Design and Prototyping of Centrifugal Pump Impeller to be used as Water Injection Pump for Hydrocarbon Artificial Lift.

by

Mohd Radzi Bin Mohd Anua

Dissertation submitted in partial fulfillment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

____

(Dr. Ahmad Majdi Abd. Rani)

UNIVERSITI TEKNOLOGI PETRONAS
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January 2006

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHD RADZI BIN MOHD ANUA

ABSTRACT

Execution of maintenance activities for mechanical equipment is essential in order to preserve and enhance plant and equipment reliability. It is common especially during corrective and preventive maintenance activities to replace defective or to-be defective components. Typically the replacement components are procured through the original equipment manufacturer (OEM). However, due to the long lead-time delivery imposed by the OEM, an alternative means of procuring spares with shorter lead-time delivery should be established, in order to reduce the downtime of critical equipment should extreme cases such as repetitive failure of certain components occur. This project was carried out with such objective by studying the feasibility of locally designing and manufacturing mechanical components to reduce shipping time, and adopting rapid prototyping technology into spare parts manufacturing, to reduce manufacturing time. A centrifugal pump impeller was chosen to be designed and manufactured. The data of operating requirements of the particular pump was acquired from an existing water injection module in an actual oil field. The project started with impeller numerical design, establishing the geometry in numerical terms. The methodology was then preceded by impeller modeling, resulting in a virtual three dimensional representation of the designed impeller. The virtual model was then rapidly transformed into a solid wax prototype using rapid prototyping technology. The wax prototype was then directly used as a pattern for investment casting process, resulting in solid metallic model of the impeller. The whole processes duration and costs was recorded. A costs-time benefit analysis was carried out in the latter part of the project, to study the feasibility of the approaches adopted in this project, and to compare the its practicality to that of the conventional spare parts procurement through the OEM, in terms of costs and led-time delivery. It was concluded from the analysis, that this project dramatically reduced the lead-time delivery, and radically reduced the product’s costs. In conclusion, the approaches adopted in this project (locally designing, locally manufacturing, and introducing rapid prototyping into spare parts manufacturing) are verified to be very feasible and favorable as far as the lead-time delivery and costs are concerned. This project also adds to plant and equipment reliability by reducing equipment downtime thus enabling continuation of production and plant operation.

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This project is dedicated to my family, who has always been there for me.

Mohd Radzi Mohd Anua

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ABBREVIATIONS AND NOMENCLATURES

ΔP	*Pressure difference*
2D	*Two Dimensional*
3D	*Three Dimensional*
API	*American Petroleum Institute*
AutoCAD	*Autodesk® AutoCAD 2005®*
avg	*Average*
B1	*Blade angle at outer radius of impeller eye*
BEP	*Best Efficiency Point on a Pump Curve*
CAD	*Computer Aided Design*
CAM	*Computer Aided Manufacturing*
CM	*Corrective Maintenance*
Cm1	*average meridianal velocity at blade inlet in ft/sec*
CNC	*Computerized Numerical Control*
Eff.	*Efficiency*
FLM	*Fused Layer Modeling*
GPM	*Gallon per Minute*
H	*Head in feet*
Hn-stg	*Head for a stage-n in feet*
Hz	*Hertz*
Hz	*Hertz*
LCVD	*Laser Chemical Vapor Deposition*
LLM	*Layer Laminate Manufacturing*
LS	*Laser Sintering*
LS	*Laser Sintering*
MPa	*Mega Pascal*
MRO	*Maintenance, Repair, and Operating Materials*
n	*Impeller speed in rpm*
NPSH	*Net Positive Suction Head*
NPSHA	*Net Positive Suction Head Available*
NPSHR	*Net Positivive Suction Head required*
Ns	*Specific speed*
OEM	*Original Equipment Manufacturer*

PM	*Preventive Maintenance*
Ps1	*Cm1 divided by factor in determining inlet blade angle*
psi	*Pound per Square Inch*
Q	*Capacity in GPM*
R1	*Factor in determining B1*
RP	*Rapid Prototyping*
SG	*Specific Gravity*
SL	*Stereolithography*
Ut	*Peripheral velocity of impeller blade in ft/sec*
WIP	*Work-In-Process Inventory*
η	*Efficiency*

1 INTRODUCTION

In utilizing the thinking capability the God has awarded us humans, we came to value knowledge, and in addition made use of it to improve our living condition. Most of the positive implication of this scenario resulted from our capability to design and manufacture tools and equipments, which in turn will be used to manufacture more advanced tools and equipments, aside from other products.

The age of industrial revolution marked a new dawn in the history of human civilization. Consumer and industrial products started to be mass produced, and in doing so mechanical equipments were employed in various industrial facilities. In the modern world as of now, diverse types of plants have been built all over the world to cater various human needs for daily consumption, such as energy, food, communication, consumer products and etc.

It is safe to state that all these industrial plants and facilities are made up of a series of equipments, tailored to work together to produce a common product. One very important category of these equipments is mechanical equipment. Mechanical equipment can be further divided into two major divisions: static machinery (non-rotating equipment such as vessels and cranes) and rotating machinery (equipment with rotating components such as engines and pumps).

In making sure the plant works, it is of utmost importance to make sure its equipments work. Many types of maintenance activities for mechanical equipments have been studied, and when proved reliable, have been adopted in plant facilities to make sure the industry could have a trouble-free equipment operation. Nevertheless, it is inevitable to replace worn and damaged parts of mechanical equipment, especially its rotating subordinates, where components are continuously rubbing and being subjected to dynamic forces during operation.

Replacement of mechanical components of rotating equipment is a common practice especially during corrective maintenance (CM) activities and several preventive maintenance (PM) activities. Therefore it is vital to have spares of mechanical components of rotating equipments to make sure the plant keeps operating. Up to now, plant operators have always depended on Original Equipment Manufacturer (OEM) in procuring spare parts for their mechanical equipments. This approach is advantageous in some ways, because as the original manufacturer, OEM should be able to fabricate the model quality of their components. OEM will also be able to assure the highest quality and reliability of the products they deliver. When newer equipment is concerned, purchasing original parts from OEM is essential in order to avoid violation of warranty, which could be very expensive especially in the first few stages of equipment operation.

This project investigates the alternative way of procuring (and manufacturing) mechanical spare parts for industrial usage. Centrifugal pump impeller is used as the subject of study, bearing the general term of “mechanical components” in this context. This is because centrifugal pump is widely used in any facility, be it small-, medium-, or large-scaled industry. Centrifugal pump is used, among others, in petroleum production facilities, chemical processing facilities, automotive industry, consumer product development facilities and etc. Consequently, centrifugal pump impeller is eligible to reflect the whole context of mechanical spare parts, as far as spare parts acquisition, manufacturing, fabrication, and utilization is concerned.

For the particular case of the study conducted within this project, the pump impeller designed and manufactured is intended for water injection purpose in a petroleum water injection facility. The concept of water injection has been widely used in developed and matured oil and gas fields bearing water drive reservoirs, to enhance oil and gas recovery.

1.1 Problem Statement

1.1.1 Long-lead Replacement Spares

When discussing issues concerning spare parts management, it is close to impossible to avoid arguments regarding lead-time delivery. The author did his internship in a petroleum production facility as a rotating engineer under maintenance engineering department. Based on his experience, most of the replacement mechanical components require more than three months of lead-time delivery, if they were to be procured through OEM.

The plant facility that the author was attached to had aged more than 20 years old, and so do most of its equipments. These ageing models of equipment are generally termed as inactive or obsolete models, where they are no longer mass produced by the OEM and manufacturing of such models’ components were limited or only initiated upon order by the customer.

Somehow this event has possibility to lead to discontinuity of plant operation. Although it is highly likely that the maintenance department had formulated good scheduling of spare parts purchasing, there is still room for unexpected incidents, such as loss of stocked spares due to natural cause (deterioration) or even assignable causes. And when such incidents happen, procurement through OEM could no longer be considered the first option, and a more rapid way of procuring spares should be mobilized.

Based on his observation during internship attachment, the author had identified two major causes that could contribute to long lead-time delivery of replacement mechanical components, which are:

i. Little or no local manufacturer for mechanical equipment.
ii. Obsolete or inactive models have possibilities of deterioration or loss of molds.

The author discovered that out of 50 multistage horizontal centrifugal pumps used in his internship facility, exactly none of them was locally manufactured. Somehow this event could contribute to the long lead-time delivery, for significant amount of time had to be allocated for the items' shipping purposes.

For the case of inactive or obsolete models of equipments, deterioration of the components' molds due to corrosion or other natural causes is a possibility, for they had aged significantly. On top of it, continuous design of more recent models would also mean that the OEM would have to allocate an extensive warehousing facility to inventory all of their molds. Subsequent to this, loss of molds during inventory could occur unless tight supervision is implemented and superior inventory management is adapted to the facility.

1.1.2 Possibility of Repetitive Failure

In the context of rotating machinery maintenance management, spare parts are usually divided into three major categories: preventive maintenance spare parts, critical spare parts, and insurance spare parts.

Preventive maintenance spare parts are ordered regularly, and often in a safe size of batch quantity, for they are regularly consumed during each preventive maintenance activities.

Critical spare parts are components that are not regularly replaced during any preventive maintenance activities, they are costly, but somehow will need to be replaced eventually. Critical spare parts are only replaced in case of failure and often, these types of spares can be refurbished if the damage is minor. If the plant has identical equipments, usually a common set of critical spare parts will be shared by every group of two or three of those equipments. The ordering of new set/unit of critical spare parts will only be initiated once the old set/unit has been consumed.

Insurance spare parts are critical components which are essential for the operation of the system in which they serve, and yet have a significant probability of not needing replacement during the whole lifetime of the system. Insurance spare parts will only be replaced if and only if there is a failure. They are very costly, thus if the plant has identical equipments, usually all the identical equipments will share a common set of insurance spares. The ordering of new set/unit of insurance spare parts will only be initiated once the old set/unit has been consumed.

A repetitive failure, if so happens, will not give much impact if it happened on preventive maintenance spare parts, for they will usually have extra parts for emergency purposes. Nevertheless, for the case of critical and insurance spare parts, no one can give a hundred percent assurance that a critical or insurance spare parts replaced today will not fail tomorrow, or an insurance spare parts replaced on Equipment A today will not be needed to replace the same component on its identical counterpart, Equipment B, tomorrow.

Therefore on such extreme occasions, spare parts procurement through OEM is no longer favorable, especially on high criticality equipments. Just one day of downtime of an 18,000 bopd crude oil transfer pump for instance, could force the host company to incur loss of revenue of more than RM 5 million. Waiting more than six months to procure the pump shaft through OEM might sound absurd. Therefore a justified way has to be studied to establish a more rapid way of procuring spares, and in the same time providing alternative to conventional spare parts procurement, preferably at a way less cost.

1.2 Objective and Scope of Study

This project has several objectives, as illustrated below:

1. To locally design a centrifugal pump impeller.
    a. To verify that mechanical design of centrifugal pump can be locally.

   b. To study the effects of locally designing mechanical components on the lead-time delivery of replacement spares.
2. To adopt rapid prototyping technology into mechanical equipment spare parts manufacturing.
   a. To verify that rapid prototyping can be adopted in the process of manufacturing mechanical component replacement spares.
   b. To conjoin rapid prototyping technology into conventional means of manufacturing mechanical spare parts, casting.
   c. To study the advantages as well as detrimental effects in embedding rapid prototyping technology into mechanical spare parts manufacturing.
3. To come up with a costs-time benefit analysis, comparing the costs and lead-time delivery of replacement component using the methods approached in this project with conventional means of acquiring spares (through OEM).
   a. To investigate the feasibility of the procedures adopted in this project to procure spare parts of mechanical equipments.
   b. To compare the practicality of the approaches implemented in this project to procurement of spare parts with conventional means (through Original Equipment Manufacturer [OEM]) in terms of costs.
   c. To compare the practicality of the approaches implemented in this project to procurement of spare parts with conventional means (through Original Equipment Manufacturer) in terms of lead-time delivery.
   d. To arrive to a conclusion as to which spare parts procurement procedure out of the two (the procedures adopted in this project and procurement through OEM) is more beneficial as far as costs and lead-time delivery are concerned.

The objectives listed above is to point to a common goal, that is to establish an alternative means of procuring replacement mechanical components with preferably LESS costs and lead-time delivery.

The scope of study employed throughout this project is as follows:

1. Data acquisition.
2. Numerical design of centrifugal pump impeller.
3. Three-dimensional virtual modeling of the impeller using CAD software.
4. Solid wax model development of the impeller using rapid prototyping technology.

5. Solid metallic model development of the impeller using investment casting technology.
6. Calculation and graphical representation for comparison of costs and lead-time delivery of this project with respect to conventional means of procuring replacement parts.

2 LITERATURE REVIEW

2.1 Water Injection Module in Petroleum Production Facilities

Water injection or waterflooding contributes significantly to current production of hydrocarbon. In some parts of the world, water injection is the most widely used oil recovery method [1]. The concept of using water as oil flow driver within the formulation was discovered as early as 1880 [2].

Water injection pump is the key component in the water injection modules. Many types of pumps are utilized to extend the life of a producing field and to enhance its oil and gas recovery [3]. In particular cases of which the injection capacity requirements exceed 10,000 bpd, centrifugal pumps are the most preferred types [3].

2.2 Centrifugal Pumps Design and Application

Centrifugal pumps increase the pressure of liquid through the concept of kinetics [4], [5]. In increasing the pressure of a particular fluid, a centrifugal pump internally imparts velocity into the fluid through the impeller(s). This kinetically energized fluid will then be channeled into the diffuser (or volute) where it will be converted to hydraulic pressure [5].

In industrial practices centrifugal pumps are the most widely used type of pumps [5], [6]. According to Kutz (2006)

> In practice the great majority of pumps are centrifugal. They are relatively inexpensive and better able to handle liquids containing inhomogeneities such as particulate matter. They are available at much larger volumetric throughputs than other types of pumps.(p.719) [5].

2.3 Centrifugal Pump Impeller

According to Karassik et al (2000), the function of the impeller is to “convert torque applied to the pump shaft to pressure and kinetic energy in the pumped liquid” (p.62) [7]. The impeller for a centrifugal type could be of many configurations, and generally three of the most widely used types are:

i. Single suction open impeller.
ii. Single suction semi-open impeller.
iii. Single suction closed impeller.

All the three types of impellers are illustrated in Figure 2.1:

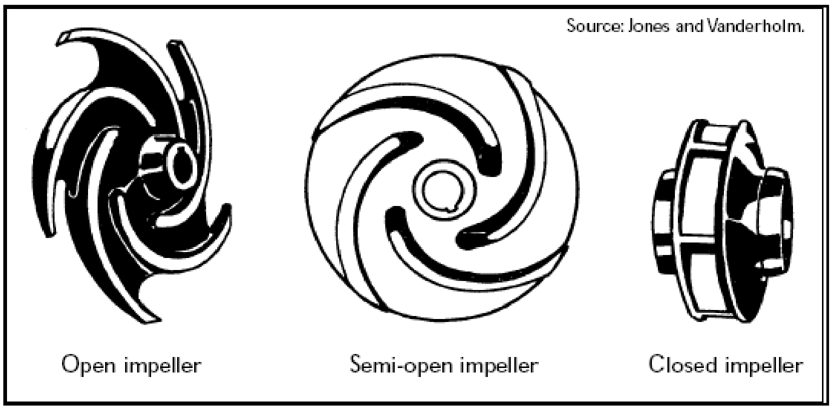

Figure 2.1: Common Impeller Types for Centrifugal Pumps [8]

Although there are various other types of impellers for centrifugal pumps used in the industry such as the double suction types, mixed flow types, Francis-vane types, axial flow types, etc., the author will not address all the supplementary information of those types of impellers, as they have no relevance to this project.

As stated by API Standard 610, all centrifugal pumps to be used in petroleum, heavy duty chemical and gas industry must be of fully enclosed types [9]. Thus, the impeller to be designed will be of closed type impeller.

Following this paragraph is the nomenclature of a typical single suction closed type impeller (Figure 2.2):

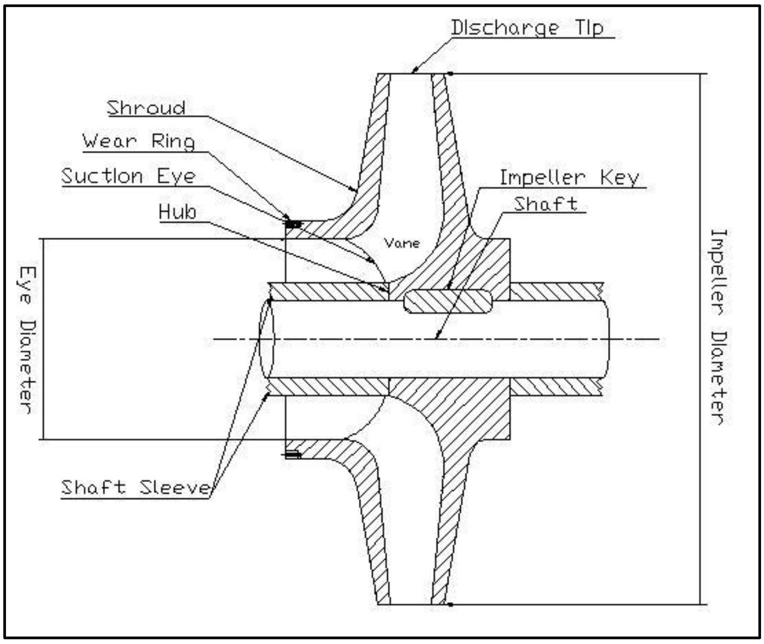

Figure 2.2: Nomenclature of a Typical Single Suction Closed Type Impeller

2.3.1 Impeller Key

The process of mounting and retention of the impeller to the shaft is very important, and depends very much on the power, speed, and material of the impeller. Usually the impellers are centered with a cylindrical slide fit and driven with impeller key. Small low-cost pumps have the impeller threaded into the shaft and locked against a shoulder. In the case of high rotative speed, usually the pump is fitted with taper mounting or shrink fits to achieve accurate centering to cater the dynamic balance requirements. For high power or severe service requirements, medium sized pumps typically employ a tapered fit, and larger pumps use a bolted flange [7].

