PETROLEUM ENGINEERING DEPARTMENT
FLOW LOOP EXPERIMENT

EXPERIMENT # 7 & 8
ELECTRICAL SUBMERSIBLE PUMPS (ESP)
ELECTRICAL SUBMERSIBLE PUMP (ESP)

OBJECTIVE

To develop the performance curve of an ESP

To study the effect of rotation speed and intake pressure to the pump performance.

To examine the Affinity Law

CENTRIFUGAL PUMP THEORY

A centrifugal pump is one of the simplest pieces of equipment in any process plant. Its purpose is to convert energy of a prime mover (an electric motor or turbine) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or diffuser. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy.

When the impeller rotates, it spins the liquid sitting in the cavities between the vanes outward and provides centrifugal acceleration. As liquid leaves the eye of the impeller a low-pressure area is created causing more liquid to flow toward the inlet. Because the impeller blades are curved, the fluid is pushed in a tangential and radial direction by the centrifugal force.

The key idea is that the energy created by the centrifugal force is kinetic energy. The amount of energy given to the liquid is proportional to the velocity at the edge or vane tip of the impeller. The faster the
impeller revolves or the bigger the impeller is, then the higher will be the velocity of the liquid at the vane tip and the greater the energy imparted to the liquid. This kinetic energy of a liquid coming out of an impeller is harnessed by creating a resistance to the flow. The first resistance is created by the pump volute (casing) that catches the liquid and slows it down. In the discharge nozzle, the liquid further decelerates and its velocity is converted to pressure according to Bernoulli’s principle. Therefore, the head (pressure in terms of height of liquid) developed is approximately equal to the velocity energy at the periphery of the impeller expressed by the following well-known formula

\[ H = \frac{v^2}{2g} \]

where \( H \) is the total head developed in feet; \( v \) is the velocity at periphery of impeller in ft/sec; and \( g \) is the acceleration due to gravity, \( g = 32.2 \text{ ft/sec}^2 \).

This head can also be calculated from the readings on the pressure gauges attached to the suction and discharge lines. Pump curves relate flow rate and pressure (head) developed by the pump at different impeller sizes and rotational speeds.

![Graph](image)

**Water performance of curve of the ESP GC6100 at Hz, one stage**

Centrifugal pumps can be single-stage or multi-stage units. Single-stage pumps are mainly used when low to medium discharge pressure is required, while multi-stage pumps are designed to overcome higher discharge pressures. This is the case of Electric Submersible Pumping (ESP) used in the petroleum industry where fluids must be lifted from deep formations.
ESP is the second most commonly used artificial lift method in oil and gas industry. ESP has been used massively in Russia and in significant number of wells in US. It is responsible for the highest amount of total fluids produced (oil and water) by any artificial lift method and an ideal method for high water cut wells. The problems with ESPs are that they are not suitable for high gas liquid ratio and high bottom hole temperature wells.

When handling free gas, the centrifugal pump head performance curve suffers degradation. The design of an ESP system using the water information for oil wells with some free gas fraction at pump intake conditions is a harder task, and is based on the prediction of performance curves by modification of the water curves. The most important parameter is the density of the mixture at the flow conditions of each stage. Applying this procedure, the ESP system often shows some degree of under or over sizing, under field operations. This can be observed comparing the expected and the real produced flow rates, and also by the amperage consumption fluctuation of the motor due to the presence of the gas phase.
The centrifugal pump operation should conform to the pump curves supplied by the manufacturer. In order to read and understand the pump curves, it is very important to develop a clear understanding of the terms used in the curves.

**Capacity, Q, GPM**

Capacity means the flow rate with which liquid is moved or pushed by the pump to the desired point in the process. It is commonly measured in either gallons per minute (gpm) or cubic meters per hour (m³/hr). The effect on the flow through a pump by changing the outlet pressures is graphed on a pump curve.

