# HIGH HEAD-LOW FLOW CENTRIFUGAL PUMPS

by

**Conrad C. Mowrey**

**Manager of Product Engineering**

**Sundstrand Fluid Handling Division**

**Arvada, Colorado**

*Conrad C. Mowrey received his engineering and management education at the University of Colorado and Denver University. He has held numerous engineering and management positions during the past 32 years at Sundstrand, first with Sundstrand Aviation, and later with the Fluid Handling Division. These positions included Test Facilities Design Engineer, Product Engineer-Compressors, Service Engineering Manager, and Manager of Product Engineering. He is currently responsible for engineering and marketing support of high speed centrifugal pumps.*

*Mr. Mowrey has presented and published in ASLE and Chemie Technik (German).*

*He presented a tutorial on high speed pumps at the University of Barcelonia, Instutito De Petrolqumica Aplicada in May 1983. A tutorial was also given on "Experience with Seals in Carbamate and Ammonia Pumps," and "Development Testing an Upstream Pumping Seal at High Speed," ASLE Annual Meeting (May 1987).*

*Mr. Mowrey is a member and past Chairman, STLE, Denver Section.*

## ABSTRACT

*Centrifugal Pumps*

Centrifugal pumps that fall into a category defined as *high head, low flow pumps* are discussed. A brief history of these pump types is presented. The principle of operation and performance envelope are addressed. Comparative data on efficiency, impellers, head coefficients, head-capacity curves and relative cost are presented. Advantages and disadvantages from the design and maintenance point of view are discussed with the intent of providing useful information to aid in pump evaluation and selection.

## INTRODUCTION

Several different types of centrifugal pumps have found a place in industry since the turn of the century. The three most commonly used types that fit into the high head, low flow category are discussed herein. While the high head-low flow envelope (400 to 3400 ft, up to 150 gpm) is only a very small portion of the overall pump envelope, it is estimated that upwards of 2500 process pumps, not including positive displacement pumps, are purchased annually worldwide. The three types of pumps discussed herein represent the largest portion of this number.

Throughout this discussion, specific speed ($N_S$) often will be mentioned. It is well known this is a characteristic number which describes the hydraulic features of a pump and is defined as

$$N_S = \frac{RPM \times GPM^{.5}}{HEAD^{.75}}$$

## HISTORY

*Rotating Casing Pump*

The rotating casing pump, commonly called a pitot pump, was first patented by F. W. Krogh, in 1923. It was studied at length in Germany from 1939 to 1945, for aircraft and rocket applications, and was studied in Britain in the late 1940s. In 1959, a pilot pump study by Nichols, McPherson and Balje was reported by the U. S. Office of Naval Research [1].

In 1962, development work was begun in the U.S. that led to the pumps commercially available today [2], (Figure 1).

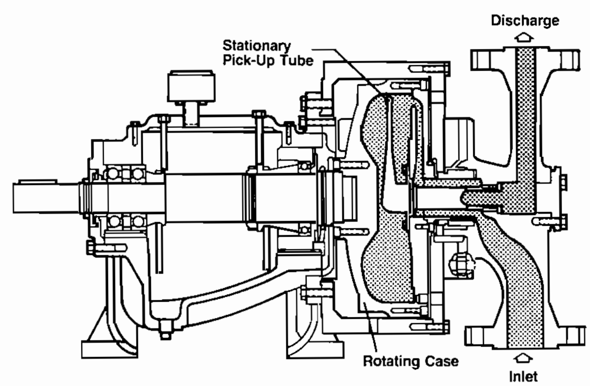


*Figure 1. Rotating Casing Pump.*

*High Speed Centrifugal Pump*

The high speed centrifugal pump emerged from work initially done in 1939-1945 time frame by Barske and was reported in papers published in 1953 and 1960 [3, 4]. A lightweight pump with generous clearances was needed to handle corrosive contaminated rocket fuels. The latter publication described the pump as "unconventional." This low specific speed design was first manufactured commercially in 1959 as a water injection pump for the Boeing 707 jet aircraft (Figure 2), to provide additional thrust on takeoff for the then shorter runways.

The first pumps for petrochemical and other applications were designed and manufactured in the early 1960s. High speed centrifugal pumps are available today in a variety of hydraulic designs, models and mounting arrangements (Figures 3 and 4).

