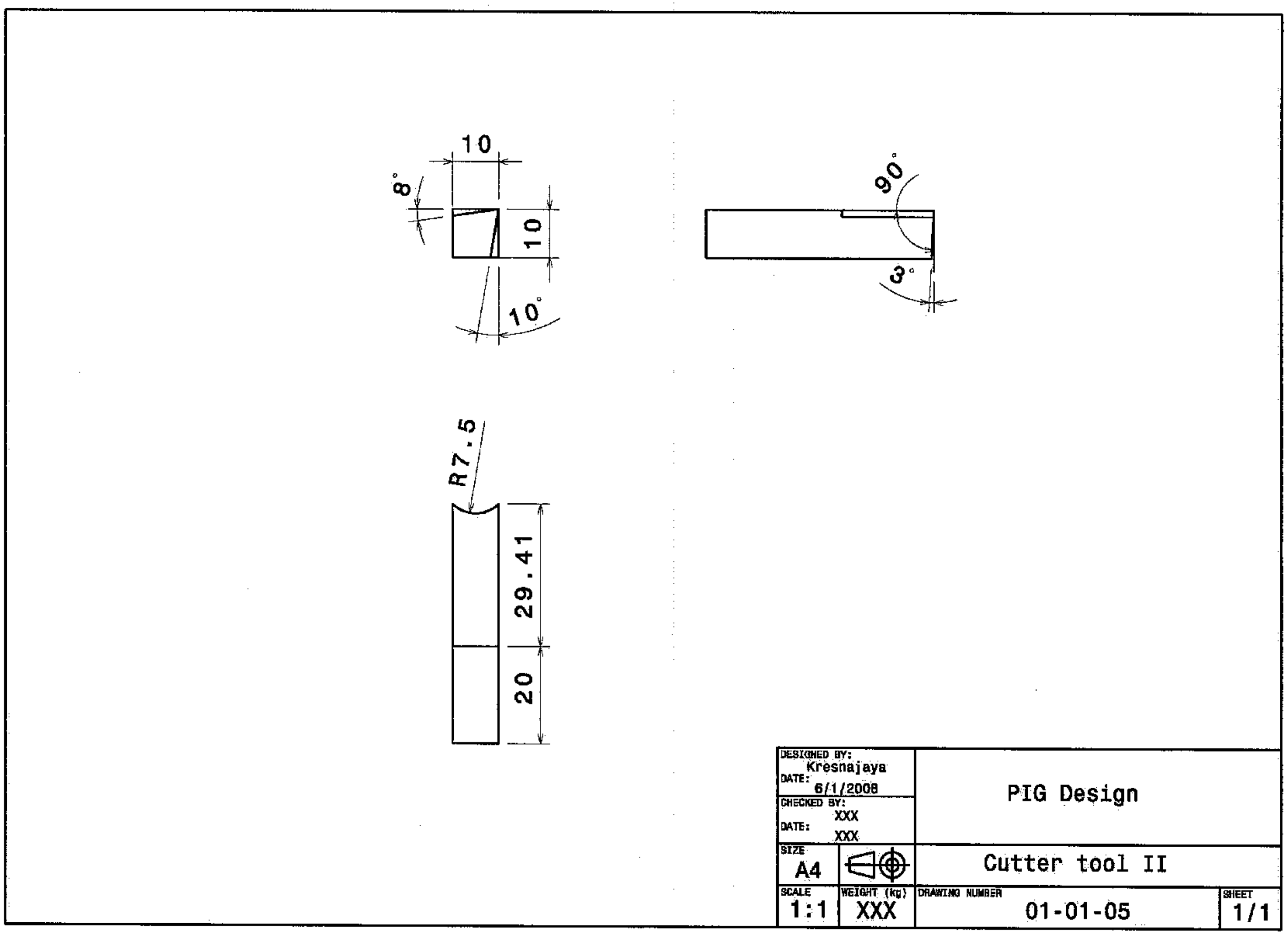
SCALE 1:1	WEIGHT (kg) XXX	DRAWING NUMBER 01-01-04	SHEET 1/1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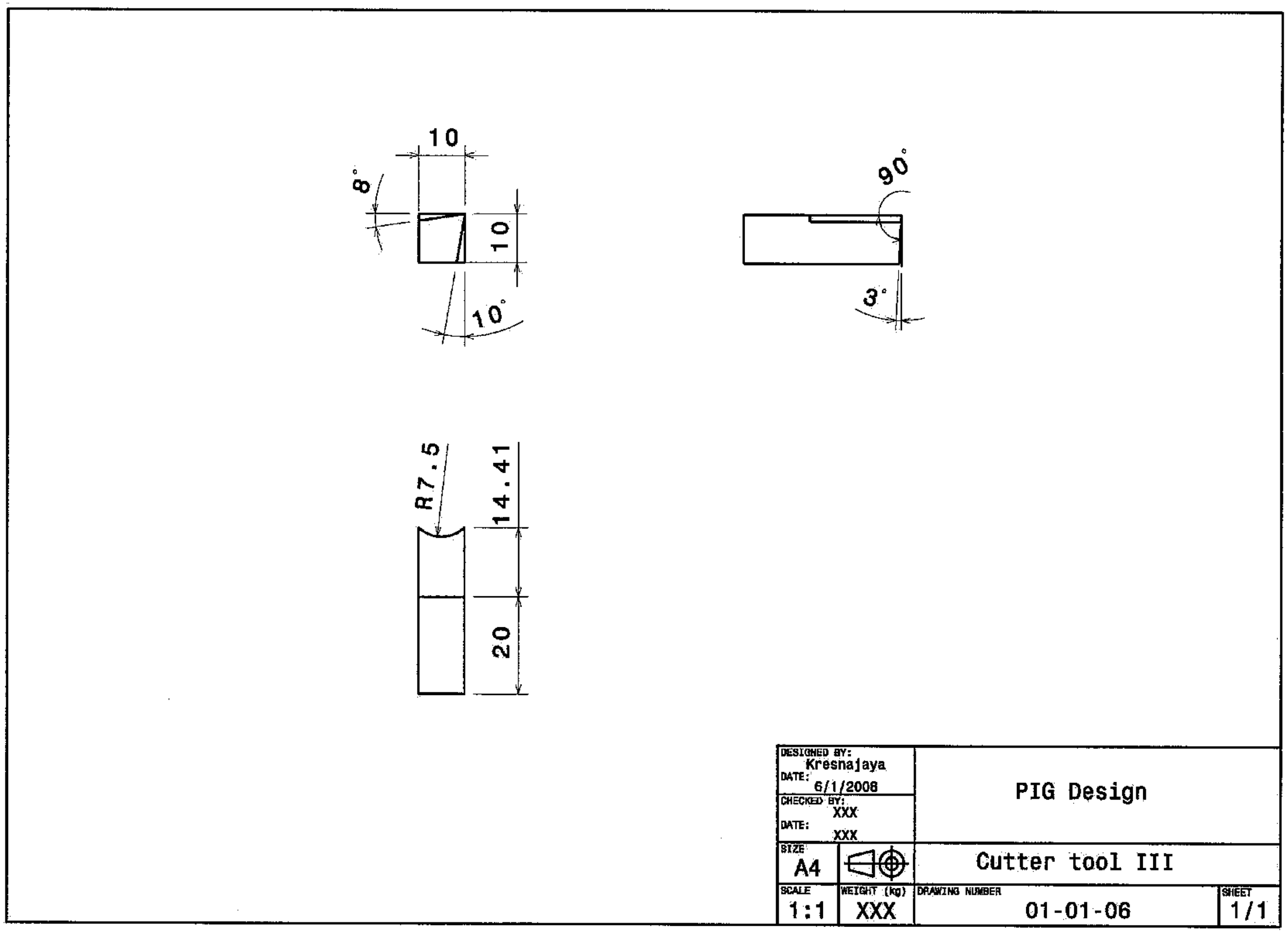
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
SIZE
A4
SCALE
1:1
WEIGHT (kg)
XXX
PIG Design
Cutter tool II
DRAWING NUMBER
01-01-05
SHEET
1/1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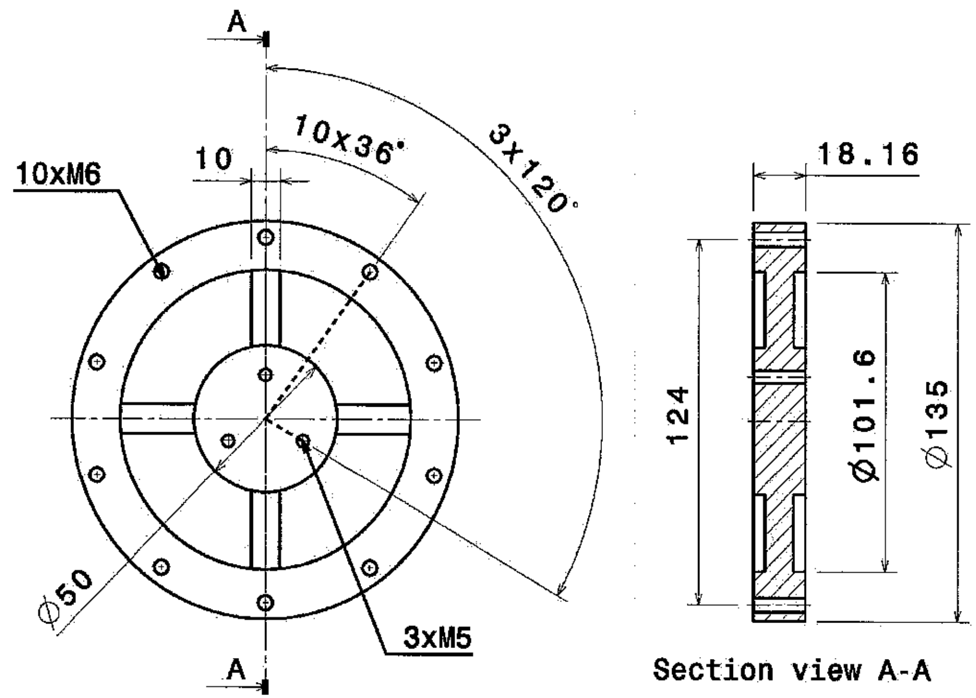
8°
10
10°
90°
3°
R7.5
14.41
20
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Cutter tool III
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-01-06
SHEET
1/1