**Head, H, ft**

The pressure at any point in a liquid can be thought of as being caused by a vertical column of the liquid due to its weight. The height of this column is called the static head and is expressed in terms of feet of liquid. The same head term is used to measure the kinetic energy created by the pump. In other words, head is a measurement of the height of a liquid column that the pump could create from the kinetic energy imparted to the liquid. Head is a term that has units of a length or feet and pressure has units of force per unit area or pound per square inch. The main reason for using head instead of pressure to measure a centrifugal pump's energy is that the pressure from a pump will change if the specific gravity (weight) of the liquid changes, but the head will not change.
Head (ft) = \frac{Pressure \ (psig)}{0.43 \times Specific \ gravity} 

**Brake Horse Power (BHP) and Hydraulic Horsepower (HHP)**

The work performed by a pump is a function of the total head and the weight of the liquid pumped in a given time period. Pump input or brake horsepower (BHP) is the actual horsepower delivered to the pump shaft. Pump output or hydraulic or hydraulic horsepower (HHP) is the liquid horsepower delivered by the pump. These two terms are defined by the following formulas.

\[ BHP = \frac{Q \times H \times \gamma}{3960 \times E}, \text{ HP} \]

\[ HHP = \frac{Q \times H \times \gamma}{3960}, \text{ HP} \]

Where Q is the capacity in gallons per minute (GPM); H is the head in feet; \( \gamma \) is the specific gravity of the liquid; and E is the pump efficiency, %

The constant 3960 is obtained by dividing the number of foot-pounds for one horsepower (33,000) by the weight of one gallon of water (8.33 pounds). BHP can also be read from the pump curves at any flow rate. Pump curves are based on a specific gravity of 1.0. The brake horsepower or input to a pump is greater
than the hydraulic horsepower or output due to the mechanical and hydraulic losses incurred in the pump. Therefore the pump efficiency is the ratio of these two values.

**Best Efficiency Point (BEP)**

Best Efficiency Point (BEP) is defined as the capacity at which the efficiency of the pump is highest. All points to the right or left of BEP have a lower efficiency. The BEP is the area on the curve where the change of velocity energy into pressure energy at a given gallon per minute is optimum; in essence, the point where the pump is most efficient. The impeller will be subject to non-symmetrical forces when operating to the right or left of the BEP. These forces manifest themselves in many mechanically unstable conditions like vibration, excessive hydraulic thrust, temperature rise, and erosion and separation cavitation. Thus the operation of a centrifugal pump should not be outside the furthest left or right efficiency curves published by the manufacturer. The centrifugal pump should be operated in a range of ±20% of the maximum efficiency $E_{\text{max}}$. The $-0.2E_{\text{max}}$ is called the lower operating range and the $+0.2E_{\text{max}}$ is called the upper operating range. If the ESP is operated out of the operating range, it will suffer under either upthrust or downthrust which causes the damage of the impellers.
**Specific Speed**

Specific Speed as a measure of the geometric similarity of pumps. Specific speed (Ns) is a non-dimensional design index that identifies the geometric similarity of pumps. It is used to classify pump impellers as to their type and proportions. Pumps of the same Ns but of different size are considered to be geometrically similar, one pump being a size-factor of the other. Specific speed Calculation The following formula is used to determine specific speed

\[
N_s = \frac{N \times Q^{0.5}}{H^{0.75}}
\]

Where Q is the capacity at the best efficiency point in GPM; H is the head per stage at BEP in feet; and N is the pump speed in RPM.

As per the above formula, it is defined as the speed in revolutions per minute at which a geometrically similar impeller would operate if it were of such a size as to deliver one gallon per minute flow against one-foot head. The understanding of this definition is of design engineering significance only, however, and specific speed should be thought of only as an index used to predict certain pump characteristics. Specific speed as a measure of the shape or class of the impellers. The specific speed determines the general shape or class of the impellers. As the specific speed increases, the ratio of the impeller outlet diameter, D2, to the inlet or eye diameter, D1, decreases. This ratio becomes 1.0 for a true axial flow impeller. Radial flow impellers develop head principally through centrifugal force. Radial impellers are generally low flow high head designs. Pumps of higher specific speeds develop head partly by centrifugal force and partly by axial force. A higher specific speed indicates a pump design with head generation more by axial forces and less by centrifugal forces. An axial flow or propeller pump with a specific speed of 10,000 or greater generates its head exclusively through axial forces. Axial flow impellers are high flow low head designs.

Ns: 500 to 5000; D1/D2 > 1.5  - radial flow pump

Ns: 5000 to 10000; D1/D2 < 1.5  - mixed flow pump

Ns: 10000 to 15000; D1/D2 = 1  - axial flow pump
Classification of Centrifugal Pumps according to Specific Speed, $n_s$

*The Affinity Laws*

The Affinity Laws are mathematical expressions that define changes in pump capacity, head, and BHP when a change is made to pump speed, impeller diameter, or both. According to Affinity Laws:
Capacity, $Q$ changes in direct proportion to speed $N$ ratio:

\[
\frac{Q_2}{Q_1} = \frac{N_2}{N_1}
\]

Head, $H$ changes in direct proportion to the square of speed $N$ ratio:

\[
\frac{H_2}{H_1} = \left(\frac{N_2}{N_1}\right)^2
\]

BHP changes in direct proportion to the cube of speed ratio:

\[
\frac{BHP_2}{BHP_1} = \left(\frac{N_2}{N_1}\right)^3
\]

The Affinity Laws are valid only under conditions of constant efficiency and very low viscosity of fluids.

