A COMPARISON OF POSITIVE DISPLACEMENT AND CENTRIFUGAL PUMP APPLICATIONS

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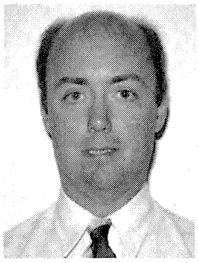

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ABSTRACT

Positive displacement and centrifugal pumps sometimes seem to inhabit different worlds. Users are generally much more familiar with one type than the other. This causes some confusion when the user's expectations are based on experience with one type and the reality of the pump's operation is based on the other type. Contrasted, herein, will be the differences in operation of the two types of pumps through real world examples where the characteristics of each were used to advantage.

Centrifugal and positive displacement pumps operate on completely different principals. With centrifugal pumps, flow results from a pressure differential created by the pump. For a positive displacement pump, pressure differential results from flow created by the pump. This is analogous to moving a truckload of tennis balls from the street to the second story of a warehouse. There are two ways to accomplish this. One could stand in the street and throw the balls through an open second story window. This is the centrifugal pump case. One could also put a few balls into a box and carry the box up the stairs, dump out the balls and bring the box back for another load. This is the positive displacement pump case. Continue the analogy by noting that some balls thrown from the street miss the window and bounce off the wall, like *recirculation* in a centrifugal pump. Similarly, some balls fall out of the box and roll back down the stairs, like *slip* in a positive displacement pump.

Imagine that as the height of the window is increased, more balls will miss and bounce back. Eventually, the window will be too high to throw any balls into, and the "shutoff" point will have been reached. At the same time, the number of balls carried up the stairs will remain relatively constant as the height of the window increases. A few more balls may roll out of the box on the taller stairs, but most of the balls will still reach the top.

Five examples of pump applications are examined to illustrate how these different characteristics may be used to good effect. First, a positive displacement pump solved problems for an aluminum can manufacturer because the insensitivity of flow rate to changes in pressure (Figure 1, A and B) improved the uniformity of a coating applied to the inside of the cans. Second, a centrifugal pump was favored to boost the suction pressure of a high pressure fuel pump on a gas turbine, because the variable flow characteristics of the centrifugal pump matched the variable demand (Figure 1, A and C). Third, positive displacement pumps were preferred for unloading tanker trucks because of their self priming characteristics and relative insensitivity to large changes in the viscosity or specific gravity of the liquid being pumped. Next, a centrifugal pump was the best choice for a large pump to circulate cooling water, and finally, a centrifugal pump was also preferred for use as a boiler feedpump.

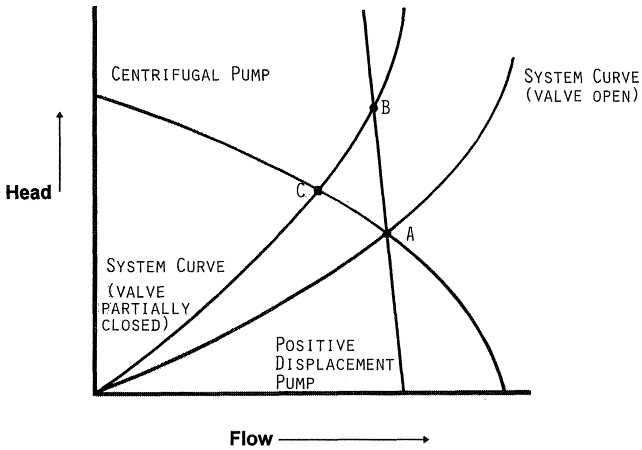

Figure 1. Characteristic Head-Flow Curves for Centrifugal and Positive Displacement Pumps. Note: Centrifugal pump flow varies from A to C, as system changes because of a valve being closed; positive displacement pump flow changes very little as it moves from A to B under the same conditions.