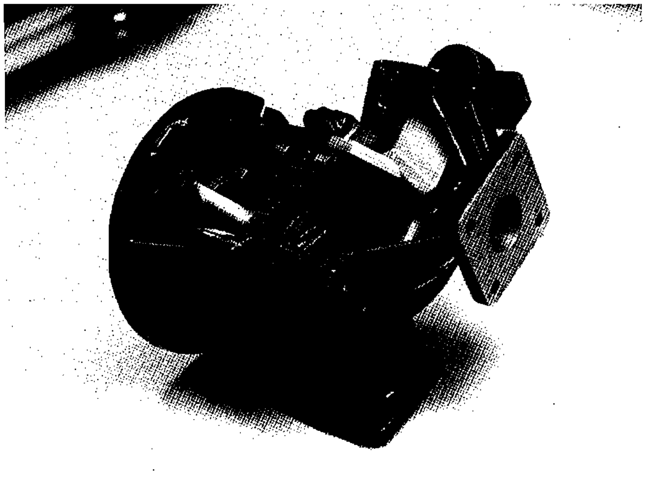

*Figure 2. Boeing 707 WAter Injection Pump.*

*Early Regenerative Turbine Pumps*

The earliest regenerative turbine pumps were manufactured in 1918 by Western Pump Company in Iowa, based on patents issued in 1915 and 1917 to a machinist, Adolph Wahle. A complete line of pumps was developed by the Westco-Chippewa Pump Company between 1925 and 1932. Since that time, several pump manufacturers have developed a line of regenerative turbine pumps. These are now available in up to four stages for horizontal mounting, and two stages for vertical inline mounting (Figure 5).

## PRINCIPAL OF OPERATION

*Head is generated in the pitot pump* by introducing fluid at the center of a closed rotating drum. The fluid velocity is increased as it moves from the center to the periphery of the drum and becomes a pressurized rotating ring of fluid, traveling at or near the same velocity as the drum near the periphery (Figure 6). A stationary pitot head with its opening facing opposite the direction of drum rotation scoops up fluid from the pressurized rotating ring and ducts it inward through the internal passage in the pitot head to the discharge port.

