AN EVALUATION OF SUBSEA PUMP TECHNOLOGIES THAT CAN BE USED TO ACHIEVE DUAL GRADIENT DRILLING

A Thesis

by

TOLULOPE OLUWADAIRO

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

MASTER OF SCIENCE

December 2007

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	Hans C. Juvkam-Wold
Committee Members,	Jerome J. Schubert
	Kuang-An Chang
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ABSTRACT

An Evaluation of Subsea Pump Technologies That Can Be Used to Achieve Dual Gradient Drilling. (December 2007)

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Chair of Advisory Committee: Dr. Hans C. Juvkam-Wold

Dual Gradient Drilling is an exciting technology which promises to solve the current technical hurdles and economic risks of Deepwater Drilling. Several techniques for Dual Gradient Drilling have been proposed to the industry. One such method involves installing a subsea booster pump at the seafloor with the aim of returning the drilling fluid back to the rig. The pump will manage annular pressures in the wellbore as circulation rates and mud weights vary and will permit early detection of wellbore influxes. Any such pump chosen to achieve this objective will be subjected to very high differential pressures and will be faced with the onerous task of lifting very abrasive and viscous mud slurries from the sea floor back to the drilling rig. This distance in deep water may be well within the range of about 4, 000 – 12,000 feet depending on the operating water depth of the rig.

Several pump technologies available to the industry were examined. Piston pumps are very efficient and can withstand the high differential pressures encountered in the Mudlift Drilling System. However, their drawbacks are their large size and weight and high initial capital cost and maintenance costs. Centrifugal pumps on the other hand are relatively smaller than piston and diaphragm pumps and are generally less expensive. Disc pumps, with their non-impingement design are able to handle solids and fluids with a high gas volume fraction but, like centrifugal pumps, are generally less efficient than reciprocating pumps. Diaphragm pumps are capable of maintaining a constant rate regardless of pressure fluctuations. They can handle very abrasive solids with limited wear on the pump. They also excel at handling very viscous fluids and they can be modified to handle up to 95% gas volume fraction. Like piston pumps, they have very high efficiencies.

The potential of each of these pump technologies to meet the requirements for the Mudlift Drilling System was examined in this thesis. The benefits and drawbacks of each of these pump technologies were highlighted and modifications to meet the demands of the mudlift system evaluated.

DEDICATION

This work is dedicated to my loving parents Olayinka and Olayiwola Oluwadairo, for always being there for me and for believing in me.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Dr. Hans C. Juvkam-Wold for his support, patience and invaluable contributions to this work. It's been a pleasure working with you.

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Clara Adeyemi, thank you for your moral support and prayers while working late on this research.

Finally, to my Lord God, thank you for giving me the grace and granting me this opportunity.

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CHAPTER I

INTRODUCTION TO MUDLIFT DRILLING

Current Deepwater Drilling Problems

The ever increasing demand for oil and gas resources has led to increased exploration in new areas that were considered inaccessible years ago. More wells are being drilled in deeper water locations. This is largely due to improvement in technology as well as favorable prices for oil and gas resources.

However, conventional Deepwater Drilling poses a lot of challenges. In deepwater locations such as the Gulf of Mexico, Offshore Brazil and the Gulf of Guinea, high pore pressures and low fracture gradients result in a narrow margin between pore pressures and fracture pressures requiring many shallow casing points when Conventional Drilling is employed. This in turn necessitates larger wellheads and thus large marine risers and eventually very large and more expensive drilling rigs or vessels to support the large risers. Well control is more difficult and it becomes even more expensive to drill as water depths increase. [1,2]

Figures 1.1 and 1.2 illustrate the narrow window between formation pore pressures and fracture pressures and compare the casing requirement for Conventional Drilling and Dual Gradient Drilling. Casing seats are indicated by the horizontal blue lines.

This thesis follows the style and format of *Journal of Petroleum Technology.*

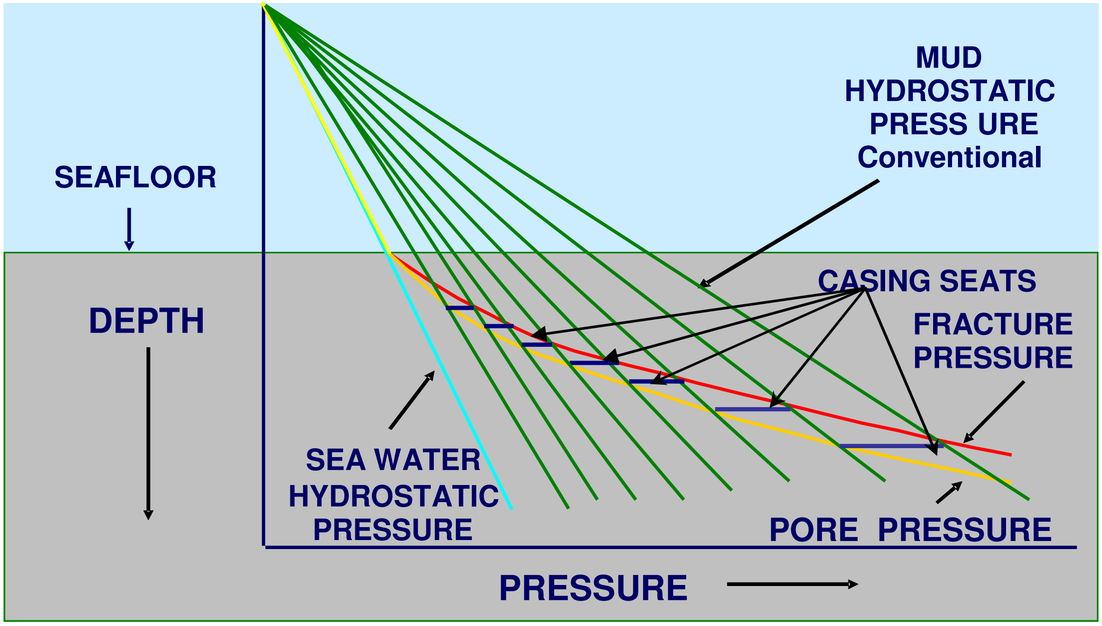


Fig.1.1—Conventional Deepwater Drilling: Several Casing Strings Required.

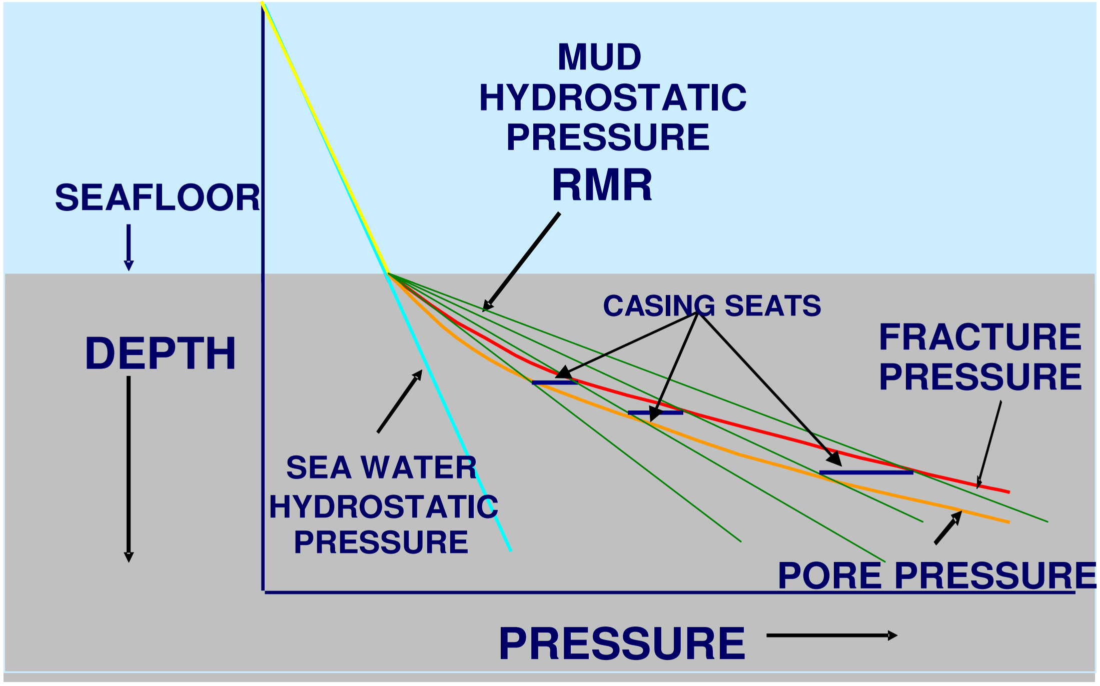


Fig.1.2—Dual Gradient Drilling: Fewer Casing Strings Required.

Benefits of Mudlift Drilling

Mudlift Drilling offers a feasible approach to the current challenges encountered in Deepwater Drilling. These benefits include:

i.) Savings from fewer casing strings required and ultimately a reduction in the time requirement to drill a well.

ii.) Larger diameter production string with increased flow capacity could be realized in a Dual Gradient Drilling System.

iii.) A considerable reduction in weight and space requirement which in turn allows the use smaller semi-submersible drilling rigs to drill to the desired target depth.

iv.) A sizeable reduction in the volume of drilling mud required to reach the target depth, easing storage requirements on the drilling rig.

v.) Zero discharge and elimination of damage to the environment which can be achieved with a closed system where the drilling fluid is recycled. This system also permits the use of more expensive specialty muds.

vi.) Shallow drilling hazards can better be controlled because the Dual Gradient Drilling System permits the use of a heavier mud. The use of a heavier mud also impacts positively on wellbore stability.

vii.) Geological targets can be reached in virtually any water depth.

viii.) An enhanced margin of safety is achieved from an expanded window between pore pressures and fracture pressures. Hence influxes and lost circulation problems can be managed more easily.[1-7]

Mudlift Drilling System Configuration

Mudlift Drilling is a form of Dual Gradient Drilling which eliminates the use of a marine riser as the return path for the drilling fluid and cuttings. Instead, it makes use of a subsea pump located on the seafloor, which acts as a choke to manage annular pressures. One or more small diameter return lines (typically two 4.5 inch ID pipes or one 6 inch ID pipe) function as the return path for the drilling fluids and cuttings.[8,9] Figure 1.3 and Figure 1.4 contrast Conventional Drilling and Mudlift Drilling.

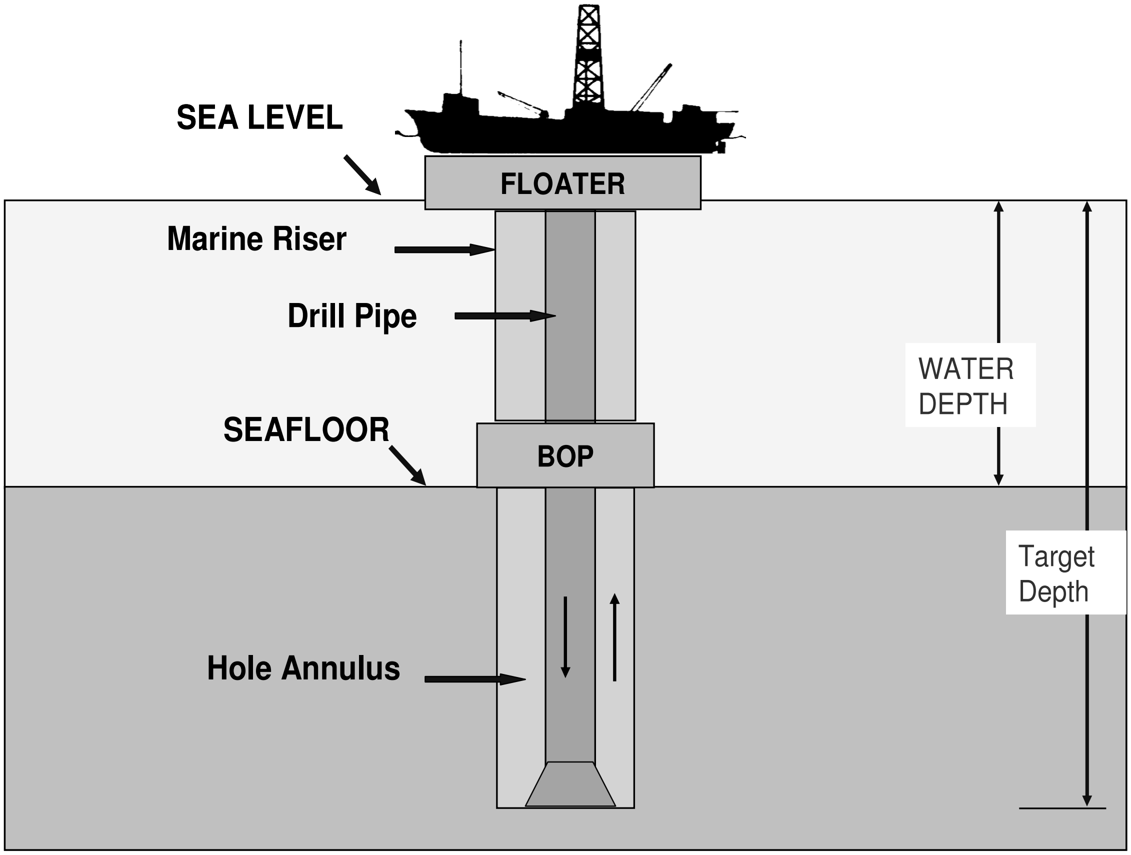


Fig. 1.3—Schematic of a Conventional Deepwater Drilling System.

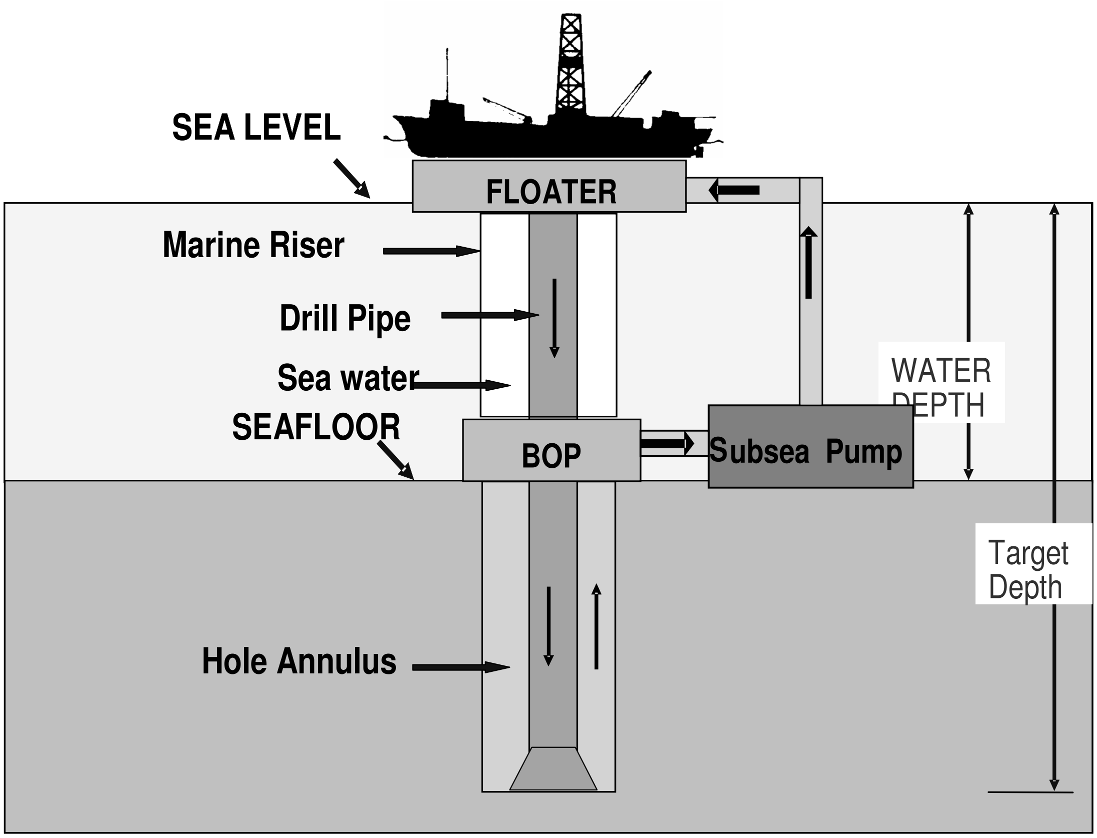


Fig. 1.4—Schematic of a Mudlift Drilling System.

Essentially, a dual pressure gradient is created in the annular section of the wellbore. An equivalent seawater hydrostatic pressure gradient is maintained from the surface to the seafloor, while a heavier mud hydrostatic column can be implemented from the seafloor to the total depth.[2] This technique has potential advantages of cost, time and environmental savings.

The subsea pump is the most critical component of the SMD system and is designed to function in 2 operational modes: The fixed inlet pressure mode and the constant circulation rate mode. A manual override mode is also available. On normal operation, the pump is set at the fixed inlet pressure mode, which may be set at exactly or slightly above seawater hydrostatic pressure. This results in a fixed bottomhole pressure as any change in the inlet pressure of the pump will result in a corresponding change in the bottomhole pressure.[3,8] Figure 1.5 shows a subsea mudlift pump built for the SMD JIP.