This particular project will comply with the standards established by the API, and utilize the usage of impeller key for the shaft to drive the impeller.

2.3.2 Impeller Wear Rings

The impeller wear rings provide economical running operation to the pump. After a justifiable period of pump operation, the running clearance between the impeller and the pump casing will increase due to wear and tear between the duo. For an impeller not fitted with a wearing ring, the operator of the pump can restore the original clearance by:

i. Building up the worn surfaces by welding, metal coating, spraying, etc., or [7]
ii. Purchasing a new part. [7].

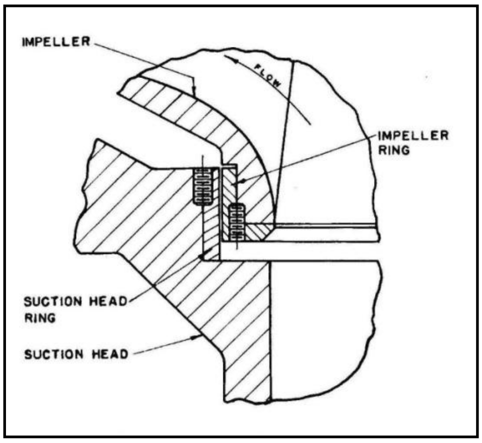

Figure 2.3: Renewable Wear Rings Fitted with Threaded Dowels [7]

The fabrication of renewable wear rings (as illustrated in Figure 2.3) to the impeller eliminates this problem, and provides an economical way to restore the original running clearance. The wear rings can be renewed during planned preventive maintenance, or exchanged with new ones during any breakdown.

The renewable wear rings can be fitted to the impeller by various means, being locked with set screws, shrink fits, interference fits with pins, or slide fit with machine screws [7]. For this particular project, the wear rings will be locked by press fit with locking pins or threaded dowels (as specified by API Standard 610).

2.3.3 Shaft Sleeves

Shaft sleeves are incorporated into the shaft design for a variety of reasons. The most common reasons are:

i. To provide corrosion resistance for the shaft in corrosive environments [10].

ii. To provide wear surfaces against packing or seals that damage shaft [10].
iii. To axially position the impeller [10].
iv. To attach a metal bellows seal onto the shaft [10].

2.4 Pump Characteristics Curve

In designing a pump, the designer must first get hold of the pump characteristics curve. The pump characteristics curve summarizes all the important parameters to design a pump from scratch.

As dynamic pumps, centrifugal pumps are able to deliver any capacity from zero to a maximum depending upon the pump size, design, and suction conditions. The total head[1] developed by the pump, power required to drive it, as well as resulting efficiency will vary with capacity. The interrelations of all these parameters can be graphically summarized by drawing the pump characteristics curve as illustrated in Figure 2.4:

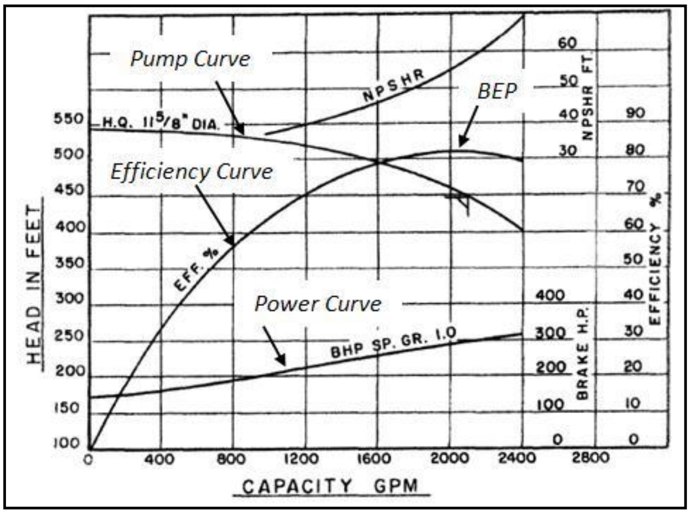

Figure 2.4: Pump Characteristics Curve [3]

Probably the most important point to be observed in the curve is the Best Efficiency Point (BEP) (as marked). The BEP points to the maximum efficiency of the operation of the pump, and correlates the best output (in terms of pressure, capacity, and power) the pump will be able to deliver for a particular unit of input. It is important to establish the BEP in order for the designer to gather these information:

[1] It is a common practice among pump manufacturers to use the term "head". Head is basically an alternative means of expressing the term "pressure rise". Fundamentally, if a pump is claimed to have static head of 3 ft, the pump should be able to lift the pumped fluid 3 ft above the centerline of the pump, against gravitational force.

- The head and capacity corresponding with BEP.
- The shut-off head value from head-capacity curve.

The shutoff head value is defined as the head rise from BEP (optimum correlations of capacity[2] and head) to zero capacity.

The pump curve is developed based on user's specifications. In the case of designing a water injection pump in petroleum industry, the characteristics of the water pumping needs will be calculated by reservoir engineers based on reservoir conditions [11]. Among other variables in determining the pumping pressures and flow rate are oil saturation, reservoir pressure, produced water-oil ratio, and many others. The pumping needs will be equated in the equation to determine basic properties of pumps, i.e. design pressures, temperatures, flow rates, etc.

2.5 Pump Specific Speed

In developing the pump curve, the pump designer need to first design the pump's specific speed. Karassik, Igor J. et al. (2000) defines specific speed as: "a non-dimensional index number which is *numerically* equal to the rotative speed at which an exact theoretical model centrifugal machine would have to operate in order to deliver one unit of capacity against one unit of total head" (p.437) [7].

It is very desirable for the designed pump to have specific speed in the range of 1000 to 3000, as those are the range of which it will have optimum efficiency [12].

2.6 Pump Shut-Off Head

Pump shut-off head is generally defined from BEP. To illustrate the definition of shutoff head, Figure 2.4 is referred. Based on the figure, when the pump is operating at BEP, the corresponding head of the pump curve is *450 ft*, and the capacity is *2,100 GPM*. The percentage head rise of the pump curve from BEP capacity to zero capacity is defined as the shut-off head.

[2] For this project, capacity will have the same definition as flow rate, and both terms will be used interchangeably inside this report.

2.7 Shaft Sizing

Shaft sizing is very critical as it involves designing the shaft to enable it to counter fatigue, taking into account the loads during starting, normal operation, as well as abnormal operation. The forces involves in operation of a pump shaft includes tension, compression, bending, and torsion. The stress produced on the shaft as a result of energy transmission from the driver is torsion. Thus the limiting value for shaft sizing depends on the maximum torsional stress. Because of the nature of the criticality of the high speed cyclic operation of the pump, obviously the maximum torsional stress is kept very low than the actual shear modulus, *G*, of the material, with a specific safety factor accounted [7],[3].

The values for nominal torsional stress for the design of centrifugal pump shaft as suggested by Karassik et al. (2000) are summarized in Table 2.1:

Table 2.1: Typical Torsional Stress of Selected Material for Shaft Design [7]

Shaft Material	*Typical Torsional Stress – Mpa (psi)*
Carbon Steel	48 (7,000)
Alloy Steel, Chrome Steel	55 (8,000)
316 Stainless Steel	35 (5,000)

2.8 Net Positive Suction Head Required

In pumping fluids, it is essential that the pressure of the liquid must not be reduced to the vapor pressure of the liquid at the corresponding temperature. The available energy that can be utilized to flow the liquid through the suction piping into the impeller is then defined as the total suction head less the vapor pressure of the liquid at the pumping temperature [7]. The Net Positive Suction Head Required (NPSHR) is therefore the required net positive suction head in order for the pump to operate at desirable condition.

2.9 Pumped Fluid

Centrifugal pumps are designed to specifically deliver a particular amount of head for a specific type of fluid. Because of varying density and viscosity of different fluids, the same pump will not deliver the same amount of head if subjected to different fluids. In any typical offshore water injection module, there will be two types of water injected into the reservoir: seawater or produced water (brine) from reservoir. Produced water generally contains much higher concentration of solids than seawater does [13]. Typical specific gravity of brine ranges from 1.02 to 1.19. Typical specific gravity of seawater at atmospheric temperature ranges from 1.022 to 1.023 [14].

2.10 Mechanical Spare Parts Classification

In the context of inventory management, the functions of inventory can be grouped under four major types; being raw material inventory, work-in-process inventory (WIP), maintenance, repair and operating materials (MRO), as well as finished goods inventory [15]. The type of inventory directly related with this project is MRO. Replacement spare parts of mechanical components are usually grouped under three major types; preventive maintenance spare parts, critical spare parts, and insurance spare parts.

Preventive maintenance spare parts are non-critical spare parts of without which machine can run, have high reliability, can be made or purchased in short notice, have substitutes, and/or available in the shelf as standard parts (such as bearings) [16]. Non-critical spares are regularly consumed during planned preventive maintenance activities.

Critical spare parts are more costly and require extra precaution in the planning and purchasing activities. Fast (2000) defined: “A critical item is a distinct, serviceable and/or replaceable element, part, component, assembly/subassembly, or tool, that performs a critical function within a system or subsystem, such that in the event of its failure or omission, the associated system/subsystem will fail to sustain its operational readiness” (p.17) [17].

Out of the three types of spare parts, insurance spares require the most careful planning due to its high cost and extreme importance. According to Walker (1997)

> “Insurance type” spares are spares for critical parts which are essential for the operation of the system in which they serve, and which have an appreciable probability of not needing replacement during the lifetime of the system. (p.1) [18].

2.11 The Design Process

The design and manufacturing process of any tool or equipment is an integrative procedure. Most of the designs started from a concept, before being transformed into preliminary design, and subsequently manufactured as a complete instrument [19]. More recent development in technology has introduced the concept of modeling or prototyping into design procedures [19].

A concept is an idea for the development of any new product or improvement of an old product [19]. In the phase of preliminary design, the designer established the feasibility of the product through various means, such as discussion, survey, or presentation [19]. Once a design has been approved, it is necessary to fabricate a prototype to examine the design. Gebhardt (2003) defined prototype as a close resemblance of the sample; produced according to production documents, whereas the only difference between a prototype and a product lies in the production process (p.16) [20].

Sometimes it is necessary to execute a short run production; to further proof a part before the mass production stage is commenced [19]. In the mass or final production stage, parts are processed (machined, injection molded, or cast) in large numbers [19]. The extensive stages undergone before mass production is started are supposed to ensure zero or minimal defects in the final product, to avoid substantial loss to the organization.

The product formation time is the duration between the first conceptualization of the new product and its series production, as illustrated in Figure 2.5 [20]:

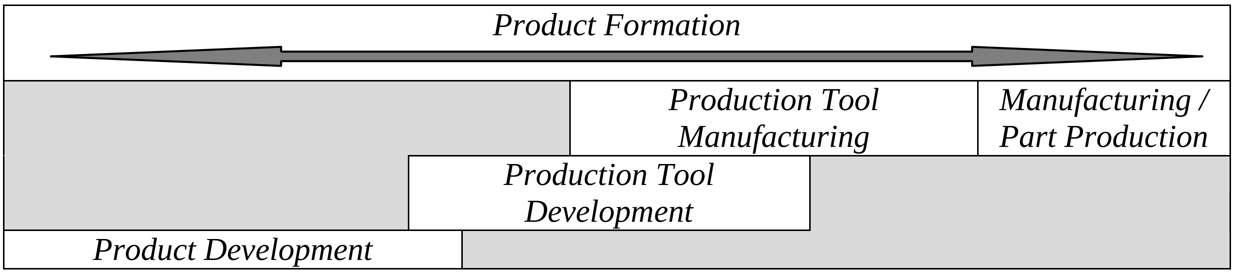

Figure 2.5: Elementary Steps of Product Formation [20]

The duration of the formation of any product should take into account not only the product design and manufacturing interval, but the time spent to manufacture the tools as well. This (tool design and development) will clearly add to the time and effort expended to develop our product. To add to that fact, traditional means of fabrication of prototypes (such as machining) could consume up to four weeks or more, depending on the level of complexity and representativeness [21].

2.12 Rapid Prototyping

According to Heizer et al., (2006), one of the direction of operations management is to promote rapid product development; operations managers should respond to technology that are faster and alliances that are more effective (p.12) [22]. This is one of the reasons why rapid prototyping even existed [23].

Rapid prototyping refers to the layer-by-layer fabrication of three-dimensional physical models directly from a Computer Aided Design (CAD). Figure 2.6 shows a complete set of rapid prototyping system:

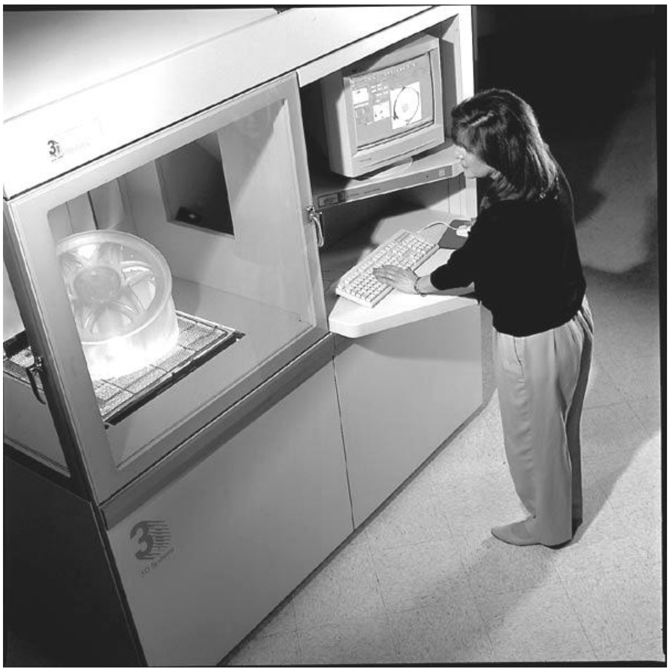

Figure 2.6: Complete Unit of Rapid Prototyping System

Rapid prototyping processes belong to the generative (or additive) production processes, as opposed to abrasive (or subtractive) processes such as lathing, milling, drilling, etc. [20]. Gerbhardt (2003) stated that all industrially relevant rapid prototyping processes work in layers, and defined as 2½D processes, that is stacked up 2D contours with constant thickness (p.30) [20].

The development of rapid prototyping technology has a major relation to the advances in the application of computers in the industry. Started with Computer Aided Design (CAD) the technology preceded to Computer Aided Manufacturing (CAM), and Computerized Numerical Control (CNC) machine tools; all of those technology are crucial in the development of rapid prototyping systems [21].

The technology of rapid prototyping has many advantages, being [23]:

i. Enables the user experiment with physical objects of any complexity.
ii. Enables designer to increase complexity of their designs with little effect on lead time and cost.
iii. Presents new capabilities and opportunities to the marketers.
iv. Enables consumer to purchase products which meet more closely individual needs and wants.

There are several means of generation of the model using rapid prototyping; the first being solidification of liquid materials photopolymerization –Stereolithography (SL), in which the underlying mechanism is solidification of monomer liquids [19],[20]. The liquids are exposed to ultraviolet radiation which sets off a spontaneous polymerization, transforming the liquid to solid polymer [20].

The other means is generation from solid phase which includes melting and solidification of powder and granules – Laser Sintering (LS). In LS process, powders or granules are arranged in a powder bed to be melted together by solid beam [20]. There is also a method called LLM or Layer Laminate Manufacturing, where the 3D model is split into 2D contoured layers, cut, and then assembled into 3D models [20]. In Fused Layer Modeling (FLM), solid wire-shaped materials of semimolten consistency are melted in a heated single- or a multi-nozzle system and deposited geometrically defined into a structure. In Laser Chemical Vapor Deposition (LCVD), matter from gaseous phase is solidified into solid [20].

On top of everything, rapid prototyping is a more economically viable means of producing prototypes compared to other conventional means, given the circumstances that the model is complex and the shortest possible time is the utmost importance for the product’s position, market-wise or application-wise [20].

2.13 Casting Processes

Casting generally means the process of pouring molten metal into a mold, where the metal takes the shape of the mold as it solidifies. In the broad term of casting, various processes have been developed to fully utilize the means of casting based on their respective applications. These processes can be grouped into three major process groups: sand casting, die casting, and investment casting [24]. Through most of the history of casting, the term "casting" itself has primarily been associated with sand moulding [24]. The sand casting process however, lacks in terms of the precision, and further process enhancement has been developed to cater this particular issue. The advent of die casting met some of the criteria for enhanced precision; however this group of techniques has its own limitations, most notably in the compatibility of alloys with the molds, as well as the shapes capable of being produced and extracted from the mold at sensible cost [24].

According to Beeley (1995)

> The concept of precision is seen to embrace, not only the aspect of dimensional accuracy and tolerances, but also surface quality and capability to produce intricate cast detail; either of the latter can be the critical factor in the choice of a forming process for a particular application (p.2) [24].

Due to the physical characteristics and quality of the molds themselves, sand casting and die casting processes inhibit the fabrication of intricately-shaped products.

2.13.1 Investment Casting

The process of investment casting involves the formation of an expendable pattern; in an expendable ceramic mold [24], [25]. Generally, the pattern is made of wax by injection molding and assembled in clusters around a common sprue and feeder system (similarly formed in wax) [24]. The pattern is then dip coated in investment slurry, beginning with primary coat, before further dipped to build the mold thickness [24]. Special heating condition is employed in the dewaxing stage, to avoid shell cracking. The molten metal is then poured into the mold and allowed to solidify. The mold cavity is in one piece, as well as the final part [25].

The investment casting process has the following advantages, as opposed to other casting methods:

i. Complex-shaped parts can be produced close to final configuration [25].
ii. Tighter dimensional tolerances are achievable [25].
iii. Fewer finishing methods are required [25].
iv. Casting has better quality and less porosity [25].