INTRODUCTION

Pump users familiar with centrifugal pumps are often confused and frustrated by positive displacement pumps because they refuse to act like a centrifugal pump. Likewise, users of positive displacement pumps expect centrifugal pumps to behave like good positive displacement pumps. The two types of pumps actually have little in common, other than that they are intended to move liquid [1]. One source of confusion is the way that manufacturers draw the head *vs* flow, or pressure *vs* flow, curves. At first glance, they look similar (Figures 2 and 3). The general trend of both is horizontal, but the axes are reversed. If plotted on the same graph (Figure 4) then one is horizontal, the other is vertical [2].

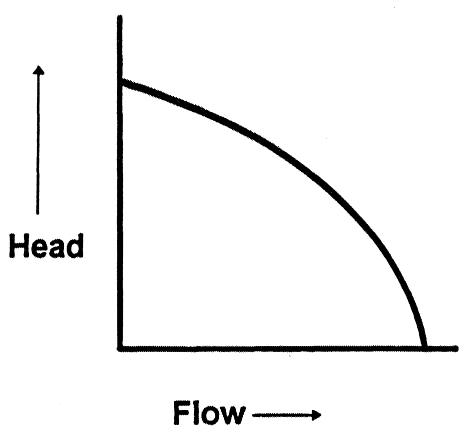

Figure 2. Typical Centrifugal Pump Curve Displacement.

This shows the fundamental difference between the types of pumps. The centrifugal pump produces a straight line head-flow curve, ignoring losses from friction and recirculation. A positive displacement pump is a constant flow device with some internal losses called "slip," due to internal leakage through the clearances around moving parts. The head *vs* flow curves shown in Figure 5 are from actual and idealized centrifugal and positive displacement pumps.

Returning to the analogy with the tennis balls in the ABSTRACT, the centrifugal pump's internal losses are the balls that miss the window and bounce back, and the positive displacement carried up the stairs. The actual and ideal curves for the centrifugal pump meet at maximum flow. The positive

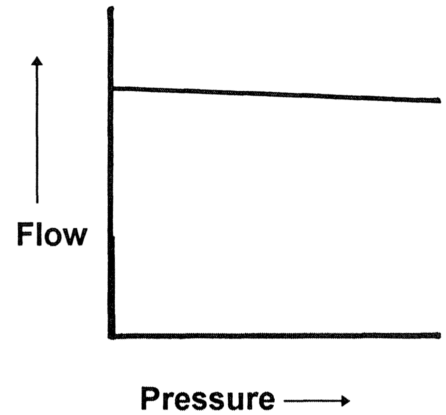

Figure 3. Typical Positive Displacement Pump Curve.

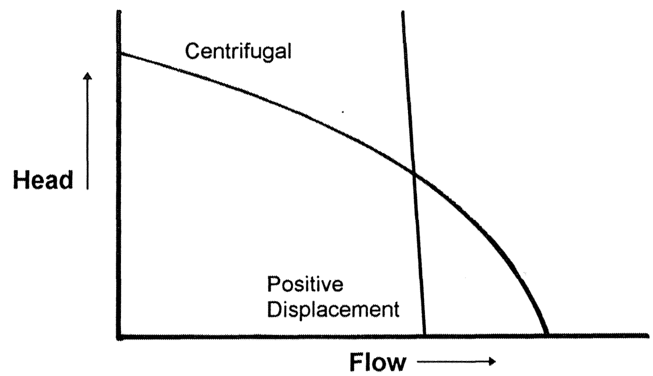

Figure 4. Centrifugal and Positive Displacement Pump Curves.

