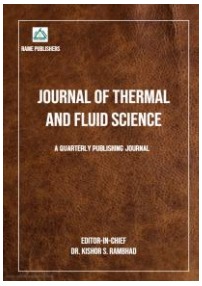

Journal of Thermal and Fluid Science
Volume 3, Issue 1, June 2022, pp 14 - 27
https://doi.org/10.26706/jtfs.3.1.arset4334

Design of Hydraulic Transportation System Using Positive Displacement Pump for Deep Sea Mining

Robin Babu[1]
r4ccet@gmail.com

[1]Assistant Professor, Mechanical Engineering Department, Christian College of Engineering and Technology, Bhilai, India

***Abstract*— Land mining operations are coping with decrease in the ore grades, increase in the demands and prices of the metal and with the accomplishments achieved by the offshore industry (oil & gas) market in mind, sea floor mining has once again become an attention-grabbing industry. This young market offers a lot of new prospects for the dredging and offshore industry, whose expertise will be required by the mining industry for operating offshore. In this paper the hydraulic transportation system using positive displacement pump for deep sea mining is designed as this type of system is undergoing a lot of research nowadays. This system is designed to vertically transport the mined manganese nodules present in Indian Ocean at a depth of 1500 m. The nodules have varied diameter and the system is designed by considering the losses which occurs during the mining process and the factors involved in transportation process. This paper hopes to give an idea about the current design procedure for the hydraulic transportation for deep sea mining using the positive displacement pump system and the various other possibilities of designing this system. The opportunities for deep sea mining have just gained scope as a result of the depletion of the resources in land-based mines and in future it may be the only option for the sustenance of human kind.**

***Keywords*—** Deep Sea Mining, Dredging, Hydraulic Transportation System, Positive Displacement Pump

I. Introduction

In this chapter, one of the deep-sea mining's technological challenges are introduced which is the vertical transport for deep sea deposits from the sea floor to the sea surface. Mankind's prosperity depends upon the availability of water, food, energy resources etc. The consumption of the natural resources is increasing worldwide due to increase in the population and the technological advancement and the increase of the developing countries. But the resources are limited and their accessibility on land is also not distributed equally because they are concentrated at specific location all around the world, thus demand for the mineral resources is also increasing worldwide. The discoveries of the Royal Navy's vessel H.M.S. Challenger were made public with the report of the oceanographer Sir John Murray and the geologist and petrographer Alphonse François Renard in 1876 about the deep sea deposits, but interest in deep sea mining as an alternative to land based mining emerged only recently with J. L. Mero's "The Mineral Resources Of The Sea" (1965). [1] Mineral resources like hydrothermal deposits, polymetallic nodules and cobalt rich manganese layer can be found in abundant in the ocean floor. Thus, the focus of ocean mining activities should be utilizing this mineral treasure for the benefit of mankind. [2] Polymetallic nodules consist of metals which are economically valued such as Cobalt, Nickel, Copper and Manganese. Thus, they are viewed as potential resources for replacing the depleting

Technical Article
Published online – 04 August 2022

Cite this article – Robin Babu, "Design of Hydraulic Transportation System Using Positive Displacement Pump for Deep Sea Mining", *Journal of Thermal and Fluid Science,* RAME Publishers, vol.3, issue 1, pp. 14-27, 2022.
https://doi.org/10.26706/jtfs.3.1.arset4331

land resources and help to manage the increasing demand of these metals.

Today manganese nodules are considered to be the most important deposits of mineral resources in the sea. These nodules, with varying sizes, contain mainly manganese, but also iron, titanium, copper, nickel, and cobalt. The manganese nodule deposits are of great attention because these nodules consist of greater amounts of other metals that are found in today's known mining deposits. [3] It is assumed that the worldwide manganese nodule occurrences in the deep ocean reserves contain more manganese significantly, than in the land reserves. [4] These occurrences are concentrated more particularly in the wide deep-sea basins of Pacific and Indian Oceans, at depths of 3500 to 6500 meters. [5] There are individual nodules which lie loosely on the seafloor, or can be sometimes covered by a thin sediment layer. Theoretically they can be easily harvested from the sea floor [6]. They can be collected from the bottom with underwater vehicles known as Remote Operated Vehicles (ROV). One of the underwater ROV models of an organization and country is shown in the figure.1 [7]. Some of them are in working while others are just the prototype model. European countries have advanced their technologies while Asian countries are beginning to realize the potential of deep-sea mining.

Figure 1. Underwater ROV models developed by Royal IHC, Netherland for deep sea mining.[7]

A. *India's Prospects in Deep Sea Mining*

India has become the Pioneer Investor in deep sea mining. India has been allotted a site in the Central Indian Ocean Basin (CIOB) by the International Sea Bed Authority (ISA) of area over 1,50,000 sq. km for exploration and technology development for polymetallic nodule mining. According to an estimate, the total mass of nodules is 380 million metric tonne in the area allocated to India in the Indian Ocean region. Each square meter of the sea floor in this area contains around 5 kgs of manganese nodules. [8] According to Department of Science and Technology, the mining license of a period of 15-years is given to India by the ISA under the United Nations Convention on Law of the Sea. The license extends 10,000 km^2 of seabed across geological formations in the Southern Indian Ocean stretching close to the Mauritius coastline. Since receipt of the license in 2014, a large amount of data and visuals have been collated across the deep-sea mining tectonic plates and exploration was being jointly implemented by the National Institute for Ocean Technology (NIOT) and the National Centre for Antarctic and Ocean Research (NCAOR) using remote operated vehicles with depth capabilities up to 6000 m. [9]

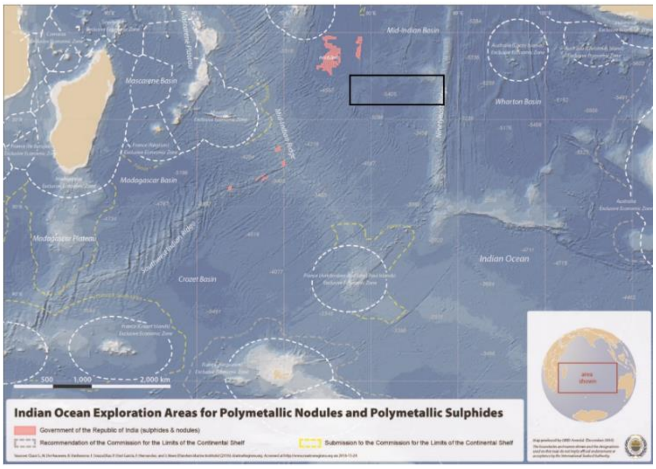

Figure 2. India's Deep Sea Mining exploration areas in Indian Ocean approved by International Seabed Authority (ISA).[9]

However, development of deep subsea technology for mining these resources is a major challenge considering the hyperbaric environment, very soft soils and other factors. The aim is to develop a highly reliable Deep sea mining system which will be able to harness the mineral resources from ocean to meet the country's growing mineral requirements. Thus, increasing the country's self-sufficiency, in the future.