2.13.1.1 Investment Casting Material

The investment casting industry has gown radically over the last sixty years, and the range of alloys compatible with the process is wider than that associated with many other casting processes [24]. For this particular project, the alloy used is Sus. 304.

Grade 304 is the most versatile and most widely used stainless steel than any other [26]. This particular grade of alloy has excellent corrosion resistance characteristics and good oxidation resistance in intermittence service [26].

The extensive material properties and description of Grade Sus. 304 is enclosed in this report as APPENDIX I [26].

3 METHODOLOGY

3.1 Research Methodology

Throughout the completion of this project, the author had accomplished three major milestones in conjunction with the project's objectives. They are:

a. Impeller design and modeling.
b. Impeller prototyping and manufacturing.
c. Costs-time benefit analysis.

The sub-methodologies and procedures of each of these major milestones are illustrated in the subsequent subsections.

The Gantt-chart representing the flow of activities approached in this project is included in this report as APPENDIX II.

3.2 Impeller Design and Modeling

3.2.1 Data Acquisition and Pump Characteristics Curve

Prior to doing the calculation of designing the impeller, the specifications of the pump were first defined. The definition of pump specifications followed actual parameters on existing water injection module of an actual oil field. The essential information in defining the specifications of the pump are:

a. Suction Pressure.
b. Discharge Pressure.
c. Design Capacity.

The specification definition of the pump will be further defined by these preceding procedures:

- Selection of Rotating Speed.
- Pump Head and Stages Definition.
- Pump Specific Speed Definition.
- Pump Shutoff Head Definition.
- Development of Pump Characteristics Curve.

3.2.2 Impeller Design

Once the pump characteristics curve is developed and essential data is compiled, the impeller design phase commenced. The methodology of impeller design followed the procedures described by Lobanoff V. S. et al., (1992) [10]. The procedures of designing the impeller are summarized as:

i. Selection of vane number and discharge angle.
ii. Calculation of impeller diameter.
iii. Calculation of impeller width.
iv. Determination of eye diameter.
v. Determination of shaft diameter under impeller eye.
vi. Estimation of impeller eye area.
vii. Estimation of Net Positive Suction Head Required (NPSHR).
viii. Determination of volute diameter.
ix. Impeller construction layout.

3.2.3 Impeller Modeling

In the modeling phase, the calculated and defined parameters of the impeller were gathered and interpreted. Using appropriate Computer Aided Design (CAD) software, the numerically designed impeller is translated into a virtual three-dimensional model.

3.2.4 Equipment and Apparatus

i. Autodesk® AutoCAD 2005® software. From this point on this particular software will be referred to as "AutoCAD" only.

3.3 Impeller Prototyping and Manufacturing

3.3.1 Impeller Rapid Prototyping

The result of CAD modeling activity under design and modeling phase of the impeller was converted to a rapid prototyping compatible file format, *.stl file. Most of CAD modeling software have built-in file converter to enable the file to be stored in *.stl format. A rapid prototyping system will directly recognize an *.stl file therefore eliminating any further adjustment to be made on the particular file.

The process of prototyping the designed impeller using rapid prototyping technology consumed less than 6 hours. For this particular Thermojet Solid Object Printer, every layer formed is 0.0016 in thick (approximately 40 microns). The concept used by Thermoject Solid Object Printer is multi jet modeling, where the thermoplastic wax is heated and the prototype is built layer by layer from bottom up. The procedures of prototyping are as explained below:

i. The Allegro Client Manager software was executed from the workstation.
ii. The file of the designed impeller CAD drawing, from *.stl format, was submitted to Thermojet Client® software.
iii. The model appeared in the software.
iv. The model was viewed in 3D and 2D setting.
v. The model was offset manually in the software to correctly place it inside the printing region.
vi. The original model of the impeller has a diameter of 11.486 in. For printing purposes, it was scaled down to 50% for reasons described below [3].
vii. The drawing was submitted to Thermojet Solid Object Printer.
viii. Thermojet Solid Object Printer warmed up for approximately 15 minutes.
ix. Thermojet Solid Object Printer started head cleaning procedures for approximately two minutes.
x. Thermojet Solid Object Printer started depositing the first layer of the prototype.
xi. Thermojet Solid Object Printer finished printing after approximately 4 hours 40 minutes.
xii. The prototype was post-processed; where support materials were manually removed from the prototype.

---

[3] For prototyping processes, the model was scaled down to half its original size because:

i. The maximum extension of prototype in the y-axis is 250 mm (9.847 in). This machine is incapable of producing the impeller at 100% scale.
ii. Due to the fact that the prototype is to be further casted, it is economically more viable to have a scaled down model so less financial capital would have to be allocated for the manufacturing processes.
iii. It is not cost-effective to produce a larger metallic prototype of the impeller, should investment casting is to be selected for further manufacturing scopes; for this final year project involves a consideration of cost constraint.

xiii. Arbitrary dimensions were recorded from the prototype to measure error.

xiv. Error in the prototyping process was analyzed.

3.3.2 Impeller Investment Casting

For the fabrication of metallic model of this impeller, investment casting technology is employed. Other casting processes will have problems in forming this particular impeller, because this impeller incorporates a series of internal structures and internal passageways, as illustrated in Figure 3.1. Due to the fact that investment casting employs a usage of expendable pattern and expendable mold, therefore this process will have minimized problem in coming up with the internal structures.

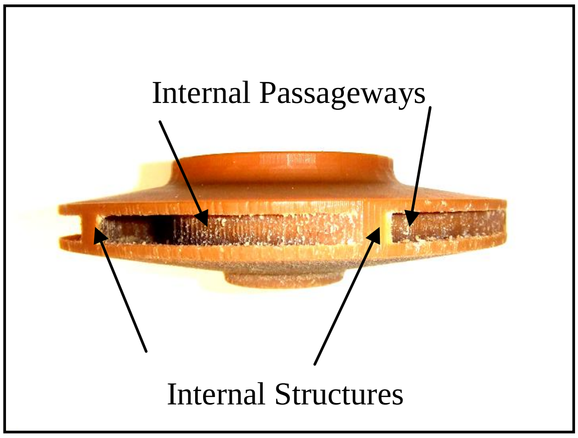

Figure 3.1: Internal Structures and Passageways on the Impeller

The investment casting procedures subsequently follows after the completion of rapid prototyping processes:

i. The rapid prototyped impeller wax pattern was assembled with natural wax having the shape of sprue and feeder system (as illustrated in Figure 3.2).

ii. The assembled wax pattern was coated in investment ceramic material (single coating)[4].

[4] The wax pattern was single coated; as opposed to multi-coating for ideal casting processes; this is due to the fact that the third party company, Primametals Sdn. Bhd., offers to absorb the cost of casting processes, and carry out the casting procedures free of charge.
Single coated ceramic molds might impose problems on the prototype, as there is a possibility for defects due to formation of void cavity or air bubbles inside the molds. However due to the fact that the impeller is only cast to prove its castability and feasibility; the risk of getting a defect impeller is acceptable. The impeller is not to be further used in an operating pump nor be subjected to experimental testing.

iii. The process of dewaxing followed (removal of the wax from the cavity).
iv. Molten metal (Sus. 304) is poured into the cavity, and allowed to solidify through cooling.
v. The mold was broken to recover the metallic impeller.
vi. Finishing operation commenced.

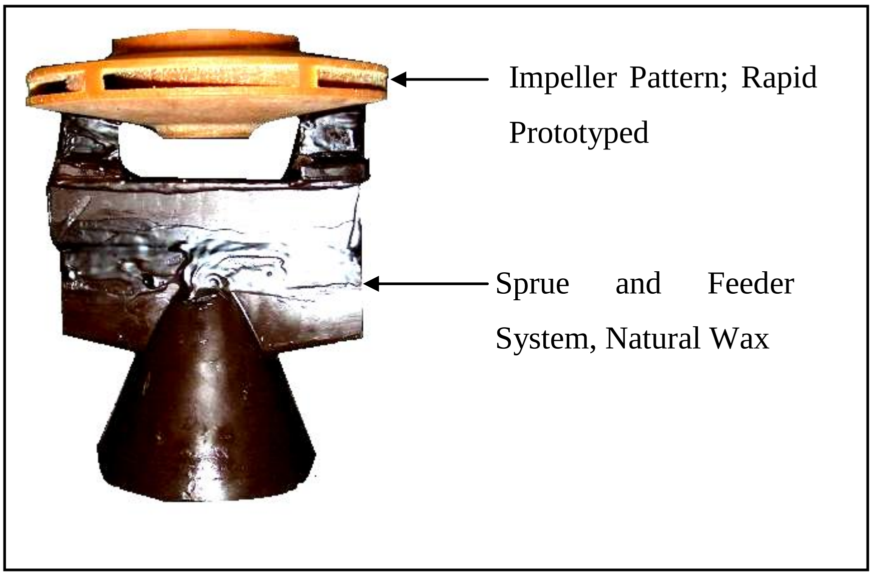

Figure 3.2: Pattern Assembly

3.3.3 Dimensional Error Analysis

Arbitrary dimensions of both the rapid prototyped wax pattern and investment cast metallic prototype are taken and compared with the actual dimension of the CAD model. Variations in the dimensions between the prototypes and the CAD model are calculated to study the error of the manufacturing processes.

3.3.4 Equipment and Apparatus

For rapid prototyping procedures, these equipments and apparatus are used:

i. Workstation.
ii. Thermojet Client® Software Version 1.01, ©3D Systems, Inc.
iii. Thermojet Solid Object Printer.
iv. Thermoplastic wax as the raw material of the prototype.

v. Manual post-processing tools:

   a. A scalpel.
   b. A rigid wire.
   c. A screwdriver.

For investment casting procedures, these apparatus and consumables are used:

i. Wax pattern from the rapid prototyping procedures (will be consumed and lost during the casting process).
ii. Natural wax bearing the shape of sprue and feeder system for the mold (will be consumed and lost during the casting process).
iii. Investment slurry for the mold (refractory particles and a liquid) (will be broken to obtain the cast material).
iv. Alloy metal; specifically Sus. 304 alloy.
v. Investment casting facility.

The investment casting process is carried out by a third party manufacturing company, Primametals Sdn. Bhd., Lahat, Ipoh, Perak.

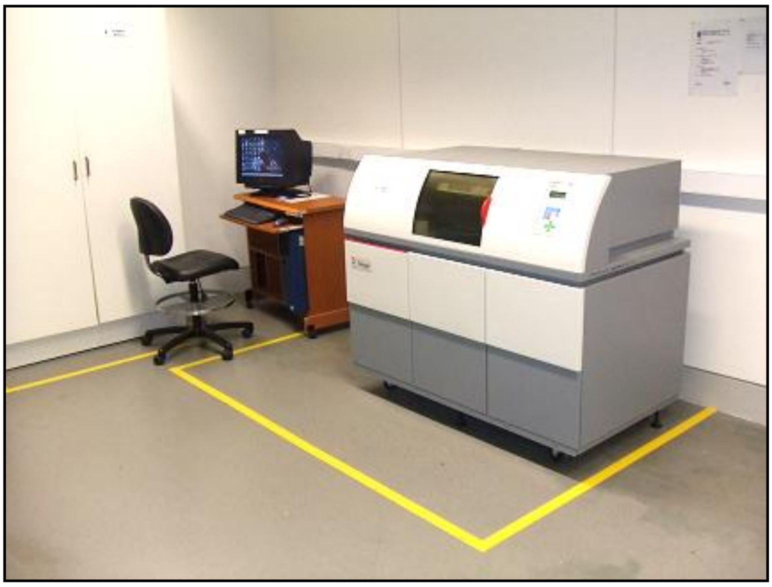

Figure 3.3: Thermojet Rapid Prototyping System

3.4 Costs-Time Benefit Analysis

A costs-time benefit analysis was carried out to investigate the project's favorability in terms of costs and lead-time delivery. The activities carried out under this objective were:

a. Data acquisition on actual costs and lead-time delivery from OEM of generally equivalent mechanical replacement part as studied in this project was conducted.
b. Analysis was carried out by calculating and putting in comparison the costs and lead-time delivery of both approaches (this project and procurement through OEM).
c. The results of the analysis were graphically represented in the form of graphs.

4 RESULTS AND DISCUSSIONS

4.1 Impeller Design

4.1.1 Data Acquisition

For this project, the design constants (pressure, volume, temperature) of the pump followed actual water injection module designed for an actual oil field, Field A. Table 4.1 summarizes the design constants for water injection pumps in waterflood system of Field A:

Table 4.1: Water Injection Pump Constants for Water Injection Module in Field A

Constants	*SI Unit*	*Imperial Unit*
Suction Pressure	*830 kPag*	*120.381 psig*
Discharge Pressure	*8000 kPag*	*1160.304 psig*
Design Temperature Max/Min	*60/0 degC*	*140/32 degF*
Design Flow Rate	*183 m^3/hr*	*805.725 GPM*

In the case of this project, the water injected in Field A is deoxygenated seawater. The specific gravity of seawater for this application is [14]:

$$SG = 1.022$$

4.1.1.1 Selection of Rotating Speed

During initial stage of design, the selection of the driver is not necessary. The driver of a centrifugal pump could be steam turbines, internal combustion engines, or gas turbines. However in order to widen the suitability of drivers, the author will select rotating speed of the pump to synchronize with Malaysia's electrical frequency, 50 Hz [27]. This selection will enable the usage of electric motor and eliminates the need to include speed converter components (belt drive, chain drive, gears, etc.) inside the drive arrangements. The rotating speed is selected to be 3000 rpm (50 Hz). Although this selection is arbitrary, the selection of speeds ranging from 2000 to 4000 rpm is essential in order to match the most efficient pump with respect to its specific speed, N_s, which will be described later.

4.1.1.2 Pump Head and Stages

The pump head for this application is defined as:

$$H = 2.31\ \frac{\Delta P}{SG}\ ;$$

$$H = 2350.511\ ft$$

H = *Head in feet*

ΔP = *Pressure difference, discharge – suction in psia*

In order to have specific speed N_s inside a desired range, the head must be in the range of 200 to 800 *ft*, which will incorporate multistage pump concept for this particular design. The author has chosen the implementation of seven stages (seven impellers) horizontal pump, to meet the desired pressure design. The seven stages will be designed to carry same amount of head, which will leave each stage with:

$$H_{n-stg} = 335.787\ ft$$

H_{n-stg} = *Head for a stage-n in feet*

From this point onwards, calculations will be focused on developing the impeller for the first stage of the pump. The word "pump" will refer to the first stage and first stage impeller of the pump, where applicable.

4.1.1.3 Pump Specific Speed

The specific speed for this particular pump stage (or impeller) will be:

$$N_s = \frac{n\sqrt{Q}}{H^{3/4}}$$

$$N_s = 1085.592$$

N_s = *Specific speed*

n = *Impeller speed in rpm*

Q = *Capacity in GPM*

From Chart of Efficiency of Pumps versus Specific Speed by Tuzson J.,(2000) [12], the correlative pump efficiency with respect to $N_s = 1085.592$ and $Q = 805.725\ GPM$ is:

$$\eta = 77\ \%$$

This chart is enclosed in this report as APPENDIX III.

4.1.1.4 Pump Shut-Off Head

This particular pump will be designed to have continuously rising characteristics, in which the head (pressure ratio) rises continuously as the capacity of the pump is decreased [7]. The selection of shut-off head and characteristics is important for the design to commence. It is typical for many pumps to have shut-off head value from BEP as 20 %, thus this pump will follow that particular value [4].

For this project, as the optimum (BEP) value of head at *Q = 805.725 GPM* is *H = 335.787 ft*, for 20% shut-off from BEP, it is assumed theoretically that its head at *Q = 0 GPM* is:

$$H_{0\ GPM} = (1.2)(335.787)$$

$$H_{0\ GPM} = 402.944\ ft$$

4.1.1.5 Pump Characteristics Curve

From the values and data gathered:

- BEP equals to 77%.
- At BEP, the pump conditions are as follows:
  - *Head = 335.787 ft*
  - *Capacity = 805.725 GPM*
- The pump characteristics curve is of *continuously rising* type, having zero capacity head of 20% higher than BEP head.

These values and information is equated to develop the Pump Characteristics Curve[5]:

[5] The development of the pump curve should be based on experimental results. However, in the design phase, it is necessary to first define the operating condition at points BEP and at zero capacity [10]. This will define the shutoff head, and is necessary to proceed with determination of number of impeller vanes [10].

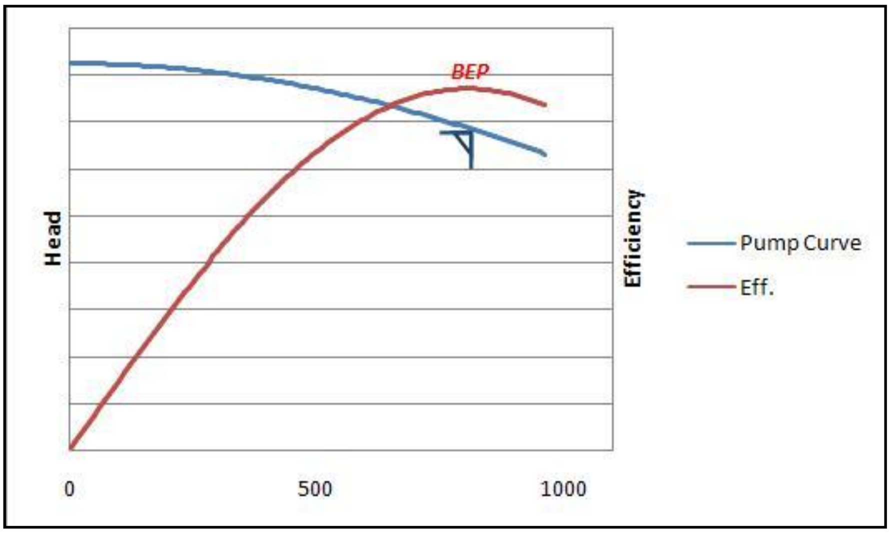

Figure 4.1: Pump Characteristics Curve with BEP marked.

