Positive Displacement Pumps
Part I – Reciprocating Pumps

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There are many pump designs that fall into the positive displacement category but, for the most part, they can be nicely divided into two basic groups. The reciprocating group operates via pistons, plungers, or diaphragms while rotary pumps use gears, lobes, screws, vanes, and peristaltic action. Their common design thread is that energy is added to the pumped fluid only periodically where, in dynamic pumps, it is added continuously.

PISTON & PLUNGER PUMPS

The piston pump is one of the most common reciprocating pumps and, prior to the development of high speed drivers which enhanced the popularity of centrifugals, it was the pump of choice for a broad range of applications. Today , they are most often seen in lower flow, moderate (to 2000 PSI) pressure applications. Its close cousin, the plunger pump, is designed for higher pressures up to 30,000 PSI. The major difference between the two is the method of sealing the cylinders. In a piston pump the sealing system (rings, packing etc) is attached to the piston and moves with it during its stroke. The sealing system for the plunger pump is stationary and the plunger moves through it during its stroke.

Reciprocating pumps operate on the principle that a solid will displace a volume of liquid equal to its own volume. The figure to the right is that of a generic double acting piston pump. If we were to remove the two valves at the left hand side of the figure and replace them with an extension of the cylinder, we would have a single acting pump. The single
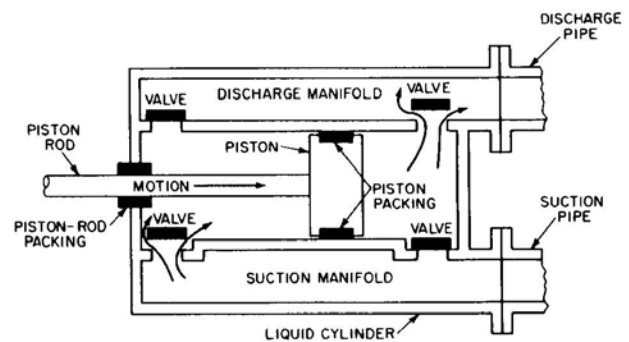
acting pump discharges water only on its forward stroke while the double acting pump discharges on its return stroke as well. During the suction stroke (right to left) the single acting pump's discharge valve closes and allows fluid to enter the cylinder via the suction valve. When the piston changes direction (reciprocates) the suction valve closes and water is discharged through the discharge valve. In the double acting pump, the same sequence occurs during both strokes and almost twice as much fluid is discharged per unit time.

Pressure

The head created by a centrifugal pump depends upon the velocity it imparts to the fluid via its impeller. Therefore, for any given impeller diameter and rotational speed, head will be some maximum, unvarying amount. Not so for reciprocating pumps. Although they will have a maximum operating pressure rating, the maximum pressure (P) attained depends upon the application. Against a closed discharge valve, pressure is limited only by the capability of the driver and the strength of the materials employed. Only the "breaking point" of some component will limit discharge pressure. Therefore some form of pressure relief must be supplied if an application is capable of exceeding the pressure rating of the pump.

Capacity

The capacity (Q) of a single acting piston or plunger pump is proportional to its displacement (D) per unit time. The displacement is the calculated capacity of the pump, assuming 100% hydraulic efficiency, and is proportional to the cross sectional area of the piston (A), the length of its stroke (s), the number of cylinders (n), and the pump's speed in rpm. In gallons per minute it is:

$$D = (A \times s \times n \times rpm) / 231$$

In the case of double acting pumps the cross sectional area of the piston or plunger is doubled and the cross sectional area of the piston rod (a) is subtracted. Again, in gallons per minute D is:

$$D = ((2A - a) \times s \times n \times rpm) / 231$$

In real life the theoretical capacity of a piston or plunger pump is tempered by several factors. One is known as slip (S). The major component of slip is the leakage of fluid back through the discharge or suction valve as it is closing (or seated). It can reduce calculated displacement from 2 to 10% depending upon valve design and condition. Increased viscosity will also adversely affect slip.

Another important factor that affects a reciprocating pump's capacity is something called volumetric efficiency (VE). VE is expressed as a percentage and is proportional to the ratio of the total discharge volume to the piston or plunger displacement. The figure to the right illustrates how we arrive at this ratio.

TOP OF BACK STROKE

$$r = \frac{C+D}{D}$$
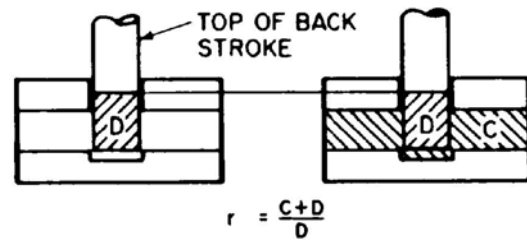
The ratio (r) is shown to be (c+d)/d where d is the volume displaced by the piston or plunger and c is the additional volume between the discharge and suction valves. The smaller this ratio, the better the volumetric efficiency. Expressed mathematically, it looks like this:

VE = 1 - (P x b x r) - S

where P is pressure, b is the liquid's compressibility factor, r is the volume ratio, and S is slip. The compressibility factor for water is quite small (3 X 10^{-6} inches per pound of pressure at ambient temperature) but at pressures greater than 10,000 PSI it does become a factor.