B. *Positive displacement pumps*

A positive displacement pump causes a fluid to move by clamping a fixed amount and forcing (displacing) the volume trapped in the discharge tube or it may also be said to have a cavity that expands on the suction side and a decrease of the cavity on the side The liquid flows into the pump as the suction side cavity expands and the liquid exits the discharge as the cavity collapses. [10]. The volume is constant given each operation cycle. But because of its operation, the pump can accumulate a very high discharge pressure and, if a valve in the discharge system is closed for any reason, serious damage can occur to the cylinder head, case or other equipment which in turn may break or the driver may stall and burnout. Therefore, a positive displacement pump must be equipped with a safety relief system on the discharge side. [11] The PD pump can be classified according to the mechanism used to move the fluid.

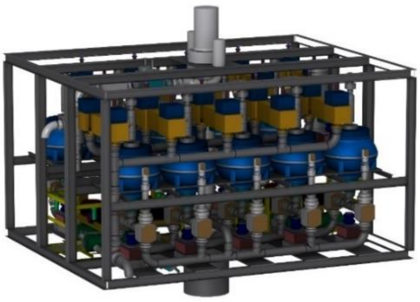

Figure 3. Model of a Positive Displacement Pump [7].

C. *Rotary-type*

Internal gear, bolts, shuttle blocks, flexible vanes or sliding blades, circular piston, helically twisted roots (e.g., Wendelkolben pump) or vacuum pumps with liquid rings. In rotary pumps, the fluid movement is achieved by mechanical displacement of the fluid produced by rotating the sealed range of rotating parts that are mixed in the pump casing. [12] These types of pumps are efficient because they naturally remove air from the lines, eliminating the need to manually clean the air from the lines. PD rotary pumps also have their own set of weaknesses. The distance between the outer edge and the rotary pump must be very close and therefore the pumps operate at a slow and constant speed. Otherwise, it will cause erosion, which will increase the gaps and reduce the efficiency of the pump. PD rotary pumps can be grouped into 3 main types.

1. Gear Pump: Two gears placed side by side with tangled teeth. The gears are moving away from each other, trapping the fluid between them and then releasing it under high pressure to the discharge system [12].
2. Screw pump: A more complicated type with two or three screws with opposing threads. The screws are mounted on parallel shafts that have gears that mesh with each other to rotate the shafts, keeping the entire system in place. This rotation of the shafts and the screws draws fluid through the pump.
3. Moving vane pump: A cylindrical rotor enclosed in a similar casing, which, when rotated, the fluid is trapped between the vanes.

Modern examples:

1. Progressing cavity pump.
2. Roots type pumps.
3. Peristaltic pumps

Advantages of rotary pumps:

1. They can deliver liquids at high pressures.
2. They are self-priming.
3. It gives a relatively smooth output, especially at high speeds.
4. It is positive acting.
5. Can pump viscous fluids.

Disadvantages of rotary pumps:

1) They are more expensive than centrifugal pumps.
2) They must not be used for liquids containing suspended particles.
3) Excessive wear if not pump viscous liquids.
4) Never be used with closed discharge as it may damage the pump.

D. *Reciprocating type (plunger or diaphragm pumps)*

Reciprocating pumps are those that use pistons, plungers, or diaphragms to pump the liquid through its reciprocating action. One of its most important parts is the suction and discharge valves that ensure fluid flows in a positive direction. These pumps can be simplex (one cylinder) to quad (4 cylinders), but most are duplex or triplex. [11] In addition, they can be "single acting" with independent suction and discharge strokes and "double acting" suction and discharge in both directions. They are powered by air or steam or through a drive belt in an engine or motor. PD Reciprocating type pumps are of following types.

E. plunger pumps

It has a cylinder with reciprocating plunger. During the suction stroke, the piston retracts and opens the suction valves, pulling the fluid into the chamber. During the discharge stroke, the plunger pushes the liquid out of the discharge valve.

DIAPHRAGM PUMPS - The plunger pressurizes the hydraulic oil to flex the diaphragm in the pumping cylinder.

An example of the PD pump is a common hand soap pump.

F. Compressed-air-powered double-diaphragm pumps

In this system, we are going to use a diaphragm pump which can be further categorized based on the cause of displacement. The diaphragm can be propelled either by a mechanical force like a motor or another fluid which is supplied by another pump, both of which are explained in the schematic diagram below. [12] A schematic diagram of the diaphragm pump and the process of pumping are explained below.

1. The first fluid is pumped into the mixture section (right side of the chamber) of the diaphragm pump. In this process, the second fluid is pumped out from the other end but since its pressure is higher than the first, it will first compress and then flow out.

2. The diaphragm pump is completely filled with the first fluid and the lower valves of the pump are closed. The diaphragm is completely extended towards the second fluid inlet. The first fluid has the pressure with which it is pumped by the pump in the first fluid inlet.

3. The upper valves are now opened. The second fluid now flows in. But it has less pressure than the first fluid in the chamber and so it compresses the first. After the point is reached where both pressures are equal, the first fluid starts flowing out.

4. Now the diaphragm pump is now filled with the second fluid and the flow of the first fluid is continued from the start.