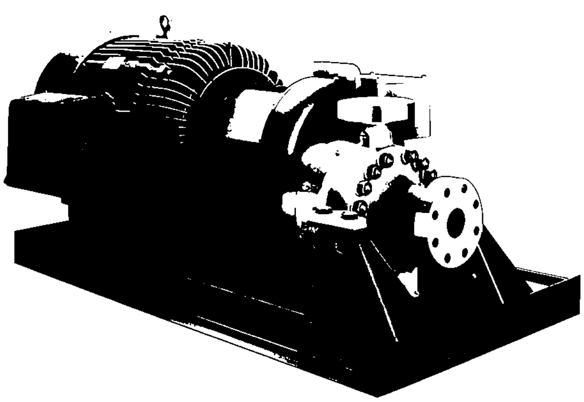

*Figure 3. High Speed Centrifugal—Horizontal Base Mounted.*

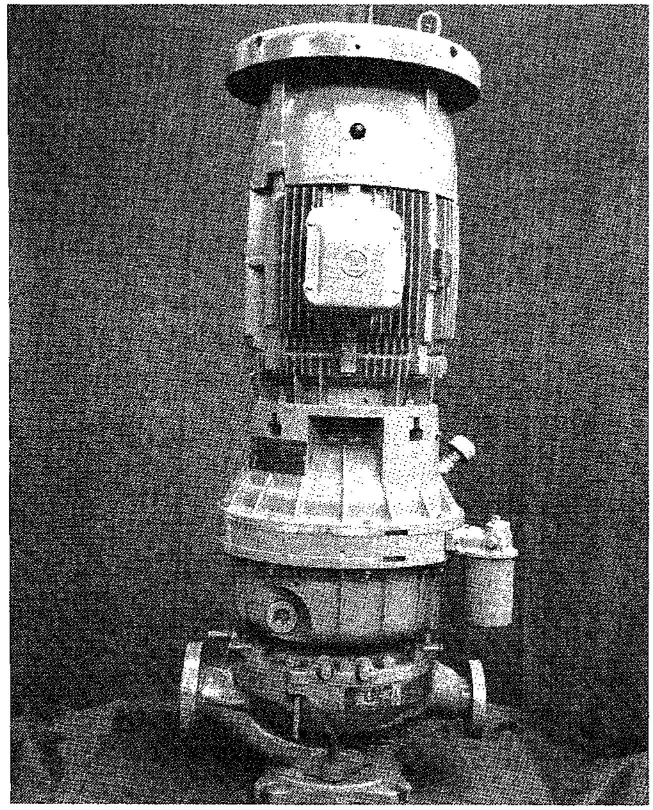

*Figure 4. High Speed Centrifugal—Vertical Inline.*

*The high speed centrifugal pump* impeller rotates within a stationary casing. Fluid is introduced at the center of the impeller. The velocity is increased as the fluid travels to the blade tip. When an open straight radial vaned impeller is used (Figure 7), the fluid exits through a single or double throat and conical section where additional pressure is generated by diffusion. When a closed swept vane impeller is used, the fluid passes through a vaned or vaneless diffusion section where additional pressure is generated. In either case, these pumps must have a speed increasing gear to develop high head in a single stage.

*The regenerative turbine pumps*, also termed drag pumps, derive the name from the pumping action. There are two conflicting theories of the drag principal.

- One is that pumping is due only to centrifugal action.
- The other, more credible theory, embraces a complex friction drag action. The flow pattern is a combination of a peripheral component and a circulatory component, extending from hub to tip (Figure 8) within the rotor and returning from tip to hub in the channel. The fluid enters and exits the impeller many times, each time entering at a different vane and continues this action (Figure 8) until it strikes the close clearance stripper between the discharge and inlet ports and is forced out of the casing. These are manufactured with up to four stages in overhung or between bearing designs as shown in Figure 9.

## PERFORMANCE ENVELOPE

For the purpose of this discussion, only pumps with capacity to 150 gpm and head to 3500 ft will be addressed, as shown in Figure 10. This does not represent the entire envelope for these pump types.