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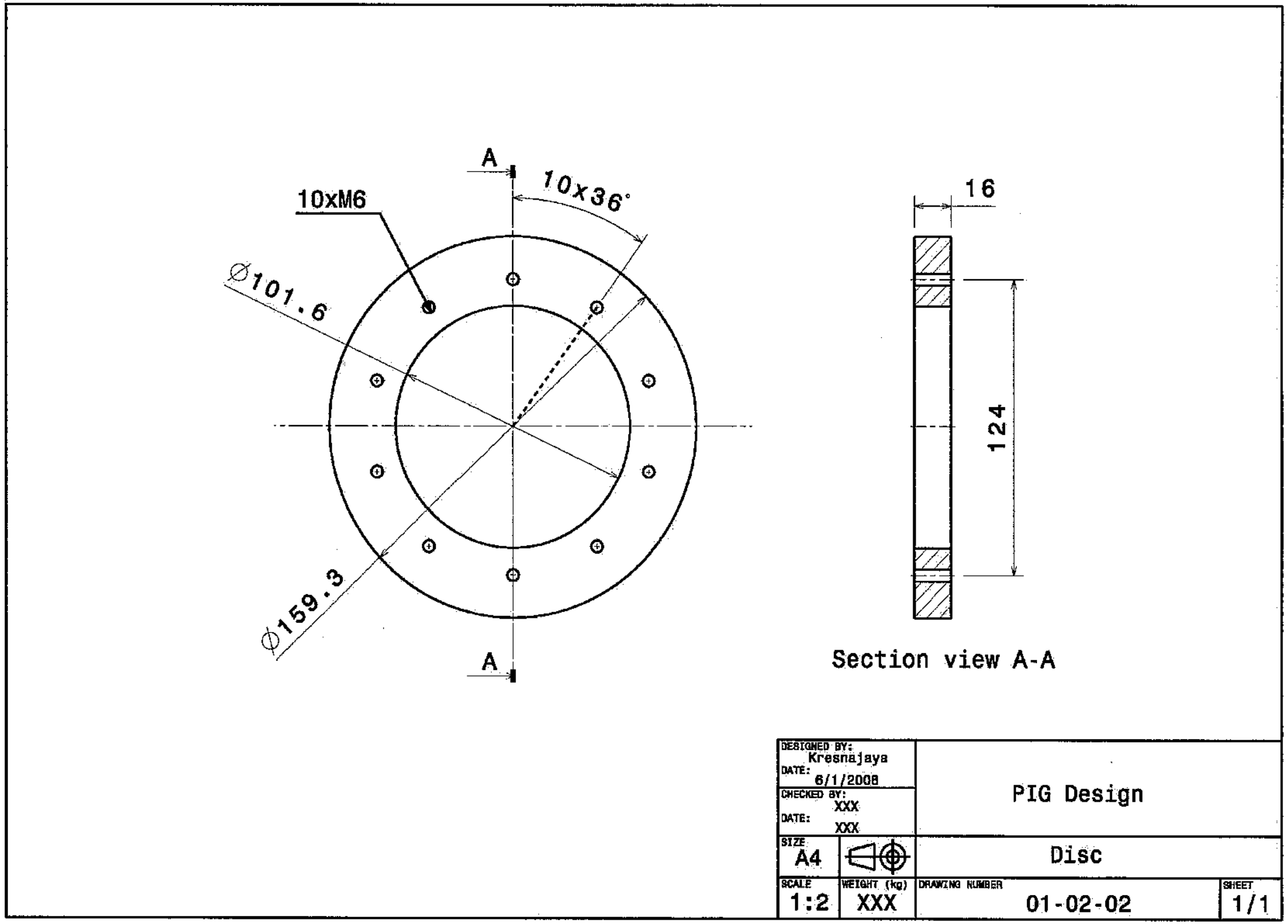
10xM6
A
10x36°
∅101.6
∅159.3
A
16
124
Section view A-A
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Disc
SCALE
1:2
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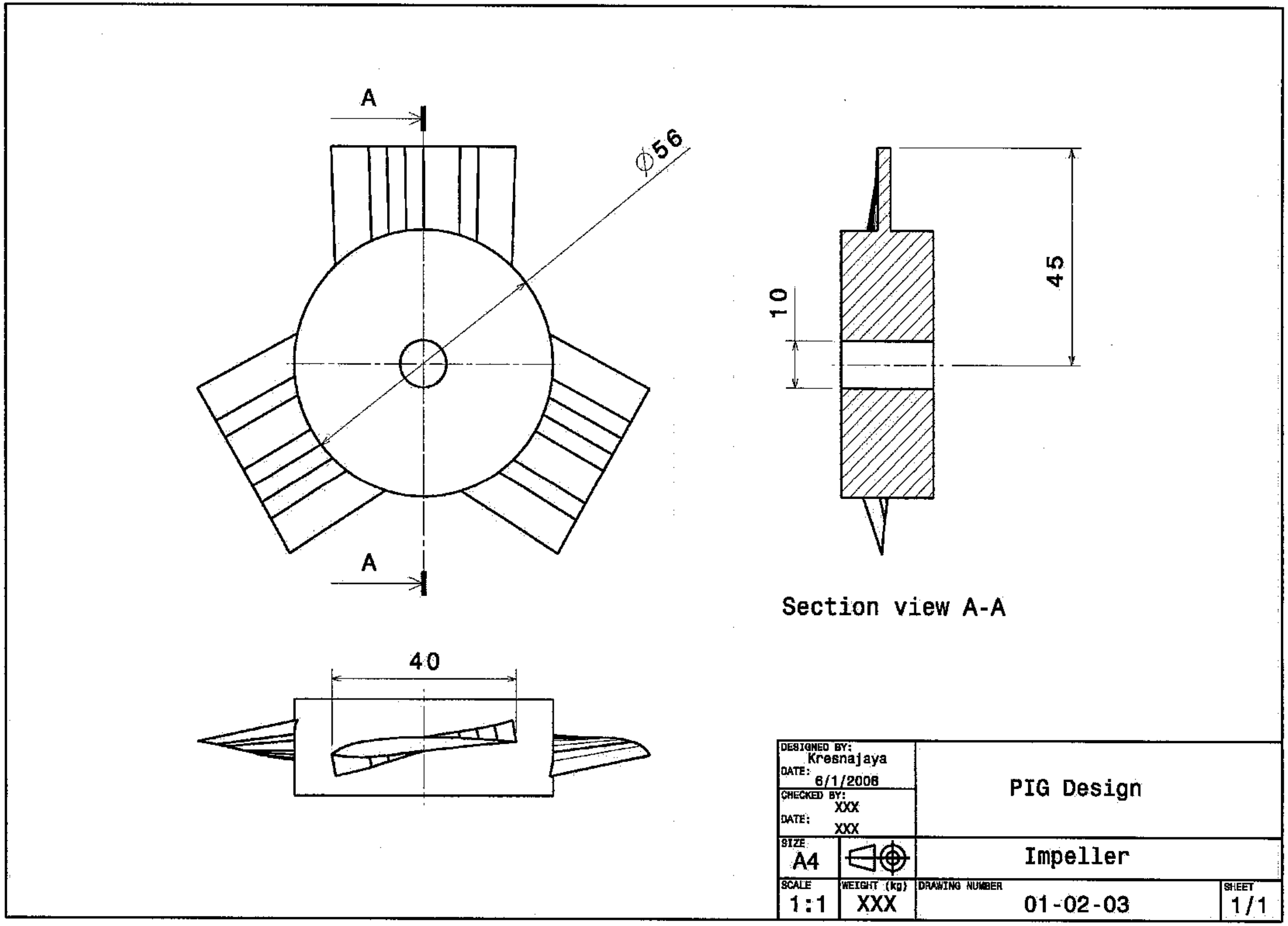
XXX
DRAWING NUMBER
01-02-02
SHEET
1/1



A
A
ϕ56
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10
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Section view A-A
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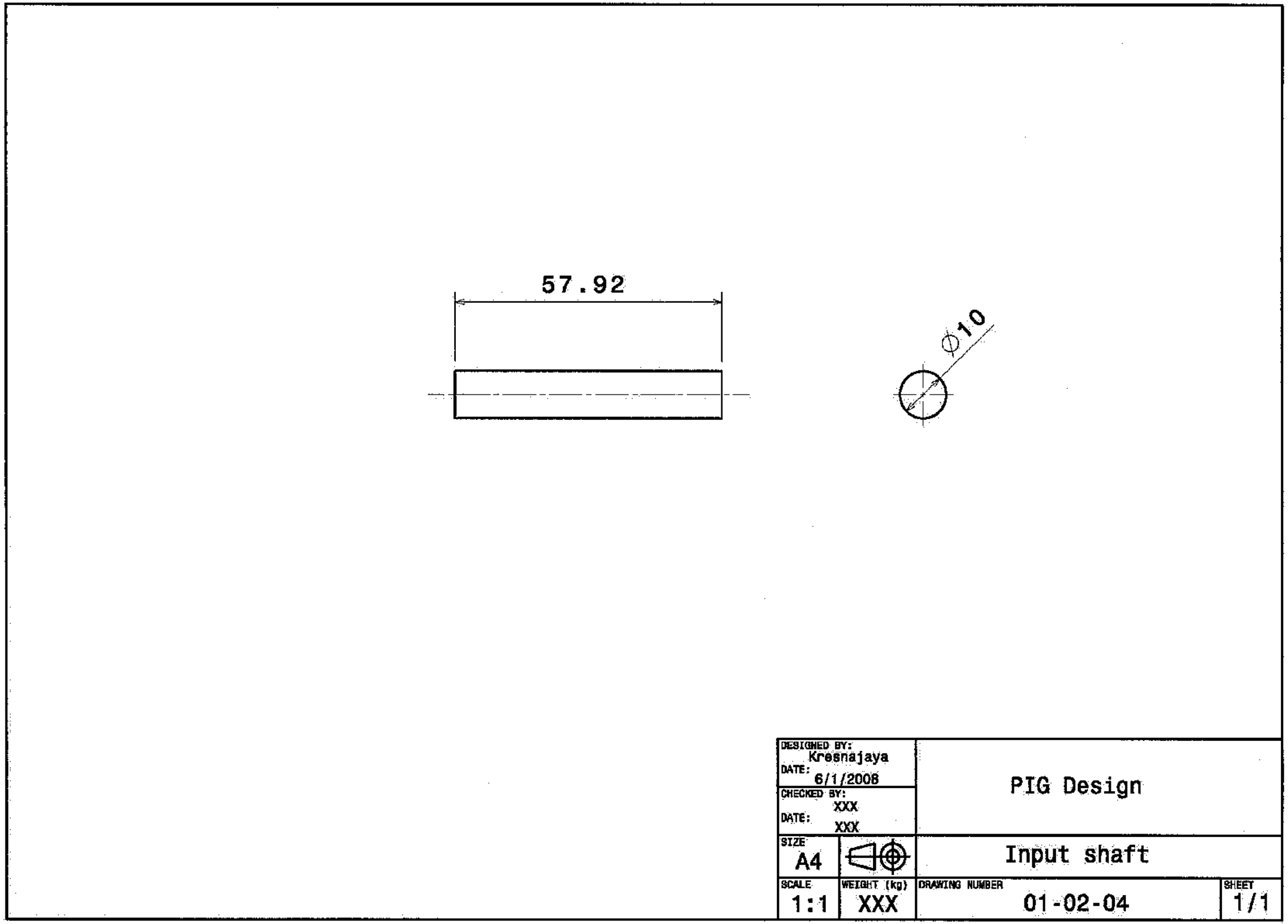
PIG Design
Impeller
DRAWING NUMBER 01-02-03
SHEET 1/1