II. Design Specifications

A. *Introduction*

India is one of the nations which has been taking interest in the deep-sea exploration and mining. The ministry of Science and Technology is testing and developing new techniques and technologies for deep sea mining and exploration including submersible underwater vehicle. These operations have taken up following the 15-year mining license granted by International Seabed Authority (ISA) on 2014 under the United Nations Convention on Law of the Sea. The mining license extends 10,000 km2 of seabed across geological formations in the Southern Indian Ocean stretching close to Mauritius coastline. [9] The location for this case study is in this region. The fig 5 shows the location for design purposes. This region has polymetallic nodules at a depth of 1500 m which is the area of interest for the design. There are various chemical components of the polymetallic (manganese) nodules in these locations. Due to this by refining these nodules various other metals can be extracted. The table 1 shows the chemical components of the polymetallic (manganese) nodules from different regions. [13]. The * in the fig shows the units in grams per tonne while the ** shows the units in percentage by weight.

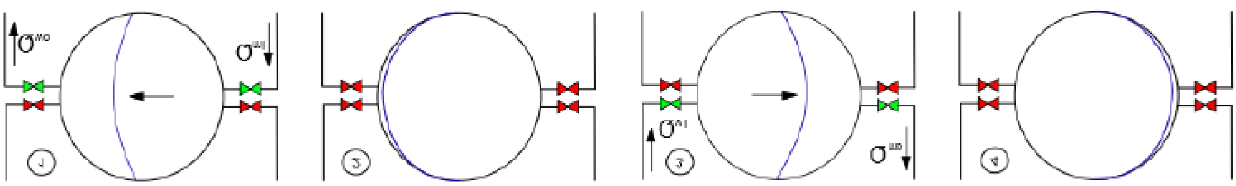

Figure 4. Schematic Diagram of a Diaphragm Pump.[12]

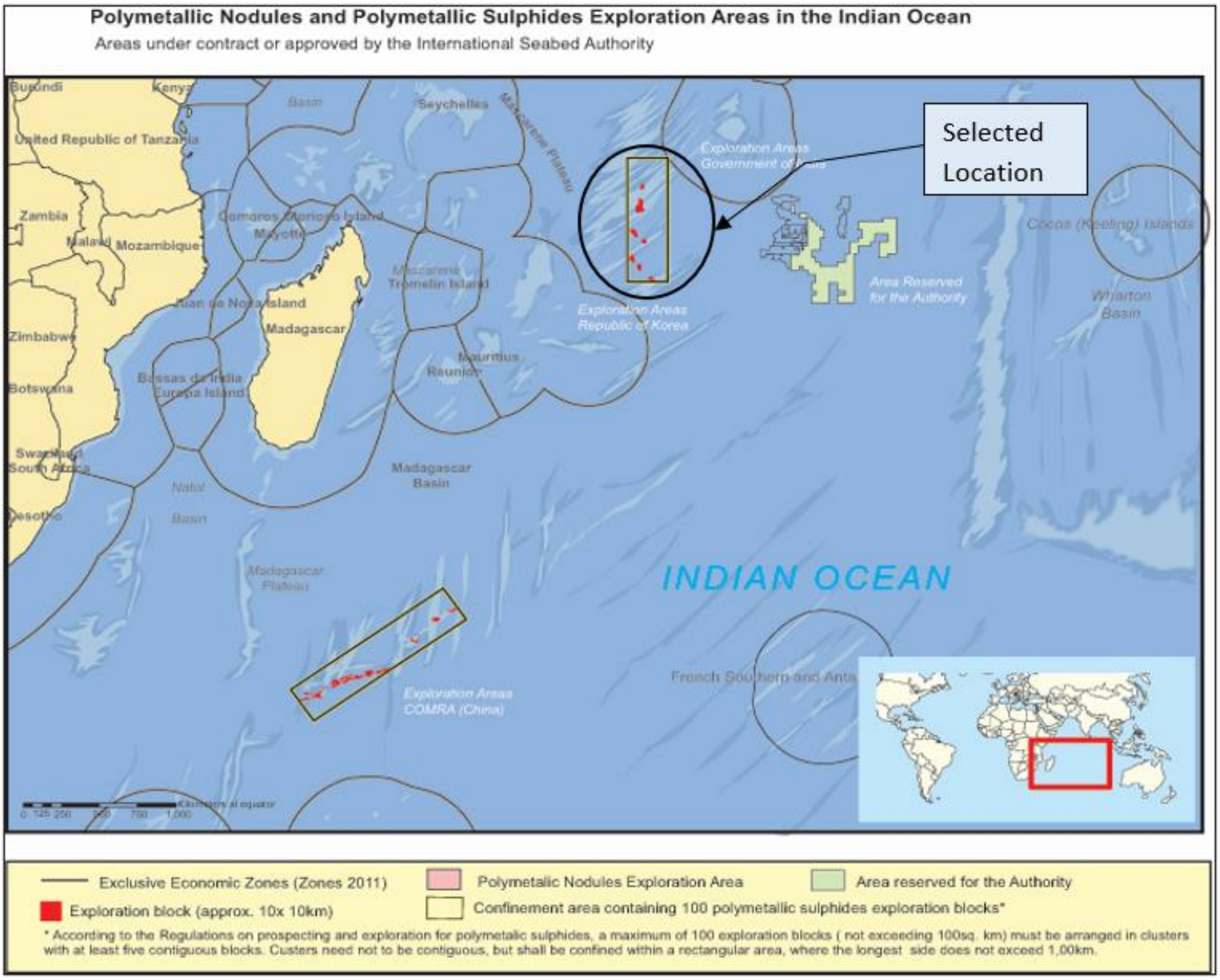

Figure 5. The polymetallic nodules located in highlighted areas in a density large enough to be mined industrially.[9]

Chemical components of manganese nodules from different marine regions				
Elements	Manganese nodules of the CCZ	Manganese nodules of the Peru Basin	Manganese nodules of the Indian Ocean	Manganese nodules of the Cook Islands area
Manganese (Mn) **	28.4	34.2	24.4	16.1
Iron (Fe) **	6.16	6.12	7.14	16.1
Copper (Cu) *	10,714	5988	10,406	2268
Nickel (Ni) *	13,002	13,008	11,010	3827
Cobalt (Co) *	2098	475	1111	4124
Titanium (Ti) **	0,32	0.16	0.42	1.15
Tellurium (Te) *	3.6	1.7	40	23
Thallium (Tl) *	199	129	347	138
Rare earth elements and yttrium *	813	403	1039	1707
Zirconium (Zr) *	307	325	752	588

Table.I. The chemical components of the polymetallic (manganese) nodules.[13]

B. Design Parameters

The area of interest for Polymetallic nodules in this case study is the Indian Ocean. The sea water temperature at several kilometers is relatively constant. The specifications for this design are given in the Table I.