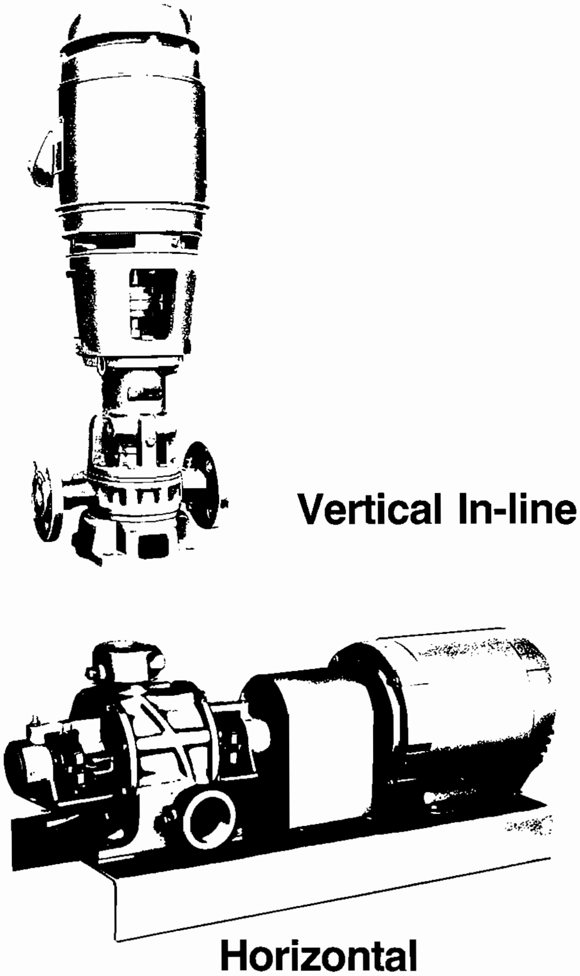


*Figure 5. Regenerative Turbine Pumps.*

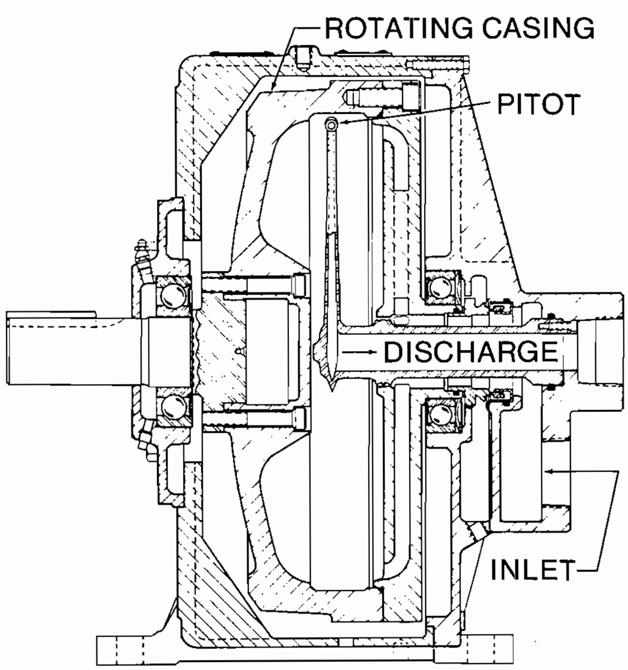


*Figure 6. Rotating Casing Pump—Cross Section.*

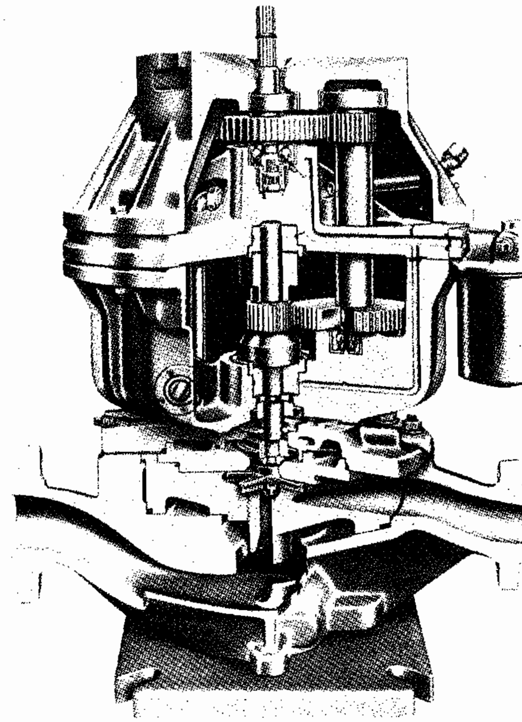

*Figure 7. High Speed Centrifugal Pump—Open Impeller.*

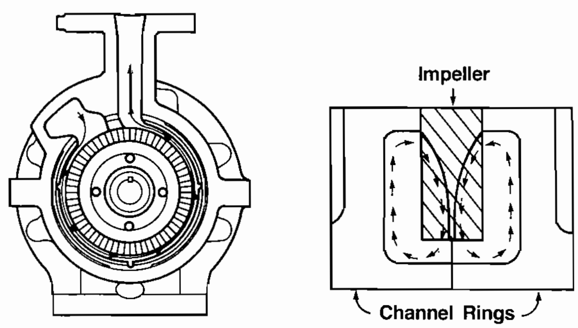


*Figure 8. Regenerative Turbine Pump—Pumping Action.*

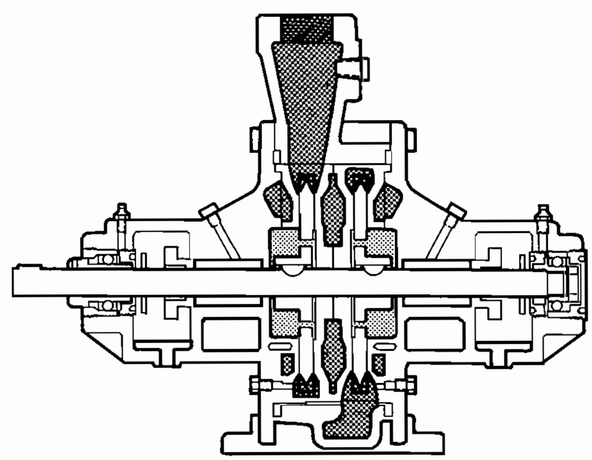

*Figure 9. Regenerative Turbine Pump—Cross Section.*

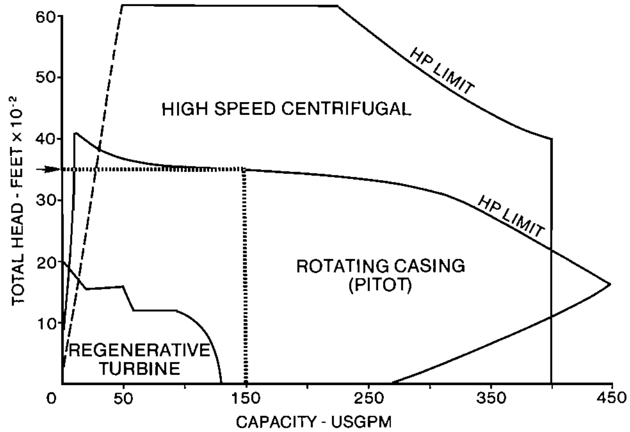


*Figure 10. High Head-Low Flow Centrifugal Pump Envelope.*

Note that the regenerative turbine envelope is much smaller than the other two. For this reason, three head capacity points were chosen for some of the comparisons to follow. Two of these fall within the range for all pump types, while the third is outside the regenerative turbine envelope. The three points are:

- 150 gpm at 3400 ft
- 50 gpm at 1200 ft
- 15 gpm at 1000 feet

## CURVE SHAPE AND IMPELLERS

The regenerative turbine pump provides a steeply rising shutoff curve, compared to either the rotating casing or the high speed centrifugal pump, as shown in Figure 11. These two pump types have historically had some droop as flowrate decreased