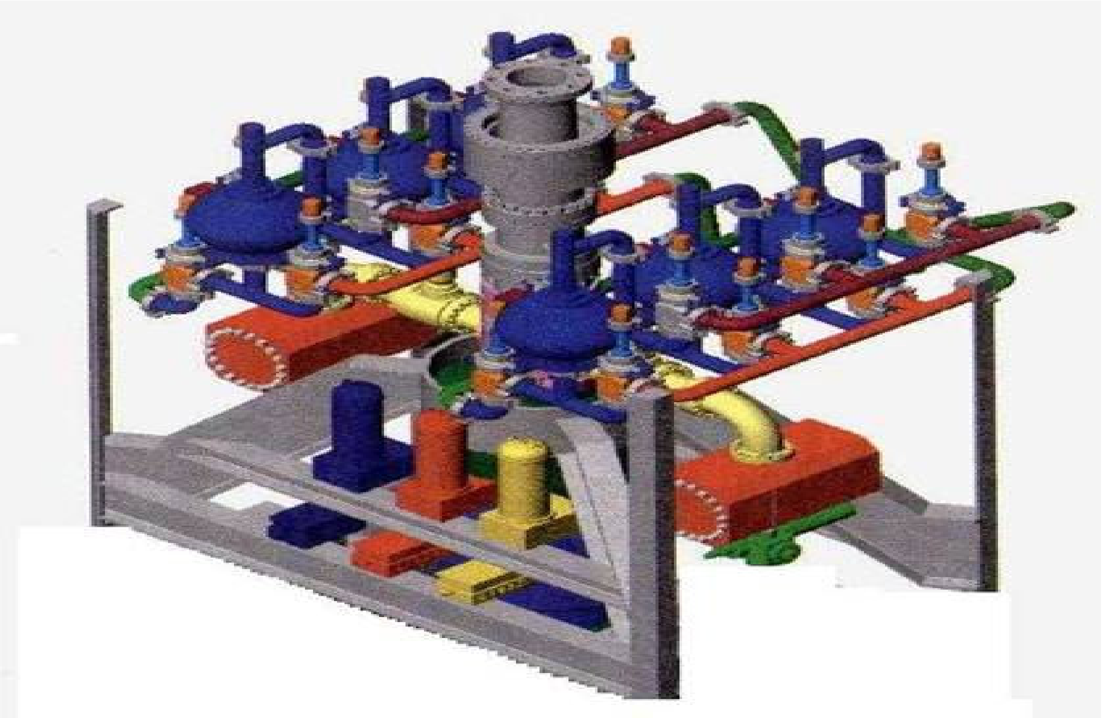


Fig. 1.5—Seawater driven Subsea Mudlift Pump.[2]

Objective

The purpose of this research is to evaluate the potentials of different pump technologies for Mudlift Drilling.

Importance

The success of any Mudlift Drilling system will depend largely on the ability of the mudlift pump to create a dual pressure gradient at the annulus, by managing wellbore pressures. The subsea mudlift pump achieves this by maintaining a constant inlet pressure while drilling and maintaining a constant flow rate to control wellbore influxes. The pump is also faced with the onerous task of returning heavy, abrasive, viscous drilling mud, laden with cuttings, junk and metal shavings from the seafloor back to the rig. This distance spans the operating water depth of the rig and may be as high as 10, 000 feet. Any such pump, faced with this burden, will have to be able to withstand very high differential pressures and horsepower requirements for the system. Success of the system will depend on the ability of these pumps to fulfill the demanding requirements of the system.

CHAPTER II

THE SUBSEA MUDLIFT PUMP

The subsea mudlift pump (MLP) is the key to achieving the objectives of a Mudlift Drilling System and it is the central equipment in the system. Its primary function is to lift the annular returns at the mud line to the surface and to keep the wellbore pressure constant by maintaining a fixed inlet pressure at the suction side of the pump.[3,9]

The mud lift pump is the most critical component of the Mudlift Drilling System. A quick overview of the flow path of the drilling fluid best explains the central role the pump plays in the system. Figure 2.1 depicts the flow path of drilling fluid in the Mudlift Drilling System.

Flow Path of Drilling Fluid in the Mudlift Drilling System

i.) The mud from the active mud pits flows to the mud pumps.

ii.) The drilling fluid is pumped through the mud pumps into the drill string.

iii.) The drilling mud goes through the Drill String Valve located in the BHA.

iv.) The mud then flows through the bit nozzles, up through the annulus to the Subsea Rotating Diverter (SRD).

v.) The SRD diverts the cuttings laden mud to the Solids processing units (SPU).

vi.) The SPU crushes the cuttings in the mud and then diverts the mud to the inlet of the Subsea mudlift pump.

vii.) The mudlift pump returns the drilling mud via the return line to the mud system.

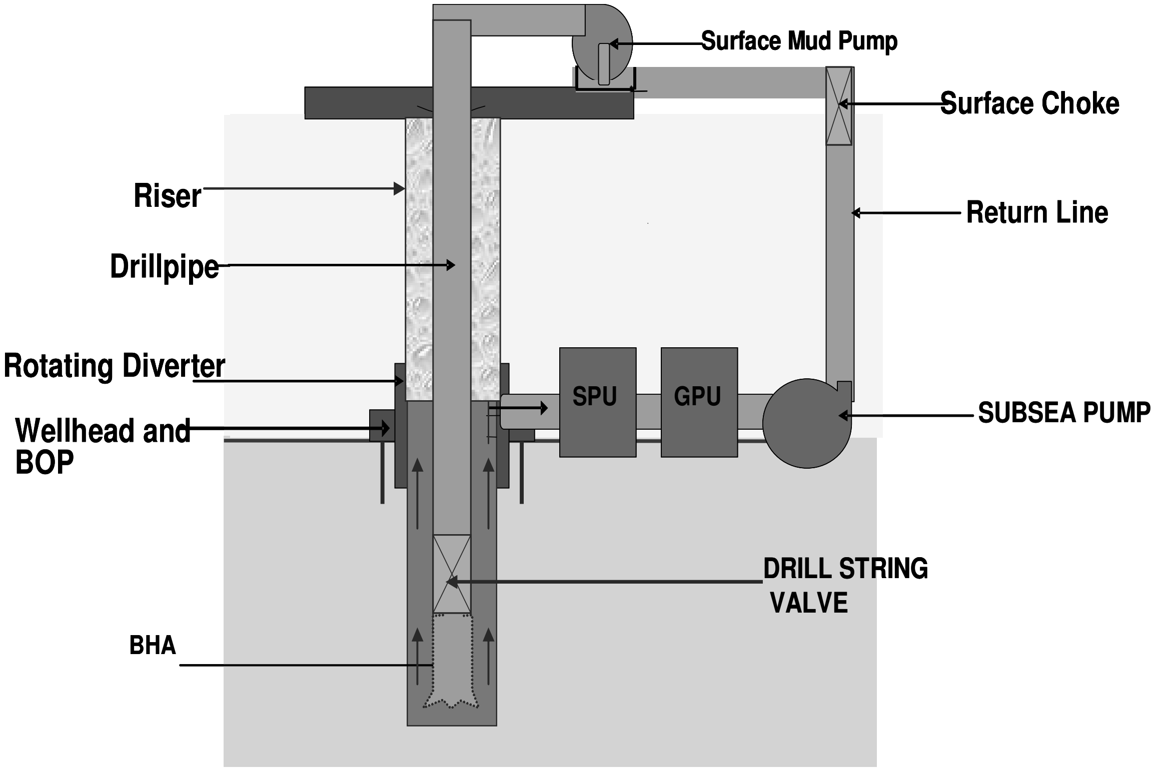


Fig. 2.1—Flow Path of Drilling Fluid in the Mudlift Drilling System.[2]

Modular construction of the pump permits several pumps to be cascaded in order to achieve a higher hydrostatic head and flow rate. In order to meet the requirements of the mudlift system, the pump is configured to work in conjunction with other ancillary equipment which includes:

i.) *The drill string valve*: The drill string valve is used to prevent u-tubing from the drill pipe to the annulus when the mud pumps are stopped.

ii.) *The Subsea Rotating Diverter (SRD)*: The subsea rotating diverter is used to isolate the annulus from the ambient seawater and mechanically divert the mud from the annulus to the subsea pump. It also prevents gas from entering the riser.

iii.) *The Solids Processing Unit (SPU)*: The solids processing unit mechanically reduces the size of solids from the wellbore.

iv.) *The Instrumentation and Control system for the pump*: This system permits monitoring of pressure and flow rate changes on the pump. It allows for control of the pump speed and imposition of a back pressure on the annulus as the pump is being stopped.

v.) *Chokes*: These may be used to impose a back pressure in the return line to prevent the hydrostatic pressure in the return line from falling too low.[3]

Functions of the Subsea Mudlift Pump (MLP)

- Returns the drilling mud and cuttings via the return line to the surface mud system to be processed and re-used.
- Provides the lift that allows the well to realize seawater gradient above the mudline.
- Permits good control of the annular pressure by adjusting the discharge rate to maintain a fixed pressure at the suction side of the pump.
- Permits early detection and control wellbore influxes observed as increasing flow rates.[3,4]

Design Requirements for the Subsea Mudlift Pump

The primary function of the subsea mudlift pump is to return the drilling fluid from the annulus at the seafloor to the surface. Once the drilling fluid is circulated through the drillstring and bit, it becomes mixed with cuttings, rock chips, gases, metal shavings and other debris. The pump will have to lift this drilling fluid, which is laden with debris from the seafloor to the surface via the return line. This distance may range from 4000 ft– 12000 ft depending on the operating water depth. Therefore, in selecting a pump to achieve this objective, the following design criteria must be met:

1. Mudlift Drilling System Specifications
    a) Water depth
    b) Pump flow rate
    c) Mud density & rheology
    d) Pump size and space requirements
    e) Pump pressure and flow rate control
2. Pump Requirements
    a) Hydrostatic head of the pump
    b) Maximum differential pressure across the pump
    c) Hydraulic horsepower requirements
    d) Shaft / Motor power
    e) Operating temperature

Based on the conclusions from the Subsea Mudlift Joint Industry project (SMD JIP), the requirements of any such pump configured to achieve Dual Gradient Drilling are very demanding. The pump must be able to pump up to 5% volume of debris which includes cuttings, metal shavings and junk. It should be able to pump up to a 100% gas volume in the event of a gas kick. The pump must also be able to pump at any rate from 0 – 1,800 gallons per minute over a static head of 10,000 ft and function properly within an operating temperature range of 28°F – 180°F.[8] Hydraulic modeling based on the flow rates and mud densities that drive the system require the pump to have a pressure differential rating of 6500 psi. Precise control of the pump pressure at the suction side of the pump and the discharge rate at the pump's outlet is vital to the success of the dual gradient mudlift system. A summary of the design parameters is shown in the Table 2.1 and Table 2.2.

Table 2.1 — Mudlift Drilling System specifications

DESIGN PARAMETER	**SPECIFICATION**
Water depth	10,000 ft
Flow rate	1800 gpm
Fluid density	8.55 - 18.5 ppg
Suction pressure	4522 psi (Seawater hydrostatic pressure + 50 psi trip margin)
Flow rate control	Pump at any rate from 0-1800 gpm and maintain a fixed rate
Pressure control	Maintain a fixed inlet pressure regardless of rate fluctuations

Table 2.2—Mudlift Drilling System fluid properties

Fluid Characteristic	**Specification**
Density	8.55 – 18.5 lb/gal.
Rheology (R_{600} / R_{300})	2/1 – 145/85.
Solids content & size	Up to 2 in. diameter and up to 5% volume fraction.
Gas content	Up to 100% volume in the event of a kick.

The mudlift system specifications are the design requirements for the subsea mudlift system. The fluid to be handled by the pump will include debris and may contain gas in the event of a kick. The type and nature of the fluid will also be a major factor that will influence pump selection. The density and viscosity of the fluid to be handled may vary widely depending on the contents of the fluid. In order to meet these specifications the mudlift pump must meet the following requirements that are summarized in Table 2.3.

Table 2.3—Mudlift Pump requirements

DESIGN PARAMETER	**SPECIFICATION**
Total Static head (ft)	10,000 ft
Differential pressure head (psi)	6500 psi
Hydraulic Horsepower	4800 HP
Operating temperature	28^{o}F– 180^{o}F

Total Static Head

The pump will have to return the drilling fluid and cuttings from the seafloor to the surface via the return line. This distance represents the total static head required of the pump. It is equal to water depth.

Total Dynamic Head

It is the work done by the pump in moving the drilling fluid from the seafloor to the surface through the return line. It includes the pressure losses in the return line due to friction.

Hydraulic Horsepower (HHP)

This is the input power required to drive the pump. It is the work performed in moving the total weight of the fluid against the differential pressure head in a given time. The hydraulic horsepower of the pump is given by the equation below:

$$HHP = \frac{Q\,\Delta P}{1{,}714}, \ \ where\ \ Q = Flow\,rate\,(gal/\mathrm{min}) \\ and\ \Delta P = Differential\ pressure\,(psi) \tag{3}$$

Efficiency (η)

This is a factor that accounts for losses in the pumping process. It is the ratio of the hydraulic horsepower required to the Motor-shaft power (brake horsepower).

It is expressed as:

$$\eta = \frac{HHP}{BHP}\ , \ \ where\ \ HHP = Hydraulic\ Horsepower\ and\ BHP = Brake\ Horsepower. \tag{4}$$

The losses in efficiency are primarily due to friction losses, slip or recirculation losses, as well as shock losses due to the rapid change in the fluid direction within the pump.

Hydraulic Analysis of the Mudlift Drilling System

In order to determine the pump requirements for a Dual Gradient Drilling System, an assessment of the wellbore hydraulics was carried out using the Marine Riserless Drilling Simulator and the Toolkit for the SMD JIP. The mud weights and circulation rates that drive the system design are shown in Table 2.4 below. These rates were chosen based on the maximum circulation rates and mud densities required to achieve effective hole cleaning. *(Refer to Appendix A for the input design data to the simulator)*

Design Data

Table 2.4—Mudlift Drilling System design parameters

HOLE SIZE	WATER DEPTH	FLOW RATE	MUD DENSITY
12.25	10, 000 ft	1, 800 gpm	8.6 ppg
12.25	10, 000 ft	1, 200 gpm	18.5 ppg

The result from the simulator based on the input data, indicate that a pump with a differential pressure of 6500 psi and a hydraulic horsepower requirement of 4550 HP will be required to return the drilling fluid back to the surface. Figure 2.2 and Figure 2.3 show the wellbore pressure profile and the simulator results respectively.

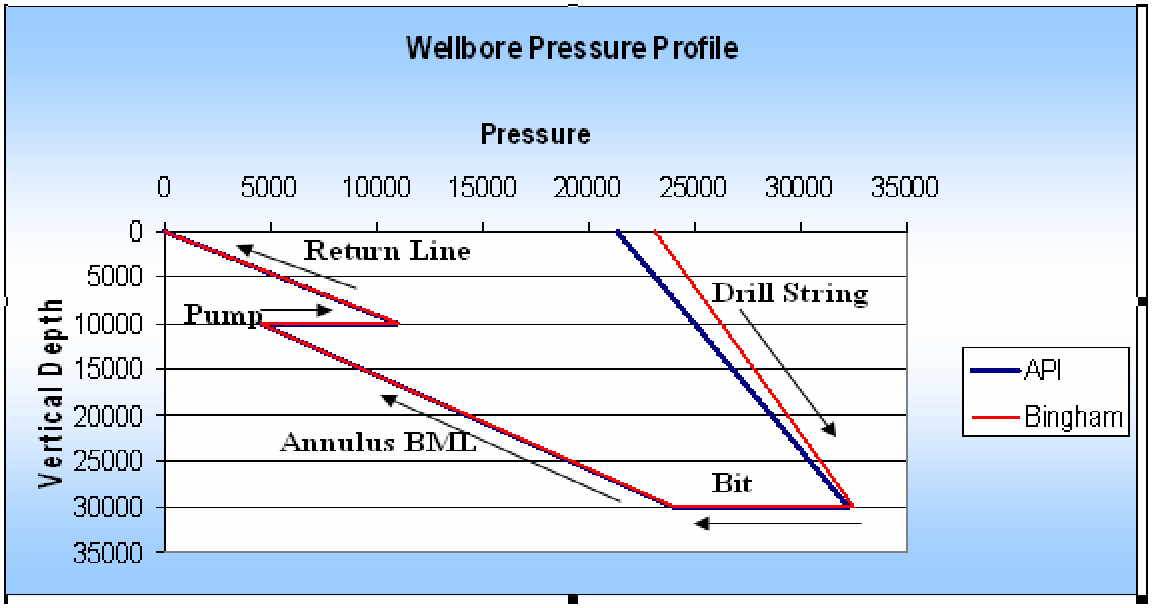
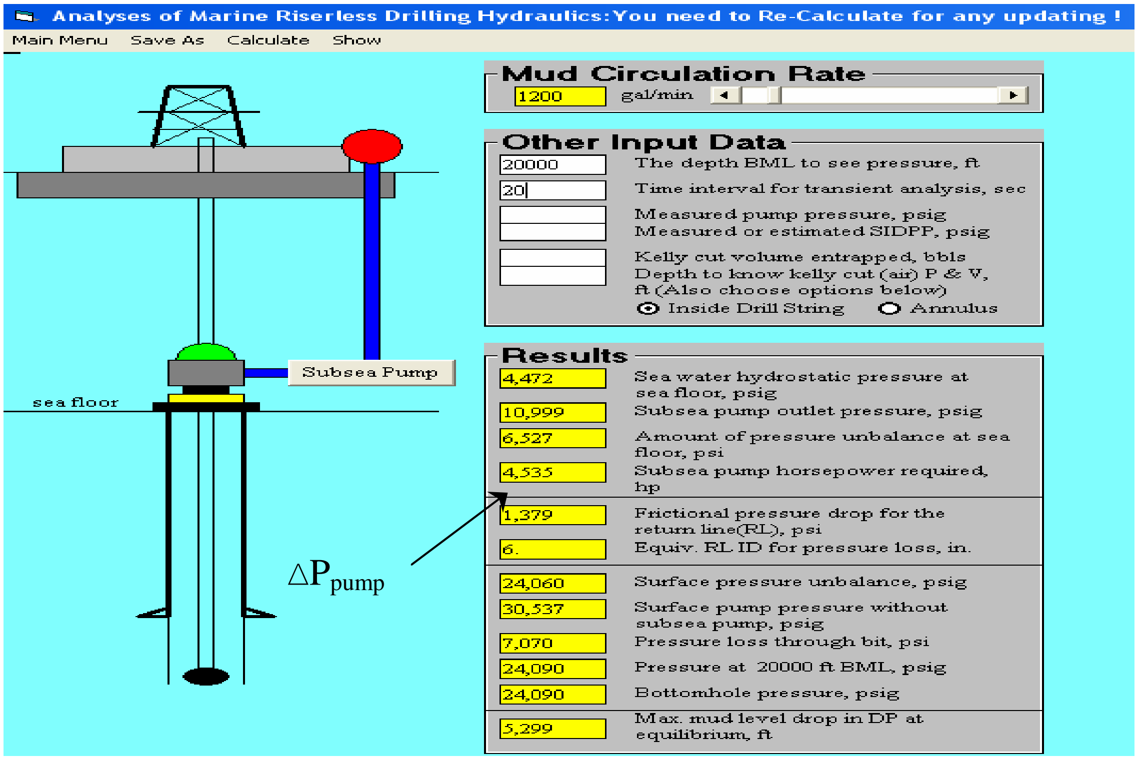


Fig. 2.2—Wellbore Pressure Profile Results from Toolkit for SMD.