TABLE II

SPECIFICATIONS FOR DESIGN.

Parameter	Description	Value
H	Water Depth	1500 m
d_S	Particle Diameter	10 – 50 mm
D	Pipe Diameter	350 mm
C_S	Volumetric Solid Concentration	10%
M_S	Production (Mixture)	300 ton/hr
C_D	Drag Coefficient	0.42
ρ_S	Density of Solid in mixture	3000 kg/m^3
ρ_L	Density of Liquid (Sea Water)	1025 kg/m^3
λ	Darcy Friction Factor	0.012
μ_L	Dynamic Viscosity of liquid	1.7 x 10^{-3} Pas

For designing the riser system, the positive displacement pump selected is used by Nautilus Minerals for Solwara deep sea mining project 1 pump which is a double acting diaphragm pump, which has an efficiency of 85% which will be used as value for the hydraulic efficiency η_h of the pump. Water flow of this pump Q_F is 1500 m^3/hr and Delivered pressure head of this pump P_r is 30,000 kPa at this efficiency [5].

C. Assumptions

For designing the hydraulic transportation system using positive displacement pumps, a number of assumptions are taken. Some of these assumptions can be taken for other systems in the future studies. The assumptions taken are as follows:

1. There is no interaction between individual particles in the Riser pipe and therefore there is no clogging up: This assumption is a subject to different study and is too little known to insert it in the designing the system here. Interaction like collision between the particles of the mixture in the system would cause a decrease in efficiency. A certain type of interaction is however considered in case of hindered terminal settling velocity of a particle, with its help velocity difference between the solids and liquid will be calculated.
2. Valve delay is neglected: The delay caused by the valve opening can be ignored, as this time period in a small diameter pipe is very short compared to the time to fill the chamber. The time necessary to fill the chamber will be more than one or a few seconds, while the closing time of the valve is generally between 0.01 and 0.05 seconds, at least a factor of 100 smaller, making it insignificant.
3. Compression delay is neglected:
   In positive displacement slurry pump, for calculation purposes the delay caused due to decompression and compression of the fluid can be neglected as well.
   The compression of water can be calculated by [14]:
   $$\frac{\Delta V_L}{V_L} = \frac{\Delta p}{K_B}$$
4. Pressure at the inlet and outlet are constant: The pressure at the inlet $p_{p,in}$ and outlet $p_{p.out}$ of the pump are not constant, but varying depending on the pressure build up by the pump and actuator and the flow through the discharge pipes. The application of multiple chambers will damp this fluctuation directly before and after the pump. [14]
5. Frictional losses for inflow and outflow are equal: The frictional losses at the inlet and outlet of the positive displacement pump is very difficult to determine theoretically, and can be analyzed by testing them experimentally. The assumption that they have equal value for inlet and outlet, and they are dependent on a constant value which is the friction coefficient ξ_c [15]. It is acceptable as long as the pressure loss over the

pump is low in comparison to the pressure loss of the complete system, which is the case when working at large water depths.

D. Equations

To calculate the hindered terminal settling velocity $v_{S,th}$, the terminal settling velocity $v_{s,\,tn}$ of a non-spherical particle is to be calculated by using the below equation. This velocity is the velocity of a particle in a quiescent liquid. This can be calculated by using the balance between the drag force and gravity. [16]

$$v_{S,tn} = \sqrt{\frac{4\, g\, d_s\, (\rho_S - \rho_L)}{3\, C_D\, \rho_L}}$$

The hindered terminal settling velocity $v_{S,th}$ is dependent on the particle Reynolds number Re_p, which is dependent on the velocity of the particle. Therefore, iteration is required to find the value which is constant. For the calculation of the Reynolds number, equation below is used where the dynamic viscosity of the liquid in this case is water μ_L is used.

$$Re_p = \frac{\rho_L\, v_{S,tn\, d_s}}{\mu_L}$$

The dependency of the Reynolds number is expressed in a factor α_h. The equation for α_h suggested by Wallis (Matousek, 2004) is given as equation below.

$$\alpha_h = \frac{4.7\ (\ 1 + 0.15\ {Re_p}^{0.687}\ )}{1 + 0.253\ {Re_p}^{0.687}}$$

The hindered terminal settling velocity $v_{S,th}$ is calculated by the equation given by Richardson and Zaki (Matousek, 2004). Equation below is used for calculating the hindered terminal settling velocity which is iterated until a constant value for $v_{S,th}$ is reached.

$$v_{S,th} = v_{S,tn}(1 - C_S)^{\alpha_h}$$

For low solid concentrations the Mixture velocity v_M in the riser system is assumed to be equal to the velocity of the liquid v_L. It can be derived by using the equation below if all the parameters are known.

$$v_M = \frac{M_S}{\rho_S\ A\ \alpha_t\ C_S}$$

The α_t in the above equation is the unknown transport factor. It can be calculated by taking the difference between solid concentration C_S within the riser and delivered solid concentration $C_{S,d}$, which is caused by the velocity difference between solids and liquid. It is calculated by using the equation below.

$$\alpha_t = \frac{v_S}{v_M} = \frac{v_M - v_{S,th}}{v_M}$$

The pressure losses of the riser system Pr_{loss} can be calculated by using the equation below. This equation consists of a part related to friction losses in the system and the geodetic or hydraulic head loss. According to Shook, the velocity / density term is split up in a separate term for the solids and liquids which is applicable for vertical flow. [15] The ξ_f in the equation is the factor for pressure losses which are independent from water depth such as the inlet losses and acceleration, while ξ_v takes the water depth dependent losses such as the losses due to valves which are applied every few hundred meters into account. Darcy friction factor λ forms the wall friction component of pressure losses.