below 40 percent of design capacity. However, over the past three to five years, development work on both types has been completed that alleviates the droop; but curve rise is quite modest below 50 percent of design capacity.

Development on the rotating casing pump is covered in a patent granted in 1981 to inventor J. W. Erickson. It essentially uses internal passages in the casing (impeller) of different length to effect some recirculation at lower flows as a means of eliminating low flow droop (Figure 12).

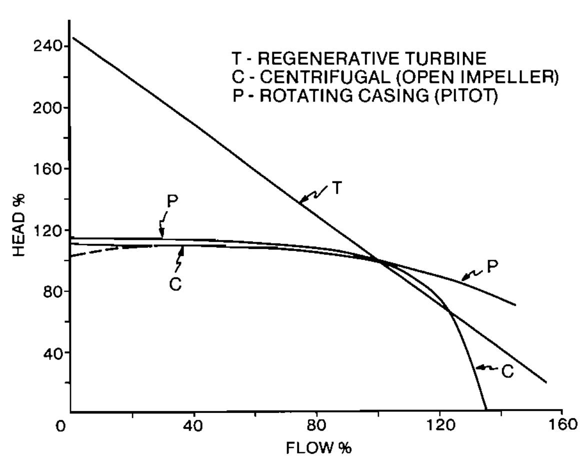


*Figure 11. Curve Shape Comparisons.*

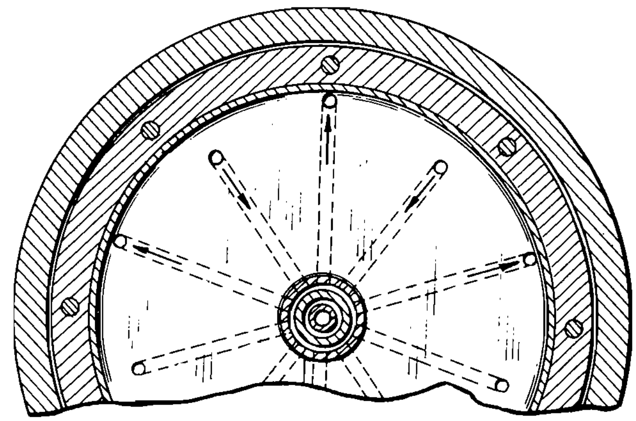

*Figure 12. Rotating Casing Pump. Recirculation allowed to control curve shape.*

Development on the high speed centrifugal included adding a high solidity impeller with 24 vanes as opposed to the original eight vane design shown in Figure 13, and using a diffuser with volute collector prior to the single conical diffuser.

In recent years, closed swept vane impellers, (Figure 14) have been used in high speed centrifugal pumps. These impellers demonstrate a continuously rising to shutoff head characteristic of 10 to 30 percent, depending on exit vane angle and number of vanes.