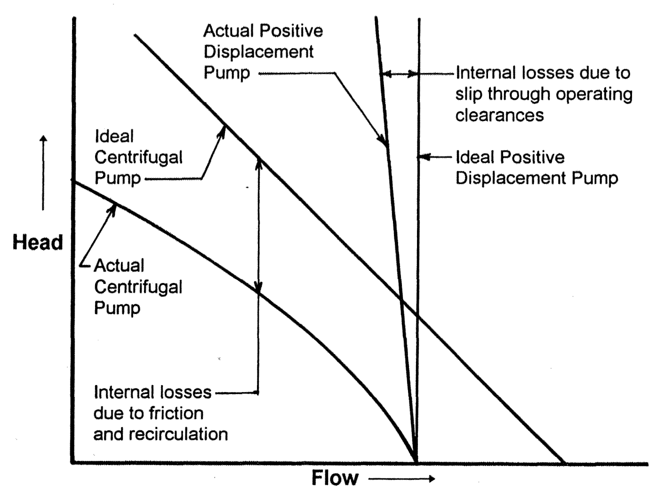

Figure 5. Idealized, Actual Centrifugal, and Positive Displacement Pump Curves.

displacement pump's curves meet at zero pressure because with no difference in pressure across the pump, there is no flow through the internal clearances.

Up to this point, another difference has been glossed over. Pressure and head have been used interchangeably, but they are not quite the same. At a constant specific gravity of the liquid, they act like different units for the same quantity. As specific gravity changes, however, the relation between head and pressure changes.

Head is the height of a column of liquid that the pump can support, given in feet or meters. Pressure is the force per unit area on the pump's internals, head = pressure (in psi) × 2.31/specific gravity [3]. Centrifugal pumps "produce" head, while positive displacement pumps react to pressure on internal components [4].

EXAMPLES

Case 1–Metering Flow to Control Coating Thickness

Aluminum beverage cans must be coated inside to prevent the contents from coming into contact with the metal. This prevents problems with contamination of the contents and deterioration of the can. This is normally accomplished by spraying the inside of each can with a thin coat of lacquer. Since the manufacture of beverage cans is an extremely high volume industry, it is important to control costs very carefully. So, on one hand, the manufacturer wants to put the minimum amount of lacquer in each can, and it must be applied very quickly because the can lines move at over 500 cans per minute. At the same time, the coating of lacquer must be above a minimum thickness to ensure that it will be impervious to the contents of the can. The solution is to make sure that the lacquer is applied at a uniform rate, so that the coating thickness will stay just above the minimum. This is complicated by the fact that the speed of the line varies, which causes the flow needed at the spray nozzles to vary. Also, one pump will supply up to five can producing lines. Lines may periodically shut down because of some upset along the line, so anywhere from one to five of these lines must be supplied by the pump at any time. Many field problems result from these types of changes in the dynamics of the system. Complete knowledge of these changes and of the interaction of the pump and system is necessary to prevent or solve these problems [5]. Typical parameters are two gpm required by four lines running at maximum speed, a spray nozzle pressure of 1000 psig, and water based lacquer with approximately 60 percent solids content. The system is shown in Figure 6.

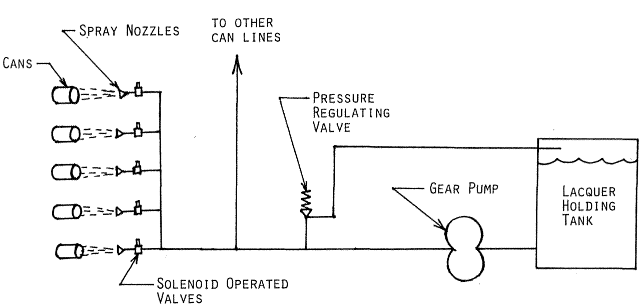

Figure 6. Lacquer Spraying System for Manufacturing Aluminum Cans.

A positive displacement pump, in this case a gear pump, was selected for this application, and was paired with a pressure regulating valve that sends excess lacquer back to the holding tank. The combination of these two elements produces the head flow curve in Figure 7. This curve is what the spray nozzles experience as the pump characteristic. It is essentially a reservoir at 1000 psi, producing any required flow at constant pressure.