The positive displacement pump is modelled on the basis of the balance of the forces over the pump. With a fluid pressure which is constant on both the sides of the pump a constant force will be working inwards through the openings with an area A_c. the inflow and outflow of the pump causes a pressure loss $p_{p,loss}$ and because of this a friction force $F_{p,loss}$ is generated [17]. The remaining force ΔFp will be the difference in the inlet and the outlet force and the friction which works on the fluids inside the pump and the diaphragm. It is calculated by

$$Pr_{loss} = \left(\xi_f + \xi_v\ h + \lambda\ \frac{h}{D}\right) \frac{1}{2}\ (\ \rho_L\, C_L\, {v^2}_L + \rho_S\, C_S\, {v^2}_L\ ) + h\ g\ (\ \rho_M - \rho_L\ )$$

$$\Delta F_p = F_{p.in} - F_{p.loss} - F_{p.out} = \frac{p_{p.in} - p_{p.loss} - p_{p.out}}{A_c}$$

In the above equation A_c denotes the inlet area of the chamber. When the valves are opened the velocity of the fluid inwards is zero. Since the velocity is dependent on the loss in the pressure, this value is also zero. The remaining force ΔF_p at that point causes an acceleration of the fluid and thus increasing the velocity. This causes the pressure loss $p_{p.loss}$ to increase which in turn decreases the remaining force ΔF_p it reaches zero. The relation between the pressure loss and the fluid velocity v_F is as follows.

$$P_{p.Loss} = \xi_C \frac{{v_{F.max}}^2}{2} (\rho_M + \rho_L)$$

The maximum velocity $v_{F.max}$ is reached when the remaining force ΔF is zero. [18] It can be calculated by using the formula

$$v_{F.max} = \sqrt{2 \frac{P_{p.In} - P_{p.Out}}{\xi_c(\rho_M + \rho_L)}}$$

Now the flow can be calculated as the velocity evolves over time inwards and outwards of either water or the mixture by using the equation below. [19]

$$Q_F = v_F \, A_c$$

The spherical geometry can be used can be used to compose the size of the diaphragm area A_d using the following equation.

$$A_d = \pi \left({x_d}^2 + \left(\frac{1}{2} D_c\right)^2 \right)$$

The behavior of one diaphragm pump chamber is now modelled, and is used to get to values for the average mixture flow of the complete pumping system Q_M, which is using multiple chambers. The various pump chambers are put out of phase of each other to minimize the peaks in pressure and mixture flow. With the pressure losses and total flow in the pump known the pressure losses along the rest of the system can be modelled. The efficiency of the system can be calculated with the help of specific energy. Specific energy E_{spec} is the amount of energy required to lift certain amount of solids from sea floor to the surface. [20] It is calculated by using equation below.

$$E_{spec} = \frac{Q_F \, p_r}{M_S \, \eta_p}$$

The energy added to the solids known as potential energy E_{pot} in joules per kilogram is to be calculated by using the equation below. The equation is derived by multiplying the solid mass m_S with the gravitational acceleration g and the height up to which they are raised divided by the same mass.

$$E_{pot} = \frac{m_S \, g \, h}{m_S} = g \, h$$

Energy efficiency of the system is defined as the ratio of the difference in potential energy between the solids at the sea floor and surface and the energy requirement of the system. The efficiency is corrected by a factor using the Archimedes principle for lifting solids, by adding a form of relative density into the equation. The equation below is used for calculation of the energy efficiency.

Thus, the equation for energy efficiency is:

$$\eta_e = \left(1 - \frac{\rho_L}{\rho_S}\right) \frac{E_{pot}}{E_{spec}}$$

So, by the use of the above equations the positive displacement pump model for hydraulic transportation system can be split into three parts. First for a certain production M_S the pressure loss in the riser system. Second is the modelling of the positive displacement pump and is used to derive the pressure losses in the system to transport the mined minerals. Third is the calculation of the efficiency of the system.

$$\eta_e = \frac{Potential\ energy\ of\ solids_{at\ seafloor} - Potential\ energy\ of\ solids_{at\ surface}}{Energy\ Requirement\ of\ the\ system}$$

E. Procedure

In the equation mentioned above a number of input parameters are coded in such a way that these parameters can be varied and iterative process can be carried out. These parameters can be given in the starting points but can be varied to see their effect on the system. The procedure for the designing of the riser system is as follows:

1. Calculation of Terminal Settling Velocity: The terminal settling velocity $v_{S,tn}$ of an individual particle is calculated. Since the Reynolds number is dependent on the hindered terminal settling velocity is in the factor $\alpha_{h.}$ The obtained value of Hindered terminal settling velocity is used to recalculate the Re_p again by replacing $v_{s,tn}$ by $v_{s,th.}$ The iteration is done until constant value of hindered terminal settling velocity is reached. The effect of the concentration on terminal settling velocity is taken into by first using $v_{S,tn}$ to calculate the Reynolds number, and in later iterations $v_{S,th}$. Using the Reynolds number and the concentration a new value of the hindered terminal settling velocity $v_{S,th}$ can be calculated, until it reaches a constant value (change in value should be smaller than 10^{-3}).
2. Calculation of Mixture Velocity: The solid velocity v_s can be approximated by taking the difference of hindered settling velocity $v_{s,th}$ from the mixture velocity v_M which is reasonable when the mixture velocity v_M is assumed to be equal to the liquid velocity v_L. As both the transport factor α_t and the mixture velocity v_M is dependent on each other thus the equations are to be iterated until a constant value is reached. Assuming the transport factor α_t as 0.85 for the first iteration, the mixture velocity is calculated. With this mixture velocity the new transport factor is calculated which is used for re-calculation of the mixture velocity. The iteration is done until the change in the transport factor is smaller than 10^{-3}.
3. Calculation of Pressure Losses: The pressure losses can be calculated by using the mixture velocity. The parameters in the equation of the pressure losses are to be substituted to find the pressure losses. The Darcy friction factor λ is assumed to be constant as 0.012 which forms the wall friction component of the pressure losses.
4. Modelling of the positive displacement pumps: The force balance over one single pump chamber is used to calculate the development of the unlimited flow inwards and outwards of the chamber. Then the flow and the volume of the chamber are used to calculate the time required to fill the chamber, including the position and velocity of the diaphragm over time.
5. Calculation of Efficiency of the Riser System: After modelling of the pumps required for the system, the potential energy and the energy used for lifting the mixture form the sea floor to the surface is calculated. Both the potential energy and energy used by the lifting system can be calculated in joules per transported kilogram. The efficiency of the riser system is calculated using the Archimedes factor.