57.92
⌀10
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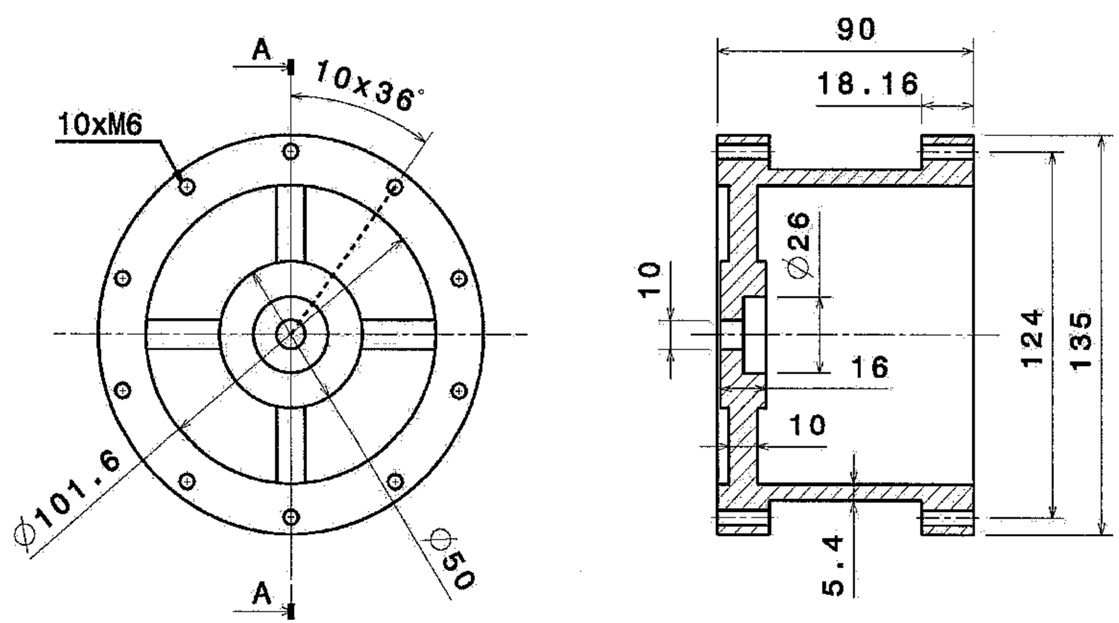
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Input shaft
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-02-04
SHEET
1/1



Section view A-A

DESIGNED BY: Kresnajaya DATE: 6/1/2008	PIG Design		
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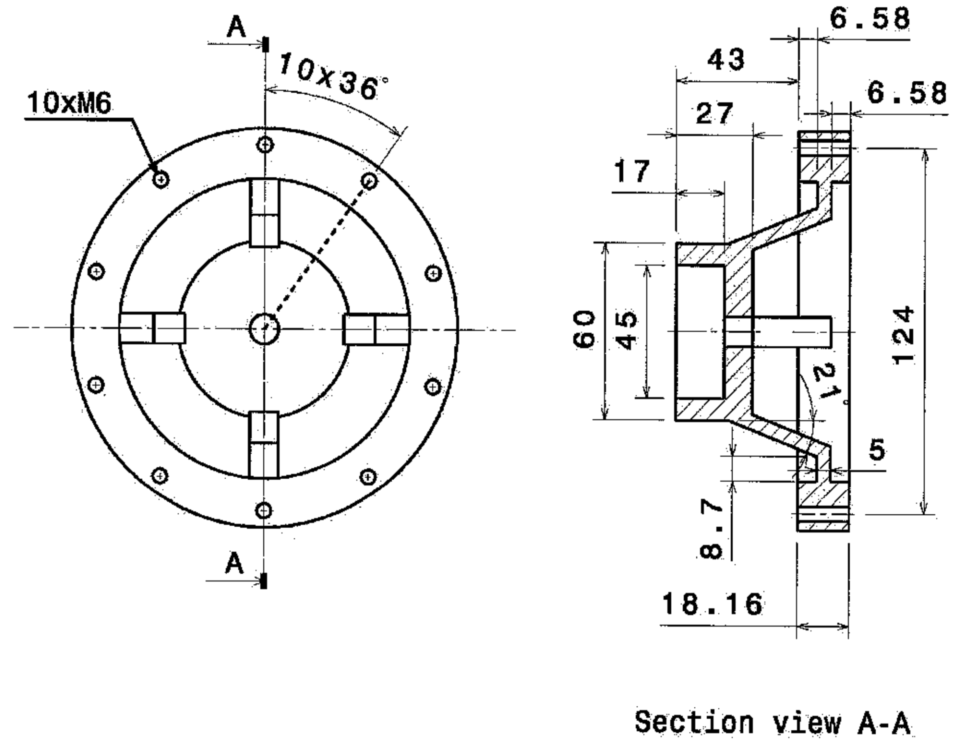