4.1.2 Impeller Numerical Design

The procedures to numerically design the impeller followed the steps defined earlier in the methodology. In order to design the impeller, raw data (design constants such as pressure, flowrate, etc.) were plugged in into a series of equation and established constant graphs. The results of these procedures are summarized in Table 4.2:

Table 4.2: Numerical Results for Impeller Design

Procedures	***Parameters***	***Results***
1	Vane Number [3]	6
2	Discharge Angle [3]	*25°*
3	Impeller Diameter [3]	*11.486 in*
4	Impeller Width [3]	*0.578 in*
5	Eye Diameter [3]	*5.169 in*
6	Shaft Diameter under Impeller Eye [7], [3], [28], [29], [30]	*2.375 in*
7	Shaft Sleeve Diameter [29]	*2.78 in*
8	Impeller Eye Area [3]	*14.915* in^2
9	Net Positive Suction Head Required (NPSHR) [3]	*22.7 ft*
10	Volute Throat Area [3]	*3.908* in^2

The extensive procedures of numerical design stage of the impeller are described in this report in APPENDIX IV.

4.2 Impeller Modeling

4.2.1 Plan View Development

Refer Figure 4.3. The impeller width b_2 is laid out at impeller full diameter. The hub and shroud profile were developed by expanding the width approximately 5º on each side. The profile change from discharge towards suction is kept as gradual as possible using AutoCAD. The hub is developed with thickness of 0.2025 in to incorporate the shaft sleeve.

4.2.2 End View Development

Refer Figure 4.3. A circle to full impeller diameter was drawn. The circle was divided into 24 segments (of 15º each) to enable the iteration of the vane in the later part of the drawing.

4.2.3 Impeller Inlet Angles

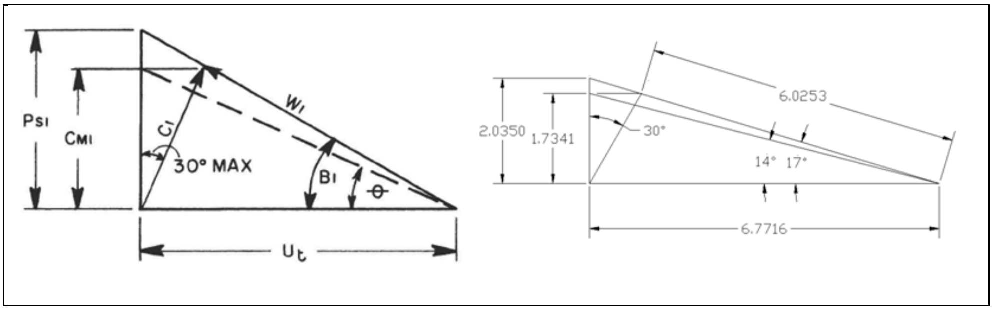

Figure 4.2: Impeller Inlet Angles

Vane inlet angle (in this case 17º) was established from a layout of velocity triangle, as shown in Figure 4.2. The vector connecting U_t and C_{m1} represents suction angle of flow. Inlet vane angle B_1 is drawn to intersect P_{s1}, and for optimum NPSH it is recommended that P_{s1} = 1.05 to 1.2 times C_{m1} [3].

4.2.4 Impeller Vane Development

Refer Figure 4.3**.** The procedures of impeller vane development started with the drawing of a line equal to discharge angle. On the end view the distance a_r was estimated and located. a_r is transmitted to discharge angle line on the vane development establishing the distance a. a is transmitted to the plan view and R1 is measured consequently. R1 is transferred back to end view to see if the established a_r is correct. Lobanoff et al. suggested a trial and error method in establishing these points and measurements.

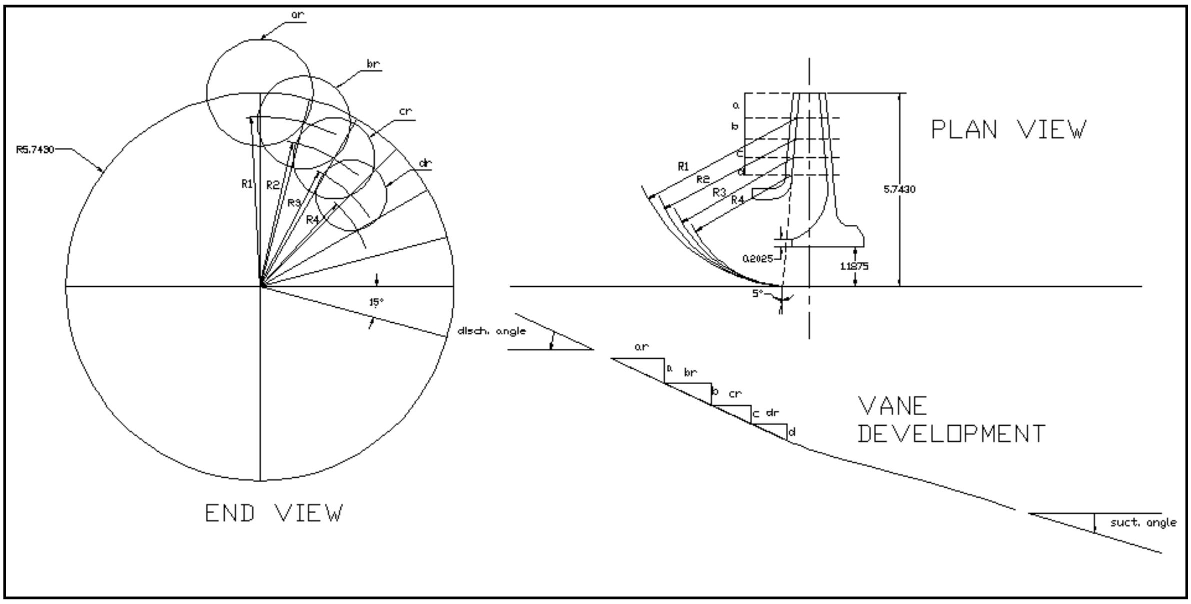

Figure 4.3: Two Dimensional Drawing of Impeller End View, Plan View, and Vane Development

The author however, came up with a simplified iterative approach to come up with the best assumptions in establishing the points:

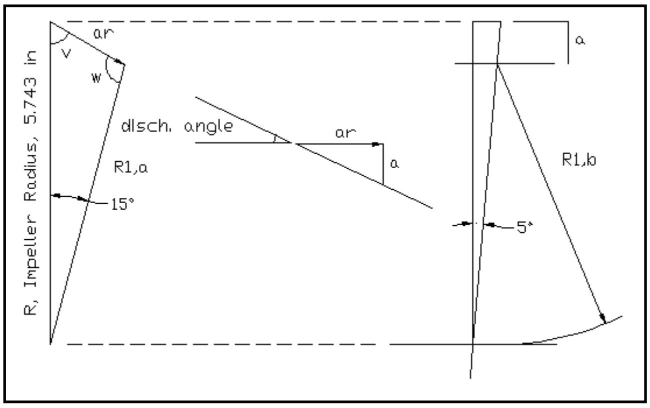

Figure 4.4: Iterative Solutions for Impeller End View Development, Point 1 to 4

$R1_a$ is a subject of a_r by this equation:

$$R1_a{}^2 = R^2 + a_r{}^2 - 2R \cdot a_r \cos v$$

$$\frac{a_r}{\sin 15} = \frac{R}{\sin w}$$

$$180° - w = sin^{-1}(\frac{R \sin 15}{a_r})$$

$$v = sin^{-1}\left(\frac{R \sin 15}{a_r}\right) - 15°$$

$R1_b$ is also a function of a_r by this equation:

$$Disch. angle = 25°$$

$$a = a_r \tan 25$$

$$R1_b = \frac{R-a}{\cos 5}$$

The iterative procedures are carried out with a_r as the variable. The resultant value of $R1_a$ and $R1_b$ is compared and the value of a_r which yields percentage difference of $R1_a$ and $R1_b$ of less than 1×10^{-5}% is used. The iteration is continued, substituting the value of accepted R1 into R for the second point, R2 into R1 for the third point, until the point no. 4, where the minimum impeller cut diameter is reached. The iteration procedures of all the four points are enclosed in this report as APPENDIX V.

The position of point 5 until 6 follows trial and error method, for the impeller shroud is no longer uniform at 5°, and the vane development is gradually altered to fit the suction vane angle.

4.2.5 Vane and Shroud Thickness

Based on the guidelines published by Lobanoff et al, the thickness of the vanes and shroud is to follow a minimum size for castability and optimum efficiency [3]. For this particular design, the thicknesses of those components are summarized in Figure 4.5 and Table 4.3:

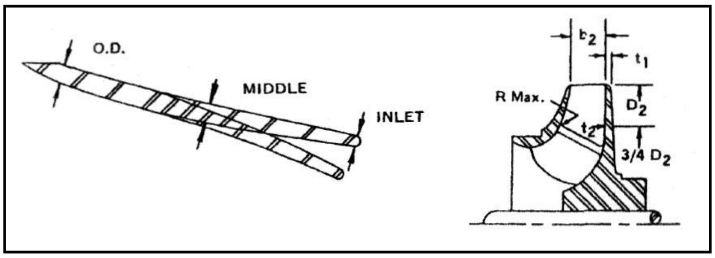

Figure 4.5: Guidelines for Vane and Shroud Thickness [3]

Table 4.3: Guidelines for Vane and Shroud Thickness [3]

Minimum Vane Thickness, in			Minimum Shroud Thickness, in	
Outer Diameter	Middle	Inlet	t_1	t_2
1/4	3/8	3/16	5/32	5/16

The completed two dimensional vane of the impeller is shown in Figure 4.6:

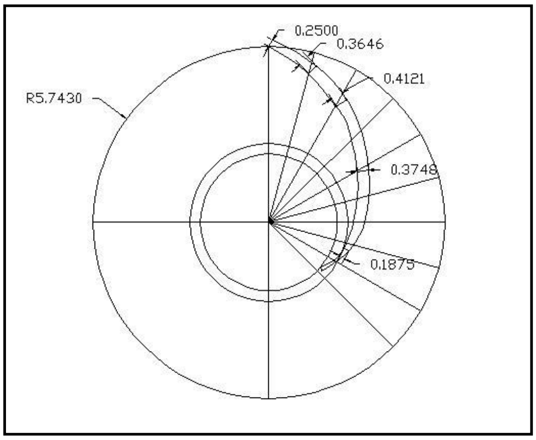

Figure 4.6: Impeller End View, with Vane Thickness Completed

Using _array (polar array) command in AutoCAD, the vanes are arrayed to fill six items in a 360° horizon inside the impeller.

4.2.6 Impeller Shroud Development

From the Plan View, using the command _revolve in AutoCAD, the front and back shroud are revolved about their center (shaft centerline). Refer Figure 4.7 for details.

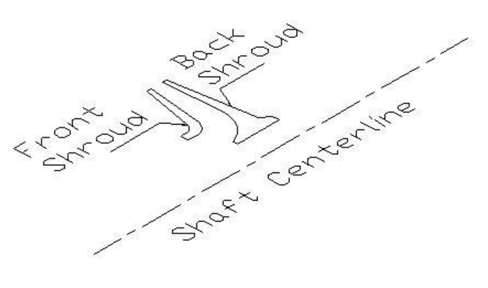	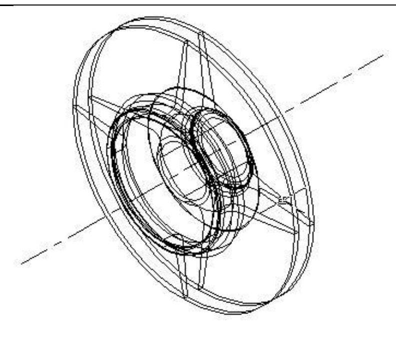
Two-Dimensional Front and Back Shroud.	Revolved, Three-Dimensional Front and Back Shroud.

Figure 4.7: Impeller Shroud Development

4.2.7 Three Dimensional Vane Development

From the established two dimensional End View, the vane is extruded to a height exceeding the impeller width. Using Boolean operations, the impeller and vanes are added (union). The excess vanes are then cut (subtract) from the needed impeller. Refer Figure 4.8 for details:

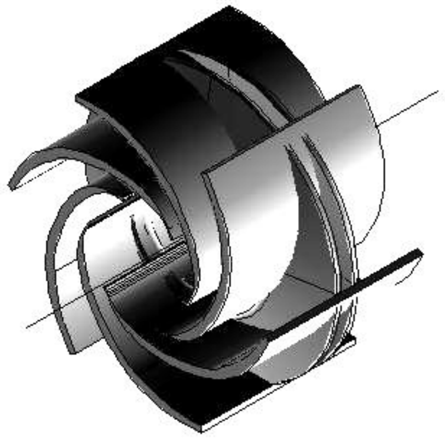	
Impeller and Vanes: Union	Impeller and Vanes with Excess Vanes Subtracted

Figure 4.8: Union of Impeller Shrouds and Vanes, and Subtraction of Excess Vanes, Resulting in Completed Impeller Model

The basic dimension of the impeller model is shown in Figure 4.9:

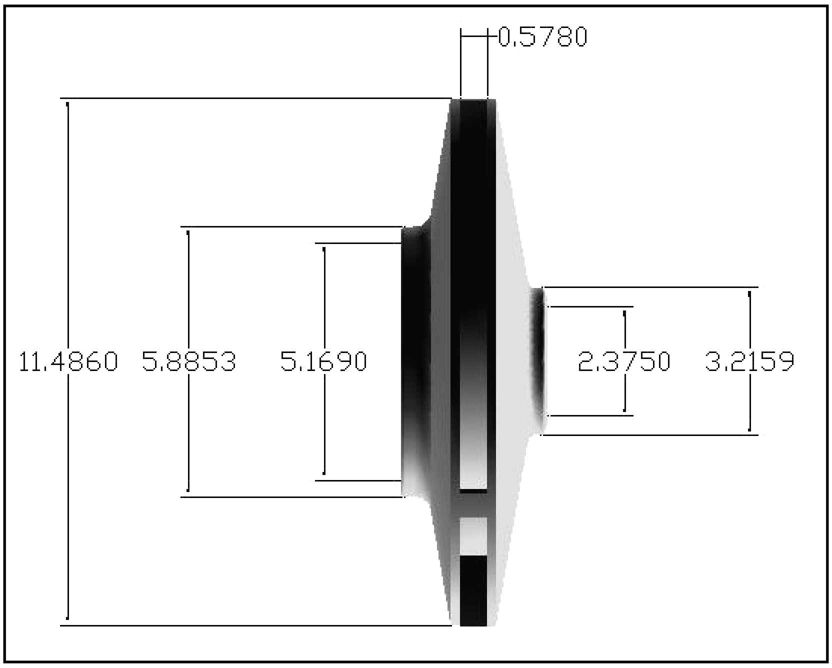

Figure 4.9: Impeller Model with Dimensions

4.3 Impeller Prototyping and Manufacturing

4.3.1 Data Transmission

The STL file submitted into the Thermojet Client® software was successfully uploaded into the program and the layout display is as shown in Figure 4.10. The Virtual model of the impeller as drawn by AutoCAD is as shown in Figure 4.11 for comparison purposes.

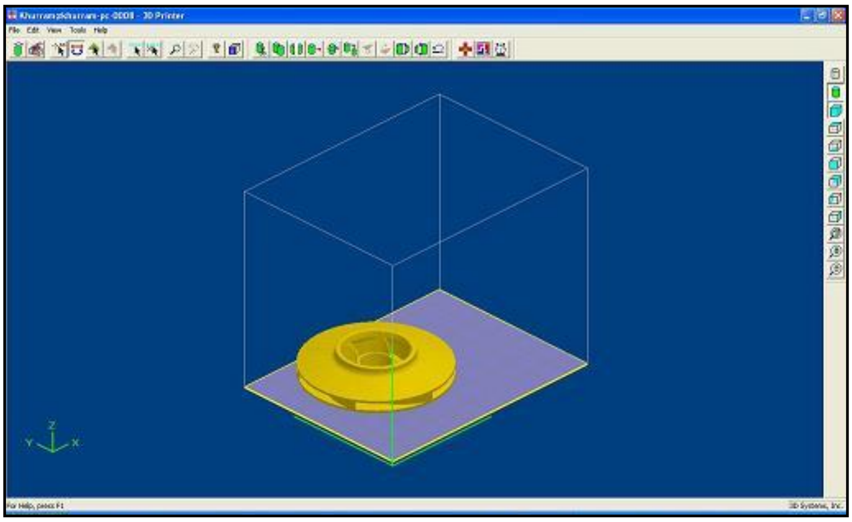

Figure 4.10: Designed Impeller Layout Display on Thermojet Client® Software

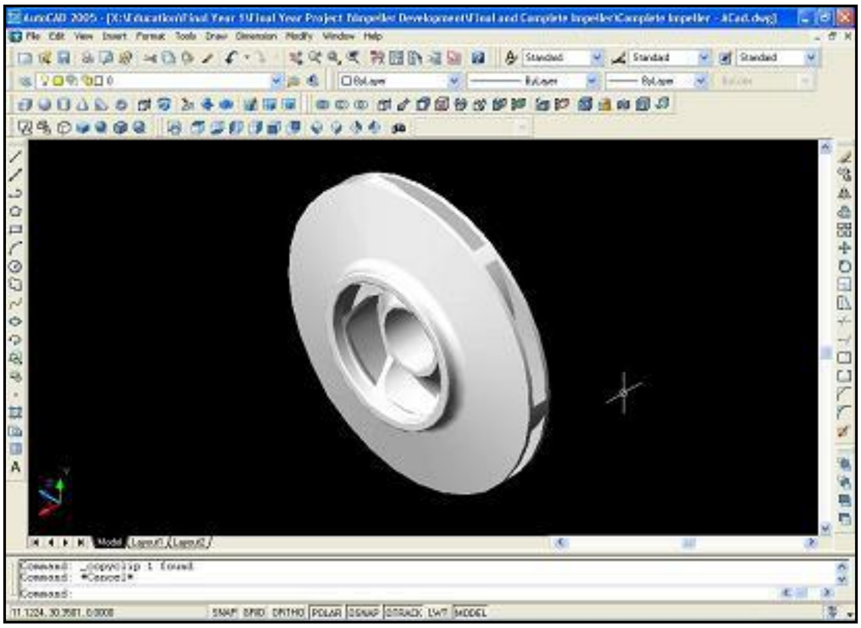

Figure 4.11: Designed Impeller Layout Display on Autodesk® AutoCAD 2005®

4.3.2 Rapid Prototyped Model

The rapid prototyped model was obtained after approximately 4 hours and 40 minutes of rapid prototyping procedures. The prototype was full of support materials, as shown in Figure 4.12:

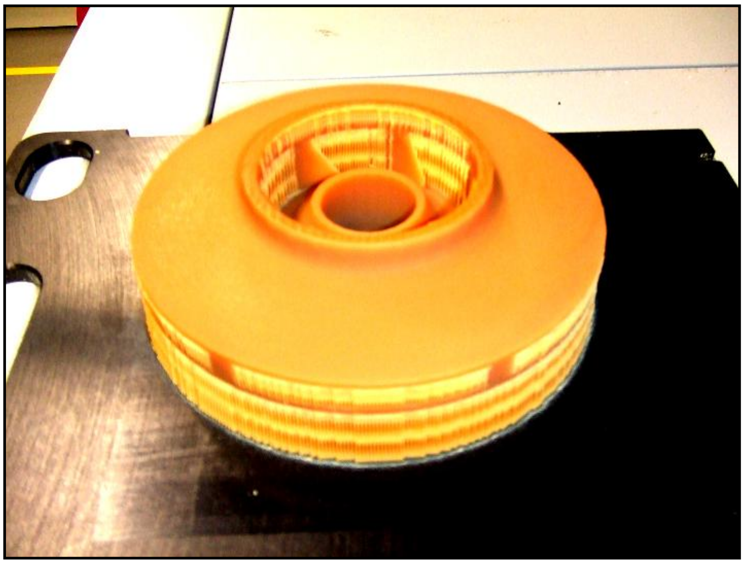

Figure 4.12: Raw Prototype of the Designed Impeller

During post processing, fragile support materials are manually removed by hand, using basic tools as described is Chapter 3. The illustration of the process is shown in Figure 4.13:

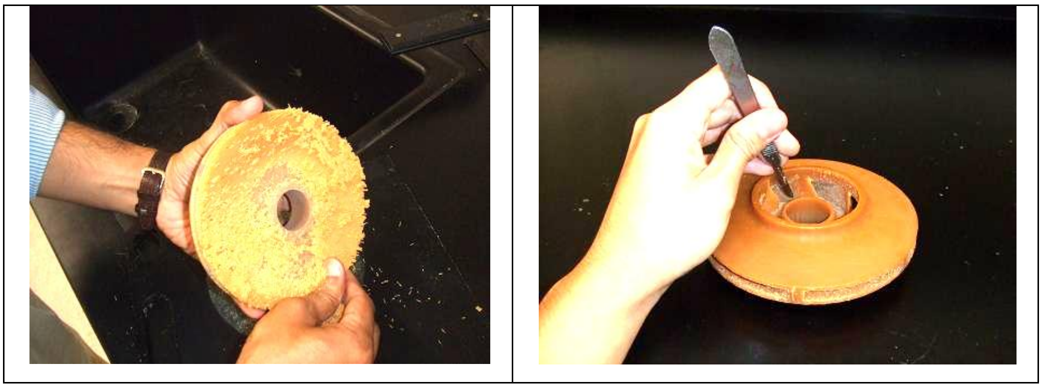

Figure 4.13: Post-processing of Rapid Prototyped Impeller.

4.3.3 Investment Cast Prototype

The investment cast prototype is as shown in Figure 4.14:

Figure 4.14: Investment Cast Impeller

As can be seen from Figure 4.14, there are several significant defects noticeable on the impeller. These defects are further addressed in the subsequent subsection. As an overall observation, the investment cast impeller comparatively takes the general shape and structures of the rapid prototyped impeller pattern. As a primary trial for investment casting, this procedure is in fact successful; and with few modifications and improvements on the design of the impeller and procedures of the investment casting, a perfect investment cast impeller is achievable.

4.3.4 Defects on the Investment Cast Impeller

Figure 4.15 shows the defects on the investment cast impeller.

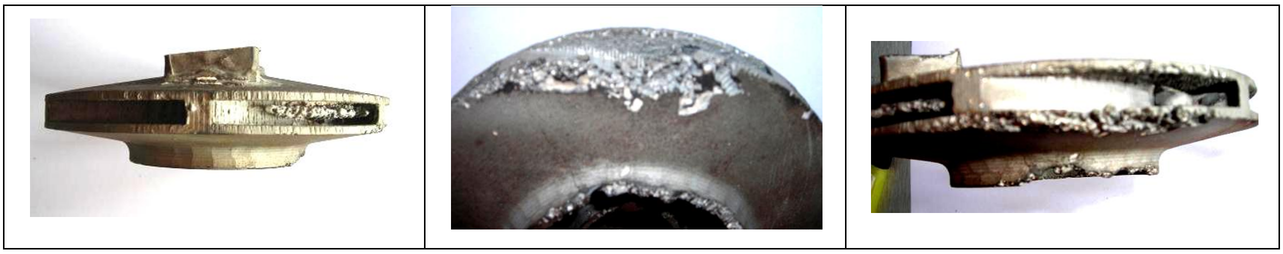

Figure 4.15: Defects on the Cast Impeller

As mentioned in Section 3.3.2, the investment casting procedures involved only single ceramic coating. Due to this, it can be seen that the impeller suffers some defects due to formation of air bubbles and voids inside the cavity; as shown in Figure 4.15. On top of that, the fact that the rapid prototyped pattern was scaled down to 50% was also a probable contributor of these defects. During the numerical design of the impeller, the author had accounted the minimum impeller vane and shroud thickness for castability. Scaling down the impeller itself; due to economic constraints; directly alter the vane and shroud thickness; which in turn probably altered the factor of castability.

Nevertheless, Primametals Sdn. Bhd., the third party manufacturing company, ensures that a high precision impeller of this particular pattern can be investment cast, with the defects eliminated, at a reasonable price with multi-coating of the slurry ceramics.

Subsequent to this, the impeller was finished in order to make it more presentable. The superfluous metal was removed using conventional milling methods. The holes on the shroud surfaces were repaired using putty or epoxy materials. The result of the impeller after undergoing finishing procedures is shown in Figure 4.16:

Figure 4.16: Final Impeller Prototype, After Finishing

4.3.5 Dimensional Error Analysis

The 50% scaled model of the original scale design should have these dimensions, as calculated by Autodesk® AutoCAD:

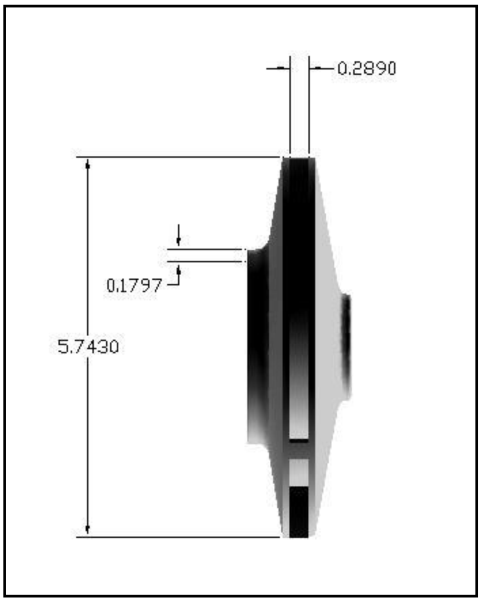

Figure 4.17: 50% Scaled Model of Actual Prototype, with Dimensions

The final products, complete with arbitrarily selected dimensions, are shown in Figure 4.18 and Figure 4.19:

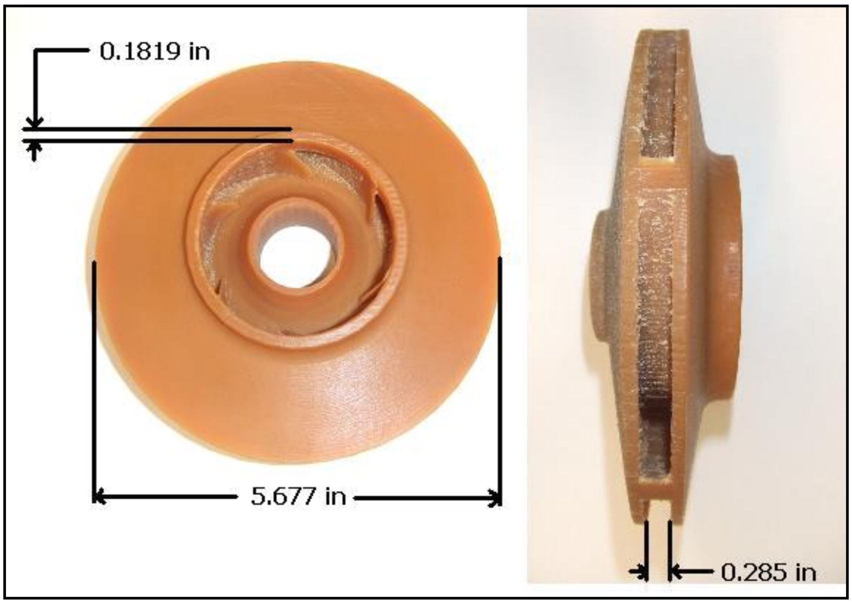

Figure 4.18: Rapid Prototyped Impeller, Complete with Dimensions

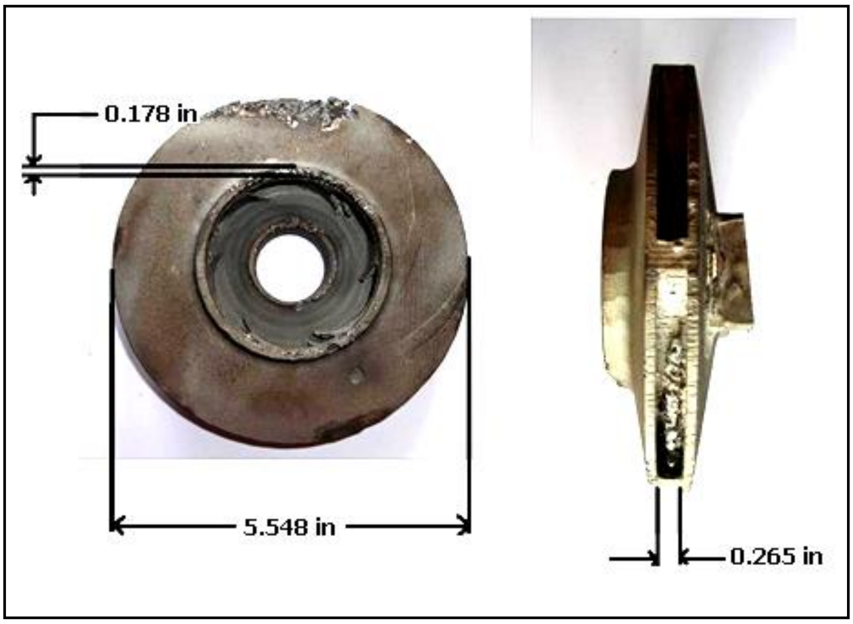

Figure 4.19: Investment Cast Impeller, Complete with Dimensions

By referring to Figure 4.7 to Figure 4.9; there are deviations or errors of the rapid prototyped model and investment cast model from the CAD model. These errors are analyzed and summarized in Table 4.4 below:

Table 4.4: Error Analysis; Comparison of Prototype Dimensions and Actual Dimensions

No.	Item	CAD Model (in)	RP Pattern (in)	Cast Prototype (in)	RP Deviation (%)	Cast Deviation (%)
1	Impeller Diameter	5.743	5.677	5.548	1.15	3.40
2	Impeller Width	0.289	0.285	0.265	1.38	8.30
3	Suction Lip Thickness	0.1797	0.18189	0.178	1.22	0.95
				Avg. Deviation	**1.25**	**4.22**

For the rapid prototyped impeller, having an error of less than 2% is relatively very small. Therefore it is desirable to implement rapid prototyping technology in circumstance where precision is of major importance.

In the case of the investment cast impeller, there are slightly higher deviations as compared to the CAD model. Part of these deviations is result of the deviations of the rapid prototyped (RP) impeller, as the RP impeller was directly used as the pattern for the investment casting process. The deviations could be further explained by the phenomena of metal shrinking, where the molten metal reduces its size through solidification during the casting process. In the process of casting the actual impeller, these phenomena and deviations must be accounted for in the CAD designing procedures.

It could also be noted that for the investment cast prototype, the dimensional error of the impeller width is significantly bigger than the other two items. This could be explained by the fact that the casting process may yield different dimensional accuracy with different planes.

4.4 Costs-Time Benefit Analysis

With the established objectives as illustrated in Chapter 1, cost-time benefit analysis was carried out and the results are illustrated as follows:

Table 4.5 shows detailed raw material data consumed in this project used as the basis of the calculation of the cost-time benefit analysis:

Table 4.5: Raw Material Properties for Rapid Prototyping and Investment Casting

No.	***Item***	***Raw Material***	***Density (kg/m^3)***
1.	Rapid Prototyping (RP) Wax	Thermojet 88	975
2.	Investment Casting Metal	Sus. 304	8000

The geometrical properties of the rapid prototyped and investment cast prototype are as shown in Table 4.6.

Table 4.6: Geometrical Properties of Rapid Prototyping Wax Impeller and Investment Cast Impeller, Half-scaled and Actual Size

No.	***Item***	***50% Scaled Model***	***Actual Size Model***
1.	Volume (in^3)	11.1037	88.8296
2.	Volume (m^3)	1.81957 x 10^{-4}	1.45566 x 10^{-3}
3.	Mass, Thermojet 88 (kg)	0.182	1.419
4.	Mass, Sus. 304 (kg)	1.456	11.645

Table 4.7 illustrates the unit costs of manpower and materials used for the completion of this project.

Table 4.7: Process and Manpower Costs per Unit of the Design and Development of the Centrifugal Pump Impeller using Rapid Prototyping and Investment Casting

No.	Item	Cost (RM)
1.	Rapid Prototyping wax. Cost per kg.	1,400.00
2.	Investment casting process cost (manpower + procedures + raw material). Cost per kg.	30.82
3.	Manpower cost for impeller numerical design (Engineer). Cost per day.	200.00
4.	Manpower cost for CAD model development (Engineer). Cost per day.	200.00
5.	Manpower cost for Rapid Prototyping model development (Engineer). Cost per day.	200.00

As illustrated in Section 3.3.1, the actually fabricated rapid prototyping impeller pattern is reduced to 50% of its original size. The structure of the impeller produced from rapid prototyping consists of actual impeller and support materials, as illustrated in Section 4.3.2. The distribution of mass of each structure of the impeller is as illustrated in Table 4.8:

Table 4.8: Distribution of Mass of Actual Impeller Structure and Support Materials of Rapid Prototyped Impeller Pattern

No.	Structure	Mass (g)	Percentage (%)
1.	Total (Impeller + Support)	292	100
2.	Actual Impeller	182	62.33
3.	Support Materials	110	37.67

Table 4.9 to 4.10 exemplifies the total costs and time consumed for the design and development of the impeller using the approaches applied in this project.

Table 4.9: Total Time Consumed and Costs Incurred for the Design and Development of the Pump Impeller, Scaled Down to 50%

No.	Work-scope	Time Consumed (Days)	Manpower Costs (RM)	Process / Materials Costs (RM)	Total Costs (RM)
1.	Impeller Numerical Design	2	400.00	0.00	400.00
2.	Impeller CAD Model Development	3	600.00	0.00	600.00
3.	Rapid Prototyping (Impeller + Support)	1	200.00	408.80	608.80
4.	Investment Casting	30	0.00	45.00	45.00
	TOTAL	36		TOTAL	1,653.80

Table 4.10: Total Time Consumed and Costs Incurred for the Design and Development of the Pump Impeller, Actual Impeller Size

No.	Work-scope	Time Consumed (Days)	Manpower Costs (RM)	Process Costs (RM)	Total Costs (RM)
1.	Impeller Numerical Design	2	400.00	0.00	400.00
2.	Impeller CAD Model Development	3	600.00	0.00	600.00
3.	Rapid Prototyping (impeller + Support)	1	200.00	3186.40	3,386.40
4.	Investment Casting	30	0.00	358.90	358.90
	TOTAL	36		TOTAL	4,745.30

Table 4.11 shows the estimated costs and lead-time delivery of an equivalent pump impeller if it were to be procured through OEM. The OEM impeller studied is analogous to the impeller designed for this project, for it has roughly the same diameter, 12 inch.

Table 4.11: Estimated Cost and Lead-time Delivery of a 12-inch Diameter Pump Impeller, Procured through Original Equipment Manufacturer

1.	Price (RM)	48,000.00
2.	Lead-time Delivery (Days)	112 - 168

Table 4.12 demonstrates the comparison of this project and procurement through OEM in terms of lead-time delivery and costs.

Table 4.12: Comparison of Procedures Approached in This Project with Procuring Spare Parts through Original Equipment Manufacturer (OEM)

No.	***Description***		***Lead-time Delivery (Days)***	***Costs (RM)***
1.	This Project	Design and Manufacturing	36	4,745.30
2.		Manufacturing Only	31	3,745.30
3.	Procuring Spares through OEM		112-168	48,000.00

The verification documents of the figures shown in section 4.4 can be accessed in this report as APPENDIX VI

The graphical representation of the results shown in Table 4.11 illustrating the comparison of procurement through approaches adopted in this project and procurement through OEM in terms of costs and lead time delivery is shown in Figure 4.20.