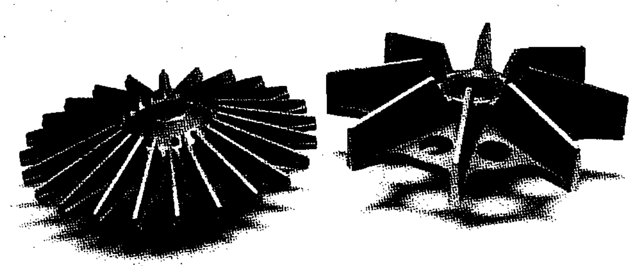

*Figure 13. Open Radial Vane Impellers. Eight and twenty-four vanes.*

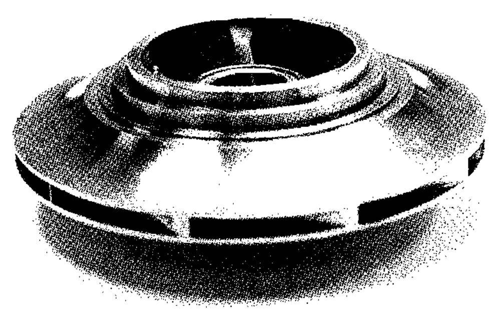

*Figure 14. Closed Swept Vane Impeller for 990 Specific Speed.*

In pitot pumps, the impeller is actually the rotating drum. There may be shallow vanes on the inside of the drum and cover or passages cast internal to the cover with inlets at the inside diameter and outlet near the drum periphery as shown in Figure 6. As mentioned earlier, modifications have been made to improve curve shape.

Several impeller types are used in the high speed centrifugal pumps. The most common type is an open strait radial eight vane design called the "Barske" impeller. This type impeller is best suited for operation in the 200 to 650 specific speed range, but produces a drooping curve below 40 percent of design flow. A similar design with 24 blades and larger inlet eye, as seen in Figure 13, is now in use as well. This was developed to eliminate low flow droop with the added benefit of noise reduction.

Closed swept vane impellers known as the "Francis" type, as seen in Figure 14, are best suited for use above 650 specific speed. At lower specific speed (low flow), the openings between shrouds and vanes are very small, resulting in high friction losses. The impeller shown in Figure 14 is designed for a specific speed of 990, yet it still has relatively small waterways. Additionally, it is difficult to cast, and must be hand polished to achieve acceptable performance. This type impeller does provide a continuously rising curve.

Semi-open and open swept vane impellers (not shown) are also used with the benefit of a continuously rising curve, however, are not as efficient as other designs. Since this design doesn't have a front shroud to support the swept vane, tip speed is limited.

Impellers for regenerative turbine pumps are all very similar with short vanes machined on both sides near the periphery of a rotating disc, (Figure 15).

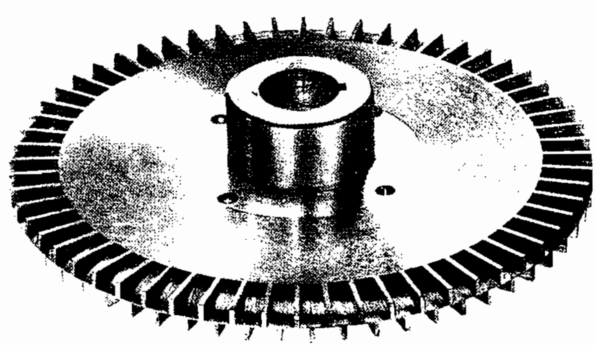

*Figure 15. Regenerative Turbine Pump Impeller.*

## HEAD COEFFICIENT FOR IMPELLER TYPES

Head coefficient ($\psi$) can be simply defined as the ratio of actual head over theoretical head

$$\psi = H_A/H_T$$

with no attempt to address the theory behind the theoretical head calculation. This detail can be found in several good technical references including *Pump Handbook* [5], *Centrifugal Pumps* [6], and *Turbomachines* [7].

As can be seen in Table 1, the head coefficient is lowest for the closed swept vane impeller and highest for the regenerative turbine pump impeller. Data presented are at best efficiency point capacity and below 800 specific speed.

*Table 1. Head Coefficient for Various Numbers.*

| Impeller Type | Closed Swept Vane (Francis) | Open Straight Vane (Barske) | Rotating Casing (Pitot) | Regenerative Turbine |
|---|---|---|---|---|
| $\psi$ | 0.55 to 0.65 | 0.7 to 0.74 | 1.6 | 1.6 to 2.0 |

This simply demonstrates that Francis-type impellers must either be larger in diameter, or run at higher speed to achieve the same head as any of the other impeller types. It can then be concluded that this is some indication of the physical size of the machine. Reviewing the theoretical head calculation in its simplest form:

$$H = \frac{U^2}{9} \text{ where } U = \frac{DN}{229} \text{ and } \begin{array}{l} D = \text{Impeller Diameter (in.)} \\ N = \text{Speed (rpm)} \\ U = \text{Tip Speed (ft/sec)} \end{array}$$

It can readily be seen that higher speeds are required to produce high head in single stage pumps.