DESIGNED BY: Kresnajaya DATE: 6/1/2008	PIG Design		
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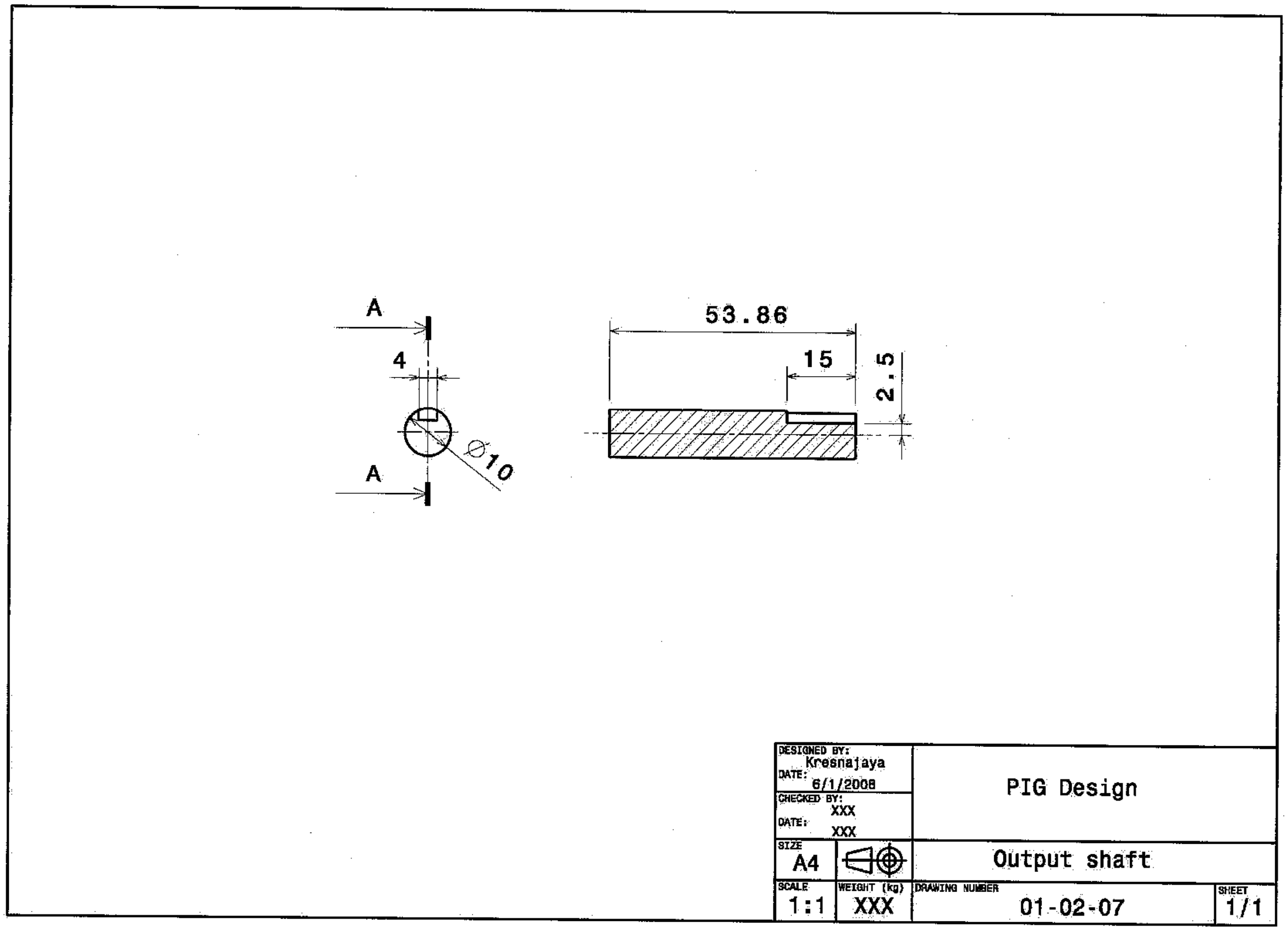
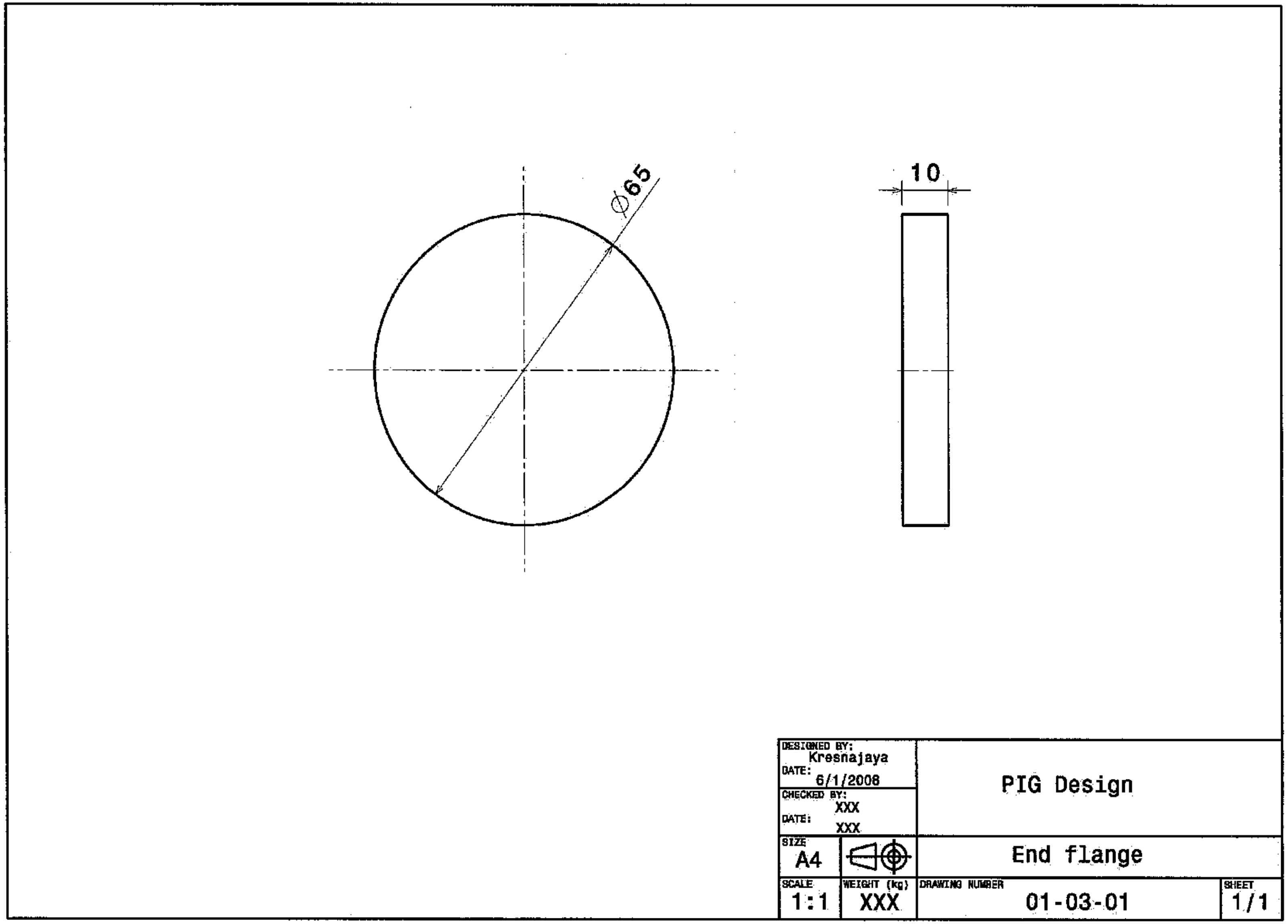
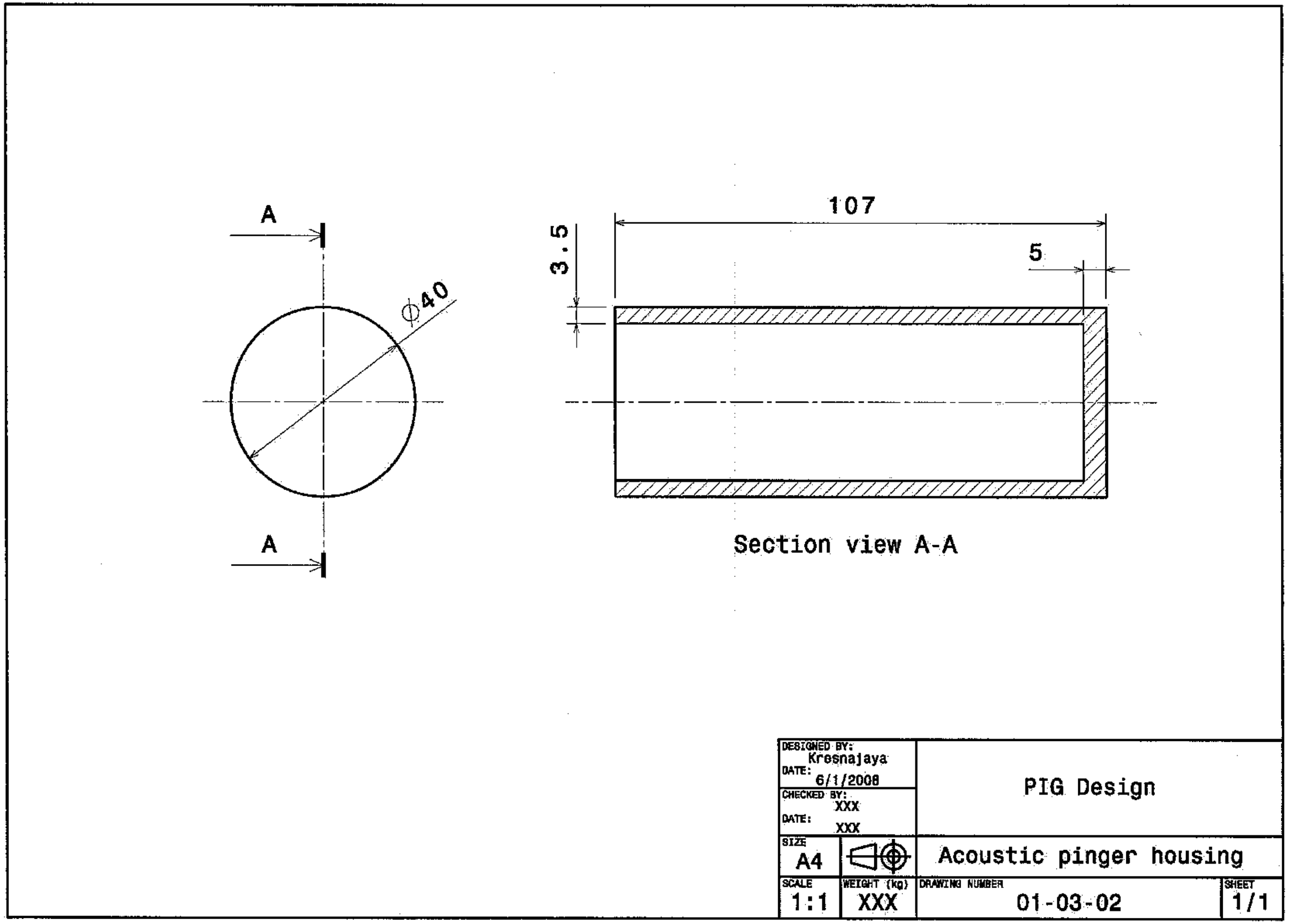
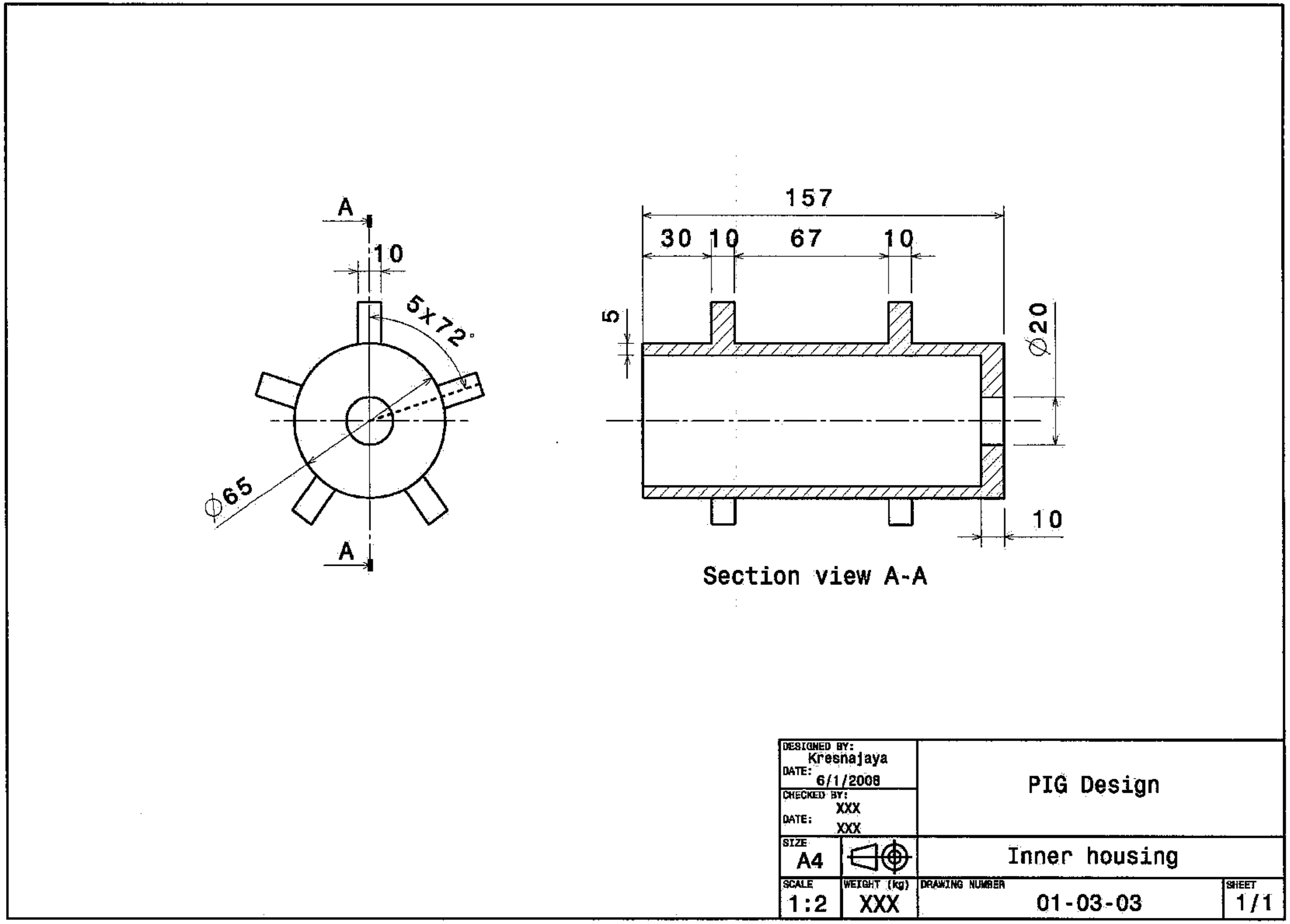
SCALE 1:2	WEIGHT (kg) XXX	DRAWING NUMBER 01-02-06	SHEET 1/1

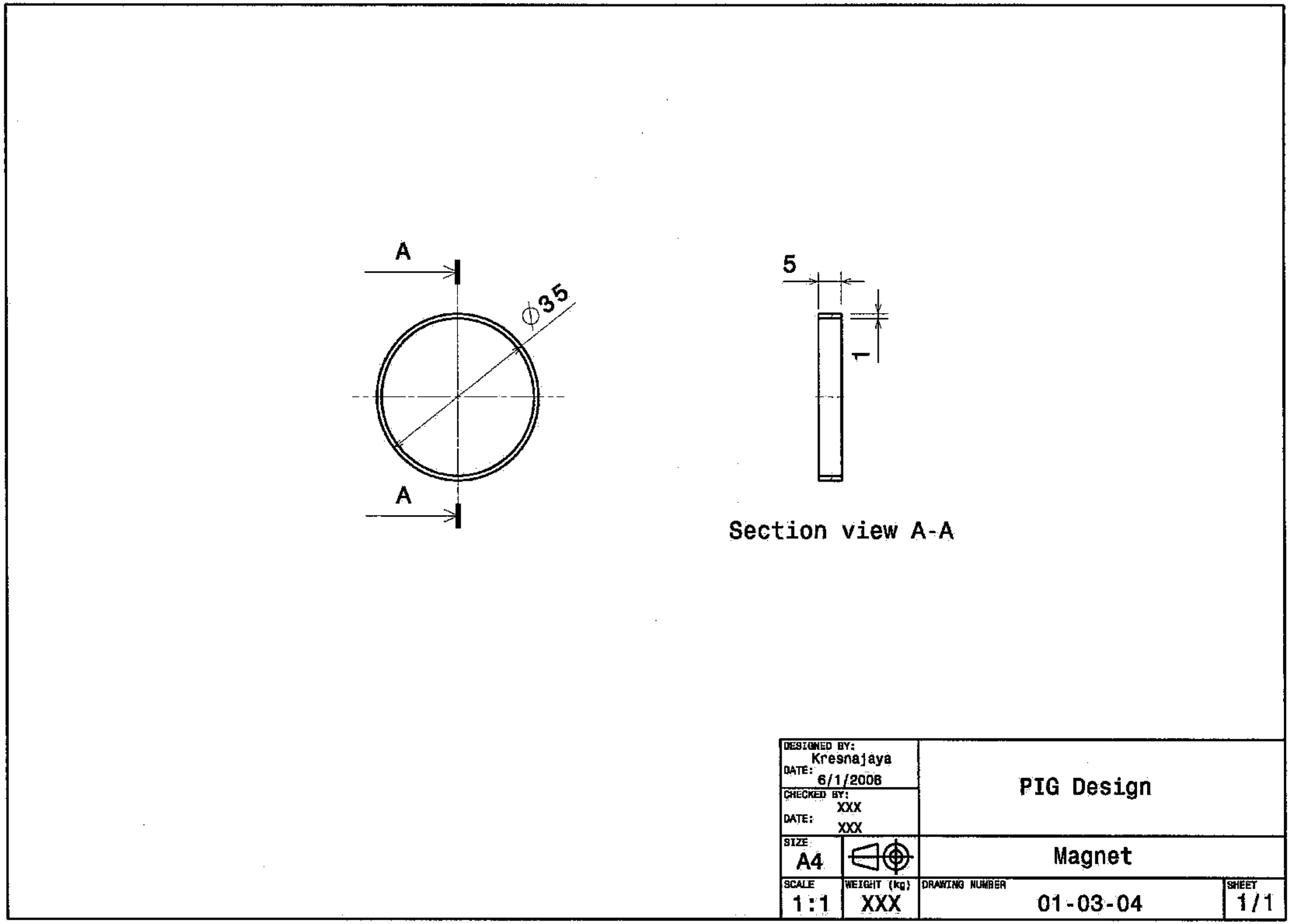

A
4
A
Ø10
53.86
15
2.5
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
SIZE
A4
PIG Design
Output shaft
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-02-07
SHEET
1/1