III. RESULTS

For effective transportation of the mined materials (polymetallic nodules) from Seafloor Mining Tool (SMT) to the Mining Support Vessel (MSV) the hydraulic transportation system is designed.

The fig 7 shows the schematic diagram of the hydraulic transportation system. In the fig 7 the system consists of a Positive displacement Pump having a pump pressure of 30,000 kPa.

This design is done with the help of the equations. The calculations are shown in the appendixes at the end. Placing of the Pump is important for assuring a minimum amount of over and under pressures in the riser, with the aim of minimizing the overall weight of the system itself. Systematic arrangement of the positive displacement pump in the hydraulic system ensures that there would be no blockage due to the reduction of pump pressure. The minimum allowable pressure follows from the structural design of the VTS and it is prescribed by design norms. Thus, it is essential that the pump arrangement is done properly. The actuator in the system helps to maintain the pressure in the chamber and ensures that the system is working without any problems.

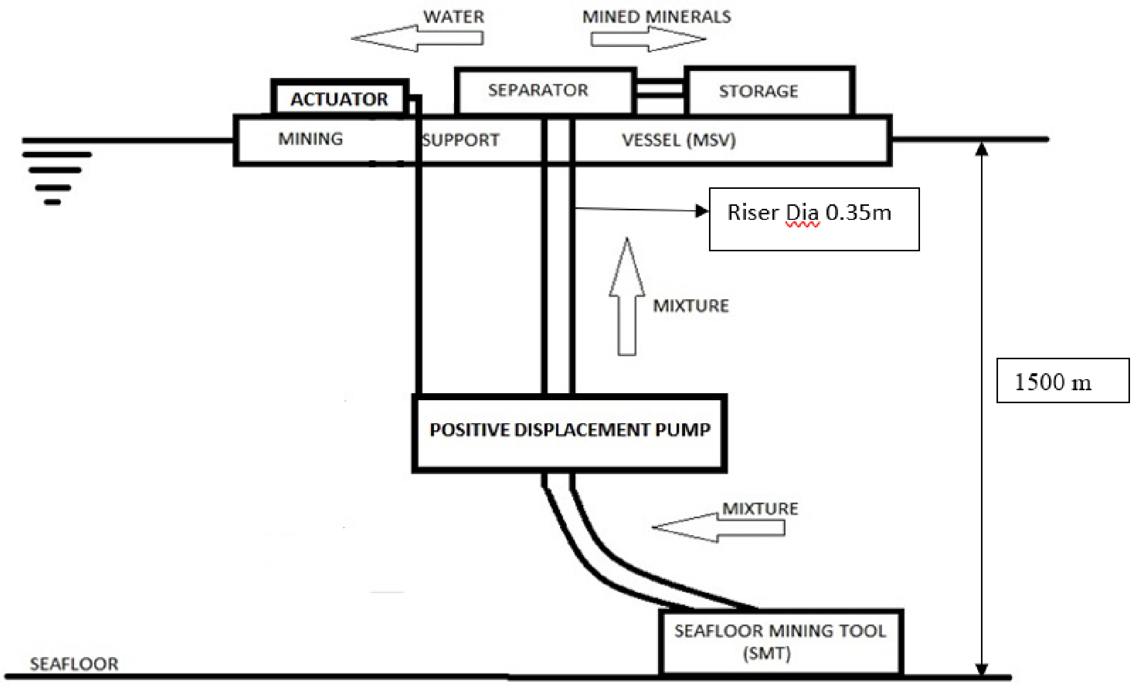

Figure 6. A Schematic design of the Vertical Hydraulic Transport System using positive displacement pump.

Fig 8 shows the graph between the terminal settling velocity vs particle diameter. This graph shows that as the diameter of the particle increases the terminal settling velocity also increases. The settling velocity of a particle is defined as the velocity attained by the particle when it falls down in still water and when the drag force acting on the particle is equal to the submerged weight of the grain. Thus, particle diameter plays an important role in the settling velocity as both the drag force and the weight are dependent on the particle diameter. The graph shows that the terminal settling velocity increases as the particle diameter increases. Due to this more amount of power is required to pump the larger dimeter particle to overcome the terminal settling velocity.

The relation between the mixture velocity and the particle diameter is shown as the graph in the fig 9. Mixture velocity is the velocity of the mixture in the riser system. This velocity decreases as the particle diameter increases. In the mixture velocity equation, the particle diameter is inversely proportional to the mixture velocity which is clearly depicted in the graph.

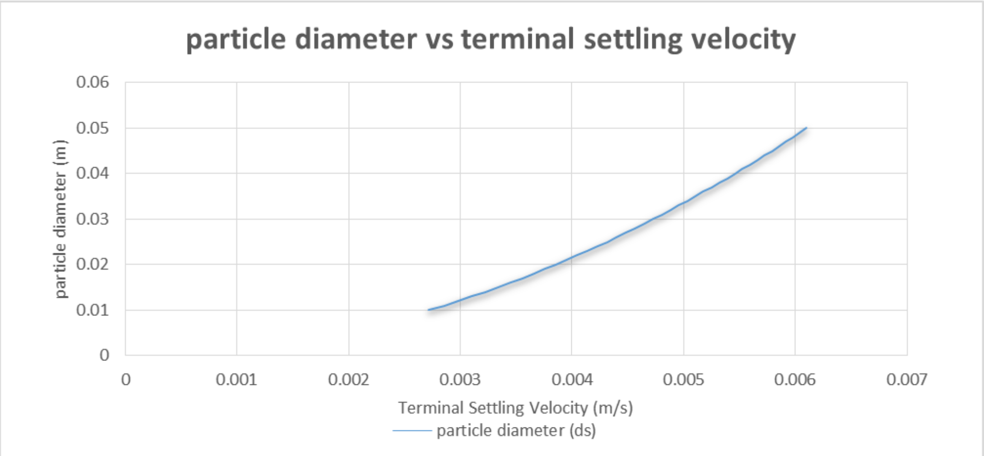

Figure 7. Graph of the terminal settling velocity vs particle diameter.