It can be clearly seen from the graph how dramatically reduced are the costs and lead-time delivery of the impeller (representing mechanical replacement parts) if somehow the procurement process were to be shifted from conventional means (through OEM) to the procedures studied in this project. These reductions can be explained by the fact that the procedures approached in this project involved only design and manufacturing of a small number of products. The OEM would have to cater extensive network of client globally, resulting in longer lead-time delivery and costs. On top of that, the fact that the OEM facilities are generally located in foreign countries, the shipping stage tends to increase the lead-time delivery and costs. The design and manufacturing procedures approached in this project were done locally, eliminating the needs for international shipping, thus reducing lead-time and costs. In a way it is a good approach to localize design and manufacturing activities of products to cut down costs where applicable; and in the same time setting global standards and procedures so that less hassle is absorbed in manufacturing common components.

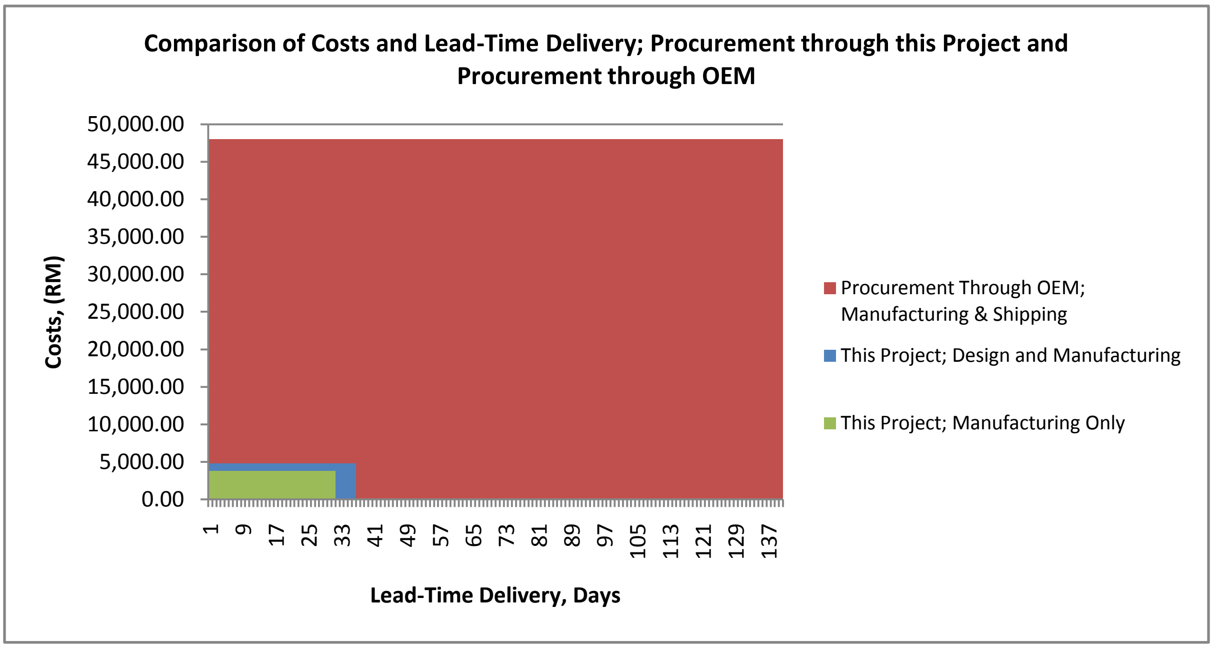

Figure 4.20: Comparison of Costs and Lead-Time Delivery; Procurement through this Project and Procurement through OEM

5 CONCLUSIONS AND RECOMMENDATIONS

One of the major objectives of any industry is to gain monetary profit by selling its product. In order to make sure continuous production of its product, a producer must first ensure that its means of production is reliable.

As far as production and manufacturing industry is concerned, reliable means of production carries the same meaning as plant reliability. In order to make sure a plant is reliable, the operators must first guarantee the reliability and operatability of its equipments. Various types of maintenance approaches have been studied, and when proved to be practical, have been adopted to maintain the reliability of mechanical equipments. Nevertheless, when it comes to purchasing replacement mechanical components, plant operators have always regarded the OEM as the only significant source of procurement.

The issues regarding procurement of spares through OEM lie in the facts that they usually force a considerably high lead-time delivery, aside from elevated costs. This scenario is generally acceptable, because replacement spare purchasing is typically done prior to equipment breakdown, where spares are available when they are needed. However, when unexpected incidents occur, such as components' repetitive failure or breakdown of equipment prior to spare parts delivery, procurement through OEM can no longer be accepted as a favorable means.

This project was done with major objective of studying the alternative ways of procuring spare parts with LESS costs and lead-time delivery. The first means of establishing the objective is by designing a mechanical component, a centrifugal pump impeller. The data for the pump operation is acquisited from an actual oil field, to establish the credibility of the design. The design involved numerical design of the impeller as well as CAD modeling of the prototype. Somehow this activity verified that mechanical equipment can be designed locally, and in doing so the lead-time delivery and costs could be reduced, by cutting down the shipping duration and costs.

The subsequent milestone in the project is the solid prototyping and manufacturing phase. The virtual CAD model was translated into a solid wax model through rapid prototyping. The RP wax model was then directly used as an expendable pattern in investment casting process to produce solid metallic model of the impeller. Somehow this activity justifies the objective by verifying that rapid prototyping technology could be conjoined with conventional method of manufacturing mechanical components, and in doing so further reduced the lead-time delivery and costs by establishing a more rapid and less costly approaches of procuring spares. Nevertheless, there are some detrimental effects encountered during this procedure, that is the defects of the investment cast product and also the fact that the surface finish of the RP model were not highly satisfying.

The next milestone of this project is analysis of the benefit of this project in terms of costs and lead-time delivery. The analysis somehow concluded that the procedures adopted in this project are feasible to be used as an alternative in procuring mechanical replacement components. The analysis also concluded that the procurement approaches illustrated in this project were way more practical than conventional means of procurement (through OEM) in terms of costs and lead-time delivery.

The author would like to suggest a few recommendations that the author believe will be able to help this project yield better results. One of the major issues encountered in this project is the surface finish quality of the RP wax model. The rapid prototyping procedure was carried out using the technique of laser printing. This technique somehow solidifies the wax and keeps the support materials connected, instead of loosed, with each other. After the post-processing procedure, the surfaces that are directly attached to support materials will suffer poor surface finish quality. The author recommends a study be conducted on ways to reduce or eliminate this effect, most probably by experimenting with geometries of the prototyping surfaces or by substitution of the RP raw materials.

This investment cast prototype also suffered defects due to improper methods of investment slurry coating. The author recommends a study be carried out to establish the minimum numbers of slurry coating on different geometries of patterns for investment casting. This study could result in a more efficient and cost-effective process of investment casting.

For the continuation of this project, the author would like to recommend a study be carried out to determine the quality of the final impeller produced in this project with respect to the actual impeller of equivalent geometries and applications produced by the OEM. This study will be able to determine whether the approaches adopted in this project are on par or not with the impeller manufactured by OEM. If somehow the impeller were of less quality than the one manufactured by OEM, further modifications on the materials and manufacturing activities could be proposed and investigated.

Finally, most of the actual manufacturing processes to mass produce mechanical components are through metal casting. To appreciate the importance of metal casting technology, the author would like to propose that Universiti Teknologi PETRONAS provide a learning-scale casting facility or foundry. By this, the students will be able to experience the actual metal casting procedures, and researchers would not be having much trouble to experiment with metal casting procedures, if required by their project.

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APPENDICES

LIST OF APPENDICES

Stainless Steel - Grade 304

Chemical Formula

Fe, <0.08% C, 17.5-20% Cr, 8-11% Ni, <2% Mn, <1% Si, <0.045% P, <0.03% S

Background

Grade 304 is the standard "18/8" stainless; it is the most versatile and most widely used stainless steel, available in a wider range of products, forms and finishes than any other. It has excellent forming and welding characteristics. The balanced austenitic structure of Grade 304 enables it to be severely deep drawn without intermediate annealing, which has made this grade dominant in the manufacture of drawn stainless parts such as sinks, hollow-ware and saucepans. For these applications it is common to use special "304DDQ" (Deep Drawing Quality) variants. Grade 304 is readily brake or roll formed into a variety of components for applications in the industrial, architectural, and transportation fields. Grade 304 also has outstanding welding characteristics. Post-weld annealing is not required when welding thin sections.

Grade 304L, the low carbon version of 304, does not require post-weld annealing and so is extensively used in heavy gauge components (over about 6mm). Grade 304H with its higher carbon content finds application at elevated temperatures. The austenitic structure also gives these grades excellent toughness, even down to cryogenic temperatures.

Key Properties

These properties are specified for flat rolled product (plate, sheet and coil) in ASTM A240/A240M. Similar but not necessarily identical properties are specified for other products such as pipe and bar in their respective specifications.

Composition

Typical compositional ranges for grade 304 stainless steels are given in table 1.

Table 1. Composition ranges for 304 grade stainless steel

Grade		C	Mn	Si	P	S	Cr	Mo	Ni	N
304	min.	-	-	-	-	-	18.0	-	8.0	-
	max.	0.08	2.0	0.75	0.045	0.030	20.0		10.5	0.10
304L	min.	-	-	-	-	-	18.0	-	8.0	-
	max.	0.030	2.0	0.75	0.045	0.030	20.0		12.0	0.10
304H	min.	0.04	-	-	-	-	18.0	-	8.0	-
	max.	0.10	2.0	0.75	0.045	0.030	20.0		10.5	

Mechanical Properties

Typical mechanical properties for grade 304 stainless steels are given in table 2.

Table 2. Mechanical properties of 304 grade stainless steel

Grade	Tensile Strength (MPa) min	Yield Strength 0.2% Proof (MPa) min	Elongation (% in 50mm) min	Hardness	
				Rockwell B (HR B) max	Brinell (HB) max
304	515	205	40	92	201
304L	485	170	40	92	201
304H	515	205	40	92	201
304H also has a requirement for a grain size of ASTM No 7 or coarser.					

Physical Properties

Typical physical properties for annealed grade 304 stainless steels are given in table 3.

Table 3. Physical properties of 304 grade stainless steel in the annealed condition

Grade	Density (kg/m^3)	Elastic Modulus (GPa)	Mean Coefficient of Thermal Expansion (mm/m/°C)			Thermal Conductivity (W/m.K)		Specific Heat 0-100°C (J/kg.K)	Electrical Resistivity (nW.m)
			0-100°C	0-315°C	0-538°C	at 100°C	at 500°C		
304/L/H	8000	193	17.2	17.8	18.4	16.2	21.5	500	720

Grade Specification Comparison

Approximate grade comparisons for 304 stainless steels are given in table 4.

Table 4. Grade specifications for 304 grade stainless steel

Grade	UNS No	Old British		Euronorm		Swedish	Japanese
		BS	En	No	Name	SS	JIS
304	S30400	304S31	58E	1.4301	X5CrNi18-10	2332	SUS 304
304L	S30403	304S11	-	1.4306	X2CrNi19-11	2352	SUS 304L
304H	S30409	304S51	-	1.4948	X6CrNi18-11	-	-
These comparisons are approximate only. The list is intended as a comparison of functionally similar materials **not** as a schedule of contractual equivalents. If exact equivalents are needed original specifications must be consulted.							

Possible Alternative Grades

Possible alternative grades to grade 304 stainless steels are given in table 5.

Table 5. Possible alternative grades to 304 grade stainless steel

Grade	Why it might be chosen instead of 304
301L	A higher work hardening rate grade is required for certain roll formed or stretch formed components.
302HQ	Lower work hardening rate is needed for cold forging of screws, bolts and rivets.
303	Higher machinability needed, and the lower corrosion resistance, formability and weldability are acceptable.
316	Higher resistance to pitting and crevice corrosion is required, in chloride environments

321	Better resistance to temperatures of around 600-900°C is needed…321 has higher hot strength.
3CR12	A lower cost is required, and the reduced corrosion resistance and resulting discolouration are acceptable.
430	A lower cost is required, and the reduced corrosion resistance and fabrication characteristics are acceptable.

Corrosion Resistance

Excellent in a wide range of atmospheric environments and many corrosive media. Subject to pitting and crevice corrosion in warm chloride environments, and to stress corrosion cracking above about 60°C. Considered resistant to potable water with up to about 200mg/L chlorides at ambient temperatures, reducing to about 150mg/L at 60°C.

Heat Resistance

Good oxidation resistance in intermittent service to 870°C and in continuous service to 925°C. Continuous use of 304 in the 425-860°C range is not recommended if subsequent aqueous corrosion resistance is important. Grade 304L is more resistant to carbide precipitation and can be heated into the above temperature range.

Grade 304H has higher strength at elevated temperatures so is often used for structural and pressure-containing applications at temperatures above about 500°C and up to about 800°C. 304H will become sensitised in the temperature range of 425-860°C; this is not a problem for high temperature applications, but will result in reduced aqueous corrosion resistance.

Heat Treatment

Solution Treatment (Annealing) - Heat to 1010-1120°C and cool rapidly. These grades cannot be hardened by thermal treatment.

Welding

Excellent weldability by all standard fusion methods, both with and without filler metals. AS 1554.6 pre-qualifies welding of 304 with Grade 308 and 304L with 308L rods or electrodes (and with their high silicon equivalents). Heavy welded sections in Grade 304 may require post-weld annealing for maximum corrosion resistance. This is not required for Grade 304L. Grade 321 may also be used as an alternative to 304 if heavy section welding is required and post-weld heat treatment is not possible.

Machining

A "Ugima" improved machinability version of grade 304 is available in bar products. "Ugima" machines significantly better than standard 304 or 304L, giving higher machining rates and lower tool wear in many operations.

Dual Certification

It is common for 304 and 304L to be stocked in "Dual Certified" form, particularly in plate and pipe. These items have chemical and mechanical properties complying with both 304 and 304L specifications. Such dual certified product does not meet 304H specifications and may be unacceptable for high temperature applications.

Applications

Typical applications include:

- Food processing equipment, particularly in beer brewing, milk processing & wine making.
- Kitchen benches, sinks, troughs, equipment and appliances
- Architectural panelling, railings & trim
- Chemical containers, including for transport
- Heat Exchangers
- Woven or welded screens for mining, quarrying & water filtration
- Threaded fasteners
- Springs

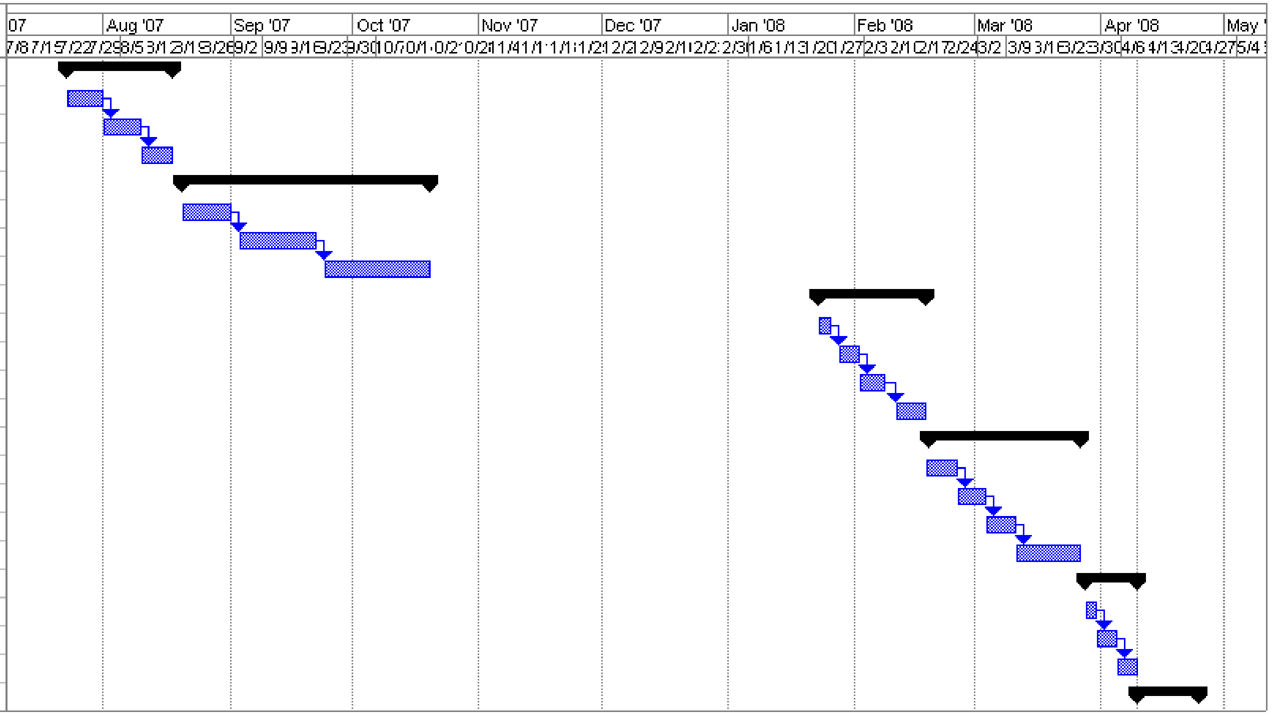
Source: Atlas Steels Australia

For more information on this source please visit Atlas Steels Australia.