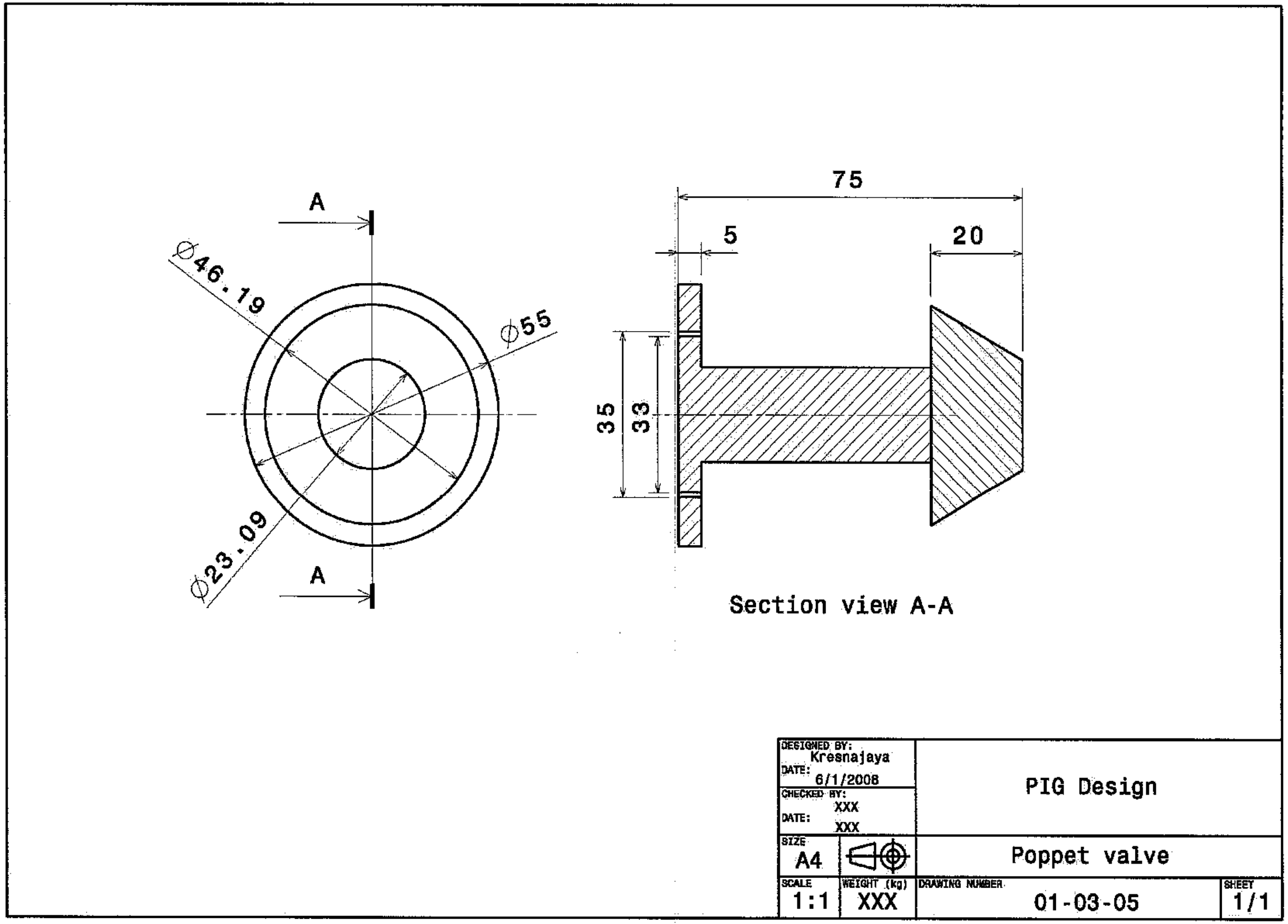


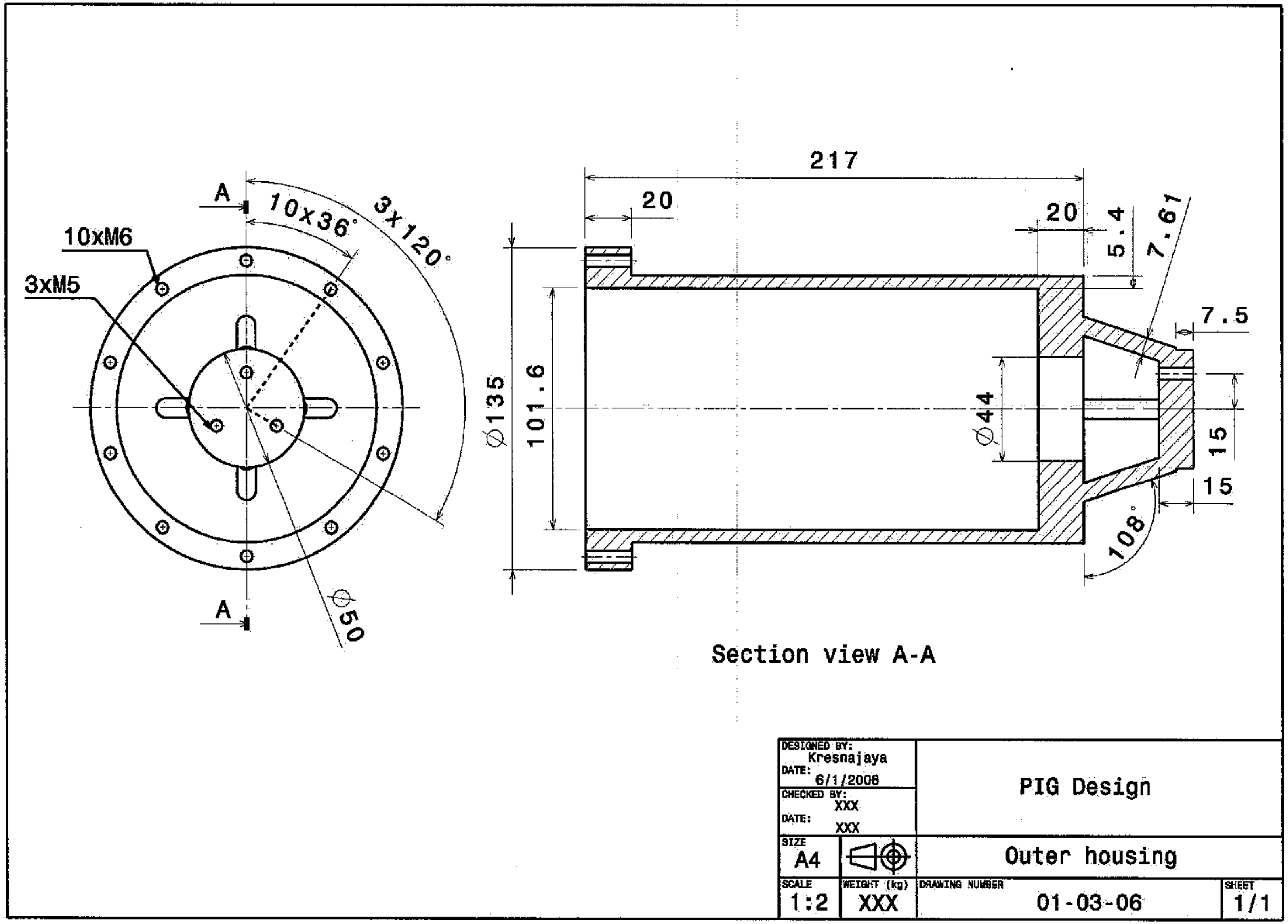
Ø65
10
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
End flange
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-03-01
SHEET
1/1