Mud Circulation Rate

1200 gal/min

Other Input Data

20000	The depth BML to see pressure, ft
20	Time interval for transient analysis, sec
	Measured pump pressure, psig
	Measured or estimated SIDPP, psig
	Kelly cut volume entrapped, bbls
	Depth to know kelly cut (air) P & V, ft (Also choose options below)

● Inside Drill String ○ Annulus

Results

4,472	Sea water hydrostatic pressure at sea floor, psig
10,999	Subsea pump outlet pressure, psig
6,527	Amount of pressure unbalance at sea floor, psi
4,535	Subsea pump horsepower required, hp
1,379	Frictional pressure drop for the return line(RL), psi
6.	Equiv. RL ID for pressure loss, in.
24,060	Surface pressure unbalance, psig
30,537	Surface pump pressure without subsea pump, psig
7,070	Pressure loss through bit, psi
24,090	Pressure at 20000 ft BML, psig
24,090	Bottomhole pressure, psig
5,299	Max. mud level drop in DP at equilibrium, ft

Fig. 2.3—Marine Riserless Drilling Hydraulic Simulator Results.

Horsepower requirements of the pump increase as circulation rates increase. This is as a result of the pressure losses due to friction as the drilling fluid flows through the return line. These friction losses constitute system resistance and as such increase the differential pressure across the pump. Figure 2.4 depicts the impact of circulation rates on the pump's horsepower requirement and Figure 2.5 is the system head curve for our mudlift system design.

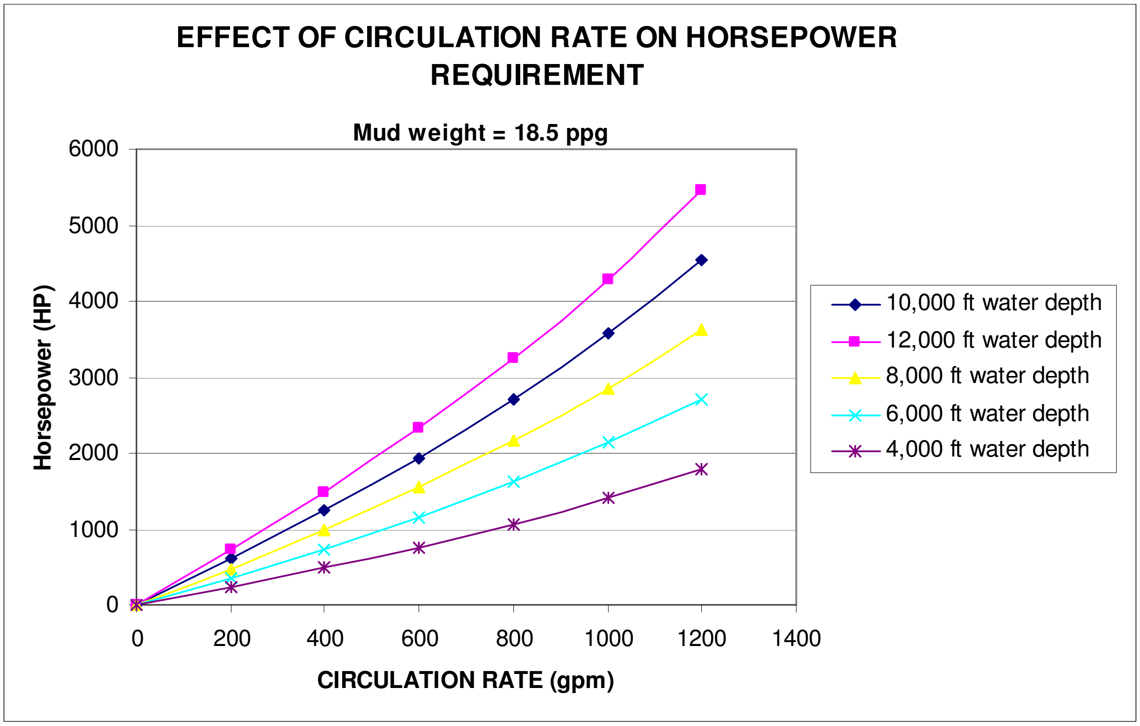


Fig. 2.4—Impact of Circulation Rates on Pump Horsepower.

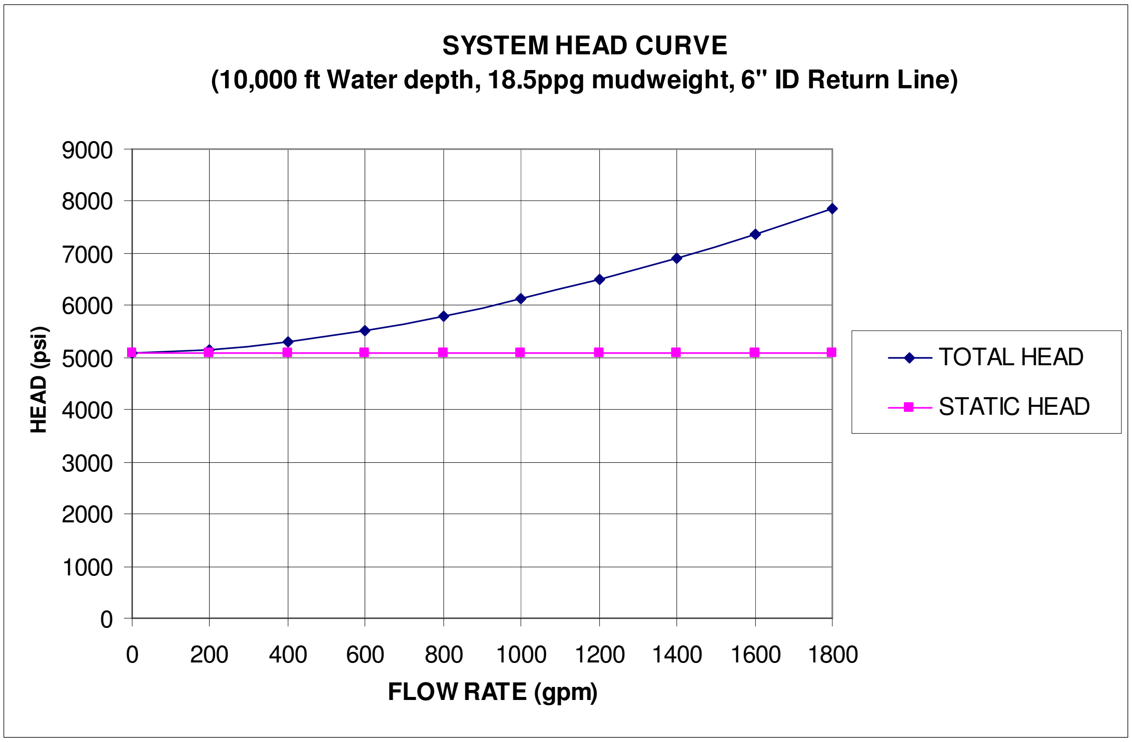


Fig. 2.5—System Head Curve for the Mudlift Drilling System.

Impact of Fluid Characteristics on the Subsea Mudlift Pump

The nature of the drilling fluid is a critical factor that must be considered in the selection of a mudlift pump to meet the system requirements. The drilling fluid may be a heavy weight, highly viscous mud. The amount of solids entrained in the fluid as well as the gas volume fraction in the fluid impact the differential pressure and consequently horsepower requirements of the pump. Figures 2.6 – 2.9 below depict the impact of fluid densities and viscosities on the pump's horsepower requirement.

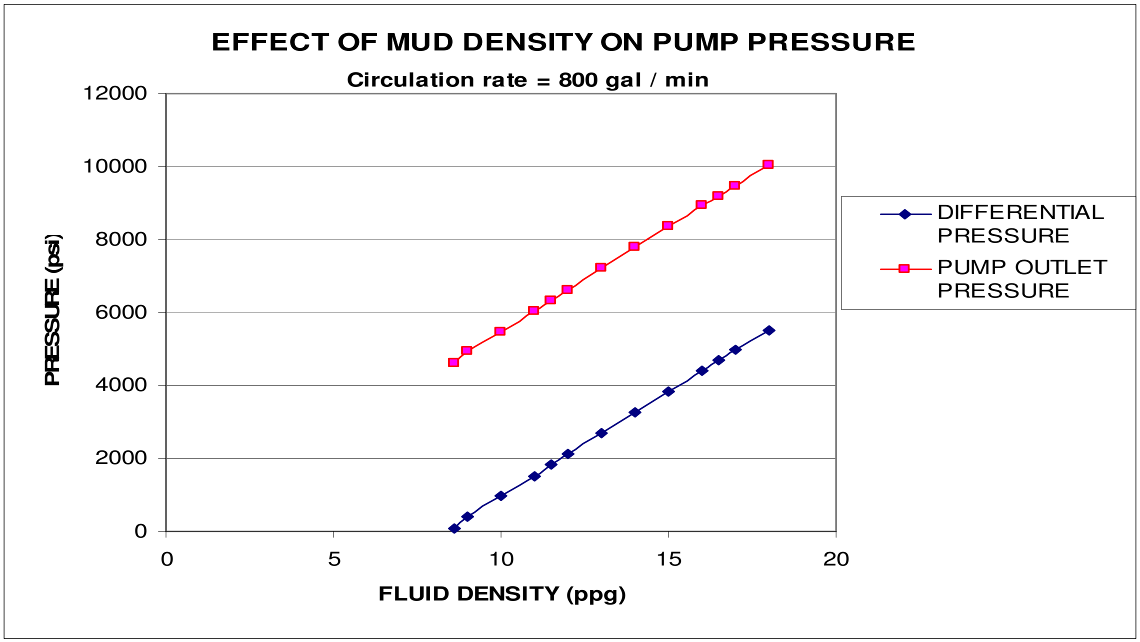


Fig. 2.6 — Impact of Mud Density on Pump Horsepower Requirements.

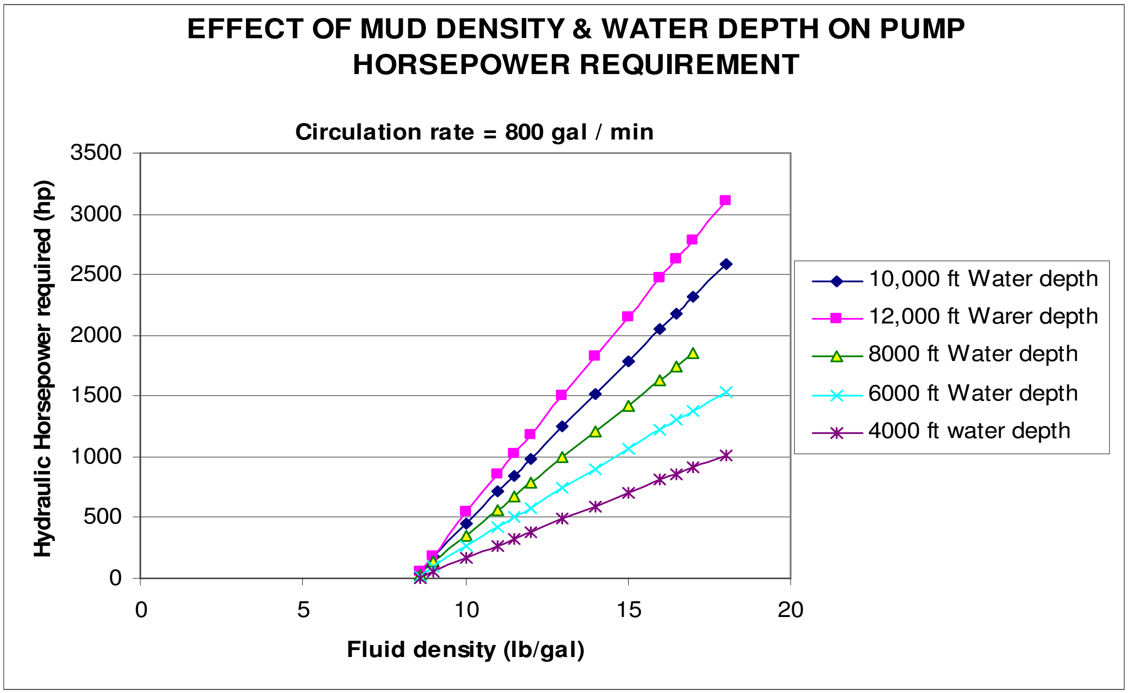


Fig. 2.7—Impact of Mud Density and Water Depth on Pump Horsepower.

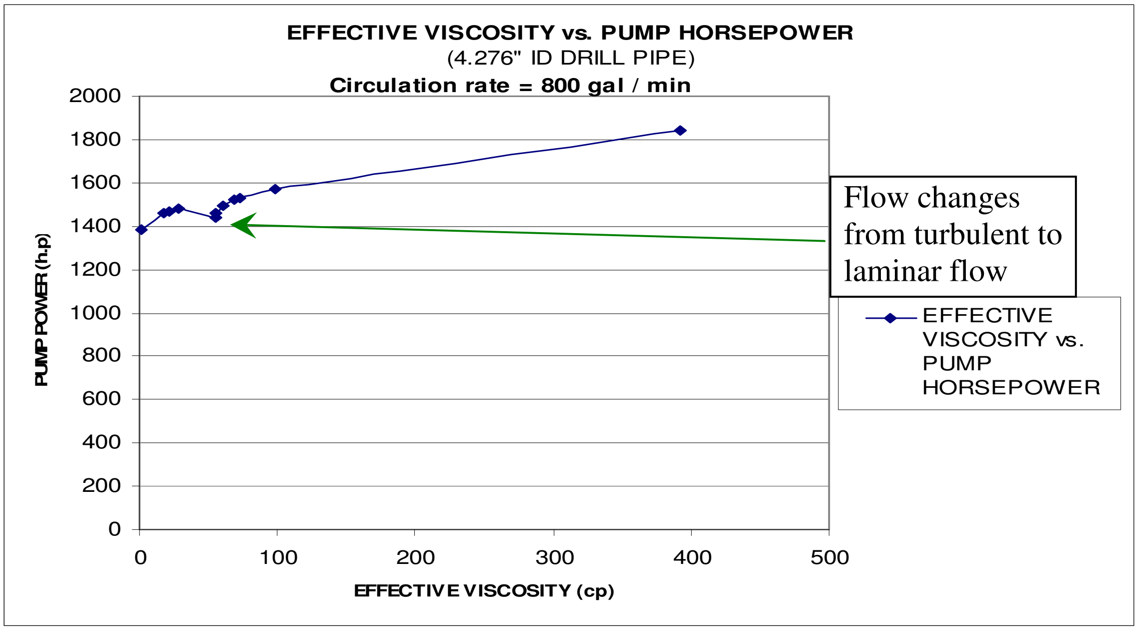


Fig. 2.8—Impact of Fluid Viscosity on Pump Horsepower Requirements.