The use of a centrifugal pump in this application, with the spray nozzles collectively acting as a throttling valve, would have produced a head-flow curve that was not horizontal, but sloped to higher head at the low-flow end. This means that at lower flows, which means lower rates of cans per minute, the pressure at the nozzles would rise and produce thicker lacquer coatings. This would be analogous to unloading a small number of tennis balls from the truck, but because the system resistance varies with time, the warehouse would be several stories tall. The objective would be

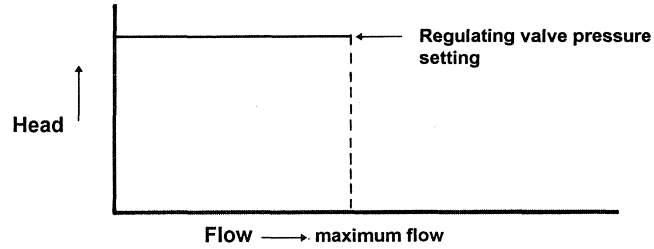

Figure 7. Head-Flow Curve for Positive Displacement Pump with Pressure Regulating Valve.

to get the same number of tennis balls on each floor, so it can be seen that the positive displacement approach of carrying the balls up the stairs would be more likely to leave the same number on each floor.

There are many applications similar to this where rotary style pumps are used to provide a constant parameter such as flow or pressure [3].

Case 2–Boosting Suction Pressure of a High Speed, High Pressure Gas Turbine Fuel Pump

Use as the high pressure fuel pump on a gas turbine is a demanding application for any pump. Lubrication is minimal, and the forces on internal parts are high. Exceptionally high reliability is paramount, and much attention must be paid to pump selection, installation, and mounting [6]. Operating the pump at high speeds can be beneficial, by reducing the size of the rotors. This reduces the area to be acted on by the high pressures, reducing the load on components. However, operation at higher speeds increases the NPSH required by the high pressure pump considerably. Add to this the fact that the vapor pressure is high for many of the fuels to be pumped, and the solution becomes to use a low pressure pump with much lower NPSH requirements to boost the suction pressure of the high pressure pump to levels high enough to prevent cavitation. As booster pumps, centrifugal pumps are preferred to positive displacement pumps for this application. The speed and power of the gas turbine is controlled by controlling flow out of the high pressure pump, either by varying its speed or by recirculating part of its flow back to its own suction (Figure 8).

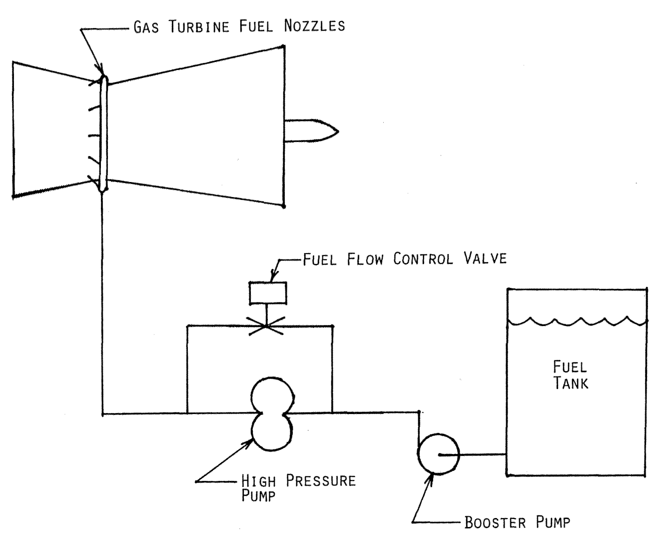

Figure 8. Simplified Gas Turbine Fuel System.

The varying flow of the high pressure pump acts as a throttling valve for the centrifugal pump. The flow of the booster pump will automatically adjust itself to match the flow of the high pressure pump, moving back and forth along the head flow curve of the centrifugal pump, Figure 1. This will cause the head produced by the booster pump to vary somewhat, but over a small enough range that it can be easily accommodated by the design of the high pressure pump. This is like tossing tennis balls from the truck into the warehouse window, and when the warehouse gets full, the balls simply bounce back to the street. As the warehouse is emptied of tennis balls, by taking them out a back door, more balls thrown from the street would stay inside.