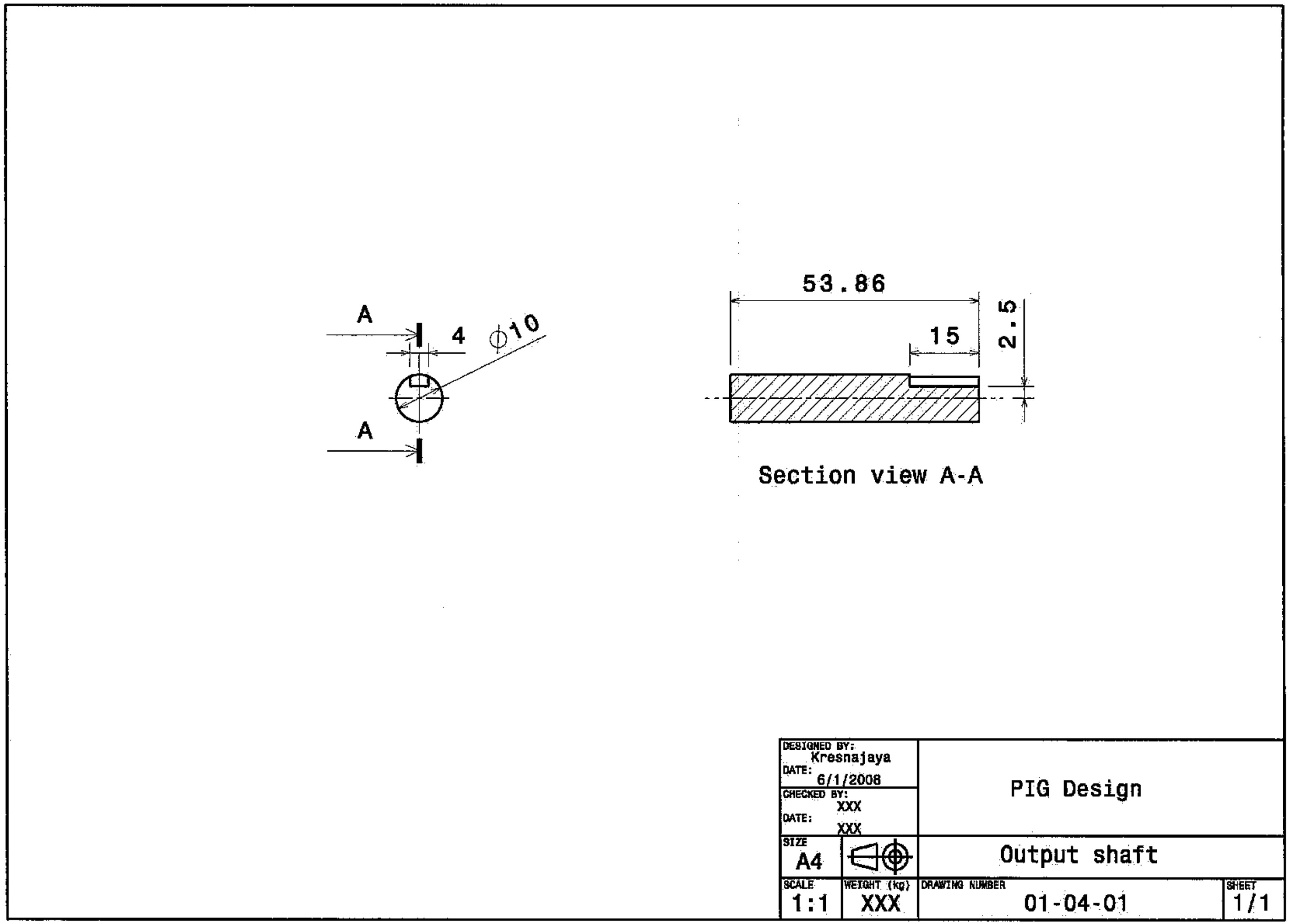

A
A
φ40
107
3.5
5
Section view A-A
DESIGNED BY:
Kresnajaya
DATE: 6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Acoustic pinger housing
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-03-02
SHEET
1/1

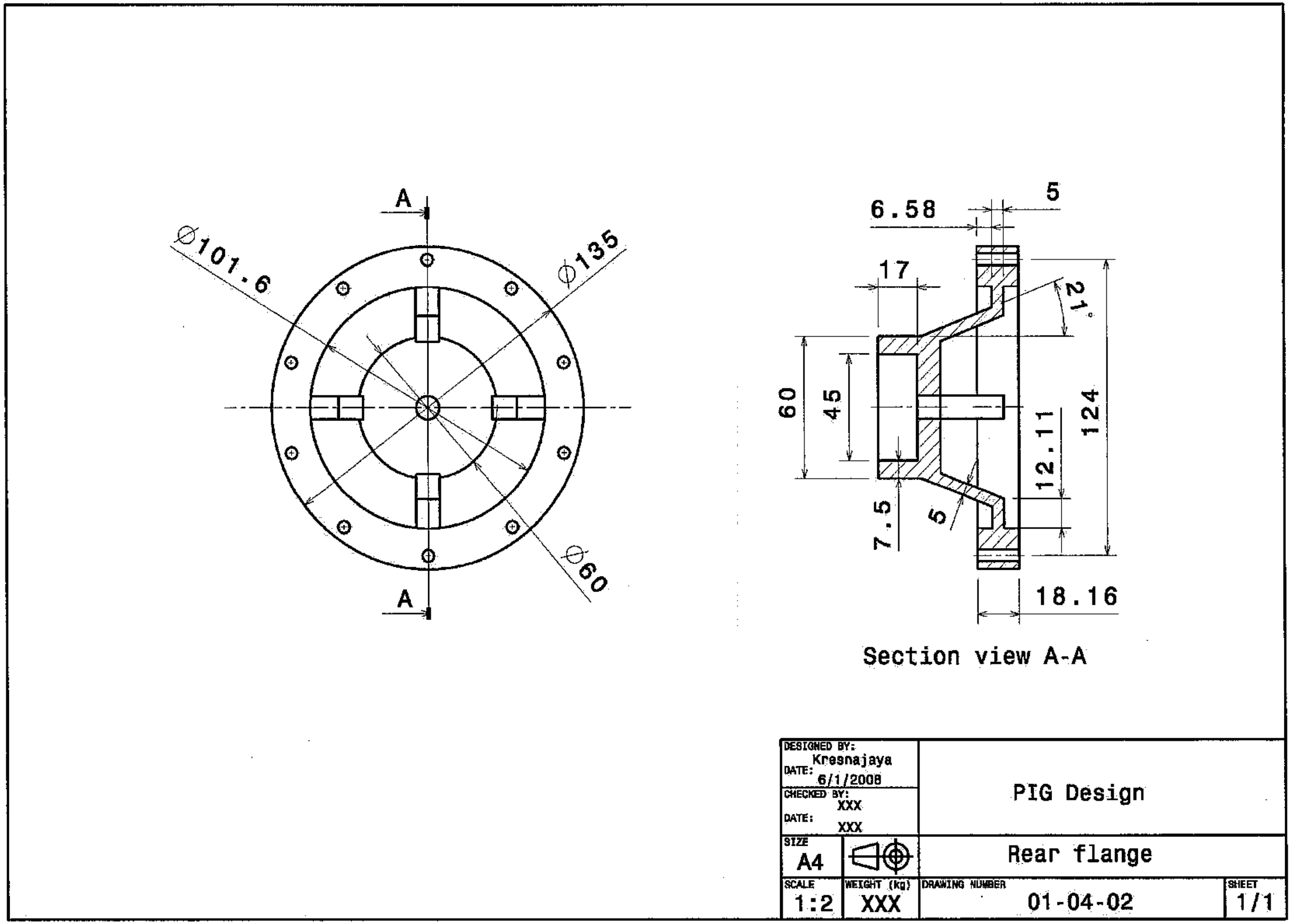

A
10
5x72°
ϕ65
A
157
30
10
67
10
5
ϕ20
10
Section view A-A
DESIGNED BY: Kresnajaya
DATE: 6/1/2008
CHECKED BY: XXX
DATE: XXX
PIG Design
SIZE A4
Inner housing
SCALE 1:2
WEIGHT (kg) XXX
DRAWING NUMBER 01-03-03
SHEET 1/1

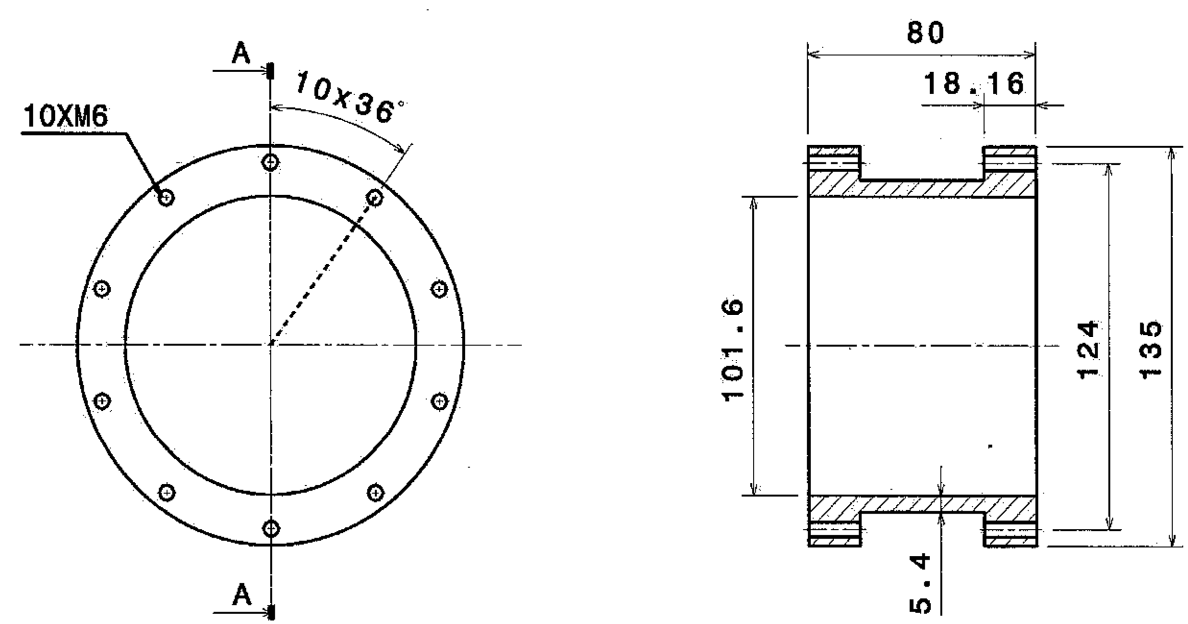

A
A
⌀35
5
1
Section view A-A
DESIGNED BY:
Kresnajaya
DATE:
6/1/2006
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Magnet
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-03-04
SHEET
1/1


A
A
Ø46.19
Ø55
Ø23.09
75
5
20
35
33
Section view A-A
DESIGNED BY:
Kresnajaya
DATE: 6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Poppet valve
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-03-05
SHEET
1/1