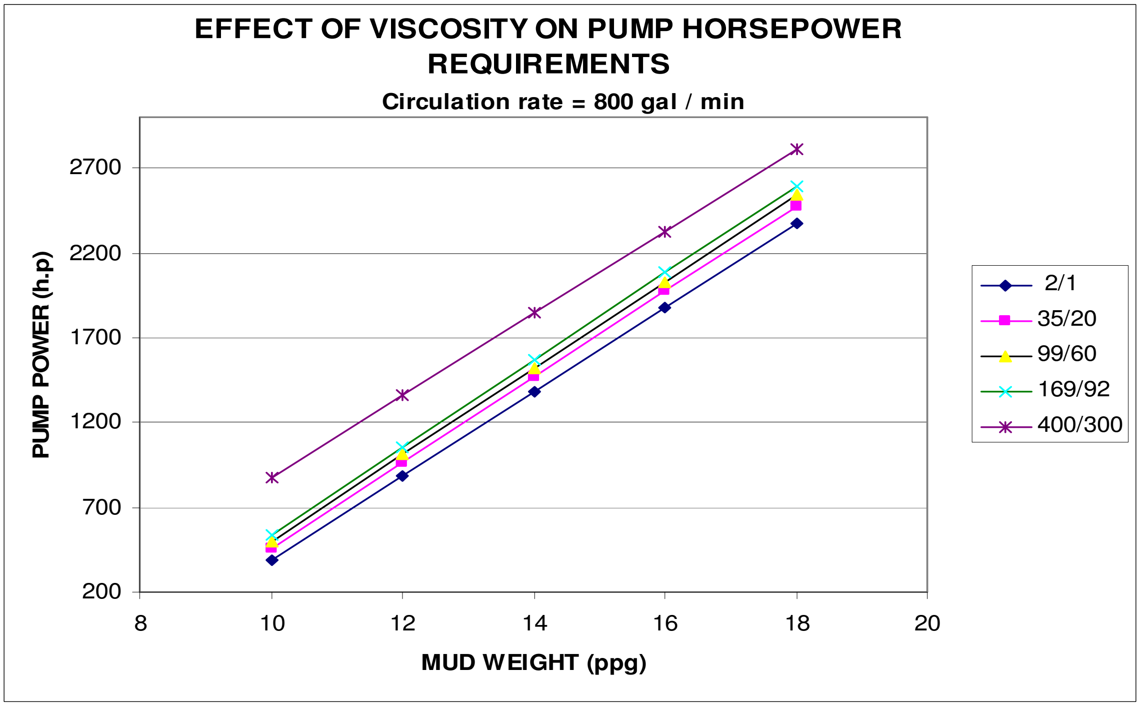


Fig. 2.9—Impact of Fluid Viscosity and Mud Density on Pump Horsepower.

Impact of Gas Kicks on the Subsea Mudlift Pump

The Subsea mudlift pump is designed to act as a choke by being able to be switched from a fixed inlet pressure to a fixed discharge rate. The fixed inlet pressure mode is the normal operating mode of the pump. A constant bottomhole pressure is maintained as long as the inlet pressure to the pump remains constant and the hydrostatic pressure of the mud below the mud line remains constant. The inlet pressure to the subsea pump can be expressed by the equation below:

$$P_{in} + 0.052\rho_m D_{BML} + \Delta P_{f,BML} = bhp \tag{2.1}$$

$where,\ P_{in} = Inlet\ pressure\,(psi),\ \rho_m = density\,(ppg),$
$D_{BML} = Depth\ below\ mudline\,(ft),\ bhp = Bottom\,hole\ pressure\,(psi)$
$\Delta P_{f,BML} = \mathrm{Pr}essure\ loss\ in\ the\ annulus\ due\ to\ friction\,(psi).$

The outlet pressure of the pump is equal to the sum of the hydrostatic pressure exerted by the mud column in the return line, the friction pressure and the pressure exerted by the surface choke. The outlet pressure of the pump can be expressed by the equation below:

$$P_{out} = 0.052\rho_m D_w + \Delta P_{f,RL} + \Delta P_{choke} \tag{2.2}$$

$P_{out} = Disch\arg e\ \ pressure\,(psi),\ D_w = Water\ \ depth\ \,(ft),\ \rho_m = mud\,density\,(ppg),$
$\Delta P_{f,RL} = Friction\,pressure\,loss\ in\ return\ line\,(psi),\ \Delta P_{choke} = Choke\ \ pressure\,(psi)$

A gas influx below the mud line reduces the density of the drilling fluid and causes a subsequent drop in the bottomhole pressure. The reduced bottomhole pressure causes more influx of gas into the wellbore and an increase in the influx rate. The influx rate continues to increase as long as the inlet pressure to the pump remains constant. As the influx rate increases, the pump's discharge rate also increases in order to maintain a constant inlet pressure.[9,10]

In order to stop the influx, the pump has to be switched to the constant rate mode and the discharge rate of the pump reduced to its initial rate. This causes the inlet pressure to the pump to build up. The increasing inlet pressure imposes back pressure on the annulus, which in turn causes an increase in the bottomhole pressure until the influx is stopped. The kick is then circulated out through the annulus below the mudline, up through the pump and then out of the hole through the return line.

When the gas influx is in the return line, a significant reduction in the hydrostatic pressure due to the expanding gas column in the return line causes a drop in the discharge pressure of the pump. If the pressure at the outlet of the pump falls too low below the inlet pressure of the pump, the pump will not be able to handle the pressure differential and this can lead to the fluid flowing through the pump due to the pressure reversal. If this happens, this will result in a drop in the bottomhole pressure and a loss of well control. This pressure reversal problem can be controlled by applying a back pressure through the choke at the surface during well control operations to provide a positive differential pressure.

The effect of an increase in kick size, kick intensity, water depth, depth below the mudline and choke pressure on pressure reversal across the pump. The results are summarized in Table 2.5 below.

Table 2.5—Impact of Gas Kicks on Differential Pressure across the Pump[9]

Parameter (Increase)	Max. Differential Pressure	Reason
Kick Size	Decrease	Reduction in hydrostatic pressure in the return line
Kick Intensity	Decrease	Increase in the inlet pressure to the pump
Water Depth	Depends	Depends on kick size
Well Depth (BML)	Decrease	Rapidly expanding gas due to pressure reduction at surface
Choke Pressure	Depends	Depends on surface choke pressure applied

Kick Size

The volume of gas influx is one of the main contributors to the pressure reversal problem that may occur across the pump. When the kick enters the return line, it causes a significant drop in the hydrostatic pressure in the return line and thus a drop in the discharge pressure at the pump. If the differential pressure between suction and the discharge side of the pump becomes the too high, the fluid will flow through the pump leading to loss of pumping action and well control. Early kick detection is necessary in order to avert a large volume of gas influx.

Kick Intensity

The kick intensity is a measure of the increase in bottomhole pressure required to balance the new formation pressure. As the kick intensity increases, the inlet pressure required to raise the bottomhole pressure also increases. An increase in the inlet pressure to the pump results in a reduction in the pressure differential across the pump.

Water Depth

The effect of water depth on the differential pressure across the pump in the event of a kick depends on the kick size and the height of the kick in the return line.

Well Depth Below the Mudline

The formation pressure is proportional to the depth of the wellbore. Therefore the deeper the well, the higher the formation pressure encountered. Gas will expand more as it rises to the surface due to the large drop in pressures from deeper formations and the lower surface pressures above the mudline. The expanding gas in the return line results in a reduction in hydrostatic pressure and consequently differential pressure across the pump.

Choke Pressure

Chokes are used to impose a back pressure on the pump. An increase in choke pressure will result in an increase in the hydrostatic pressure in the return line. Consequently, the differential pressure across the pump is increased.[10]

CHAPTER III

MUDLIFT PUMP TECHNOLOGIES

Several pump technologies are currently available in the industry. These can be divided into two broad categories:

- Positive Displacement Pumps
- Rotodynamic pumps.

Positive Displacement Pumps

Positive displacement pumps operate based on the principle that the volume of fluid transferred through the pump is proportional to the volume created by the pumping chamber and the speed at which that fluid is moved. A fixed volume of fluid is forced from the inlet pressure section of the pump into the discharge section. With reciprocating pumps, this is performed intermittently, while with screw pumps, this is performed continuously. The fluid is moved into a fixed cavity so that when the fluid exits, the vacuum that is created draws in more fluid. Positive displacement pumps are suitable for liquids with high viscosities and for applications that require high pressures. Positive displacement pumps can further be grouped into:

a) Rotary Pumps

Rotary pumps have rotating parts which trap fluids at the suction port and force it out at the discharge port. A known quantity of fluid is displaced with each revolution of the pump shaft. They include Progressive Cavity (single screw) pump, Twin screw pump, Gear pumps, Lobe pumps and Vane pumps *b) Reciprocating Pumps*

Reciprocating pumps make use of a reciprocating piston or diaphragm as the pumping element. The fluid enters the pump through a suction valve and is pushed out through a discharge valve by the reciprocating action of a piston or diaphragm. These pumps are generally utilized in applications that require very high pressures and relatively low rates. Their drawback is their pulsating flow and large size. Piston and diaphragm pumps are classified as reciprocating pumps.

Rotodynamic Pumps

Rotodynamic pumps on the other hand raise the pressure of the fluid by first imparting kinetic energy to it and then converting the kinetic energy exerted on the fluid to pressure. The impellers rotate within the fluid and impart a tangential acceleration to the fluid and consequently an increase in energy of the fluid. This energy is converted into pressure when the centrifugal forces arising form the radial flow through the impeller creates an angular momentum. This angular momentum is converted to pressure when the fluid is slowed down and re-directed through a stationary diffuser. Rotodynamic pumps generally have lower efficiencies than Positive Displacement pumps but operate at relatively higher speeds and thus permit higher flow rates relative to their smaller size. They include Multi-Stage Electrical Submersible pumps, Centrifugal pumps, Disc pumps and Helico-axial (Poseidon) pumps. Figure 3.1 shows a general pump classification.

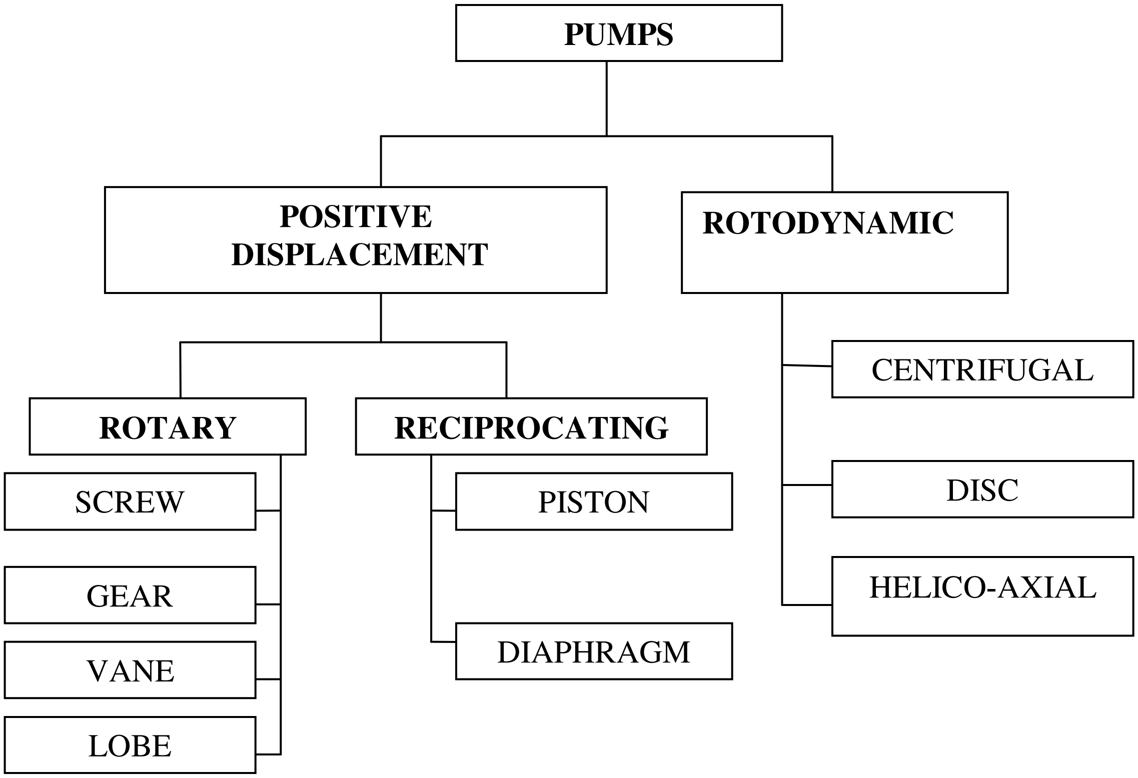


Fig. 3.1—General Pump Classification.[11]

Several pump technologies are available in the industry for use as the Subsea pumps in order to achieve a dual gradient and return mud from the seafloor back to the rig. Four such pumps have been designed for dual gradient development between 1996 and 2005 timeframe. These pumps include:

a) Centrifugal Pump
b) Diaphragm Pump
c) Piston Pump
d) Disc Pump

The objective of this research is to compare and contrast these pump technologies for use in Dual Gradient Drilling.

Centrifugal Pump

Centrifugal pumps generate pressure by converting a velocity head into a static head. A centrifugal pump contains a central rotating wheel or impeller which imparts a high velocity to the incoming fluid. The flow of the fluid through the impellers generates centrifugal forces which impart an angular momentum on the fluid and thus increase its energy. This energy is converted into a static pressure head in the diffusing section of the pump casing. Centrifugal pumps typically operate at relatively high rotation speeds ranging from 1500 rpm – 3600 rpm. However, some high speed designs have a rating ranging from 5000 rpm - 25000 rpm.

Unlike reciprocating pumps, the flow is uniform and pulsationless. The differential pressure across a centrifugal pump varies with its flow rate. The pump's pressure characteristic is such that a small change in head will cause a relatively large change in flow. Diaphragm and Piston pumps on the other hand, will deliver an almost constant flow rate regardless of pressure fluctuations. Figure 3.2 below compares the pressure - rate (H-Q) characteristic of a centrifugal pump and a positive displacement pump at constant speed.

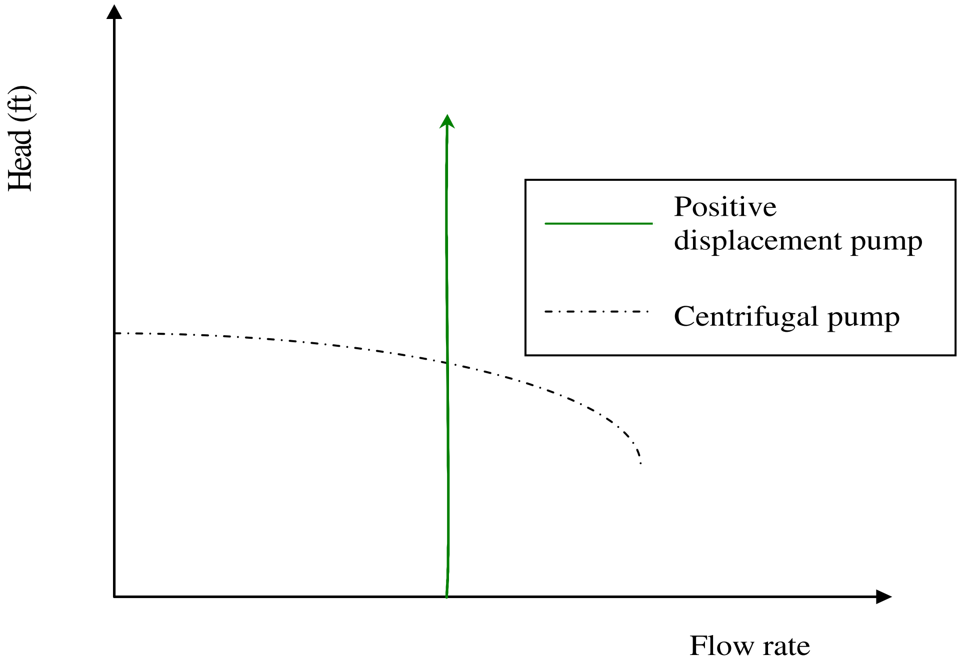


Fig. 3.2—Comparison of the H-Q curve of a Centrifugal Pump and a PD Pump.

Two basic designs based on the casing design and the direction of flow of the fluid through the pump. These are:

a) *Radial Flow Design*

This design employs a fluted impeller with a turbine style shape. The casing split is perpendicular to the shaft axis. Head is developed by the action of centrifugal force in the radial flow design. The fluid enters through the center of the wheel and is propelled radially outside. This design provides the highest- pressure increase per stage.

b) *Axial Flow Design*

This design employs a propeller shaped impeller. The casing split is in the same plane as the shaft axis. These pumps develop their head by a propelling or lifting force applied to the fluid by the impeller vanes. The flow is parallel to the pump shaft axis. The diameter of the impeller is the same at the suction and discharge sides. The kinetic energy due to the velocity of the fluid is converted into pressure by stationary diffuser vanes.

Mode of Operation of the Centrifugal Pump

The centrifugal pump has a simple construction. It comprises a volute, an impeller mounted on a shaft which is supported by bearings and mounted in a bearing housing. A drive coupling mounted at the free end of the shaft couples the prime mover to the shaft. The volute is a diverging channel which is cast into the discharge section of the casing. The high velocity fluid through the impellers is slowed to the discharge line velocity at the volute and this causes a corresponding pressure increase. Centrifugal pumps may have single or double volute passages.