The figure above also clearly illustrates the volumetric displacement operating principle of these pumps. Although there is no cylinder wall around the plunger at the bottom of its stroke, it still displaces fluid equal to its own volume. Now, we can finally state the actual capacity of a reciprocating pump. It is quite simply:

Q = D x VE

Power

The power required to drive a reciprocating pump is quite straight forward. It is simply proportional to pressure and capacity. In brake horsepower it is:

bhp = (Q X P) / (1714 X ME)

where 1714 is the bhp conversion factor and ME is mechanical efficiency. Mechanical efficiency is the percentage of the driver power that is not lost in the pump's power frame and other reciprocating parts. The mechanical efficiency of a piston or plunger pump ranges between 80 and 95% depending upon speed, size, and construction.
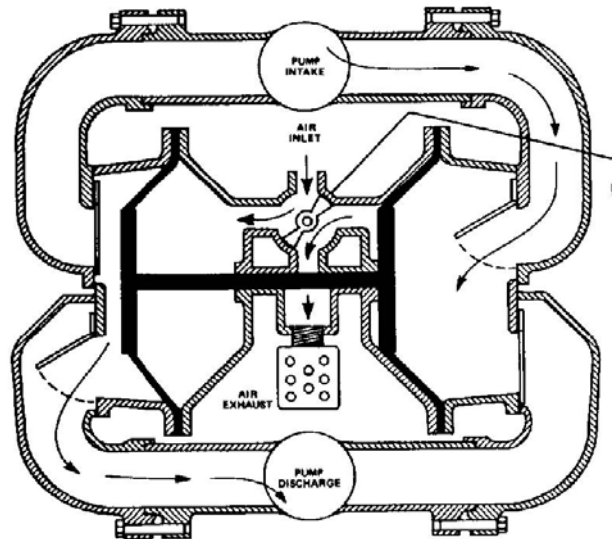
DIAPHRAGM PUMPS

Diaphragm pumps are reciprocating positive displacement pumps that employ a flexible membrane instead of a piston or plunger to displace the pumped fluid. They are truly self priming (can prime dry) and can run dry without damage. They operate via the same volumetric displacement principle described earlier. The figure on the right shows the operational cycle of a basic, hand operated single diaphragm pump.

Were its operation any simpler, it would compete with gravity. The upper portion of the figure shows the suction stroke. The handle lifts the diaphragm creating a partial vacuum which closes the discharge valve while allowing liquid to enter the pump chamber via the suction valve. During the discharge stroke the diaphragm is pushed downward and the process is reversed. Hand operated pumps are designed to deliver up to 30 gpm at up to 15 feet but actual capacity is extremely dependent upon the physical condition of the driver. Air, engine, and motor drive units are also available and offer capacities to 130 gpm. Both suction and discharge head vary from 15 to 25 feet.
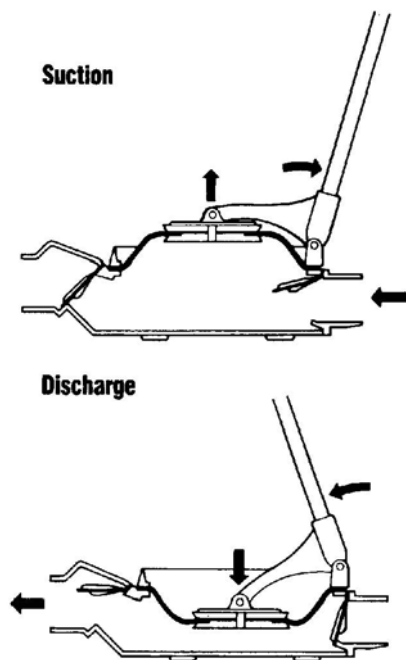
You will note that, unlike pistons and plungers, diaphragms do not require a sealing system and therefore operate leak free. This feature does, however, preclude the possibility of a double acting design. If nearly continuous flow is required, a double-diaphragm or duplex pump is usually employed. The figure below is a cross section of an air operated, double diaphragm pump.

The double diaphragm pump utilizes a common suction and discharge manifold teamed with two diaphragms rigidly connected by a shaft. The pumped liquid resides in the outside chamber of each while compressed air is routed to and from their inner chambers. In the figure, the right hand chamber has just completed its suction stroke and, simultaneously, the left chamber completed its discharge stroke. As would be expected, the suction check is open so that liquid can flow into the right chamber and the discharge check of the left chamber is open so that liquid can flow out. Except for the double chamber configuration, its operation is just like the double acting piston pump seen earlier. The difference, of course, resides within the inner chambers and the method in which the reciprocating motion is maintained. This is accomplished by an air distribution valve that introduces compressed air to one diaphragm chamber while exhausting it from the other. Upon completion of the stroke the valve rotates 90 degrees and reciprocation occurs.

I introduced this section with the statement that diaphragm pumps are positive displacement in nature. Generally this is an accurate statement but they can also be referred to as "semi" positive displacement. The reason for this is the elasticity of the diaphragm and a corresponding reduction in volumetric efficiency as discharge pressure increases. Also, check valve leakage is often significantly greater than that experienced by piston and plunger pumps.

AFFINITY

Although we tend to associate affinity laws with centrifugal pumps, other mechanical devices also exhibit these "natural" relationships. In the case of positive displacement pumps the affinity laws are very straight forward.

Flow - Flow varies directly with a change in speed. If the rotational speed is doubled, flow is also doubled.

Pressure - Pressure is independent of a change in speed. If we ignore efficiency losses, the pressure generated at any given rotational speed will be that required to support flow.

Horsepower - Horsepower varies directly with a change in speed. If we double the rotational speed, twice as much power will be required.

NPSHr - Net Positive Suction Head required varies as the square of a change in speed. If we double the rotational speed NPSHR increases by four.