## EFFICIENCY COMPARISON

Efficiencies for three head-capacity points, (3400 feet at 150 gpm, 1200 feet at 50 gpm, and 1000 feet at 15 gpm) are shown on the efficiency/specific speed graph, Figure 16. The first condition 1) is outside regenerative turbine pump performance envelope. Because all these pump types operate at different speeds, the specific speed varies widely between pumps. Note that for condition 1), the high speed centrifugal pump shows an efficiency advantage of 11 percent over the rotating casing pump. This is due in part to the ability to run at higher speed, hence higher specific speed. However, for conditions 2) and 3), the rotating casing pump shows an efficiency advantage of six to eight percent over the high speed centrifugal, largely due to lower parasitic losses, such as impeller disc friction and diffusion losses.

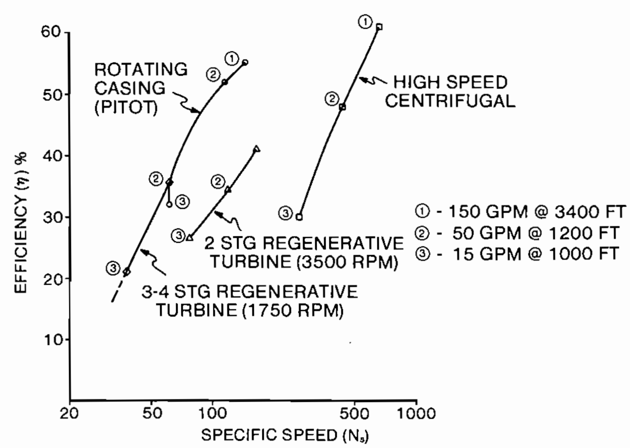


*Figure 16. Efficiency Comparison Graph.*

Regenerative turbine pump efficiencies are generally lower than either of the other pump types as shown for conditions 2) and 3). Efficiency improves as the number of stages decrease and speed increases, as indicated by the two separate curves for the regenerative pump. The best efficiency attainable is not necessarily shown due to the head-capacity points chosen.

## NPSH-INDUCERS

A comparison of NPSH required for the three performance conditions considered is provided in Table 2. NPSH required for regenerative turbines is shown with and without inducers, because not all pumps of this type are available with inducers. High speed pump performance is shown with inducers. Pitot pumps do not have inducers. Additionally, a column is provided for suction specific speed ($S_s$) for each pump type. For reference:

$$S_s = \frac{NQ^{.5}}{NPSH^{.75}}$$

*Table 2. NPSH and Ss Comparisons.*

| H/Q | Rotating Casing | | High Speed | | Regenerative Turbine | |
|---|---|---|---|---|---|---|
| | NPSH | $S_S$ | NPSH | $S_S$ | NPSH | $S_S$ |
| 3400/150 | 12 | 10,300 | 25 | 24,000 | - - | - - |
| 1200/50 | 7 | 5,380 | 7 | 20,200 | 2<br>6 | 7,360<br>3,230* |
| 1000/15 | 6 | 2,826 | 4 | 16,900 | 2<br>3 | 4,025<br>2,970* |

* Without Inducer

The comparison demonstrates that higher speeds require the ability to operate at significantly higher $S_s$ for the same NPSH performance.

## ADVANTAGES AND DISADVANTAGES

*Rotating Casing Pumps*

*Advantages are:*

- Physically smaller than positive displacement or multistage centrifugal pumps
- Rising to shutoff head characteristic.
- Does not require wear rings.
- Has few moving parts.
- Low maintenance due to simplicity.
- Relatively good efficiency at low specific speeds.

*Disadvantages are:*

- High internal velocities make pump subject to erosion if abrasives are present.
- Gas and vapor handling characteristics are relatively poor.
- The pitot pump is not readily converted to alternate operating conditions.
- The pitot pump has low suction pressure capability.
- Pitot pump requires a belt drive or speed increasing gear for high head applications.