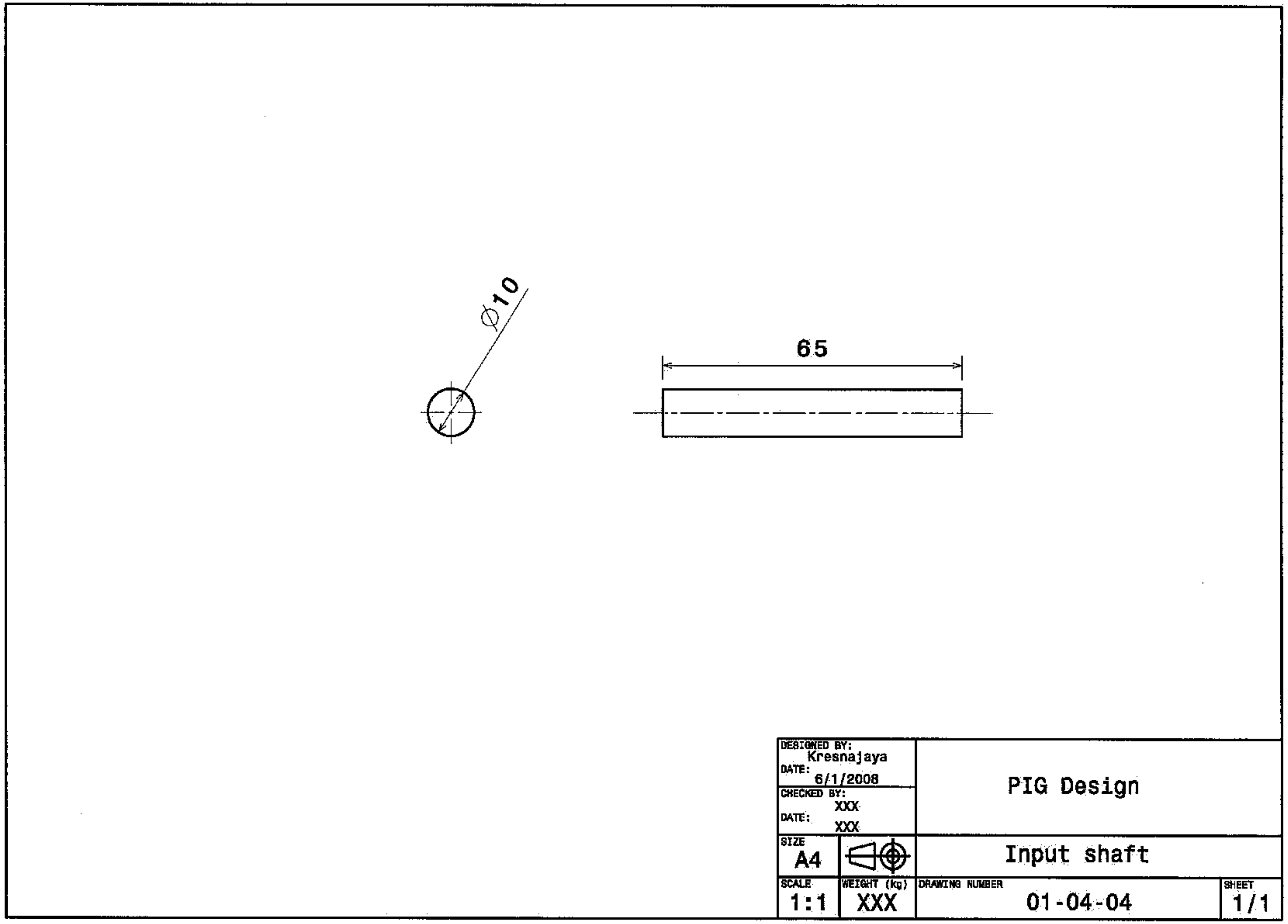

10xM6
3xM5
A
A
10x36°
3x120°
⌀50
⌀135
101.6
217
20
20
5.4
7.61
7.5
15
15
108°
⌀44
Section view A-A
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Outer housing
SCALE
1:2
WEIGHT (kg)
XXX
DRAWING NUMBER
01-03-06
SHEET
1/1


A
4
ϕ10
A
53.86
15
2.5
Section view A-A
DESIGNED BY: Kresnajaya
DATE: 6/1/2008
CHECKED BY: XXX
DATE: XXX
PIG Design
SIZE A4
Output shaft
SCALE 1:1
WEIGHT (kg) XXX
DRAWING NUMBER 01-04-01
SHEET 1/1

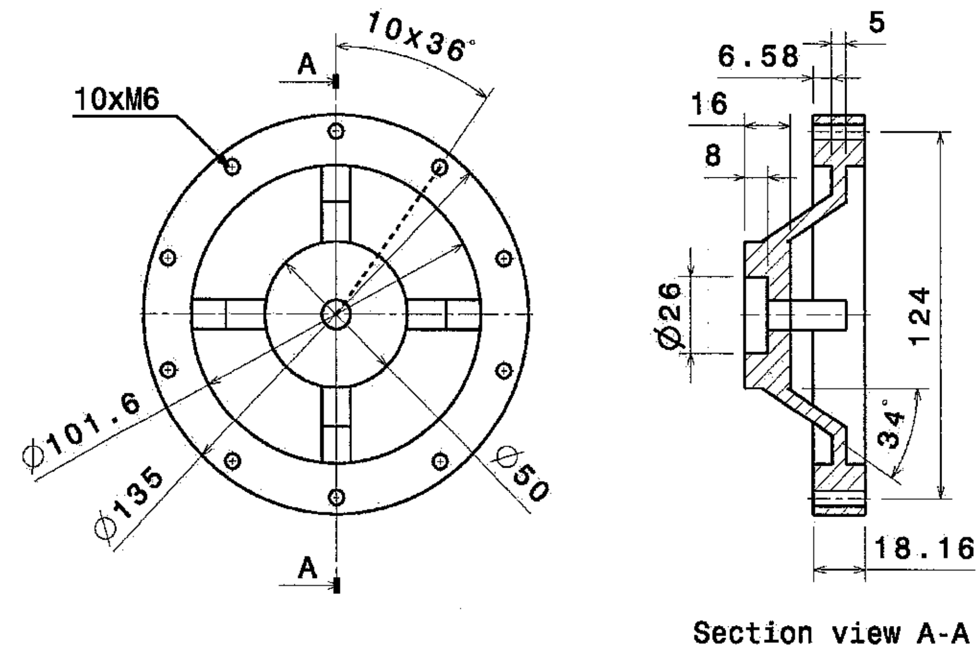

A
A
Ø101.6
Ø135
Ø60
6.58
5
17
21°
60
45
124
12.11
7.5
5
18.16
Section view A-A
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
SIZE
A4
SCALE
1:2
WEIGHT (kg)
XXX
PIG Design
Rear flange
DRAWING NUMBER
01-04-02
SHEET
1/1



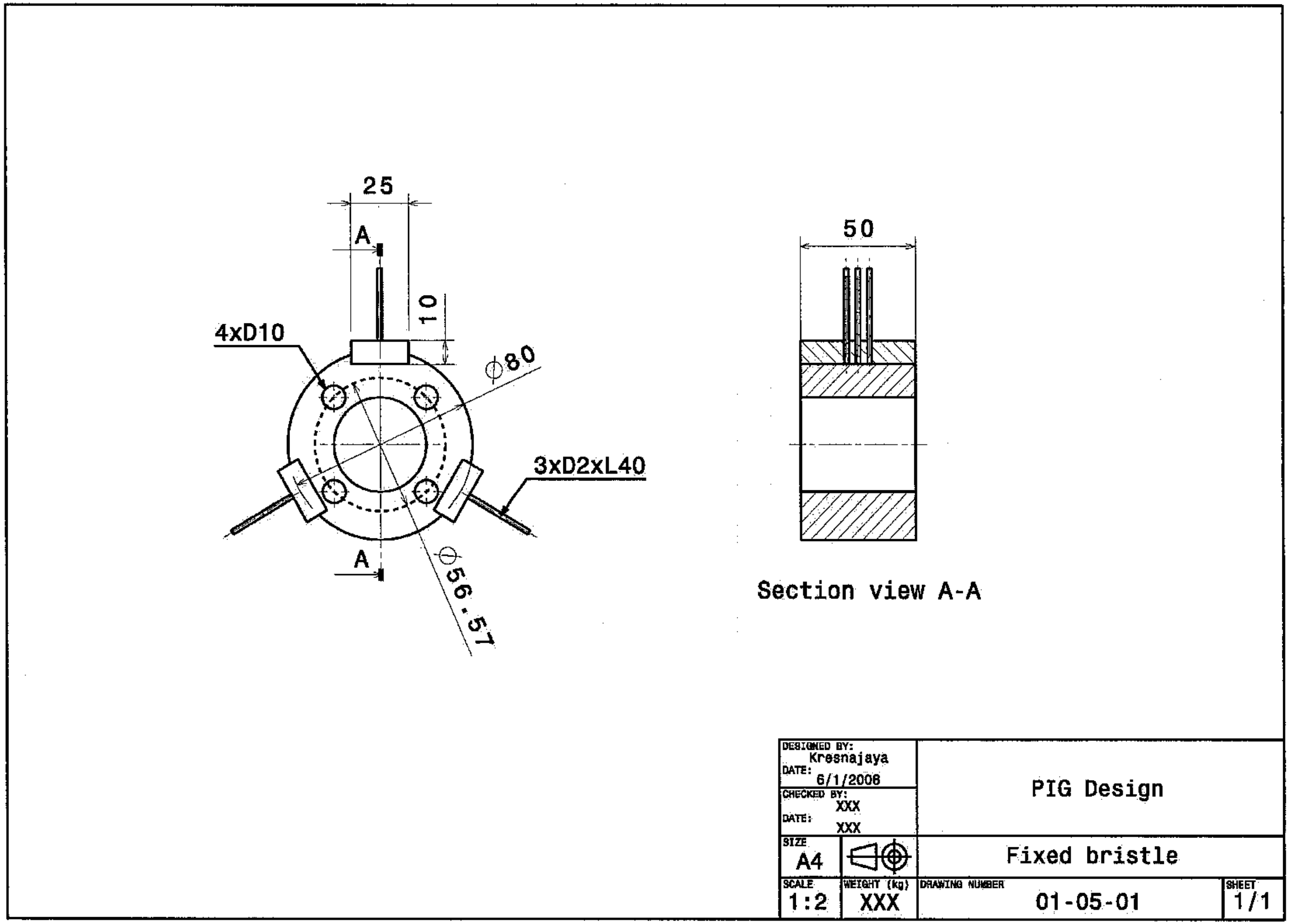
DESIGNED BY: Kresnajaya DATE: 6/1/2008	PIG Design	
CHECKED BY: XXX DATE: XXX		
SIZE A4	Housing	
SCALE 1:2 / WEIGHT (kg) XXX	DRAWING NUMBER 01-04-03	SHEET 1/1

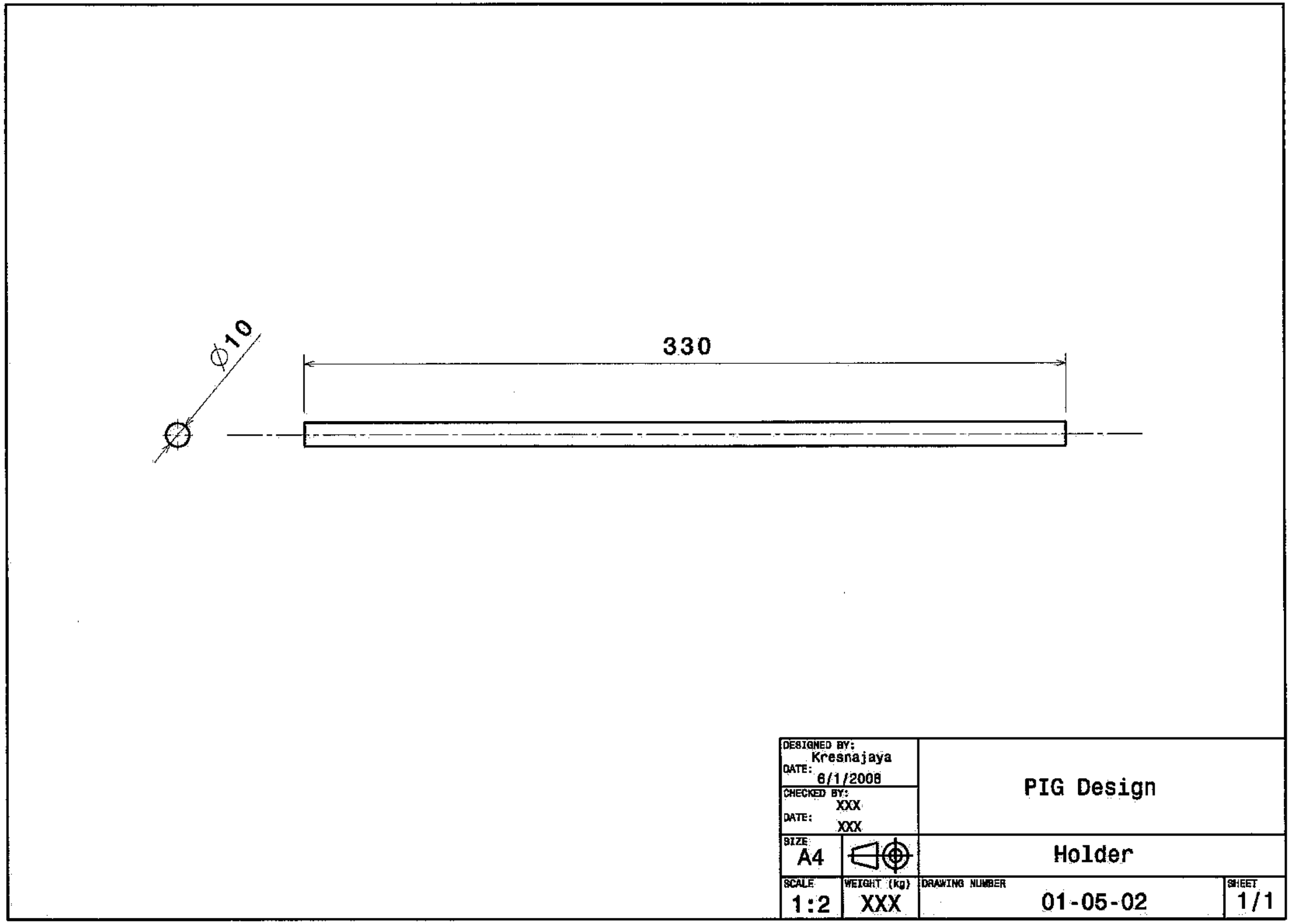


Ø10
65
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Input shaft
SCALE
1:1
WEIGHT (kg)
XXX
DRAWING NUMBER
01-04-04
SHEET
1/1