If a positive displacement pump were used as the booster pump, the adjustment of its flow to the requirements of the high pressure pump would still be possible, but would not be automatic. The system would become unnecessarily complicated by the addition of a system to vary the speed of the booster pump or by the addition of a second recirculation loop around the booster pump, which would be like adding a second staircase to carry unneeded boxes of tennis balls back to the street when the warehouse becomes full.

However, in the last few years, variable speed drive technology has advanced significantly. It now provides reliable and economical new ways to vary the flow, without depending on pressure [4]. This way, a rotary pump could be used to automatically vary flow in response to demand by varying the speed of the drive in response to a control signal.

Case 3–Tanker Truck Loading and Unloading

Tanker trucks are used to haul all sorts of liquids, from milk to asphalt. They have come to be involved in the transportation of almost every sort of liquid product at some point. Most tanker trucks have pumps, because liquid must be moved at both ends of the truck's journey, onto the truck and off the truck. Positive displacement pumps are used in most cases because of their ability to handle a wide variety and unpredictability of the conditions encountered by the pumps.

The trucks are loaded, in some cases, from above ground tanks, where static head is available to fill lines and pump before operation. At other times, trucks must be loaded from below ground tanks, so the pumps must be self-priming. Because the trucks often switch types of cargo from one load to the next, the inherent self-priming ability of a positive displacement pump is better than a self-priming centrifugal, because its priming chamber would have to be drained, flushed, and refilled with the new liquid before each use.

Positive displacement pumps are also preferred because of their relative insensitivity to changes in discharge head, and liquid viscosity and specific gravity [7]. The positive displacement pump will load or unload the truck in the same amount of time, regardless of the liquid involved or the discharge head required. The system head that the pump encounters will vary tremendously because the truck will be loading and unloading at a wide range of pipe sizes and numbers of valves and fittings. The tank involved may be next to the truck or it could be hundreds of yards away. All of this could mean that a centrifugal pump could take several times as long to unload the truck one time as it would another time. This would be like having to unload the tennis balls at many different warehouses that have windows at differing levels from the street. Tossing the balls through the windows would make the unloading slower when the window was higher. Carrying the balls up in boxes would produce a more uniform result. A photo of a typical truck mounted positive displacement pump is shown in Figure 9.

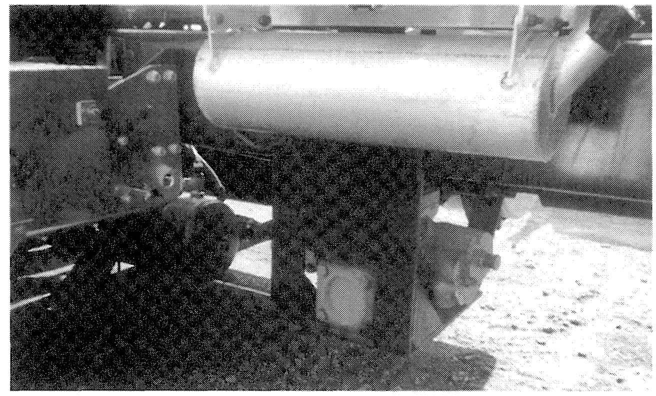

Figure 9. Truck Mounted Pump.

Case 4

The next example is of a centrifugal pump that a positive displacement pump would have a difficult time replacing. It is a large pump used to circulate cooling water. This pump application requires a pump that will deliver water at a flow of 120,000 gpm and at a head of 120 ft with a required net positive suction pressure, NPSHR, of 31 ft. These conditions can be met by a large single stage, double suction type pump running at 444 rpm. The design performance conditions are shown in Table 1.

Table 1. Design Performance Conditions of the Circulating Water Pump.