*High Speed Centrifugal Pump*

*Advantages are:*

- Physically smaller than positive displacement or multistage centrifugal pump.
- Available in vertical inline, horizontal basemount, or direct motor flange mount.
- Pump can be easily converted to alternate operating conditions and is easily maintained.
- Open impeller type has no close internal clearances and will not seize due to dry running. Hydraulically balanced impeller reduces thrust loads and seal cavity pressures.
- Pump is capable of high suction pressures.

*Disadvantages are:*

- High internal relative velocities make this type subject to erosion in the diffuser bowl and throat areas of open impeller type, if abrasives are present.
- May be subject to erosion/corrosion in some media when materials are used that form a protective surface layer in that media.
- Closed impeller type radial wear ring subject to seizure if run dry, has high thrust loads and high seal cavity pressure.
- Efficiency loss is significant with increased wear ring leakage.
- A speed increasing gear is normally required above 600 ft. head

*Regenerative Turbine*

*Advantages are:*

- This pump is smaller in size than most other types and can handle relatively large amounts of gas or vapor.
- Available in horizontal base mount, vertical inline mount or direct drive motor flange mount.

*Disadvantages are:*

- This type pump is not well suited for handling even small amounts of solids, or corrosion due to close tolerances between the impeller, channel rings and stripper.
- Pumps are limited to low suction pressure applications.
- Care must be taken to control shaft deflection due to high radial loads in single stage designs.
- Clearance setting during maintenance is difficult on some designs that fix the impeller to the shaft, as opposed to slip fit design.

## RELATIVE COST

Relative costs for the three types of pumps discussed and for the three head capacity points considered are provided in Table 3. Such a comparison must be viewed in a very general way, and is not intended to be accurate for every application. The rotating

*Table 3. Centrifugal Pump Relative Costs for Similar Services.*

| H/Q | Material | Service | Rotating Casing | High Speed Centrifugal | Regenerative Turbine |
|---|---|---|---|---|---|
| 3400/150 | Standard<br>316 SS | All<br>All | Base<br>Base | Equivalent<br>Highest | - -<br>- - |
| 1200/50 | Standard<br>316 SS | API<br>API | Base<br>Base | Highest<br>Highest | Lowest<br>Lowest |
| 1200/50 | Standard<br>316 SS | Chemical & Other<br>Chemical & Other | Base<br>Base | Lower<br>Lower | Lowest<br>Higher |
| 1000/15 | Standard<br>316 SS | API<br>API | Base<br>Base | Highest<br>Highest | Lowest<br>Lowest |
| 1000/15 | Standard<br>316 SS | Chemical & Other<br>Chemical & Other | Base<br>Base | Lowest<br>Lowest | Lower<br>Lower |

casing pump is used as the base line, with the cost of other types relative to it. Standard material relates to the manufacturer's standard material build and is not necessarily the same for each pump type.

## SUMMARY

Every piece of mechanical equipment has its strengths and weaknesses. It is hoped that the foregoing discussion will provide new or additional information on the features, advantages, and disadvantages of high head, low flow centrifugal pumps, especially for those who have limited experience with the three types. Final selection obviously depends on the individual's perception of features, installed cost, maintainability, and reliability.

## REFERENCES

1. Balje, O. E., et al., "Study of Turbine and Turbopump Design Parameters," Final Report, *4*, Low Specific Speed Turbopump Study, S/TD No. 1735, Department of the Navy, Office of Naval Research, Contract No. NONR 2292(00), Task Number NR094-343.
2. Erickson, J. W., and Grumet, W. H., "A Revolutionary New Concept in High Pressure Pumps," U. S. Trade Center Symposium, Frankfort, Germany (December 1972).
3. Barske, U. M., "High Pressure Pump," Engineer, London, *195*, p. 550 (1953).
4. Barske, U. M., "Development of Some Unconventional Centrifugal Pumps," Proceedings of the Institution of Mechanical Engineers, London, *174*, (2) (1960).
5. Karassik, I. J., et al., *Pump Handbook*, New York: McGraw-Hill (1976).
6. Lobanoff, U. S., and Ross, R. R., *Centrifugal Pumps Design and Application*, Houston: Gulf Publishing Company (1985).
7. Balje, O. E., *Turbomachines*, New York: John Wiley and Sons, Incorporated (1981).