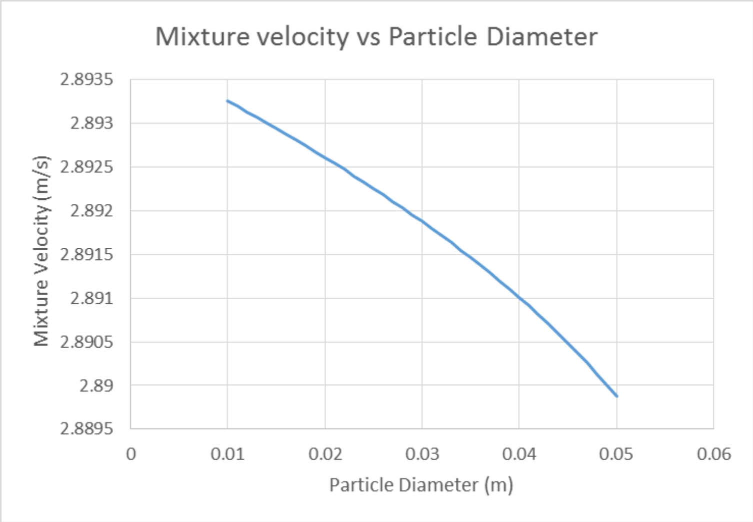

Figure 8. Graph of Mixture velocity vs Particle diameter.

The small variations in the mixture velocity as the particle diameter increases can cause a lot of trouble while in operation. The pump pressure is needed to overcome the resistance offered by the particle diameter to transport the mixture efficiently to the Mining Support Vessel (MSV).

In the fig 9 it is shown that the particle having the diameter of 10 mm has the higher mixture velocity than the particle having the diameter of 50 mm. The maximum mixture velocity goes up to 2.8935 m/s. This shows that in the riser, the mixture velocity changes from particle to particle with varying diameters which makes it necessary to monitor the particle diameter while the mining operations.

Efficiency of the riser system signifies how well the system works under the various conditions such as varying depths. It also depends on the amount of production done by the system. As the energetic efficiency is defined as the difference in potential energy between the solids at seafloor and surface, divided by the energy requirement of the system, the particle diameter can affect the energy of the solids at seafloor and surface. Thus, varying the efficiency of the system. Energy requirements can be influenced by a change in depths in two ways. As the depth increases there is rise of the efficiency to a certain limit then it decreases as shown in the graph. It also increases the energy per pressure losses caused due to friction. For a fixed production requirement, the depths can be influenced by altering either the particle diameter or the concentration. The change in efficiency of the system is calculated for varying particle diameters, by keeping the other parameters as constant. The result is displayed in fig 10.

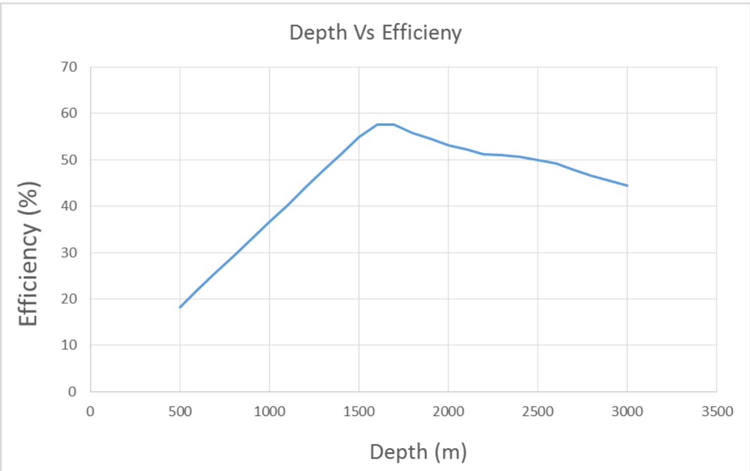

Figure 9. Graph of Depth vs Efficiency.

The efficiency of the riser system depends mainly on two parameters. One of them being the particle diameter and the other being depth at which the system works. The fig 10 shows that the relation between the Depth and the efficiency of the system. In the fig it can be seen that as the Depth increases the efficiency is increases for a certain value and then it begins to decline. The efficiency varies from 18% to 58% as shown in the graph. The efficiency of the system continuous to reduce when the depth is further increased. Thus, trying to reduce the working depth increases the chances to improve the efficiency of the system.

Fig 11 shows the graph between the production and the efficiency of the hydraulic transportation system. The production of the mined polymetallic nodules is also an important aspect in determining the efficiency of the system. As mentioned earlier energy requirement can be influenced by changing the concentration and production of the mixture. This in turn affects the mixture velocity. If the mixture velocity is changed then the pump pressure is also changed. Thus, affecting the efficiency of the system.

In the graph it is shown that initially when the production is low the efficiency of the system is also low. But as the production is increased the efficiency also starts to increase up to a certain value and then it starts to decrease as the production increases. The value up to which efficiency is maximum, this value is the optimum concentration. This optimum value of production of the mixture can ensure high efficiency of the system.

IV. Conclusions And Recommendations

In this design, the vertical hydraulic transport for deep sea mining by using positive displacement slurry pumps for transporting the polymetallic nodules from the sea floor at a depth of 1500 m by using Seafloor Mining Tool (SMT) to the Mining Support Vessel (MSV) with the help of Riser system is done. The system's designing was done and its efficiency was calculated. The effect of the systems efficiency on various parameters was also studied. Effective method for transportation of the polymetallic nodules was studied by using the riser and positive displacement slurry pump.

The recommendations for future studies are as follows:

- A study can be done for the vertical hydraulic transport for deep sea mining by using airlift method, mechanical lifting etc.
- For increasing the efficiency of the riser system, crushing method can be used. In Crushing method, the diameters of the nodules are reduced by means of mechanical energy. An optimum force should be calculated for the optimum particle diameter to get higher efficiency.