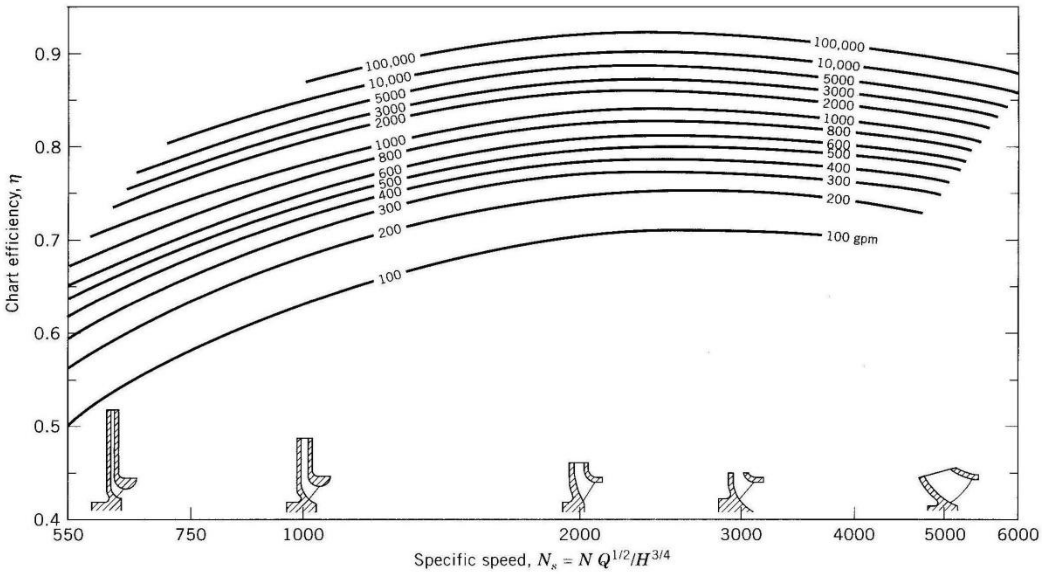
Design and Prototyping of Centrifugal Pump Impeller to be used as Water Injection Pump for Hydrocarbon Artificial Lift

Project Activities Flow – Gantt Chart

ID	Task Name	Duration	Start
1	**Preliminary Research**	20 days	Jul 23
2	Topic Selection	7 days	Jul 23
3	Topic Award	7 days	Aug 1
4	Ref. Materials Acquisition	6 days	Aug 10
5	**Impeller Design and Modeling**	45 days	Aug 20
6	Data Acquisition	10 days	Aug 20
7	Numerical Design	15 days	Sep 3
8	CAD Model Development	20 days	Sep 24
9	**Rapid Prototyping**	20 days	Jan 23
10	Preliminary Study	3 days	Jan 23
11	Preparation	5 days	Jan 28
12	Compatibility Test	5 days	Feb 2
13	Printing	6 days	Feb 11
14	**Investment Casting**	28 days	Feb 19
15	Preliminary Study	6 days	Feb 18
16	Preparation	5 days	Feb 26
17	Casting Process	6 days	Mar 4
18	Finishing Activities	12 days	Mar 11
19	**Cost-Time Benefit Analysis**	11 days	Mar 28
20	Preliminary Study	2 days	Mar 28
21	Data Acquisition	5 days	Mar 31
22	Analysis	4 days	Apr 5
23	**Project Finalization**	11 days	Apr 10



Efficiency of Centrifugal Pumps vs. Specific Speed Chart



APP IV: PROCEDURES OF IMPELLER NUMERICAL DESIGN

APP IV.1 Selection of Vane Number and Discharge Angle

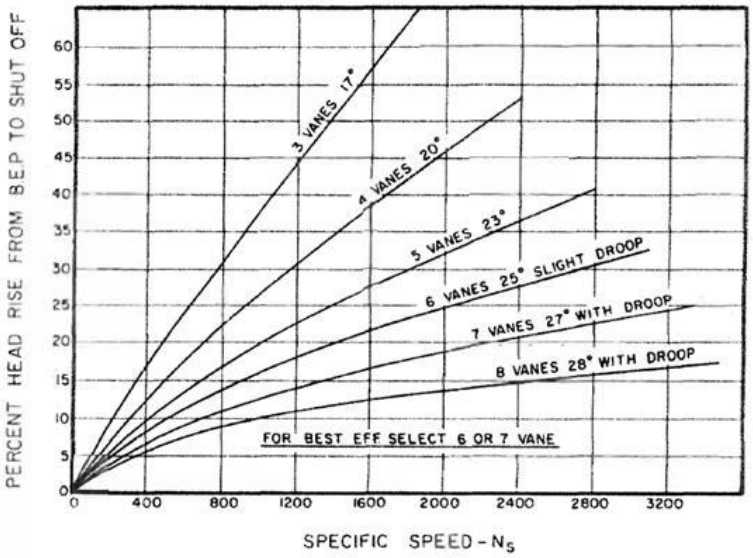


Figure APP IV.1: Vane Number Selection Graph

From Vane Number Selection Graph (Figure APP IV.1) [3], for Shutoff Head – BEP Head percent rise of 20% and specific speed of 1085.592, the suitable number of vanes, *Z,* and discharge angle, β_2, is:

Z = 6;

β_2 = 25°

APP IV.2 Calculation of Impeller Diameter

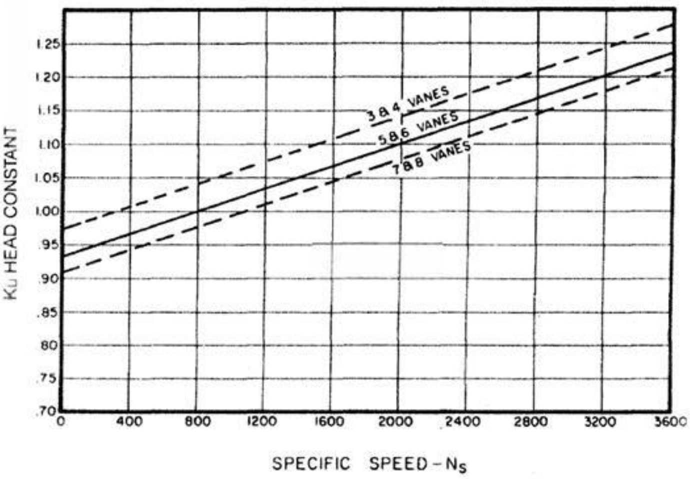


Figure APP IV.2: Head Constant Graph

From Head Constant Graph (Figure APP IV.2) [3], the corresponding value of Head Constant, K_u, for this impeller is:

K_u = 1.022

The impeller diameter, D_2, is therefore:

$$D_2 = \frac{1840\,(K_u)(\sqrt{H})}{n}$$

$$D_2 = 11.486\ in$$

APP IV.3 Calculation of Impeller Width

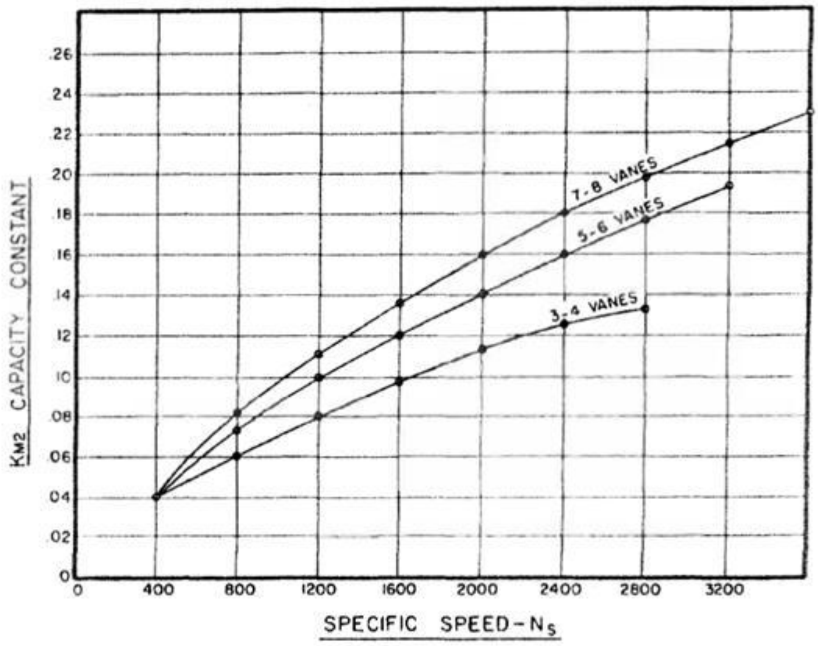


Figure APP IV.3: K_{M2} Capacity Constant Graph

From K_{M2} Capacity Constant Graph (Figure APP IV.3) [3], the corresponding value of K_{M2} is:

$K_{M2} = 0.092$;

$$C_{M2} = (K_{M2})\sqrt{2gH}$$

$C_{M2} = 13.523\ ft/s$;

$$b_2 = \frac{0.321Q}{C_{M2}(D_2\pi - ZS_u)}$$

$$b_2 = 0.578\ in$$

K_{M2} = *Capacity Constant*

C_{M2} = *Radial Velocity at Impeller Discharge*

g = *gravitational acceleration constant, 32.174 ft/s^2*

b_2 = *impeller width in inches*

S_u = *Vane thickness at D_2. Assumed to be 0.5 inch. Will be confirmed during vane development. This calculation repeated if necessary,*

APP IV.4 Determination of Eye Diameter

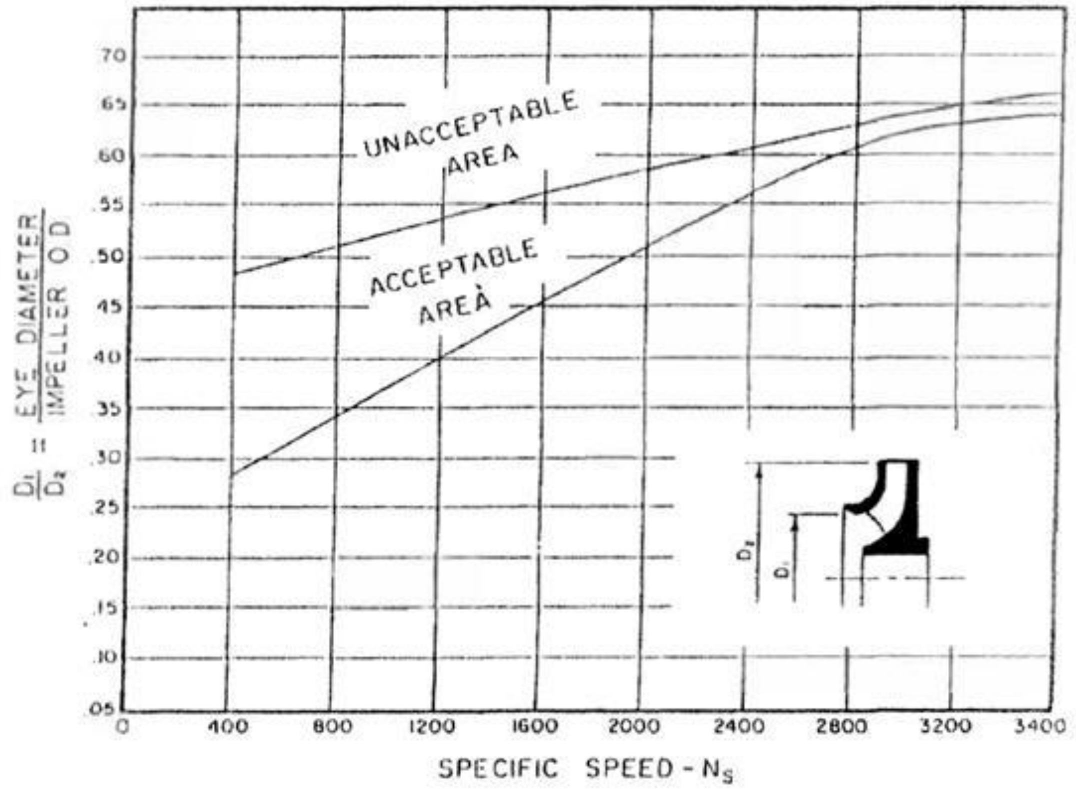


Figure APP IV.4: Impeller Eye Diameter / Impeller Diameter Ratio Graph

From Impeller Eye Diameter / Impeller Diameter Ratio Graph (Figure APP IV.4) [3];

$\frac{D_1}{D_2} = 0.45;$

$D_1 = 5.169\ in$

APP IV.5 Shaft Sizing

To determine shaft diameter for this particular application, the author would have to first select the suitable material for seawater pumping purposes. Based on material selection chart provided by Goulds Pumps, the suitable and economical material would be alloy 2205 duplex stainless steel [28]. This material combines high strength and high corrosion resistance to produce high corrosion fatigue strength, and therefore can be subjected to aggressively corrosive environment such as handling seawater [29]. Alloy steels exhibits mechanical properties superior to that of ordinary carbon steel with respect to hardenability, toughness, or reduction of environmental degradation under specific service conditions [30].

As suggested by Karassik et al., typical torsional stress for alloy steel is [7]:

τ = 55 MPa (8,000 psi);

The pump is going to be built with only one shaft, that is, all the seven stages share a common shaft. Thus, the procedure of sizing the shaft would have to take into account the power developed by the whole seven stage, instead of just one. As specified before, the seven stages will be carrying the same amount of head, with the total head adds up to *2350.511 ft*. With efficiency of *77%*, the power required by the pump at BEP would be:

$$P = \frac{Q \cdot H \cdot SG}{3960 \cdot \eta}$$

$$P = 634.777\ hp$$

The pump will not be allowed to operate to the right of the BEP. That is, the BEP is the maximum power that is going to be supplied into the pump. However to cater for unexpected power leap by the driver, failure of equipment's instrumentation and control system, or any undesirable operating conditions by the injection fluid, a factor of safety of 1.5[6] is incorporated into this value for the shaft sizing. The maximum power for the pump would now be:

$$P_{max} = 952\ hp$$

The procedures of sizing the shaft are as follows:

$$\tau = {T \cdot r}/{J}$$

$$J = {\pi \cdot D^4}/{32}$$

$$P = T\omega$$

Hence:

$$ {T \cdot r}/{J} = {P \cdot r}/{\omega J} = {16 \cdot P}/{\omega \cdot \pi \cdot D^3}$$

Solving for *D:*

$$D = ({16P}/{\tau\omega\pi})^{\frac{1}{3}}$$

$$D = \left(\frac{16 \times 952\ hp \times 550\ \frac{ft \cdot lb}{hp \cdot sec} \times 12 \frac{in}{ft}}{3000\ rpm \times 0.10472\ \frac{rad}{rpm \cdot sec} \times \pi \times 8000 \frac{lb}{in^2}}\right)^{\frac{1}{3}}$$

[6] Driver for any mechanical devices would be operated at variable speeds and powers according to operation requirements. These speeds / powers may be less than the designed values for driver. The power reduction as specified by Waukesha Engines ranges from 0.67 to 0.83 of the maximum power [31]. Thus any leap of power would be a factor of 1.2 to 1.5.

$D = 2.335\ in$

For design, the diameter is round up to nearest $\frac{1}{8}$ in increment:

$D = 2.375\ in$

T	*= torque in in·lb*
r	*= shaft radius in in*
J	*= polar moment of inertia of the cross-section of the shaft*
D	*= shaft diameter in in*
ω	*= shaft rotational speed in rad/s*
P	*= power input into the pump, in lb·in/sec*

APP IV.6 Key Sizing

According to ANSI-B17.1, the general practice is to use key size of height (W) of one-fourth of the shaft diameter [3]:

$W = {}^{2.375}/_{4}$

$W = 0.56375\ in\ (round\ up\ to\ 0.75\ in)$

For the design of impeller key, the author selected alloy 316 austenitic stainless steel for the material. The reasons why this material is used are:

i. Similar to the shaft material, stainless steel 316 provides extraordinary range of corrosion resistance.
ii. The impeller key is going to be replaced more frequently during maintenance and services rather than the impellers and shaft itself, thus stainless steel 316 is the better choice than alloy 2205 based on:
    a. Most commonly used corrosion resistant alloy (widely available) [5].
    b. Falls in moderately price range [5].

The key design is commenced with calculation of torque transmitted:

$T = \frac{bhp \times 5250}{N}$

$T = 1666\ ft \cdot lb = 19{,}992\ in \cdot lb$

The force on the key is:

$F = \frac{T}{r}$

$F = 16835.368\ lb$

Key material data of the key:

- Material: stainless steel 316

- Yield Strength: 205 MPa (29732.7 psi) [5]
- Poisson's Ratio: 0.27 [32]
- Shear Strength: 11705.787 psi
- Safety Factor: 1.5 [3]
- Design Stress: 7803.858 psi

Shear Stress Equation:

$$\tau_1 = {}^{F}/_{A_1}$$

$$L = {}^{F}/_{\tau_1} \times W$$

$$L = 2.876\ in\ (round\ up\ to\ 3\ in)$$

τ_1 = design stress in psi

A_1 = key area in in^2

L = key length in in

W = key width / height in in

The key is illustrated in Figure APP IV.5:

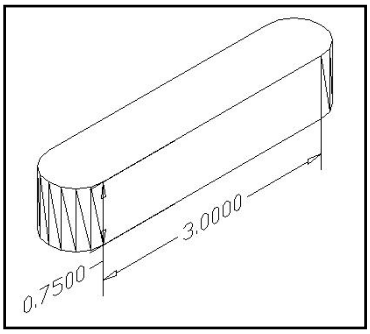


Figure APP IV.5: Illustration of Impeller-Shaft Key (all units in inches)

APP IV.7 Shaft Sleeve Sizing

Shaft sleeve is incorporated in this design with a specific aim to axially locate the impeller on the shaft:

Calculation of axial force:

$$F = P_{dis} \times \frac{\pi(D_2)^2}{4}$$

$$F = 120{,}226.248\ lb$$

F = Force, in lb

P_{dis} = Discharge pressure of the whole multistage pump, in psi

Obviously the actual axial force acting on the impeller is less than this value, due to the facts that:

i. The maximum axial pressure acting on the impellers is less than the pump's discharge pressure (the maximum axial pressure acting on the impellers is about equal to the suction pressure of the last stage impeller).
ii. The maximum axial pressure does not act perpendicular to the whole diameter of the impeller, instead the contours inside the impeller will deviate the fluid pressure to move in radial direction. Therefore the actual effective axially pressured area is less than the whole impeller diameter.

However this value will be used in the calculation, thus will eliminate the needs for factor of safety.