Liquid --	Water
Specific Gravity --	1.0
Temperature --	33 to 90°F
Capacity --	120,000 GPM
Total Developed Head --	120 FT.
Speed --	444 RPM
Net Positive Suction Head, Required ------------------------	31 FT.
Rated Power --	4000 BHP

A cross sectional view of the pump is shown in Figure 10. This pump meets the desired performance conditions and has the performance curve that is shown in Figure 11.

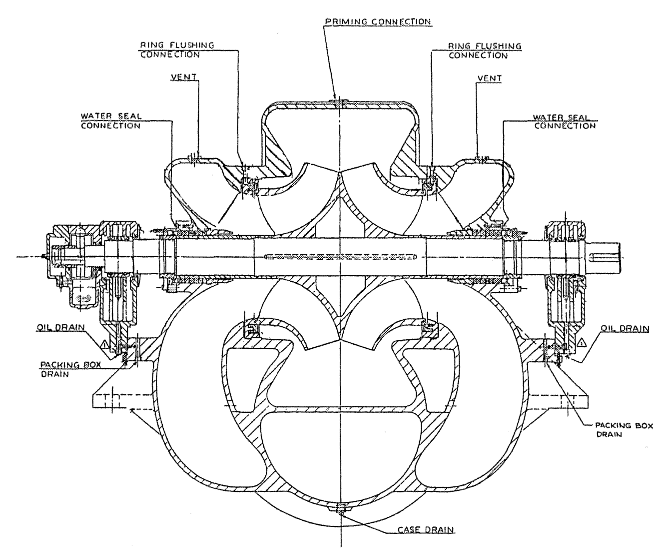

Figure 10. Cross Section View of a W 60/54 (60 inch inlet, 54 inch discharge) Single Stage, Double Suction Circulating Water Pump.

This pump is a large single stage, double suction, motor driven centrifugal pump with a suction flange diameter of 60 in and a discharge flange diameter of 54 in. The pump case is horizontally split and is made of cast iron. After water enters the suction, it

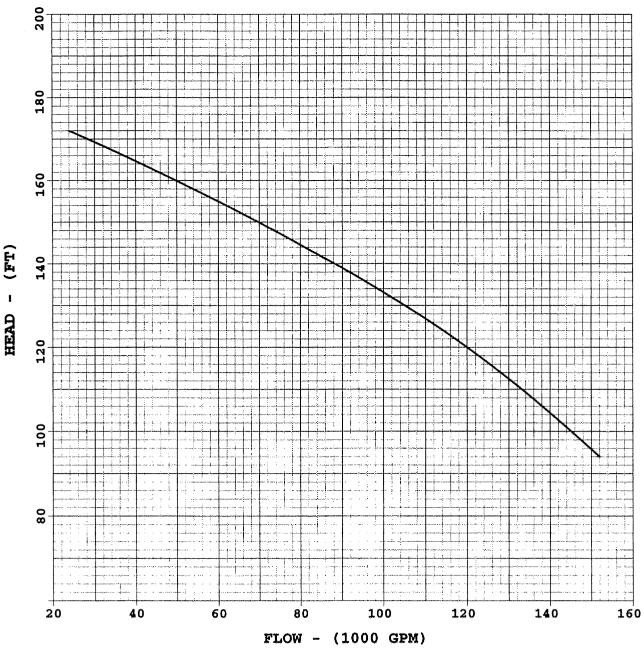

Figure 11. Performance Curve of the W 60/54 Circulating Water Pump.

splits in half, with each half entering each eye of a bronze, double suction impeller. When the flow exits the impeller, it enters a double volute in the pump case that guides the flow to the discharge flange. The impeller is mounted on a shaft and is straddled by two ring oil lubricated split sleeve bearings. Although a single stage, double suction pump is inherently axially balanced, any residual thrust is carried by a double acting tilting pad thrust bearing.