**EXPERIMENTS**

Note that we have two pumps connected in series. With two pumps in series, we can simulate an ESP with 2 stages. We can also simulate the two pumps in series in a different way: the first pump is to simulate the bottom hole pressure or the intake pressure of the ESP; meanwhile, the second pump is simulated as an ESP with 1 stage. We can change the speed of the ESP by controlling the VFD. Similarly, the intake pressure of the ESP can be varied by adjusting the return valve.

This procedure is applied for those who are very familiar with the flow loop. If students have any questions or concerns, please check with the T.A.

1. Keep the “manual/auto” switch in the speed control panel in the manual mode.
2. Adjust all the valves in the right positions: we need to have the flow through the two pumps, ¾” pipe and through the ½” pipe (No flow through the orifice).
3. Mass flow meter will be used for all ESP tests

**Experiment # 7: Develop the pump performance’s curves of an ESP**

**Procedures:**

1. Keep the discharge pressure of the first pump (intake pressure of the second pump) at 30 psig by adjusting the return valve on the return line of the first pump.
2. On the speed control panel, set a speed of 3,500 RPM for the second pump.
3. Start recording the data
4. Use the end valve as circle in the flow loop schematic to change the flow rate of the fluid. In the beginning, the end valve must be open. The end valve will be changed from fully open to fully close with 10 different openings. Talk with the T.A. if you need help.

5. Repeat steps 2 to 4 with different pump speed for the second pump: 3,200, 3,000, 2,700, 2,400, 2000, 1500 RPM.

6. Stop recording the data.

7. Stop the two pumps.

8. Copy the data and then turn off the production lab program.

Calculation:

1. Convert the flow rate to barrel per day (BPD) and m$^3$/s
2. Convert the differential pressure between intake and discharge pressure to head in the unit of ft and meter.
3. Calculate the hydraulic horse power developed by the second pump.
4. Calculate the specific speed of the pump.
5. Develop the performance curve of the pump by plotting these relationships in one graph: head (ft and meter) vs. flow rate (bbl/day and m$^3$/s); specific speed vs. flow rate (bbl/day); hydraulic horse power vs. flow rate (bbl/day).
6. Plot the performance curve for the two-stage pump (two pump in series). Assuming the intake pressure is zero.
Questions:

1. What is the principle of building head in a centrifugal pump?
2. What are the differences between a conventional centrifugal pump and an ESP?
3. What are the advantages and disadvantages of an ESP.
4. What are the problems if the ESP is operated out of the operating range?
5. How does the pump speed change the pump performance curves? Why?
6. Based on the calculated specific speed, how would you classify this centrifugal pump?

Experiment # 8: The effects of intake pressure on the pump performance curves - Affinity Law

Procedure:

1. Apply the same procedure in the experiment # 7 but with only two pump speed of 3,200 RPM and 3,000 RPM and different intake pressure of 10, 20, 40, and 50 psig.

Calculations:

Note that for all the calculations below, flow rate is expressed in bbl/day and head in feet.

1. Use the performance curve at 3,500 RPM and intake pressure of 30 psig obtained from the experiment # 7 as a reference. Apply the Affinity Law to predict the performance curves at different pump speed of 3,200, 3,000, 2,700, 2,400 RPM.
2. Plot in the same plot the performance curves predicted by the Affinity Law and the performance curves obtained from experimental data in the experiment # 7.
3. Plot the relationship between head and flow rate at 3,200 RPM at different intake pressure: 10, 20, 30, 40, and 50 psig.
4. Generate a similar plot as step 3 but with the pump speed of 3,000 RPM

Questions:

1. Describe the Affinity Law? What are the limitations of the Affinity Law?
2. How does the Affinity Law match with the experimental data? What may cause the discrepancy between the prediction of Affinity Law and the experimental data
3. Based on the experimental data, how does the intake pressure affect on the pump performance? What would you predict the effect of the intake pressure on the pump performance if the fluid is two phase: liquid and gas?