The Prime-Mover is usually an electric motor, hence the name electrical submersible pump (ESP). It provides torque needed to drive the shaft and impeller. As the impeller rotates and the fluid is displaced within itself, more fluid is drawn into the impeller provided the pump is properly primed. The kinetic energy imparted on the fluid increases the velocity of the fluid and thus energy of the fluid which is then converted into pressure at the volute. The pressurized fluid has to be contained within the casing without leaking and this is achieved by the seals which are installed in seal housing. Figure 3.3 below depicts the basic parts of a centrifugal pump.

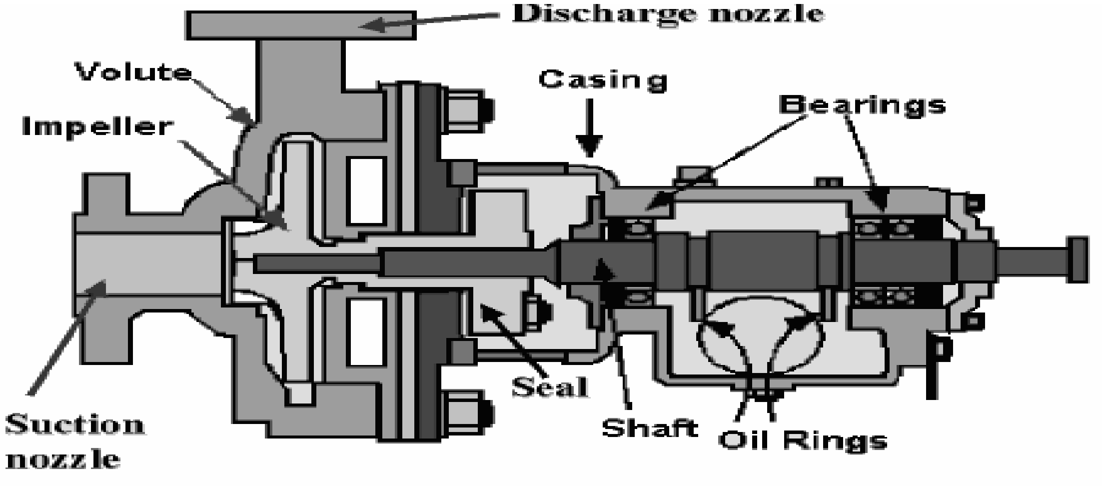


Fig. 3.3—Cross-section of a Centrifugal Pump.[12]

Design Considerations of the Centrifugal Pump for Mudlift Drilling

There are four key variables to pump performance. These include:

- Speed
- Head
- Capacity
- Power

The relationship between these parameters is governed by the affinity laws as shown below:

i.) For the same impeller diameter;

$$\frac{Q_1}{Q_2} = \left(\frac{N_1}{N_2}\right), \quad \frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2, \quad \frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3 \tag{3.1}$$

ii.) For the same pump speed;

$$\frac{Q_1}{Q_2}=\left(\frac{D_1}{D_2}\right),\ \frac{H_1}{H_2}=\left(\frac{D_1}{D_2}\right)^2,\quad \frac{BHP_1}{BHP_2}=\left(\frac{D_1}{D_2}\right)^3 \tag{3.2}$$

Speed

The rotational speed of a centrifugal pump is the number of revolutions the impeller makes per minute. For the same impeller diameter, the horsepower, flow rate and head are proportional to the operational speed of the pump. However, it can be seen from Equation 3.1 above that pump head developed is directly proportional to the square of the pump speed. Therefore, any change in pump speed will have a geometric effect in the head. The horsepower requirement for a centrifugal pump also varies geometrically with the pump speed.

From Equation 3.1 and 3.2, it can be seen that by varying the speed of the pump and the diameter of the impeller, we can vary the flow rate, head and horsepower requirements of a centrifugal pump. For the Mudlift Drilling System, it is impractical to adjust the diameter of the impeller in order to control the pressure and rate of the pump. Pressure and flow rate control is achieved by throttling a discharge valve at the pump's outlet or by controlling the pump speed with the aid of a variable frequency drive (VFD) mechanism. Throttling valves at the discharge end of the pump increases the back pressure on the pump and the system's resistance to flow. The increased pressure and head requirements, cause a shift to the left in the operating point of the pump along the performance curve, away from its best efficiency point (BEP). This results in loss in the pump's efficiency. Variable speed drives provide a more efficient flow control alternative by precise control of the pump's speed.

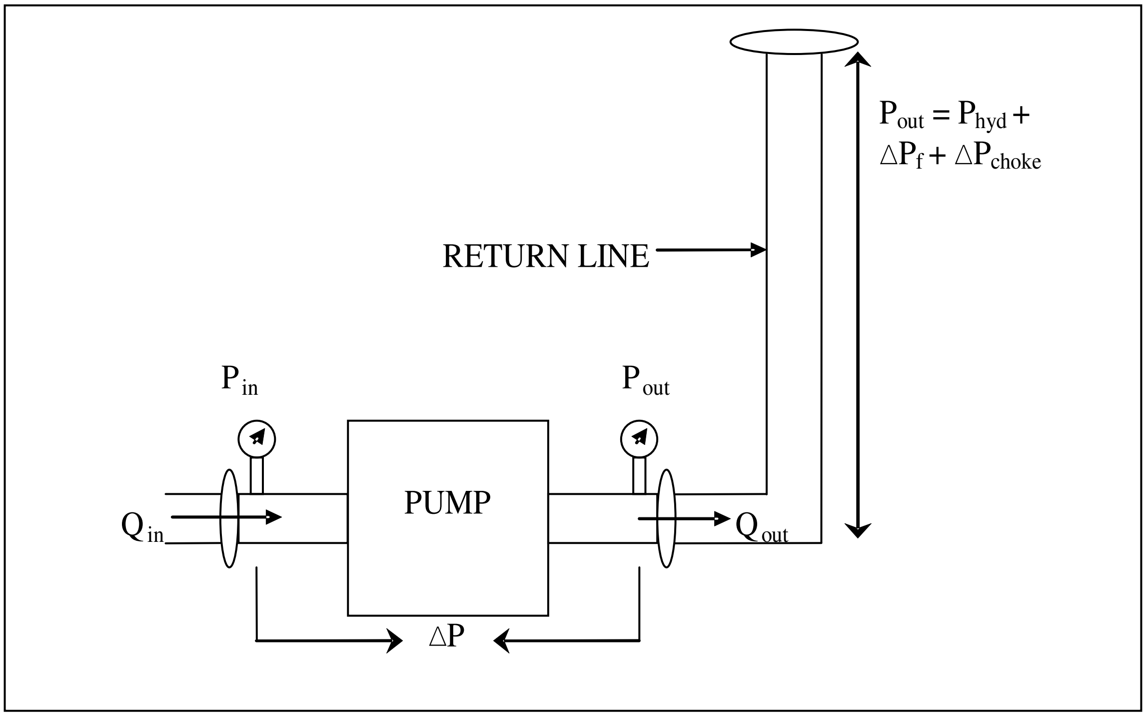


Fig. 3.4—Pressures and Rates across the Subsea Pump.

Figure 3.4 is a schematic of the subsea pump and the return line showing the pressures and rates as process variables. There are 4 variables that drive the system. These are:

- The inlet pressure (P_{in})
- The inflow rate (Q_{in})
- The Outlet pressure (P_{out})
- The discharge rate (Q_{out})

As discussed in Chapter II, there are two operational modes required of the subsea pump for Mudlift Drilling. These include:

- **Fixed Inlet Pressure Mode**

  The fixed inlet pressure mode requires that the inlet pressure be maintained at a constant value regardless of the inflow rate. The outlet pressure of the pump is equal to the sum of the hydrostatic pressure of the fluid in the return line, the choke pressure at the surface and the frictional pressure drop due to flow in the return line. The inlet rate is equal to the circulation rate of the system. This leaves us with the discharge rate and the inlet pressure as the two variables of the pump. The discharge rate is the controlling variable and the inlet pressure is the controlled variable. In the event of a kick, the pump being set to maintain a fixed inlet pressure will speed up and thus increase its discharge rate in order to maintain the prevailing constant inlet pressure setting. From equation 3.1, it can be seen that an increase in pump speed for the same impeller diameter will result in an increase in rate. As more of the kick fluid enters the wellbore, the pump continues to speed up and consequently the discharge rate continues to increase in order to maintain the same inlet pressure. The kick fluid is less dense than the mud, so the bottomhole pressure keeps decreasing and consequently more kick fluid enters the wellbore.

- **Fixed Discharge Rate Mode**

  In order to control the influx, the pump will have to exert some pressure at its suction side in order to raise the bottomhole pressure to a value equal to or greater than the formation pressure. This is achieved by reducing the discharge rate back to the initial circulation rate. To achieve a reduction in discharge rate, the pumps slows down. Equation 3.1 again shows that a reduction in the pump speed will also result in a reduction in the discharge rate. The reduction in the discharge rate imposes a back pressure at the pump's suction side and consequently increases the bottomhole pressure. The influx rate gradually reduces and stops when the bottomhole pressure is equal to the formation pressure. With continuous circulation, the kick begins to rise until it is completely circulated out of the hole. Therefore in order to achieve pressure control and flow rate control which are essential factors for success of the Mudlift Drilling System, good control of the speed of the pump is essential.

Head

The centrifugal pump is a velocity machine which converts mechanical energy from a rotating impeller into pressure energy. The amount of energy transferred to the fluid depends on the velocity of the impeller or rotational speed of the pump.

$$H = u^2 / 2g \tag{3.3}$$

$where\ H = Head\,(ft),\ u = impeller\ veleocity\,(fps)$

$and\ g = acceleration\ due\ to\ gravity\,(ft/s^2)$

This energy per unit weight is defined as the pump head and is expressed in feet. A centrifugal pump with a given impeller diameter and speed will raise a fluid to a particular height regardless of the density of the fluid. The pressure from a centrifugal pump will change if the density of the fluid pumped changes, but the head in feet will remain the same.

The parameters that establish the maximum head in feet of fluid that a centrifugal pump can attain include:

i.) Pump rotational speed (rpm):

ii.) Impeller diameter

iii.) Number of Impellers in series combination

The rotational speed of a centrifugal pump is governed by Equation 3.4 and 3.6.

$$N = \frac{229.2\,U}{D} \tag{3.4}$$

$$U\,(fps) = \sqrt{2gH} \tag{3.5}$$

$where\ \ N = rotational\,/\,pump\ \ speed\,(rpm)$

$U = velocity\,(ft\,/\,s^2)$

$D = impeller\ \ diameter\,(in.)$

$g = acceleration\ due\ \ to\ \ gravity\,(ft\,/\,s^2)$

$H = Head\,(ft)$

Based on hydraulic analysis of our system, a differential pressure head of 6500 psi is required to lift fluid of 18.5 ppg through a height of 10000 ft. The design head in feet required of the pump can be calculated from Equation 3.6 below.

$$H = \frac{\Delta P_{pump}}{0.052 \times M.W} \tag{3.6}$$

Using the equation above, the design head of the system is about 6760 ft. Neglecting the effect of viscosity on total head, a centrifugal pump with a 10 inch impeller diameter, will require a speed of 15,120 rpm to achieve the design head of 6760 ft while one with a 20 inch impeller diameter will require a pump with a speed of 7600 rpm.

The design of the impeller and blade angle has no effect on the developed head, but affects the slope and shape of the head – capacity curve.

Capacity

The capacity of a centrifugal pump is the volumetric flow rate of the pump. It is proportional to the cross-sectional area between the impellers and casing and the peripheral velocity of the impeller. A larger cross-sectional area between the impeller and the casing will result in a greater flow capacity. Therefore the physical size of the centrifugal pump is proportional to the flow capacity of the pump. Equation 3.7 below shows the relationship between flow rate, velocity and impeller – casing cross-sectional area.

$$Q = \frac{UA}{0.321} \tag{3.7}$$

$where\ Q = flow\, rate\, (gpm),\ U = impeller\ velocity\, (fps),$
$A = cross - sectional\ area\ (in.^2)$

The capacity of a centrifugal pump can be changed by varying the speed of the pump. For a pump running at a fixed speed, with a fixed impeller diameter, the capacity of the pump can only be changed by varying the differential pressure across the suction and discharge ends of the pump. The capacity of a centrifugal pump decreases as the differential pressure across the pump increases. The effect of a change in pump pressures on the capacity of a centrifugal pump can be observed on the Head – Capacity (H-Q) curve of the pump. This curve is unique to the pump and is supplied by the manufacturer.

Power

The hydraulic horsepower required to drive a pump is the power required to lift the fluid mass at a specified flow rate from one elevation to another. The power requirement is proportional to the flow rate and the differential pressure head across the pump. Equation 3.8 describes the relationship between the hydraulic horsepower, flow rate and pressure head.

$$HHP = \frac{Q \times H_T \times S.G}{3960} \tag{3.8}$$

$where\ HHP = hydraulic\ horsepower,\ Q = capacity\, (gpm),$
$H_T = total\ differential\ head\, (ft)\ and\ S.G = specific\ gravity\ of\ the\ fluid$

An electric motor supplies the power required to drive the pump shaft. Not all the energy supplied by the motor is converted to pressure. Some energy is used up in overcoming friction losses between the impeller and the fluid, recirculation losses at the wearing rings and bushings and also friction in the seals, gland packings and bearings. Therefore, the power supplied by the motor has to be greater than the hydraulic horsepower required in order to account for the losses. The ratio of the brake horsepower to the hydraulic horsepower is termed the efficiency of the pump. Equation 3.9 below describes the relationship.

$$\frac{BHP}{HHP} = \eta_p \tag{3.9}$$

where BHP=brake horsepower and η_p *= pump efficiency*

Therefore from Equation 3.8 and Equation 3.9;

$$BHP = \frac{Q \times H_T \times S.G}{3960 \times \eta_p} \tag{3.10}$$

Hence, a centrifugal pump with 80% efficiency, a circulation rate of 1200 gpm and differential pressure head of 6760 ft and pumping an 18.5 ppg mud will require a motor with a brake horsepower rating of 5700 HP. The efficiency of a centrifugal pump is unique property of the pump and it varies depending on the flow rate at which the pump is pumping. The efficiency of the motor also varies with load on the motor. The more the load is applied on the motor, the less the efficient the motor is. The flow rate at which the losses in the pump are lowest is termed the best efficiency point.

Fluid Viscosity (μ)

The viscosity of a fluid is its resistance to shear motion. The dynamic viscosity is the ratio of the shear stress to the shear rate. In centrifugal pumps, the impellers rotate through the fluid and impart energy to the fluid. As the viscosity of the fluid pumped increases, more energy will be required by the impeller to perform the same amount of work. The viscosity range is a major factor to be considered in selection of centrifugal pumps. The performance of the pump can deteriorate rapidly with increasing viscosity. Hydrodynamic losses in the pump increase with increasing viscosity. The thicker the fluid, the more power is needed to rotate the impeller through the fluid. Increasing the diameter of the impeller to recover the lost head will result in an increase in frictional losses. The viscosity of a liquid decreases with increasing temperature hence, the viscosity of a fluid should be specified at a given temperature. The impact of high fluid viscosities on centrifugal pumps includes:

- A reduction in the pressure head generated by the pump
- A reduction in the pump efficiency
- An increase in the brake horsepower requirement
- Reduction in the flow capacity of the pump

Figure 3.5 illustrates the impact of fluid viscosity on pump pressure and flow rate.

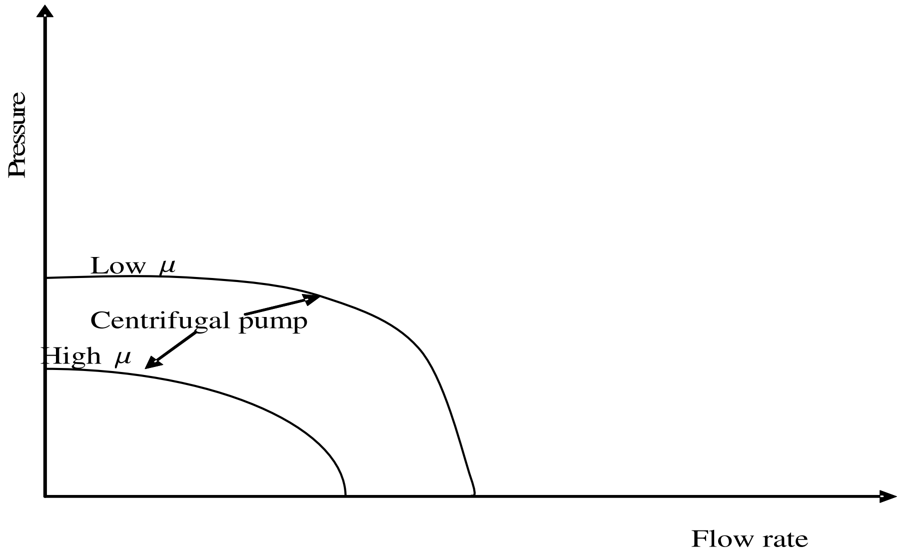


Fig. 3.5—Impact of Fluid Viscosity on Pump Pressures and Rates.

Fluid Density

The density of the fluid pumped affects the pressure head developed by the pump. The energy input required to move the liquid also increases with increasing density. Hence the brake horsepower requirement of a centrifugal pump is proportional to the fluid density.