The material for the shaft sleeve will be of the same type as the shaft itself, due to its superiority in corrosion resistance. The sleeve will not be allowed to operate further than its yield strength, therefore:

$\sigma_{yield} = 74\ ksi$ [29]

$A_{sleeve} = {}^{F}/_{\sigma_{yield}}$

$\pi({r_{sleeve}}^2 - {r_{shaft}}^2) = 1.625$

$r_{sleeve} = 1.388\ in$

$D_{sleeve} = 2.78\ in$

σ_{yield} = Yield strength, in ksi (kilo psi)
A_{sleeve} = Cross sectional are of the shaft sleeve, in in^2
r_{sleeve} = Radius of shaft sleeve, in in
r_{shaft} = Radius of shat in in
D_{sleeve} = Diameter of sleeve in in

APP IV.8 Estimation of Impeller Eye Area

$Eye\ area = A_{eye\ diameter} - A_{shaft+sleeve}$

$Eye\ area = 20.985 - 6.07$

$Eye\ area = 14.915\ in^2$

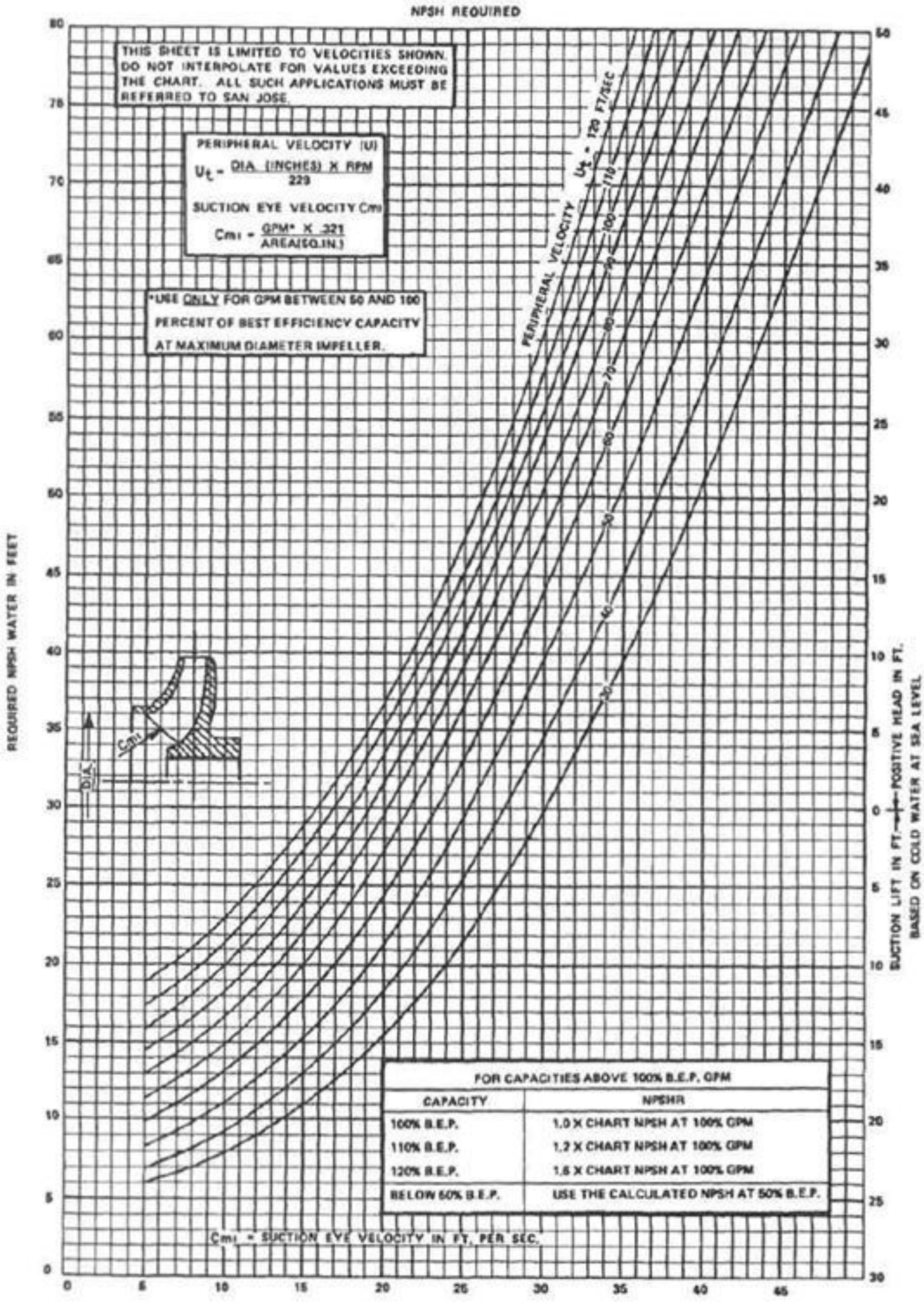


Figure APP IV.6: NPSHR Prediction Chart

APP IV.9 Estimation of Net Positive Suction Head Required (NPSHR)

$C_{m1} = \frac{0.321Q}{Eye\ Area} = 17.341\ ft/sec$

$U_2 = {D_1 \times n}/{229}$

$U_2 = 67.716\ ft/s$

From NPSHR Prediction Chart (Figure APP IV.6) [3];

$NPSHR = 22.7\ ft$

$N_{ss} = \frac{n\sqrt{Q}}{NPSHR^{0.75}}$

$N_{ss} = 8{,}188.329$

C_{m1} = average meridianal velocity at blade inlet in ft/sec

U_2 = impeller peripheral velocity in ft/sec

N_{ss} = suction specific speed

APP IV.10 Determination of Volute Diameter

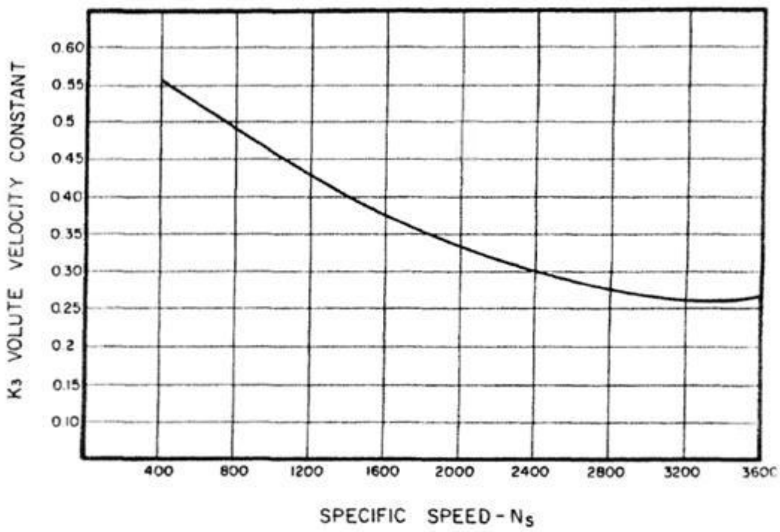


Figure APP IV.6: Volute Velocity Constant Graph

Although this project only focuses on designing the impeller, volute design must also be covered to consider any limitation on the pump casing.

From Volute Velocity Constant Graph (Figure APP IV.6) [3];

$K_3 = 0.45$

$A_g = {0.04Q}/{K_3\sqrt{H}}$

$$A_g = 3.908\ in^2$$

K_3 = *volute velocity constant*

A_g = *volute throat area in in^2*

This value of A_g is final for the type of pump designed in this project, which is single volute centrifugal pump.

In establishing the volute width, the author took into account the needs to accommodate impellers of different diameter and width for future modifications / efficiency upgrade of the pump. The distance from impeller shrouds to casing should be sufficient enough to allow any manufacturing accuracies yet maintain a minimum end play.

According to values published by Stepanoff in Table APP IV.1 [3]:

Table APP IV.1: Guidelines for Volute Width

Specific Speed, N_s	Volute Width, b_3
<1000	2.0 b_2
1000-3000	1.75 b_2
>3000	1.6 b_2

$$b_3 = 1.75 b_2$$

$$b_3 = 1.0115\ in$$

Careful consideration must be taken in designing the cutwater diameter[7] in order to prevent noise, pulsation, and vibration [3]. The vibration will be multiplicated at vane pass frequency[8]. According to guidelines for cutwater diameter table, Table APP IV.2 [3]:

Table APP IV.2: Guidelines for Cutwater Diameter

Specific Speed, N_s	**Cutwater Diameter, D_3**
600-1000	$D_2 \times 1.05$
1000-1500	$D_2 \times 1.06$
1500-2500	$D_2 \times 1.07$
2500-4000	$D_2 \times 1.09$

$$D_3 = 1.06D_2$$

$$D_3 = 12.175\ in$$

[7] Cutwater diameter is the gap between the impeller diameter and volute lip.
[8] Vane pass frequency vibration is the vibration generated at speed of (no. of blades *x* rotating speed of equipment). This vibration is inherent in pumps, compressors, and blowers.

Coordinate Iteration for Impeller End View, Point 1 through 4

Point 1

ar	5deg	15deg	25deg	v,rad	v,deg	R1,a	R1,b	% Dev
1.5745311	0.087266	0.261799	0.436332	0.972829	55.73899	5.027918	5.027917	-2.9E-05
1.5745312	0.087266	0.261799	0.436332	0.972829	55.73898	5.027918	5.027917	-2.4E-05
1.5745313	0.087266	0.261799	0.436332	0.972829	55.73897	5.027918	5.027917	-1.9E-05
1.5745314	0.087266	0.261799	0.436332	0.972828	55.73896	5.027917	5.027917	-1.4E-05
1.5745315	0.087266	0.261799	0.436332	0.972828	55.73895	5.027917	5.027917	-8.8E-06
1.5745316	0.087266	0.261799	0.436332	0.972828	55.73894	5.027917	5.027917	-3.7E-06
1.5745317	**0.087266**	**0.261799**	**0.436332**	**0.972828**	**55.73893**	**5.027916**	**5.027917**	**1.38E-06**
1.5745318	0.087266	0.261799	0.436332	0.972828	55.73892	5.027916	5.027917	6.47E-06
1.5745319	0.087266	0.261799	0.436332	0.972828	55.73891	5.027916	5.027916	1.16E-05
1.574532	0.087266	0.261799	0.436332	0.972827	55.7389	5.027916	5.027916	1.67E-05
1.5745321	0.087266	0.261799	0.436332	0.972827	55.73889	5.027915	5.027916	2.18E-05
1.5745322	0.087266	0.261799	0.436332	0.972827	55.73888	5.027915	5.027916	2.69E-05
1.5745323	0.087266	0.261799	0.436332	0.972827	55.73887	5.027915	5.027916	3.2E-05
1.5745324	0.087266	0.261799	0.436332	0.972827	55.73886	5.027914	5.027916	3.71E-05
1.5745325	0.087266	0.261799	0.436332	0.972826	55.73885	5.027914	5.027916	4.22E-05

Point 2

ar	5deg	15deg	25deg	v,rad	v,deg	R2,a	R2,b	% Dev
1.3784801	0.087266	0.261799	0.436332	0.972829	55.73899	4.401872	4.401871	-2.6E-05
1.3784802	0.087266	0.261799	0.436332	0.972829	55.73898	4.401872	4.401871	-2E-05
1.3784803	0.087266	0.261799	0.436332	0.972828	55.73896	4.401872	4.401871	-1.5E-05
1.3784804	0.087266	0.261799	0.436332	0.972828	55.73895	4.401871	4.401871	-8.7E-06
1.3784805	**0.087266**	**0.261799**	**0.436332**	**0.972828**	**55.73894**	**4.401871**	**4.401871**	**-2.9E-06**
1.3784806	0.087266	0.261799	0.436332	0.972828	55.73893	4.401871	4.401871	2.96E-06
1.3784807	0.087266	0.261799	0.436332	0.972828	55.73892	4.40187	4.401871	8.78E-06
1.3784808	0.087266	0.261799	0.436332	0.972827	55.7389	4.40187	4.401871	1.46E-05
1.3784809	0.087266	0.261799	0.436332	0.972827	55.73889	4.40187	4.401871	2.04E-05
1.378481	0.087266	0.261799	0.436332	0.972827	55.73888	4.40187	4.401871	2.63E-05
1.3784811	0.087266	0.261799	0.436332	0.972827	55.73887	4.401869	4.401871	3.21E-05
1.3784812	0.087266	0.261799	0.436332	0.972827	55.73886	4.401869	4.401871	3.79E-05
1.3784813	0.087266	0.261799	0.436332	0.972826	55.73884	4.401869	4.401871	4.37E-05
1.3784814	0.087266	0.261799	0.436332	0.972826	55.73883	4.401868	4.401871	4.95E-05
1.3784815	0.087266	0.261799	0.436332	0.972826	55.73882	4.401868	4.40187	5.54E-05

Point 3

ar	5deg	15deg	25deg	v,rad	v,deg	R3,a	R3,b	% Dev
1.20157	0.087266	0.261799	0.436332	0.97284	55.73961	3.836977	3.836965	-0.00033
1.201571	0.087266	0.261799	0.436332	0.972837	55.73948	3.836974	3.836964	-0.00027
1.201572	0.087266	0.261799	0.436332	0.972835	55.73934	3.836971	3.836964	-0.0002
1.201573	0.087266	0.261799	0.436332	0.972833	55.7392	3.836968	3.836963	-0.00013
1.201574	0.087266	0.261799	0.436332	0.97283	55.73907	3.836965	3.836963	-6.5E-05
1.201575	**0.087266**	**0.261799**	**0.436332**	**0.972828**	**55.73893**	**3.836962**	**3.836962**	**2.12E-06**
1.201576	0.087266	0.261799	0.436332	0.972825	55.73879	3.836959	3.836962	6.89E-05
1.201577	0.087266	0.261799	0.436332	0.972823	55.73866	3.836956	3.836961	0.000136
1.201578	0.087266	0.261799	0.436332	0.972821	55.73852	3.836953	3.836961	0.000203
1.201579	0.087266	0.261799	0.436332	0.972818	55.73838	3.83695	3.83696	0.000269
1.20158	0.087266	0.261799	0.436332	0.972816	55.73825	3.836947	3.83696	0.000336
1.201581	0.087266	0.261799	0.436332	0.972814	55.73811	3.836944	3.836959	0.000403
1.201582	0.087266	0.261799	0.436332	0.972811	55.73797	3.836941	3.836959	0.00047
1.201583	0.087266	0.261799	0.436332	0.972809	55.73784	3.836938	3.836959	0.000537
1.201584	0.087266	0.261799	0.436332	0.972806	55.7377	3.836935	3.836958	0.000603

Point 4

ar	5deg	15deg	25deg	v,rad	v,deg	R4,a	R4,b	% Dev
1.04737	0.087266	0.261799	0.436332	0.972834	55.7393	3.344558	3.344552	-0.00018
1.047371	0.087266	0.261799	0.436332	0.972832	55.73914	3.344555	3.344551	-0.0001
1.047372	**0.087266**	**0.261799**	**0.436332**	**0.972829**	**55.73899**	**3.344552**	**3.344551**	**-2.6E-05**
1.047373	0.087266	0.261799	0.436332	0.972826	55.73883	3.344548	3.34455	5.11E-05
1.047374	0.087266	0.261799	0.436332	0.972823	55.73867	3.344545	3.34455	0.000128
1.047375	0.087266	0.261799	0.436332	0.972821	55.73852	3.344542	3.344549	0.000204
1.047376	0.087266	0.261799	0.436332	0.972818	55.73836	3.344539	3.344549	0.000281
1.047377	0.087266	0.261799	0.436332	0.972815	55.7382	3.344536	3.344548	0.000358
1.047378	0.087266	0.261799	0.436332	0.972812	55.73805	3.344533	3.344548	0.000434
1.047379	0.087266	0.261799	0.436332	0.97281	55.73789	3.34453	3.344547	0.000511
1.04738	0.087266	0.261799	0.436332	0.972807	55.73773	3.344527	3.344547	0.000588
1.047381	0.087266	0.261799	0.436332	0.972804	55.73758	3.344524	3.344546	0.000664
1.047382	0.087266	0.261799	0.436332	0.972802	55.73742	3.344521	3.344546	0.000741
1.047383	0.087266	0.261799	0.436332	0.972799	55.73726	3.344518	3.344546	0.000818
1.047384	0.087266	0.261799	0.436332	0.972796	55.73711	3.344515	3.344545	0.000894

mohd radzi mohd anua <radzianua@gmail.com>

Request for Quotation

1 messages

hazri@primametals.com <hazri@primametals.com> **Mon, Mar 3, 2008 at 2:46 PM**
Reply-To: hazri@primametals.com
To: mohd radzi mohd anua <radzianua@gmail.com>

> dear Radzi,...

Thank you for your interest in our process , I am pleased to quote our final price confirmation as follow:

Item	Price(Rm)/pcs	material	Validity
1. Impeller casting	Rm45.00	Sus 304.	1 Month

We trust the above quotetion is competitive and if you have any queries,please do not hesitate to contact us and shell be looking forward to receive order confirmation in due couse.

Thank & regards

hazri
[Quoted text hidden]

mohd radzi mohd anua <radzianua@gmail.com>

Enquiry on pump impeller approximate lead-time and cost

2 messages

mohd radzi mohd anua <radzianua@gmail.com> **Thu, Apr 3, 2008 at 2:02 PM**
To: mtan@flowserve.com

Dear Mr. Michael Tan,

My name is Mohd Radzi from PCSB SKO, regarding our phone conversation just now, I was required to find out rough **estimates** of these information:

Item: Pump Impeller
Size: 12 inch (diameter)

Approximate price:
Lead-time delivery:

Thank you in advance for your kind consideration.

Regards,

Radzi Anua

mtan@flowserve.com <mtan@flowserve.com> **Thu, Apr 3, 2008 at 2:51 PM**
To: mohd radzi mohd anua <radzianua@gmail.com>

Estimated price US$15k and 16 - 24 weeks delivery time.

[Quoted text hidden]