Case 5

The last example is a centrifugal pump that a positive displacement pump would have a difficult time replacing. It is a boiler feedpump used in electric power production. Consider a pump application requiring the ability to pump hot boiler water at a temperature in excess of 480°F at a flow of 14,350 gpm and head of 10,853 ft. These conditions have been met by a double case centrifugal pump running at 5225 rpm.

The specific hydraulic performance requirements are shown in Table 2. The high pressure, high temperature, and relatively high flow demands a specially designed centrifugal pump that runs at high speeds.

Table 2. Design Performance Conditions of the Boiler Feedpump.

Liquid	Water
Specific Gravity	.799
Temperature	483.7°F
Capacity	14,350 GPM
Total Developed Head	10,853 FT.
Speed	5225 RPM
Suction Pressure	756 PSIG
Rated Power	37,860 BHP

A multistage pump configuration, shown in Figure 12, has impellers mounted in series and facing in the same direction that provides the required performance, as shown in Figure 13. Boiler water enters the suction nozzle, passes through the impellers, and exits through the discharge nozzle. Each pump stage consists of an impeller that discharges water into a diffuser (which converts velocity head into pressure) that discharges the water into a return vane section to guide the flow into the next stage. Each stage adds an increment of pressure until the desired discharge pressure is obtained. In this case, five stages are used to achieve the necessary discharge pressure.

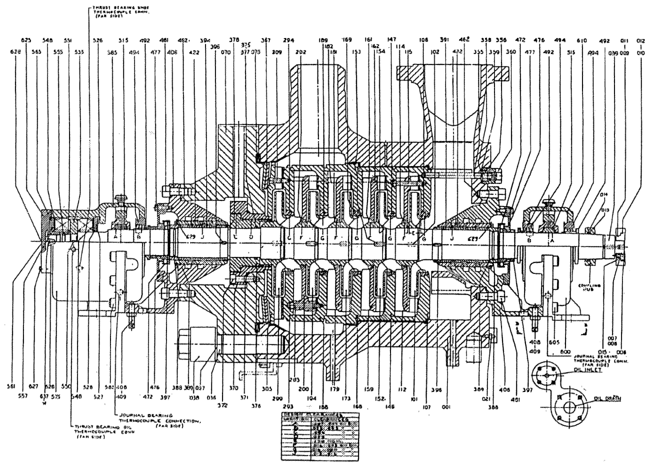

Figure 12. Cross Section View of the Boiler Feedpump (5BD × D520).

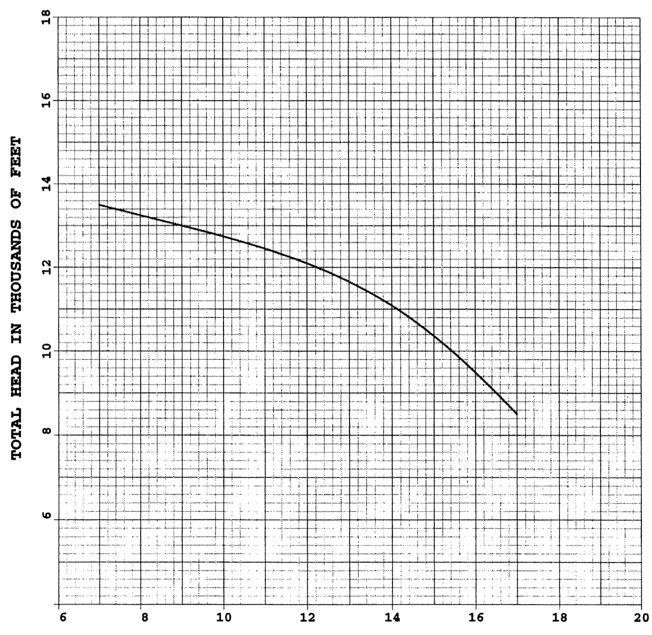

Figure 13. Performance Curve of the Boiler Feedpump (5BD × D520).