Gas Content

Centrifugal pumps can handle fluids with gas volume fraction of up to 5 % by volume. The presence of gas creates a low pressure area at the impeller eye and restricts the flow of liquid into the pump. This results in lower volumetric efficiency and lower lift per stage. Flow may eventually cease if the gas volume becomes excessive. This condition is known as gas lock. In Mudlift Drilling, water depth ranges from about 4,000 ft - 12,000 ft and seafloor pressures at such depths are very high ranging from 1700 psi – 5400 psi.

Ambient seawater temperatures at such depths are also very low. As such, the net positive suction head available is increased improving the ability of centrifugal pumps to handle high gas volume fractions. At such high pressures, the gas moves rapidly through the pump and chances of gas accumulation at the impeller and subsequently gas lock is reduced. A gas compression stage may also be employed. This may be achieved with a multi-phase pump located upstream of the mudlift pump. Some companies have explored the use of the Helico-axial pump developed by the Poseidon group for use as a gas compression stage for centrifugal pumps. This pump stage has been shown to deliver a significant increase in volumetric efficiency of the centrifugal pump and can handle up to 75% free gas.

Solids Content

Entrained solids in the liquid pumped tend to increase the hydraulic resistance of the fluid. This resistance is proportional to the concentration of solids in the liquid. The consequence of this is a reduction in the flow rate and head developed by the pump. The brake horsepower requirement increases with increased concentration of solids and the efficiency is also lower with increased concentration of solids. Smaller sized solids form a homogenous mixture with the fluid pumped and pump characteristic resembles a fluid handling a higher viscosity. Larger sized solids will require larger tip clearances between the impeller and casing and consequently bigger size pumps. The effect on tip clearances on the efficiency of centrifugal pumps is inconclusive trends have shown a reduction in head and efficiency of the pump. The maximum acceptable solids size and concentration that a pump can handle efficiently will be specified by the manufacturer.

Specific Speed

The specific rotational speed is different from the operational speed of the pump. It is the speed of the pump in question operated at the best efficiency point. The specific rotational speed is independent of the operational speed of the pump. It is the speed at which a pump with a similar geometric design would produce 1gpm at a head of 1 foot per stage if sufficiently reduced in size. It is a correlation of pump flow, head and speed at optimum efficiency.[12] A pump with a high specific speed is termed a high speed pump while that with a low specific speed is termed a low speed pump. The specific speed of a pump is given by Equation 3.11 below.

$$N_s = N\frac{\sqrt{Q}}{H^{3/4}} \tag{3.11}$$

$$\text{where } N_s = \text{Specific speed},\quad N = \text{pump speed}\,(rpm),\quad Q = \text{flow rate}\,(gpm)$$
$$\text{and } H = \text{head}\,(ft)$$

Advantages of the Centrifugal Pump

- Centrifugal pumps can run at a constant speed and deliver a wide range of flow rates. Capacity adjusts automatically to changes in pressure.
- Moderate to high discharge pressures can be achieved by multi-staging.
- Small size and space requirements.
- Low cost

Disadvantages of the Centrifugal Pump

- Pressure control is limited. A change in pressure across the pump will result in a corresponding change in flow rate.
- Large solids and high concentration of solids in the mud, increase wear on the rotating parts of the pump and lower the pump's efficiency.
- Low efficiencies due to large tip clearances required to handle solids.
- Multi-staging is required to achieve high heads.
- Performance deteriorates rapidly as the viscosity of the mud increases.
- Can only handle a limited volume fraction of gas up to 15% by volume.

Diaphragm Pump

The diaphragm pump is a positive displacement pump, which operates by the reciprocating action of a flexible diaphragm moving back and forth in a fixed chamber. The pumping chamber has a membrane or diaphragm which separates the fluid to be pumped from the hydraulic fluid. The diaphragm is flexed by the pulsating action of hydraulic fluid on the drive side causing the volume of the pump chamber to increase and decrease. The decrease in volume in one chamber causes an increase in pressure in that chamber and consequently, the fluid is forced out via a check valve into a discharge conduit. Conversely, an increase in volume in one chamber will result in a decline in pressure in that chamber and consequently, more fluid is sucked into the chamber via a check valve. The hydraulic fluid may be compressed air, hydraulic oil, steam or seawater. Figure 3.6 below is schematic of a Seawater Driven Diaphragm Pump built for the SMD JIP.

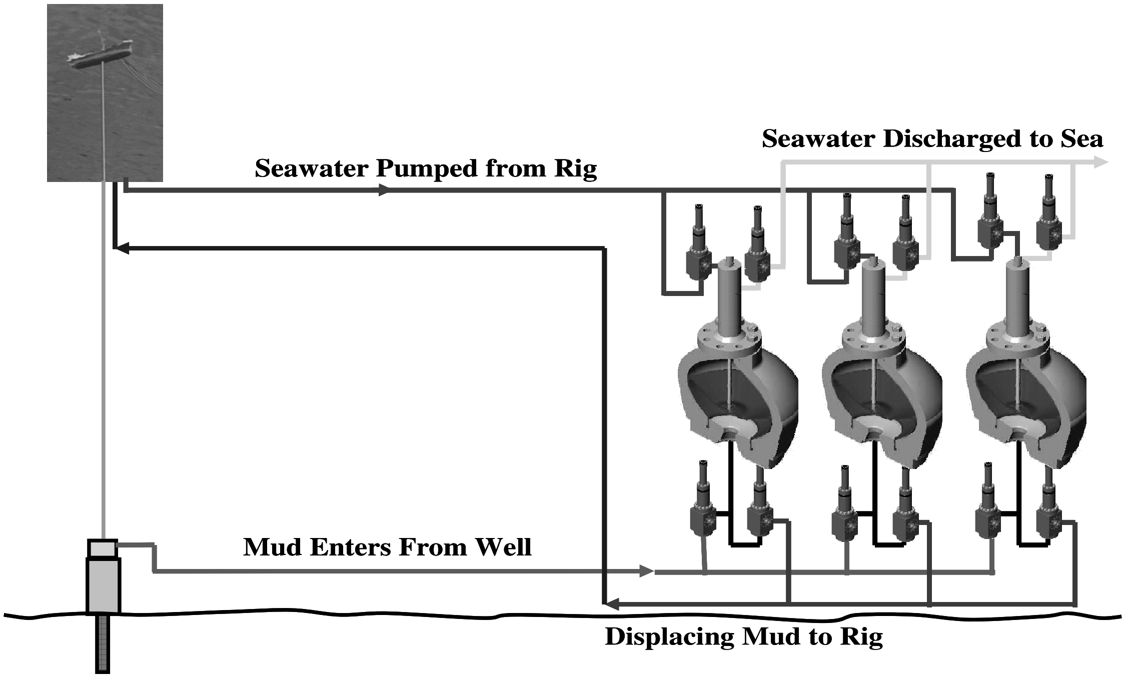


Fig. 3.6—A Seawater Driven Diaphragm Pump.[2]

Another design makes use of a crankshaft as the prime-mover. The diaphragm is flexed by the electro-mechanical action of the crankshaft. One side of the pump chamber contains the fluid to be pumped while the other side is open to air. The disadvantage of this design for the Mudlift Drilling System is the large size and heavy weight of the pump. The reciprocating piston mechanism used in displacing the diaphragm and the crankshaft used in driving the piston are responsible for this heavy weight. The size of such pumps may be as large as 20 feet × 20 feet × 20 feet and may weigh as much as

180,000 lbs. Non-return check valves prevent reverse flow of the fluid. These valves may be flapper or reed type valves made of flexible materials and operated by a pressure differential across the valve to open and close them. Figure 3.7 below is a schematic of a crank shaft driven diaphragm pump.

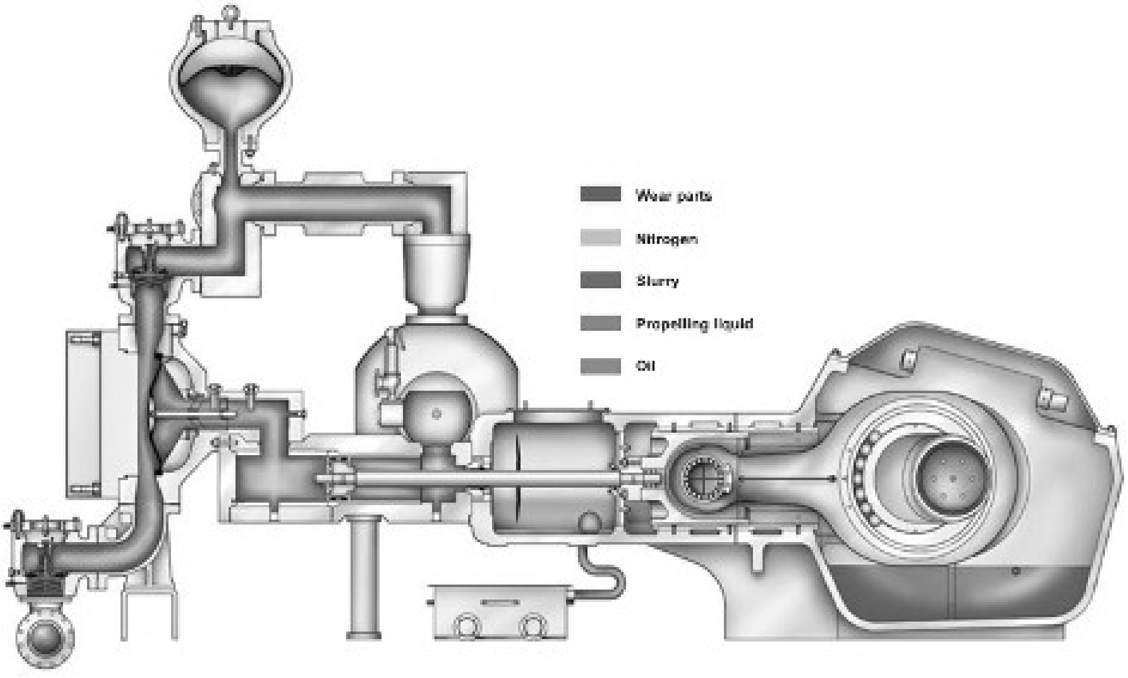


Fig. 3.7—A Crankshaft Driven Diaphragm Pump.[13]

Mode of Operation of the Diaphragm Pump

A diaphragm pump has been built for the SMD JIP which makes use of seawater as the hydraulic fluid. The seawater is supplied through a conduit from the rig to the pump. The pumping chambers are divided into two sections by an elastomeric membrane or diaphragm. Figure 3.8 below illustrates the operating principle of the pump.

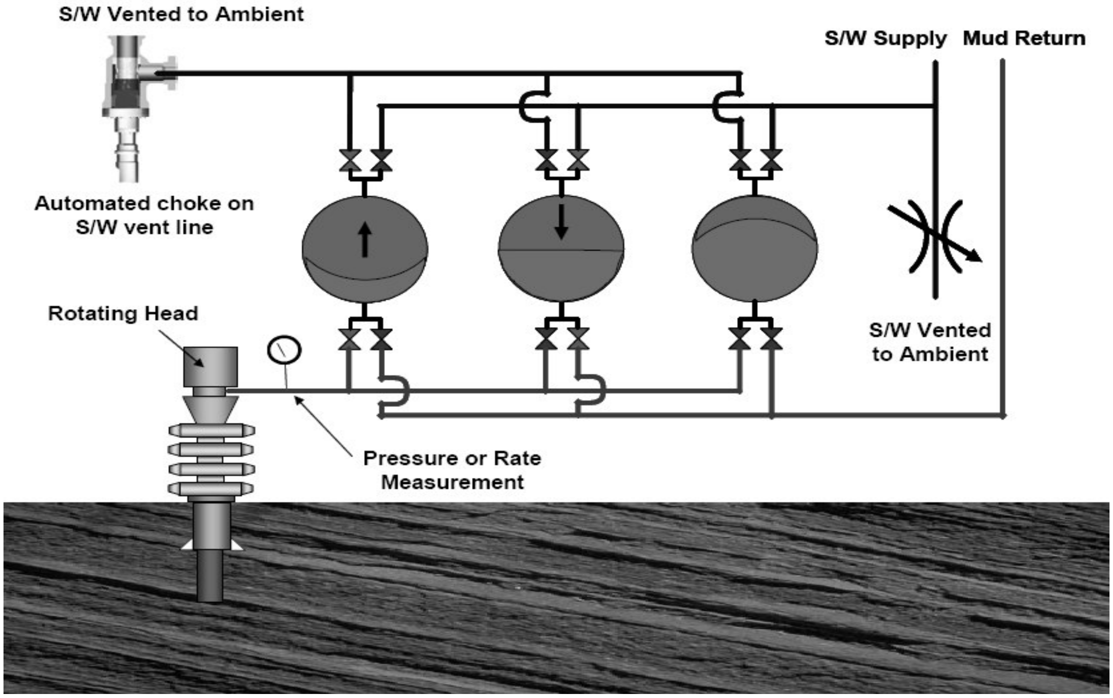


Fig. 3.8—Seawater and Mud Flow Path in a Seawater Driven Diaphragm Pump.[3]

A Subsea Rotating Head isolates the drilling fluid from the ambient seawater and channels the drilling fluid to the inlet manifold of the subsea pump. The inlet pressure to the pump, upstream of the manifold is monitored as this is the controlled variable.

Up-Stroke

i. Valves are opened and drilling fluid enters the lower end of the first pump chamber and expels seawater from the upper end of the chamber.
ii. The expelled fluid is channeled out through the seawater vent line to the ambient seawater.
iii. An automatic choke on the seawater vent line controls the discharge rate of the seawater.

Down-Stroke

i. Seawater from the rig is channeled through a manifold to the upper end of the second pump chamber.
ii. The drilling fluid is expelled from the lower end of the chamber into a discharge manifold.
iii. The drilling fluid is channeled back through a return conduit to the rig.

A change in the discharge rate of seawater out of the pump will cause a corresponding change in the suction rate of drilling fluid into the pump and consequently a change in the inlet pressure at the manifold. The pressure and flow rate on the seawater end is almost equal to pressure and flow rate on the drilling fluid end. There is relatively no differential pressure across the diaphragm. The efficiency of the diaphragm pump is very high as the pump achieves an almost 1:1 pumping ratio.[3]

Design Considerations of the Diaphragm Pump for Mudlift Drilling

Pump Pressure

Diaphragm pumps, like other positive displacement pumps create flow. The system's resistance to flow is what generates a pressure differential across the pump. The ability of the pump to withstand high pressures depends on the strength and reliability of the materials used for constructing the pump. The shape of the diaphragm and the number of pump heads also play significant roles in determining the maximum attainable pressures that diaphragm pumps can withstand. By having several pump heads of the same design, higher pressures can be attained.

Pump Rate

The flow rate of the diaphragm pump used in SMD is controlled by the speed of the drive and the swept volume of fluid. By having larger pumping chambers, the volume of fluid displaced with each flexure of the diaphragm is higher. This increases the volume of fluid displaced with each stroke and reduces the number of strokes per minute that the diaphragm makes.

Diaphragm

The diaphragm has a great effect on the performance of the pump. The diaphragm is flexed with each stroke of the pump. It is also handles abrasive drilling muds and completion fluids that may be corrosive in nature. As such, the diaphragm will encounter fatigue and failure will occur at some point in its operating lifetime. The characteristics of the diaphragm have a significant influence the performance of the pump. These characteristics include:

- **Shape of the diaphragm**

  The flow rate and pressure level that the diaphragm pump can attain is also dependent on the shape of the diaphragm. Based on the requirements for Mudlift Drilling, a molded diaphragm will provide an effective seal for high pressure and high flow rate applications as opposed to a flat shaped diaphragm.

- **Integrity of the elastomer material**

  The presence of solids may contribute to premature wear of the elastomer material. The average lifetime of the elastomer materials for diaphragms is about 10, 000 hours. One manufacturer has developed an advanced elastomer material, Ethylene Propylene Diene Monomer rubber (EPDM) that could last up to 20, 000 operating hours.

Valves

The inlet and outlet valves are opened and closed repeatedly while the pump is being operated. This makes the valves subject to wear and tear. The fluid being pumped in SMD is also laden with cuttings and debris which may plug the valve openings. Hydraulically actuated valves have been developed for subsea applications with drilling fluids and they have been proven to be reliable. Hydraulically actuated valves also eliminate the tendency for vapor or gas lock. If the gas volume fraction of the fluid in the pump is very high, sufficient pressure may not be generated to open the valves. This may cause flow to cease despite the fact the pump continues to run. The use of hydraulically actuated valves eliminates this problem. Figure 3.9 below depicts hydraulically actuated valves used to control the diaphragm pump built for the SMD JIP.