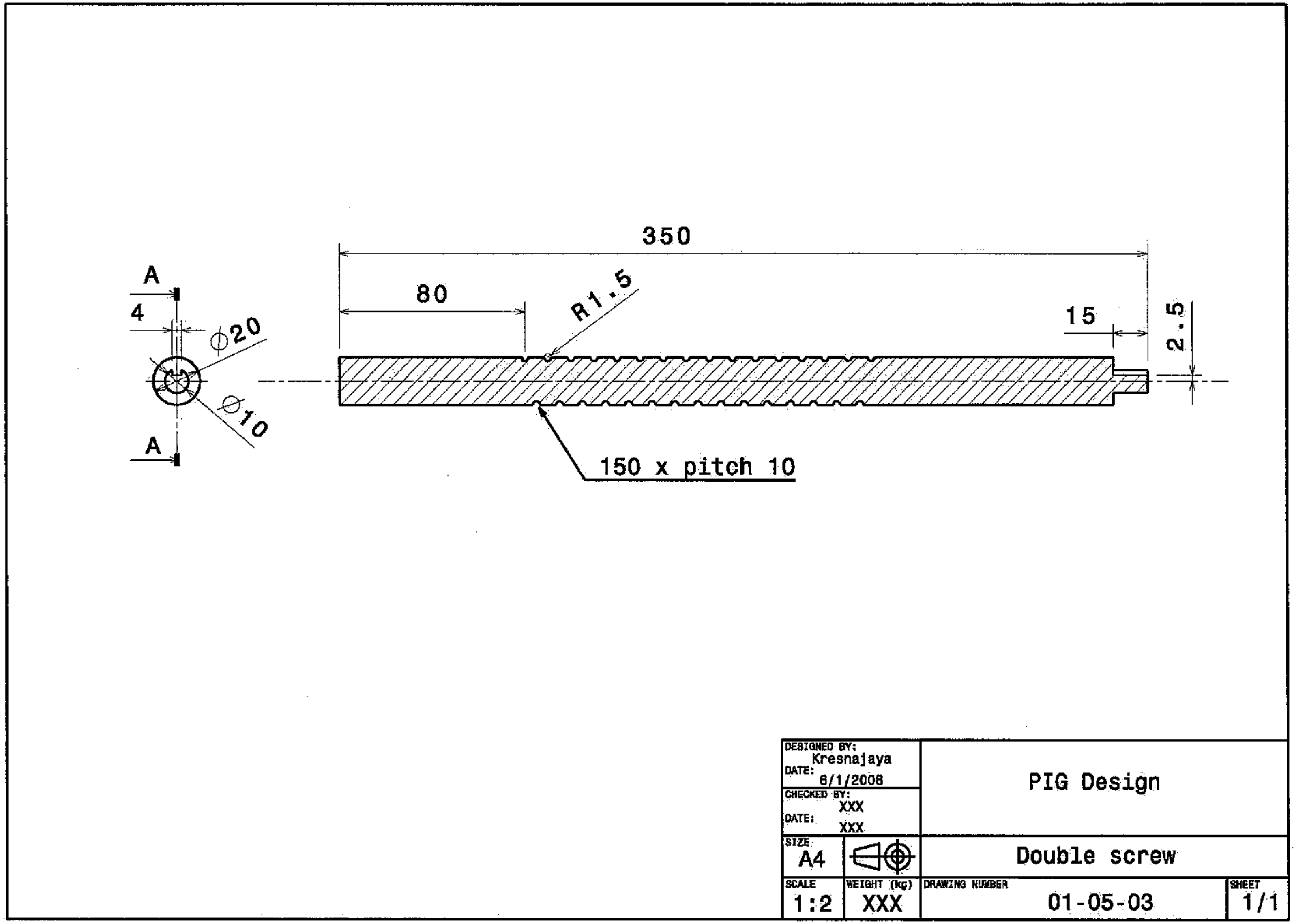


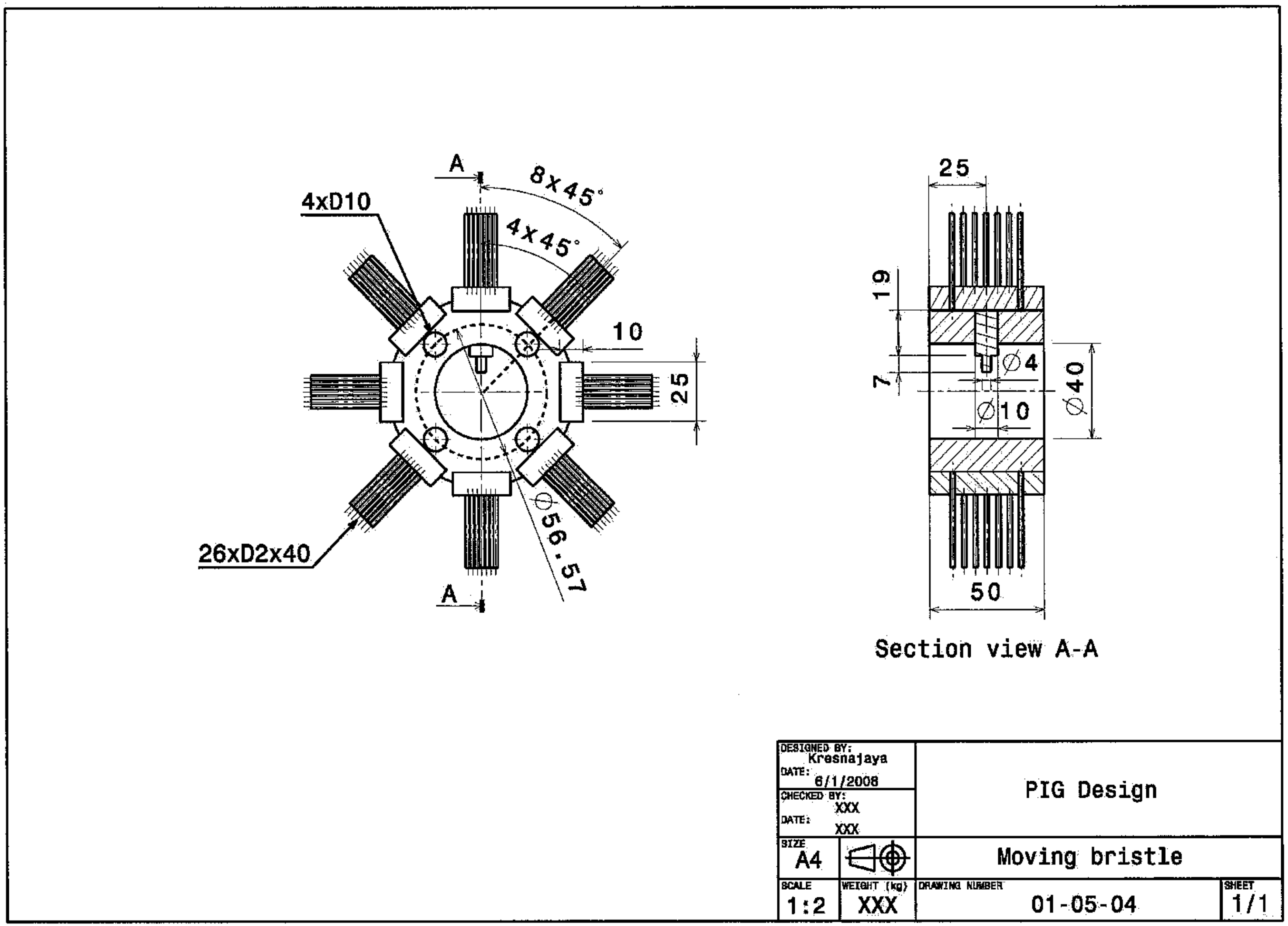
DESIGNED BY: Kresnajaya DATE: 6/1/2008		PIG Design	
CHECKED BY: XXX DATE: XXX			
SIZE A4		Front flange	
SCALE 1:2	WEIGHT (kg) XXX	DRAWING NUMBER 01-04-05	SHEET 1/1


25
A
10
4xD10
⌀80
3xD2xL40
A
⌀56.57
50
Section view A-A
DESIGNED BY: Kresnajaya
DATE: 6/1/2006
CHECKED BY: XXX
DATE: XXX
PIG Design
SIZE A4
Fixed bristle
SCALE 1:2
WEIGHT (kg) XXX
DRAWING NUMBER 01-05-01
SHEET 1/1



Ø10
330
DESIGNED BY:
Kresnajaya
DATE:
6/1/2008
CHECKED BY:
XXX
DATE:
XXX
PIG Design
SIZE
A4
Holder
SCALE
1:2
WEIGHT (kg)
XXX
DRAWING NUMBER
01-05-02
SHEET
1/1


350
80
R1.5
15
2.5
A
4
Ø20
Ø10
A
150 x pitch 10
DESIGNED BY: Kresnajaya
DATE: 6/1/2008
CHECKED BY: XXX
DATE: XXX
PIG Design
SIZE A4
Double screw
SCALE 1:2
WEIGHT (kg) XXX
DRAWING NUMBER 01-05-03
SHEET 1/1


4xD10
A
8x45°
4x45°
10
25
Ø56.57
26xD2x40
A
25
19
7
Ø4
Ø10
Ø40
50
Section view A-A
DESIGNED BY: Kresnajaya
DATE: 6/1/2008
CHECKED BY: XXX
DATE: XXX
PIG Design
SIZE A4
Moving bristle
SCALE 1:2
WEIGHT (kg) XXX
DRAWING NUMBER 01-05-04
SHEET 1/1