The pump shown in Figure 12 has an outer casing, or barrel (a forged cylindrical shell), with suction and discharge nozzles welded in place to form an integral part of the barrel and contain the high pressure boiler water. The barrel is supported on its pedestal at its horizontal centerline on keys, and pinned and keyed on the bottom to permit radial and axial expansion with temperature without changing alignment or causing distortion. The coupling end of the pump is pinned to maintain axial position of the coupling hub.

The inner assembly consists of diaphragms, diffusers, and rotor, which are assembled together as a single unit. It is positioned within the outer casing by cylindrical fits. The radial internal joints between the inner assembly and outer casing form metal-to-metal seals. The mating surfaces at these joints are accurately machined for flatness, smoothness, and parallelism to obtain the required sealing contact. The pressure generated within the pump act to maintain the seal. The outer casing is overlaid in the seal areas with stainless steel to prevent erosion and corrosion of these surfaces.

Another unique design feature of this pump is the use of deflection plates or Belleville springs. They not only preload the high pressure seal face, but allow for differential thermal expansion between the inner assembly and outer case during rapidly changing operating temperatures. This allows the inner assembly the freedom necessary to prevent binding of the rotor or opening of static seals.

This pump also has impellers produced from accurate investment (lost wax) casting that have all their external surfaces accurately machined. This gives the necessary repeatability of hydraulic performance required of these pumps.

The rotor is supported on tilting pad bearings and axial thrust is compensated axially by a balance drum. The balance drum has a variable orifice that makes axial rotor balancing compliant with variable hydraulic thrust which is dependent on the operating point. A tilting pad thrust bearing is used to separate the radial faces of the balance drum at initial pump startup and final pump shutdown.

The shaft end seals are of a double injection, serrated sleeve, bushing type design. The seal consists of a seal housing containing a throttle bushing and a serrated type shaft sleeve. Cool injection water is used to "block" the escape of high temperature water from within the pump.

Although this is only one example of a boiler feedpump, most boiler feedpumps are multistage centrifugal pumps that positive displacement pumps would have a difficult time replacing.

SUMMARY

As has been seen from the preceding examples, the different characteristics of centrifugal and positive displacement pumps may be used to advantage to suit the needs of the application. As in the analogy of unloading the truckload of tennis balls, the centrifugal pump, like throwing the tennis balls through the second story window, provides flexibility of flowrate. On the other hand, the positive displacement pump, like carrying boxes of tennis balls up the steps, provides a steady flow that is relatively unaffected by changing conditions. The best choice for any given application will depend on how quickly the truck is to be unloaded of tennis balls and the height of the warehouse window above the street. Both types of pumps are used successfully in a great many applications.

REFERENCES

1. Nelik, L., "Pumps," *Kirk-Othmer Encyclopedia of Chemical Technology*, Fourth Edition, New York, New York: John Wiley & Sons, Inc. (1996).
2. "American National Standard for Rotary Pump Tests," Section 3.6.4.10, Hydraulic Institute, ANSI/HI 3.6 (1994).
3. "Engineering Data Book," Hydraulic Institute, Second Edition (1990).
4. Little, C. W., Jr. "Section 3.5, Rotary Pumps," *Pump Handbook*, Second Edition, Edited by Karassik, Krutzsch, Fraser, and Messina, New York, New York: McGraw Hill Book Co. (1986).
5. Joseph, J. P., II, "The Use of Basic Hydraulics to Solve Maintenance Problems," *Proceedings of the Thirteenth International Pump Users Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, p. 181 (1996).
6. Monroe, P. C., Jr., "The Road to Reliable Pumps," *Proceedings of the Twelfth International Pump Users Symposium*, Turbomachinery Laboratory, Texas A&M University, College Station, Texas, p. 125 (1995).
7. Whitmire, K., "Installing and Maintaining Gear Pumps," Chemical Engineering, *103*, (3), pp. 96-98 (March 1996).