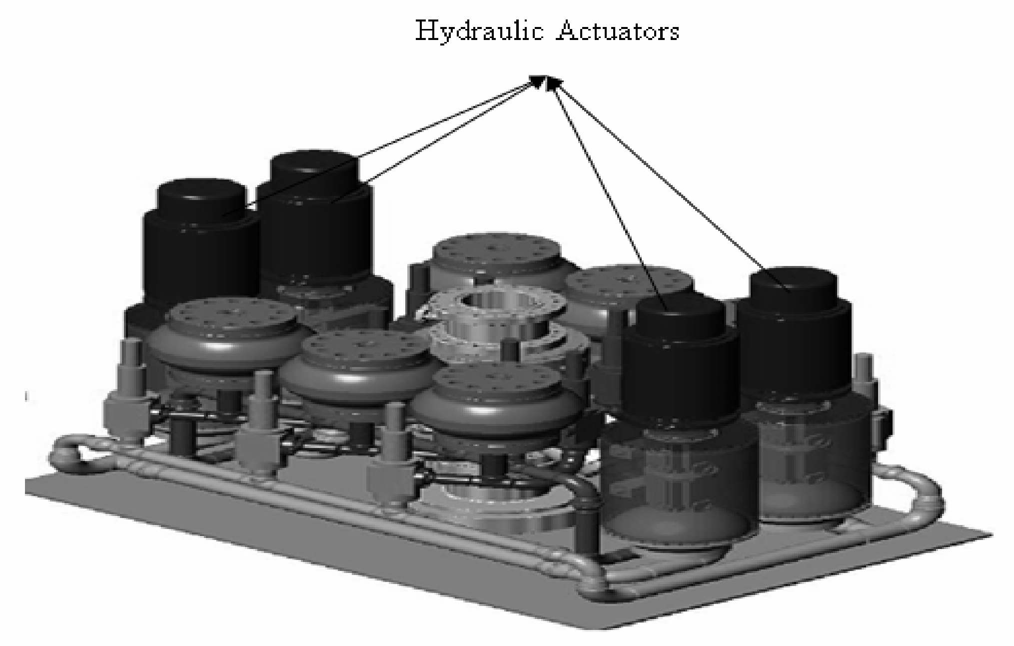


Fig. 3.9 — Hydraulic Actuators for a Seawater Driven Diaphragm Pump.[2]

Power

As discussed earlier, the diaphragm may be hydraulically driven or driven by the electro-mechanical action of a motor and crankshaft used in driving a piston. Based on the design specifications, horsepower requirements for the SMD system is about 4550 HP. The speed of the motor has a significant effect on the performance of a diaphragm pump. The flow rate and the time required to achieve a pressure head will depend on the speed of the pump. Hydraulically driven diaphragm pumps may be powered at the surface by a hydraulic drive unit. The hydraulic unit consists of a motor driving a variable displacement pump and control valves to supply the hydraulic fluid from the drilling vessel to the subsea pump. Subsurface power systems have also been studied whereby electrical submersible pumps (ESP) located at the seafloor, supply hydraulic fluid to the subsea pump. The disadvantage of this method for SMD is the low pumping efficiency of ESP's. However, no such pump has been developed that can handle pressures at that depth (10, 000 ft).

Advantages of the Diaphragm Pump

- Pressure control can be achieved without an impact on the flow rate. For a given speed, the flow rate is relatively constant regardless of the pressure.
- High pressures can be attained with a diaphragm pump
- Diaphragm pumps do not require seals.
- The efficiency of the pump is very high. Changes in pressure and rate have little effect on efficiency.
- The pump can handle very viscous fluids because the pump operates at lower speeds compared with centrifugals
- The pump can handle solids due to the absence of close tolerances in the pump chamber.
- The pump can also handle high gas volume fractions.
- The diaphragm pump does not require corrosion and wear resistant materials for its construction.

Disadvantages of the Diaphragm Pump

- Large size and weight compared with centrifugal pump and disc pumps.
- Pulsating flow. High net positive suction head required to fill the pump.

- Valves must be resistant to abrasive solids and must be able to allow large solids to pass through.
- Diaphragm is prone to rupture due to repeated contraction and expansion.

Piston Pump

The piston pump makes use of the reciprocating action of a piston rod or plunger to move fluid through a cylindrical chamber along an axis. As the piston moves through the cylinder, pressure builds up in the cylinder to force the fluid to be pumped through the pump. The pressure in the cylinder actuates the valves at both the suction and discharge ends. The flow of the fluid through the pump is pulsating due to the to and fro movement of the piston through the cylinder. The prime mover could be steam, turbine hydraulic drive mechanism or an electric motor. Piston pumps are capable of differential pressures of up to 10,000 psi and moderate flow rates.

Mode of Operation of the Piston Pump

A body will displace a volume of fluid equal to its own volume. Positive displacement pumps obey this principle. On the suction stroke, the piston retracts and moves from its initial position to an extreme position; the pressure inside the cylinder drops. This causes the suction valves to open and the fluid pumped to rush into the pump’s cylinder. In the discharge stroke, the piston pushes the fluid out to the discharge header and moves back from its extreme position to its initial position, the fluid is compressed and the pressure builds up within the cylinder. The pressure builds up and forces the fluid out. The pressure built within the cylinder is marginally over the pressure in the discharge. A dynamic seal mechanism separates the fluid to be pumped from the hydraulic fluid.

Design Considerations of the Piston Pump for Mudlift Drilling

Pressure

Unlike the centrifugal pump, the maximum attainable pressure of a piston or in general positive displacement pump depends on the application it is being used for and is limited only by the breaking point of some component within the pump. All piston pumps have a maximum operating pressure rating. Against a closed discharge valve, the maximum attainable pressure rating is limited to the speed of the drive and the strength of the materials used in the pump's construction. It is therefore critical for piston pumps to have a pressure relief valve in order to avoid excessive build up of pressure which may damage the pump.

Capacity

The capacity of a piston pump is the product of its displacement and volumetric efficiency. The equation below shows the relationship between the capacity volumetric efficiency and displacement of a positive displacement pump.

$$C = D \times V.E$$

$where\ C = capacity\,(gpm),\ D = displacement\,(gpm)\ and\ V.E = volumetric\ efficiency$

The displacement is the calculated capacity assuming a 100% hydraulic efficiency. The displacement is proportional to the cross-sectional area of the piston, the stroke length, and the number of pistons and the speed of the drive. The displacement of a piston pump can be expressed by the equation below.

$$D = \frac{ALnN}{231}$$

$where;\ D = displacement\,(gpm),\ A = cross - sectional\ area\ of\ the\ piston\,(ft^2),$
$L = stroke\ length\,(ft),\ n = number\ of\ pistons\ and\ N = speed\,(rpm)$

It is impractical for any pump to achieve 100% hydraulic efficiency. The actual volume of fluid discharged will be different from the theoretical volume delivered. This difference is caused by internal leakage of fluid back through the discharge or suction valve as it is closing. This leakage is called the slip and is affected by the design and the conditions of the suction and discharge valves as well as the viscosity of the fluid being pumped. Slippage is useful for pump lubrication and may account for between 2 -10% reduction in efficiency. Also, not all the fluid contained in the pump chamber or cylinder is displaced by the piston. Some fluid will still be trapped between the suction and discharge ends of the pump. The ratio of the volume displaced by the piston to the total volume (sum of the volume displaced by the piston and the volume trapped between suction and discharge ends) affects the volumetric efficiency of the pump. The volumetric efficiency of the pump increases as this ratio increases. The third factor that can affect the volumetric efficiency of the pump is the compressibility of the fluid. The volumetric efficiency of positive displacement pumps decreases as the compressibility of the fluid being pumped increases. Hence, the presence of gas in the drilling fluid when circulating out an influx through the pump, will adversely affect the efficiency of the pump. Also, at very high pressures, the compressibility of liquids increases leading to pressure losses and an increase in recirculation losses and consequently a drop in volumetric efficiency. Equation 3.11 shows the relationship between the volumetric efficiency, discharge ratio and compressibility factor for a piston pump.

$$V.E = 1 - S - (\Delta P \times c \times r) \qquad 3.11$$

$$\begin{aligned}&where\ S = slip,\ \Delta P = differential\ pressure\ across\ the\ pump\ (psi)\\ &c = compressibility\ of\ fluid\ (psi^{-1})\ and\ r = disch\arg e\ ratio\end{aligned}$$

The volumetric efficiencies of piston pumps are usually very high, usually in the range of 93 – 98% which makes them good candidates for Mudlift Drilling.

Power

The power required to drive a reciprocating pump is directly proportional to the differential pressure across the pump and the capacity of the pump. Mathematically, the brake horsepower required to drive a reciprocating pump is given by Equation 3.12 below.

$$BHP = \frac{Q \Delta P}{1714 \times M.E} \qquad 3.12$$

$$\begin{aligned}&where\ Q = capacity\ (gpm),\ \Delta P = differential\ pressure\ (psi)\\ &BHP = brake\ horsepower\ (HP)\ and\ M.E = mechanical\ efficiency\end{aligned}$$

The mechanical efficiency is the percentage of the pump's drive power that is lost to the mechanical parts of the pump. It ranges between 80 and 95% depending on the speed, size and design of the pump. The speed of the drive mechanism is proportional to the power supplied to the driver. Since the capacity of a piston pump is proportional to the speed of the drive mechanism, the capacity of the pump is proportional to the power supplied to drive the pump.

Seals

The seals of a piston pump are an essential part of the pump and their function is to separate the hydraulic power fluid from the fluid being pumped and keep the pressurized fluid contained within the cylinder. The seals of a piston pump must be able to withstand the high pressures encountered while pumping. Seals for a long stroke piston pump, which are capable of handling pressures over 6500 psi were developed for the SMD JIP project as a back up for the diaphragm pump.

Materials

Careful consideration should be given to the materials selected for construction of the pump. This is due to the high pressures developed within the pump and the abrasive nature of the mud being pumped. As discussed earlier, one of the limiting factors to the maximum pressure that a reciprocating pump can attain is the strength and reliability of the materials used in the pump's construction. The cylinder may be constructed with high grade steel. The nature of the fluid being pumped should be considered when selecting materials for the construction of the piston rod, valves and other parts that would be in contact with the fluid.

Advantages of the Piston Pump

- Very high pressures are attainable.
- Pressure control is possible without an impact on flow rate. The rate of discharge is relatively constant regardless of head.
- High efficiency. Changes in pressure and rates have little effect on efficiency.
- Can handle very viscous fluids. The velocity of the fluid being pumped is kept at low rates. Volumetric efficiency improves as viscosity increases.
- Can handle high gas volume fractions.
- Can handle solids provided valves are properly designed.

Disadvantages of the Piston Pump

- Large size and weight due to crankshaft and mechanism required to drive the pump.
- High cost.
- Pulsating flow. High net positive suction head required to fill the pump.
- Mechanical parts are prone to wear. Wear resistant materials are necessary for construction of parts exposed to abrasive slurries.
- Valves must be resistant to abrasive solids and must be able to allow large solids to pass through.
- Close tolerances exist between cylinder wall and piston rod. Reliability of seals must be ensured, due to the nature of the fluid being pumped.

Disc Pump

Unlike centrifugal pumps and the positive displacement pumps, the disc pump does not make use of an impingement device like the impeller vanes of a centrifugal pump, piston rods, diaphragm, screws, gears or lobes in a positive displacement pump to push the fluid through the pump. Instead, it relies on the principle of boundary layer/viscous drag to pull the fluid through the pump. The flow through the pump is laminar and pulsationless. The first disc pumps had very small spacing between successive discs. This greatly limited the ability of the pump to handle viscous fluid and solids. The efficiency of the pump was also greatly limited. The concept was looked at again in the 1970s and it was discovered that the spacing between successive discs could be widened up to 20 inches with the boundary layer / viscous drag principle still functional.

Mode of Operation of the Disc Pump

The disc pump operates based on the principle of a boundary layer-viscous drag. The pumping mechanism consists of a series of equally spaced parallel discs. When the fluid to be pumped enters the pump, molecules of the fluid adhere to the surfaces of the rotating discs causing a film coat or boundary layer on the surface of the discs. As the discs rotate, the boundary layer remains stationary relative to the rotating discs and acts as a protective buffer against abrasive wear and separates the fluid being pumped from the discs. The boundary layer attracts and drags successive layers of fluid molecules into smooth, parallel, laminar flow streams. Kinetic energy is transferred to successive layers of fluid between the discs. This imparts a velocity to the fluid and consequently, pressure gradient across successive discs. The fluid travels increasingly faster towards the center of opposing discs relative to the disc surfaces. The combination of boundary layer and viscous drag effectively generates a powerful dynamic force field which pulls the fluid through the pump in layers of smooth, laminar, parallel flow streams. Figure 3.10 below shows the cross-section of a disc pump.

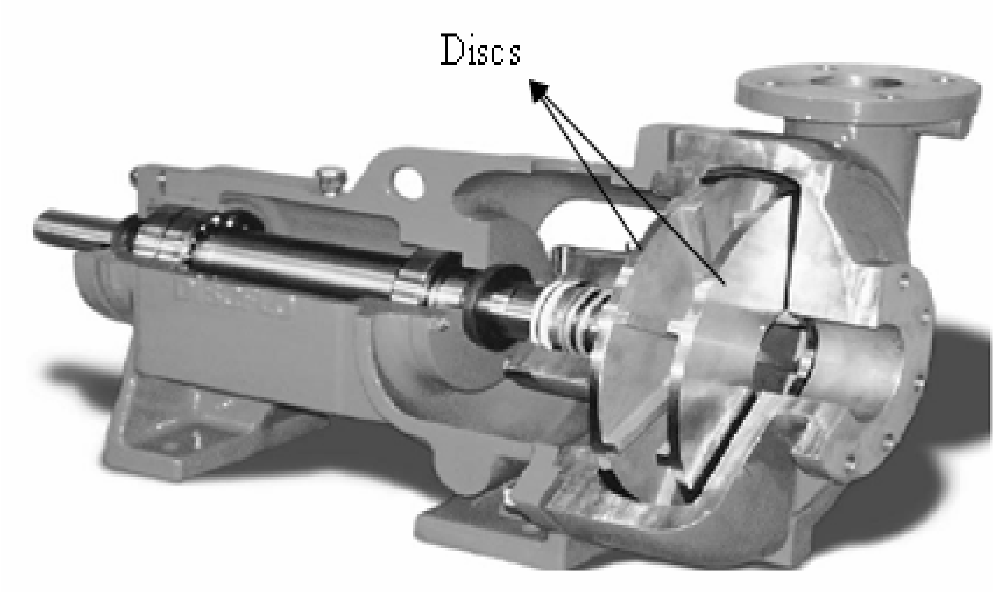


Fig. 3.10 — Cross-section of a Disc Pump.[14]

Design Considerations of the Disc pump for Mudlift Drilling

The performance of a disc pump is affected by the head, capacity, power and speed of the pump. The same affinity laws that govern the relationship between these variables in a centrifugal pump also apply to a disc pump. Equations 3.13 and 3.14 describe the affinity laws for a disc pump.[15]

i.) For the same disc diameter, D;

$$\frac{Q_1}{Q_2} = \left(\frac{N_1}{N_2}\right), \quad \frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2, \quad \frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3 \qquad 3.13$$

ii.) For the same pump speed, N;

$$\frac{Q_1}{Q_2} = \left(\frac{D_1}{D_2}\right), \quad \frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2, \quad \frac{BHP_1}{BHP_2} = \left(\frac{D_1}{D_2}\right)^3 \qquad 3.14$$

Head

The head developed by a disc pump is function of the energy transferred to the fluid. The amount of energy transferred to the fluid depends on the tip speed of the rotating discs. The energy per unit weight is defined as the pump head. Therefore, it can be said that the head developed by the disc pump is a function of the tip speed. The tip speed is dependent on the speed of the motor or driver. Increasing the diameter of the disc surfaces and the number of discs also increases the head developed by the disc pump. Disc pumps have been designed that could achieve up to 1000 ft of head and 1400 psi working pressures. Higher head values and discharge pressures can be achieved by operating a number of these pumps in series. [15]

Capacity

The capacity of a disc pump is a measure of the volume of liquid that the pump discharges in a given length of time. The factors that affect the capacity of a disc pump are the pump speed, the diameter of the discs, the number of discs and the height of the ribs on the inner surfaces of the discs. Like centrifugal pumps, a change in pressure will also cause a corresponding change in flow rate. Disc pumps generally have flatter Head – Capacity curves than centrifugal pumps operating at the same speed. This allows them to deliver much higher flow rates. Disc pumps have been designed with flow capacities up to 10,000 gpm. [15]

Power

The power required to drive a disc pump depends on the weight of the fluid being pumped. Power is supplied to the pump via an electric motor. The power requirement is calculated the same way as for a centrifugal pump. Like the centrifugal pump, the brake horsepower requirement of a disc pump is a function of the efficiency of the pump. Due to the non-impingement design of disc pumps, the efficiency of such pumps is lower than similar centrifugal pumps for low viscosity fluids. Their efficiency improves and becomes much better than an equally rated centrifugal pump as viscosity increases. Hence, the viscosity of the fluid being pumped has a significant impact on the brake horsepower requirements of the pump.

Speed

The speed of the disc pump is the number of revolutions the discs makes per minute. The amount of kinetic energy imparted to the fluid being pumped depends on the tip speed of the discs. Based on the affinity laws, the capacity and head developed by the disc pump is a function of the speed of the pump. Therefore, higher speed pumps are required in order to achieve higher heads and higher flow capacities. Pump speeds of up to 3600 rpm are currently available in the industry. Speed control can be achieved with a hydrodynamic fluid circuit or a variable frequency drive.