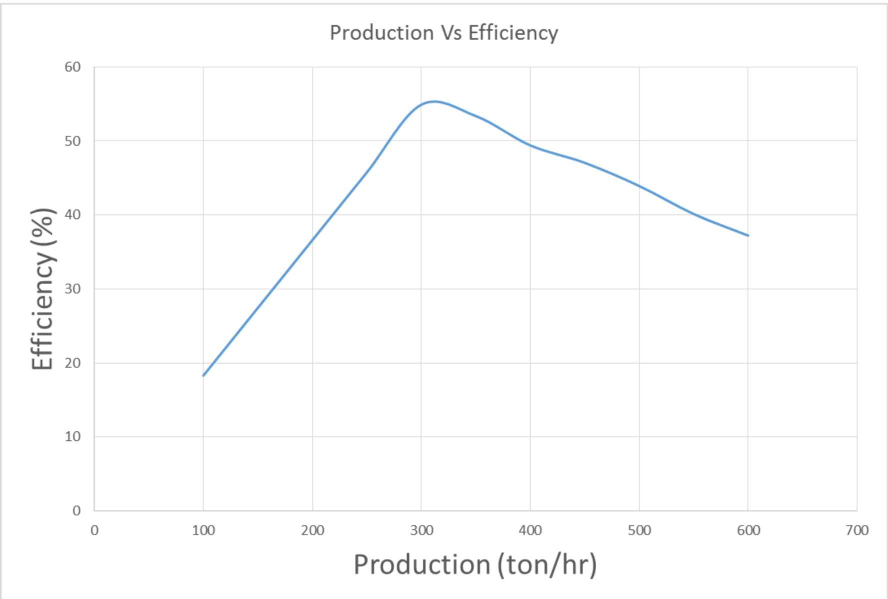

Figure 10. Graph of Production vs efficiency.

- A study can be made by changing the flow in the pump and comparing various other types of transportation methods.
- An experimental study can be done for the feasibility of the vertical hydraulic transport for deep sea mining at various depths and for different minerals.
- A survey for finding different nodules present in Indian Ocean can be done and then different nodules present there can be identified and their properties can be tested at various depths.
- A study can be done for the feasibility of refining the minerals nodules onshore or offshore depending on the location.
- A study on different types of chemical process for refining the nodules can be done.
- A study on environmental aspects of deep-sea mining can be done and prevention of the harmful effect of the deep sea mining process can be studied.

ACKNOWLEDGMENT

I wish to thank Dr. K.V.K.R. K. Patnaik, Faculty, Indian Maritime University, Visakhapatnam Campus for his guidance and support during the work for this paper.

REFERENCES

[1] Bath, Deep sea mining technology: recent developments and future projects, OTC, 1989. https://doi.org/10.4043/5998-ms.

[2] BlueMining, "Blue mining project website for Deep Sea Mining," BlueMining, [Online]. Available: https://bluemining.eu/ [Accessed 30 November 2017].

[3] "Vertical hydraulic transport," [Online]. Available: http://www.bluemining.eu/vertical-transport

[4] European Union, "MIDAS project - Managing Impacts of Deep-seA reSource exploitation," Seascape Consultants Ltd., 1 November 2013. [Online]. Available: http://eu-midas.net/ [Accessed 1 December 2017].

[5] Nautilus Minerals, Solwara 1 Copper-Gold Project in Papua New Guinea report., Nautilus Minerals, 2012, doi: https://doi.org/10.1163/9789004230941_014

[6] "Solwara Deep Sea Mining Project," [Online]. Available: http://cares.nautilusminerals.com/irm/content/solwara-1-project.aspx?RID=339 .

[7] "Deep sea mining," [Online]. Available: https://www.royalihc.com/en/products/mining/deep-sea-mining.

[8] Interim Report under FWC- MARE/2012/06 - SC E1/2013/04, "Study to Investigate State of Knowledge of Deep Sea Mining.," ECORYS, Nederland BV, 2013,url: https://webgate.ec.europa.eu/maritimeforum/system/files/Annex%201%20Geological%20analysis%20rev_1.pdf

[9] National Institute of Ocean Technology, "Deep Sea Mining," NIOT, 2019. [Online]. Available: https://www.niot.res.in/index.php/node/index/135/. [Accessed 15 November 2017].

[10] P. Jaeyoung Lee, "Introduction to Offshore Pipelines & Risers," Houston, Texas, 2009, url: https://www.scribd.com/doc/238620580/Introduction-to-Offshore-Pipelines-Risers-Jaeyoung-Lee.

[11] J. B. Herbich, Coastal & Deep Ocean Dredging, U.S.: Gulf Publishing Company, 1975.

[12] S. Schulte, Vertical transport methods for Deep Sea Mining, Delft, 2013, url: https://repository.tudelft.nl/islandora/object/uuid:86da5533-5a17-4c06-b725-022794f0d84/datastream/OBJ/download

[13] Maribus Ggmbh, Pickhuben, D-20457 Hamburg, Germany, "World Ocean Review," 2014. [Online]. Available: https://worldoceanreview.com/en/wor-3/mineral-resources/manganese-nodules/. [Accessed 2017].

[14] P. C. a. E. E. C. E. Condolios, "Pumping ores up vertical shafts," Canadian Mining and Metallurgy Bulletin, 1963.

[15] C. A. S. A. Bartosik, "Prediction Of Vertical Liquid Solid Pipe Flow Using Measured Concentration Distribution," Particulate Science and Technology, vol. 13, no. 2, pp. 85-104, 1995, https://doi.org/10.1080/02726359508906672.

[16] A. B. C. A. Shook, "Particle—wall stresses in vertical slurry flows," Powder Technology, vol. 81, no. 2, pp. 117-124, 1994. https://doi.org/10.1016/0032-5910(94)02877-x.

[17] Pipe Flow Software, "Pipe Elevation Changes and Effect on Pressure Loss," [Online]. Available: http://www.pipeflow.com/pipe-pressure-drop-calculations/pipe-elevation-changes. [Accessed 30 November 2017].

[18] A. Bartosik, "Influence of Coarse-Dispersive Solid Phase on the ‘Particles–Wall’ Shear Stress in Turbulent Slurry Flow

with High Solid Concentration," The Archive Of Mechanical Engineering, vol. VOL. LVII, no. 1, pp. 45-68, 2010. https://doi.org/10.2478/v10180-010-0003-1.

[19] American Society of Mechanical Engineers [ASME], ASME B31.4-2012: Pipeline Transportation Systems for Liquids and Slurries, Multiple. Distributed through American National Standards Institute (ANSI), 2012,doi: https://doi.org/10.1115/b31.

[20] A. B. a. K. C. Wilson, "Derivation Of The Regime Equations From Relationships For Pressurized Flow By Use Of The Principle Of Minimum Energy - Degradation Rate.," Proceedings of the Institution of Civil Engineers, vol. 36, no. 1, pp. 47-62, 1967. https://doi.org/10.1680/iicep.1967.8590.