Solids Handling

Disc pumps can handle solids efficiently due to their boundary layer of fluid that is formed on the surfaces of opposing discs. This boundary layer prevents abrasives from grinding on the disc surfaces resulting in little wear on the discs. Due to the relatively large spacing between discs, disc pumps can handle very large solid sizes typically up to 10 inches in diameter. The pump can handle up to 80% concentration without clogging.

Gas Handling

The non-impingement, laminar flow nature of the fluid flow through the disc pump, allows smooth flow of gas bubbles through the pump and prevents the bubbles from imploding in the pump chamber. Disc pumps are capable of handling up to 70% gas volume fraction.[16]

Advantages of the Disc Pump

- Can run at constant speeds and can deliver a wide range of flow rates.
- They can handle very viscous fluids. Efficiency improves with viscosity.
- Can handle solids up to 80% concentration and 10 inches in diameter.
- Flow is smooth, laminar and pulsationless.
- No close tolerances and non-impingement design makes the pump virtually clog free and eliminates wear on moving parts.
- Can handle fluids containing as much 70% gas volume fraction.
- Small size and weight.
- Low maintenance cost due to less wear and tear on moving parts.

Disadvantages of the Disc Pump

- Series connection required. Maximum head per stage is about 1400 psig.
- Pressure control is limited as a change in pressure across the pump will cause a change in flow rate.
- Series connection is necessary to attain high heads.
- Low pumping efficiencies typically between 35% and 50%.
- High Horsepower requirement.

CHAPTER IV

COMPARISON OF THE SUBSEA PUMP TECHNOLOGIES

The requirements of the Mudlift Drilling System will be demanding for any subsea pump. Based on our design, the pump must be able to pump at any rate from 0 – 1800 gpm and achieve a discharge pressure of 6500 psi. The pump must also be able to handle very viscous and abrasive mud slurries which may be laden with debris of up to 5% in volume with particle sizes up to 2 inches in diameter. The pump must also be able to handle gas entrained in the drilling fluid due to a kick. So far, we have examined four pump technologies available to the industry. Each of these pumps has its advantages and drawbacks.[17] A comparison of the characteristics and performance of these pumps is shown in Table 4.1 below.

Table 4.1—Comparison of Pump Technologies for Mudlift Drilling

CENTRIFUGAL PUMP	DISC PUMP	DIAPHRAGM PUMP	PISTON PUMP
DESIGN PRESSURE / HEAD (psig)			
Low head. Multi-staging will be required. High speed centrifugal pumps have been developed to achieve up to 5800 psig of head.	Low head. Maximum design head developed is about 1400 psig. 5 – 6 pumps will have to be operated in series to meet the design requirement	High heads attainable. Capable of achieving very high pressures. A 6500 psig triplex pump was developed for the SMD JIP.	Very high heads are attainable. Up to 30, 000 psig. Maximum pressure attainable is limited only by the strength of the materials.

Table 4.1 (Contd.)

CENTRIFUGAL PUMP	DISC PUMP	DIAPHRAGM PUMP	PISTON PUMP
CAPACITY (gpm)			
Large range of capacities of up to 10,000 gpm for single stage pumps. Capacity varies with changes in head.	Large range of capacities of up to 10, 000 gpm. Capacity varies with changes in head. H – Q curves of disc pumps are generally flatter than centrifugal pumps.	Low discharge rates. Higher rates can be achieved by having several pump chambers. Discharge rate is practically constant for a given speed.	Moderate to high rates depending on the volumetric efficiency of the pump. Discharge rate is practically constant for a given speed.
EFFICIENCY (%)			
Efficiency changes with flow rate. Efficiency initially rises to a peak and then drops. Overall efficiencies range between 30% and 60 %. Efficiencies of up to 85% can be achieved in special designs.	Efficiencies vary with flow rate and are generally lower than centrifugal pumps. Efficiency increases as viscosity increases. Operating efficiencies are typically between 35% and 50%.	Very high overall efficiencies of over 85%. Changes in pressure and flow rate generally have no effect on efficiency.	Very high overall efficiencies of over 85%. Changes in pressure and flow rate generally have no effect on efficiency.

Table 4.1 (Contd.)

CENTRIFUGAL PUMP	DISC PUMP	DIAPHRAGM PUMP	PISTON PUMP
SOLIDS HANDLING			
Can handle up to 3.5 in. diameter solids. Efficiency and power requirements of the pump reduces as solids concentration increases	Can handle up to 80% solids concentration. This is due to its non-impingement and No close tolerance design. Can handle up to 10 in. particle size.	Can handle solids provided valves are properly designed. No close tolerances in the pumping chamber and no moving mechanical parts. Solids handling is only limited by the valve design.	Very close tolerances exist between piston and cylinder wall. Solids handling capability is limited by the design of the valves and the construction materials of the pump.
GAS HANDLING			
Multistage ESP centrifugals can handle up to with 15% gas volume. Above this, flow is reduced and may eventually cease.	Can handle up to 70% entrained air or gas without foaming or vapor locking	Can handle up to 50% gas volume fraction without modification and up to 95% gas volume fraction with modification	Can handle up to 50% gas volume fraction without modification and up to 95% gas volume fraction with modification.

Table 4.1 (Contd.)

CENTRIFUGAL PUMP	DISC PUMP	DIAPHRAGM PUMP	PISTON PUMP
RATE CONTROL			
Rate control is possible by varying the speed of the driver. Can run at relatively constant speeds.	Rate control is possible by varying the speed of the driver. Can run at relatively constant speeds.	The pump can run at relatively constant speeds. Rate can be controlled by varying the speed of the pump.	The pump can run at relatively constant speeds. Rate can be controlled by varying the speed of the pump.
PRESSURE CONTROL			
Pressure control will cause change in rate. Centrifugal pumps deliver a constant flow rate at a constant head.	Pump is sensitive to changes in pressure. A small change in pressure will cause a relatively large change in flow rate.	Pressure control is achievable without any adverse change in flow rate. Discharge rate is constant regardless of head.	Pressure control is achievable without any adverse change in flow rate. Discharge rate is constant regardless of head.
SIZE			
Relatively small size and weight compared with Piston pumps and diaphragm pumps	Relatively small size and weight compared with Piston pumps and diaphragm pump	Large size and weight. The triplex diaphragm pump skid built for the SMD weighed over 140, 000 lbs.	Very large size and weight. A single pump head may weigh over 160, 000 lbs

Table 4.1 (Contd.)

CENTRIFUGAL PUMP	DISC PUMP	DIAPHRAGM PUMP	PISTON PUMP
MUD RHEOLOGY			
Cannot handle very viscous fluids. Performance deteriorates significantly as viscosity increases.	Can handle very viscous fluids. Viscous drag increases as viscosity increases. Efficiency improves with viscosity.	Can handle very viscous fluids. The velocity of the fluid being pumped is kept at low rates.	Can handle very viscous fluids. Viscous fluid fills the close clearances between the cylinder and piston. Volumetric efficiency is higher.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The objective of this research was to evaluate the potentials of different pump technologies available in the industry for Mudlift Drilling. Four pump technologies were examined. These included; Centrifugal pumps, Diaphragm pumps, Piston pumps and Disc pumps. The evaluation criteria were based on the inherent performance characteristics of each of these pumps as well as the ability of the pumps to meet the mudlift system requirements and the design objectives of the Mudlift Drilling System.

Several factors were considered in the evaluation of the different pumps for the Mudlift Drilling System. Selection of a subsea mudlift pump for any mudlift system depends on the system specifications and requirements. These are:

- Operating water depth
- Mud weight and rheology
- Circulation rate
- Solids size and concentration,
- Gas volume fraction,
- Power requirements
- Size and weight of the pump
- Pressure and rate control

The diaphragm and piston pumps meet most of the requirements for Mudlift Drilling. They are capable of handling very high differential pressures and can deliver moderate flow rates sufficient to satisfy the requirements for mudlift by using several modules. They can maintain a relative constant flow irrespective of changes in pressure. This makes them good candidates for Mudlift Drilling. They can also handle very viscous fluids. Their ability to handle solids is limited by the design of their valves and seals and the integrity of the materials used in their construction. They have very high efficiency which remains relatively constant with respect to changes in flow rate. Their main drawbacks are their large size and weight, and their high cost.

Centrifugal pumps are smaller in size and simpler in design and are cheaper than piston and diaphragm pumps. They can run at constant and very high speeds and also deliver a wide range of flow rates. However, they generally develop low heads and depending on the operating water depths, line losses and system pressures, multi-staging may be required to achieve the required head. One major draw back is pressure control. Centrifugal pumps deliver fluid at a given flow rate at a particular head. Any variation in differential pressure across the pump will cause a corresponding change in flow rate. Centrifugal pumps cannot handle very viscous fluids. The efficiency of centrifugal pumps deteriorates as the viscosity of the fluid increases and is also sensitive to changes in pressure. For optimum performance, centrifugal pumps should be operated at their best efficiency point (BEP).

Disc pumps, with their non-impingement design and large spacing between discs excel at handling very viscous fluids, solids and fluids with a high gas volume fraction. They are also generally smaller than piston and diaphragm pumps and are relatively cheaper. These pumps are also relatively maintenance free over their operating lifetime. However, just like centrifugal pumps, the head developed by these pumps is compromised. Series connection of pumps will be required to attain high heads. Disc pumps generally have flatter Head – Capacity curves in comparison to similarly rated centrifugal pumps. Therefore, a small change in pressure across the pump will result in a large change in flow delivered by the pump. This makes pressure control difficult and limited. Compared with centrifugals they have lower efficiencies, but their efficiencies improve as the viscosity of the fluid being pumped increases.

In conclusion, selection of any pump for Mudlift Drilling will depend on the system requirements for the pump and the pumps' ability to meet these requirements. The ability of the pump to meet system requirements is enhanced by proper design of the pump's mechanical parts and the ancillary packages that support the Mudlift Drilling System.

Recommendations

The requirements of the Subsea drilling system have been examined and the capabilities of four different pump technologies to meet these requirements have been assessed. Table 5.1 below suggests the best pump suited to meet various system requirements.

Table 5.1—Recommended Pumps for Various Mudlift System requirements

DESIGN CRITERIA	CENTRIFUGAL PUMP	DIAPHRAGM PUMP	PISTON PUMP	DISC PUMP
Top Hole Drilling	Yes	Yes	Yes	Yes
High Heads (> 5800 psig)	Multi-staging will be required	Yes	Yes	Series Connection required
Limited weight and Size	Yes	No	No	Yes
High fluid viscosity	No	Yes	Yes	Yes
Large Solids size	Solids processing unit	Solids processing unit will be required	Solids processing unit required	Yes
Cost	Low Cost	High Cost	High Cost	Low Cost

NOMENCLATURE

A	Cross-sectional Area
BEP	Best Efficiency Point
BHA	Bottomhole Assembly
bhp	Bottomhole Pressure
BHP	Brake Horsepower
BOP	Blowout Preventer
BML	Below Mudline
c	Compressibility
D	Displacement
D_1	Impeller/Disc of Pump 1
D_2	Impeller/Disc of Pump 2
D_W	Water Depth
D_{BML}	Depth Below Mudline
EPDM	Ethylene Propylene Diene Monomer rubber
ESP	Electrical Submersible Pump
fps	feet per second
g	acceleration due to gravity
gal/min	gallons per minute
H	Head
HHP	Hydraulic Horsepower

HP	Horsepower
H_T	Total Differential Head
H-Q	Head – Capacity
ID	Internal Diameter
JIP	Joint Industry Project
MLP	Subsea Mudlift Pump
M.E	Mechanical Efficiency
M.W	Mud Weight
N	Pump Rotational/Operational Speed
n	Number of Pistons
OD	Outer Diameter
PD	Positive Displacement
P_{in}	Inlet Pressure
P_{out}	Outlet Pressure
ppg	pound per gallon
Q	Flow Rate/Capacity
r	Discharge Ratio
RL	Return Line
S	Slip
S.G	Specific Gravity
SMD	Subsea Mudlift Drilling
SPU	Solids Processing Unit

SRD	Subsea Rotating Diverter
U	Impeller Velocity
V.E	Volumetric Efficiency
VFD	Variable Frequency Drive
$\triangle P$	Differential Pressure
$\triangle P_{choke}$	Choke Pressure
$\triangle P_f$	Pressure Loss Due to Friction
$\triangle P_{f, BML}$	Pressure Loss in the Annulus Due to Friction
$\triangle P_{f, RL}$	Friction Pressure Loss in the Return Line
ρ_m	Mud Density
η_p	Pump Efficiency
μ	Fluid Viscosity

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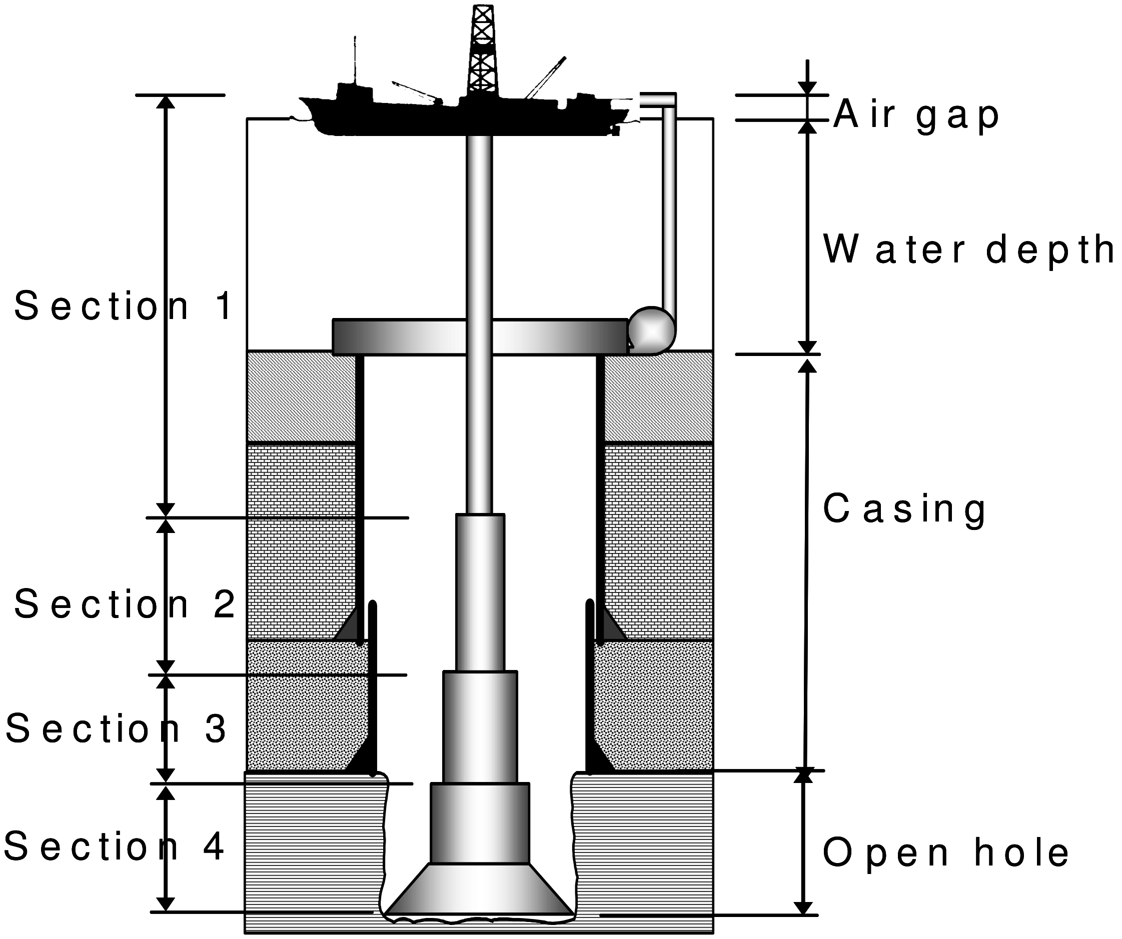
APPENDIX A

SMD SIMULATOR INPUT DATA



Wellbore geometry from Toolkit for SMD 100201.xls

I. Well Geometry

HOLE SECTION	**LENGTH (ft)**
Water depth	10,000
Casing	15000
Open hole	5000
TVD (Kelly bushing)	30000
DRILL STRING	**LENGTH (ft)**
Section 1 – Drill pipe	29100
Section 2 - H.W.D.P	600
SECTION 3 – Drill collar	300

II. Wellbore and Annulus Data

Drill pipe diameter	5” O.D, 4.276” ID
HWDP diameter	5.5” O.D, 3” ID
Drill collar diameter	8” O.D, 3.25” ID
Casing diameter	12.615” ID
Open-hole diameter	12.25”
Bit nozzle diameter	16/32” × 3 nozzles

III. Fluid Data

Plastic Viscosity	64
Bingham yield point	20
Mud Weight (ppg)	18.5
Seawater density (ppg)	8.6
Critical Reynolds Number	2100
Gas specific gravity	0.65
Surface Temperature (^{o}F)	70
Mud Temperature gradient (0F/100ft)	1
Water Temperature gradient (oF/100ft)	-0.9
Minimum seawater temperature (^{o}F/100ft)	32

IV. Return Line Data

Number of Return Lines	1
Return Line Length (ft)	10, 000
Return Line ID (in)	6

V. Pump Data

Pump rate per stroke (bbl/st)	0.2
Circulation rate while drilling (gpm)	650
Inlet pressure – S.W Hydrostatic (psi)	50

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