



Centrifugal Pumps

An Online Continuing Education Course for Engineers

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Introduction

The centrifugal pump is second only to the electric motor as the most widely used type of rotating mechanical equipment in the world. It is not surprising that this is true in the typical nuclear or fossil fuel power plant, refinery, petrochemical, or chemical complex, where the use of centrifugal pumps is so prevalent. Since this is where the process design engineer plies his or her wares, it is necessary that engineers be familiar with the theory and application of centrifugal pumps.

The portion of this lesson on pump system curves was adapted from "A Pump Handbook for Salesmen", written by D. B. Barta, now retired from the Ingersoll Rand Company. This handbook was never published, and was informally distributed within the Ingersoll Rand Company as part of a training program.

You may notice some inconsistencies in the symbol definitions in different parts of the text. For instance, the symbol ω is used for rotational speed (rpm) in some cases, while the symbol N is used for rpm in conjunction with the pump affinity laws, because the affinity laws always seem to use that symbol. I have tried to define, or possibly redefine, the symbols used for each set of equations.

The Centrifugal Pump

Centrifugal pumps offer important advantages over other types of pumps. Since they operate at considerably higher speeds, they are smaller and lighter. The suction and discharge flows are smooth and relatively free from pulsations. Because there is a maximum differential pressure which they can develop known as the shutoff differential pressure, discharge piping can be designed without the necessity of relief valves and the pump can be started against closed discharge shutoff or check valves. Since there are not as many wearing parts, maintenance and downtime are lower than for other types of pumps.

On the other hand, centrifugal pumps do not perform well at low flows or high viscosities. For applications under these conditions, it is frequently better to use a rotary or reciprocating pump. The centrifugal pump consists of a casing to contain the liquid being pumped, an impeller which rotates thus transferring energy to the pumped liquid, a shaft to which the impeller is attached, a stuffing box containing a mechanical seal or packing to prevent leakage at the point where the shaft passes through the casing, bearings to support the shaft, a coupling to connect the pump shaft to the driver shaft and a driver, which is normally either an electric motor or a steam turbine, although engines and gas turbines are occasionally used to drive pumps. Sometimes a gear increaser or decreaser is used between the pump and drive to obtain a desired pump speed. Liquid enters the casing through the suction nozzles and is propelled outward toward the discharge nozzle by the rotating impeller. As the liquid passes from the center of the impeller to the periphery, its angular momentum is increased. After leaving the

impeller, the velocity, which was created in the impeller, is converted or diffused into a pressure increase by decelerating the liquid in the outer zone of the casing known as the diffuser, or volute.

Performance Parameters

When specifying a centrifugal pump, it is necessary to provide information on its performance characteristics in units that are universally understood and agreed upon. Generally speaking, these are as follows:

Flow

Flow through a pump is generally understood as the volumetric Flow, rather than the weight or mass flow, and normally is expressed in U. S. gallons per minute (gpm). cubic meters per second (1 cu.m/min = 4.4 gal/sec), or on large capacity pumps in cubic feet per second (cfs) (one cfs = 449gpm).

Specific gravity

Specific gravity is the standard method of expressing the density of the liquid being pumped, and is generally understood to be the ratio of the density of the liquid to the density of the water at standard conditions.

Suction Pressure

Suction pressure is the pressure at the suction nozzle of the pump expressed in pounds per square inch gauge.

Discharge Pressure

Discharge pressure is the pressure at the discharge nozzle of the pump expressed in pounds per square inch gauge.

Differential Pressure

Differential pressure is the difference between the discharge pressure and the suction pressure measured in pounds per square inch.

Differential Head (Also known as Total Dynamic Head or TDH)

Differential head is the energy per unit weight necessary to create the pump differential pressure. Its true unit of measure is foot-pounds per pound; however, if one cancels out the pounds in both the numerator and denominator, the result is the generally accepted unit of measure for head which is

simply feet. From this it can be deduced that the head could also be interpreted as the height of a static column of liquid which would have a pressure at its base equal to the differential pressure of the pump.

A formula relating the differential pressure, the specific gravity and the differential head can be derived by applying the first law of thermodynamics as follows:

$$h_1 + v_1^2/2g + p_1/\gamma + Q + w = h_2 + v_2^2/2g + p_2/\gamma$$

where:

h =elevation

v = velocity

g = gravitational constant

w = work per unit weight which by definition is the differential head. Q = heat transfer

p = pressure

γ = specific weight

Subscripts 1 and 2 indicate suction and discharge conditions respectively.

If we assume that the elevation and velocity at the suction and discharge are the same and that the heat transfer, Q, is negligible, the first law can be simplified to the following:

$$w = (p_2 - p_1) / \gamma = H$$

where H is the differential head. Since we wish to express H in feet, $(p_2 - p_1)$ must be in pounds per square foot, and the specific weight must be in pounds per cubic foot. Noting from our previous definition of specific gravity, that the specific weight equals the specific gravity times the specific weight of water at standard conditions, we have:

$$H = \frac{\Delta p \text{ lb/in}^2 \times 144 \text{ in}^2/\text{ft}^2}{\text{Specific gravity} \times 62.4 \text{ lb/cu ft}}$$

$$H = \frac{2.31 \Delta p}{\text{Specific gravity (sg)}}$$

Where H is in feet and p_1 and p_2 are in psig.

Net Positive Suction Head (NPSH)

The suction pressure, expressed in feet of liquid, required at the eye of the impeller to prevent cavitation. This required NPSH (NPSHr) is usually determined by a test performed by the pump manufacturer. The available NPSH (NPSHa) is a function of the system design and operation, and must exceed the NPSHr or else cavitation will occur.

Hydraulic Horsepower

The hydraulic horsepower of a pump is the work which would ideally be required to produce the pressure rise in the pumped liquid. Recalling our definition of head as the energy per unit mass necessary to create the pump differential pressure, we can easily calculate the horsepower for a given flow and differential head by multiplying the head times the flow in pounds per minute and dividing the result by 33,000 foot pounds per minute per horsepower.

Noting that the flow in pounds per minute is 8.33 lb per gal x sg x gpm (where 8.33 lb per gal is the density of water at standard conditions), we have:

$$\text{Hydraulic Horsepower} = \frac{8.33 \text{ lb per gal} \times \text{sg} \times \text{gpm} \times \text{feet of head}}{33,000 \text{ ft lb per HP min}}$$

$$\text{Hydraulic Horsepower} = \frac{\text{sg} \times \text{gpm} \times \text{head}}{3,960}$$

If we substitute $2.31 (p_1 - p_2)/\text{sg}$ for the head, we have:

$$(4) \text{ Hydraulic Horsepower} = \frac{\text{gpm} (p_1 - p_2)}{1,714}$$

Brake Horsepower

Brake horsepower is the actual horsepower transmitted to the pump by the driver through the shaft coupling. In order to accurately measure the brake horsepower, it is necessary to measure the speed (rpm) and torque at the coupling. If these two values are known, the brake horsepower can then be calculated as follows:

$$\text{Brake horsepower} = \text{work in foot pounds per minute} / 33,000$$

$$\text{Work} = \text{Force} \times \text{Distance}$$

$$\text{Force} = \text{Torque} / \text{Radius}$$

$$\text{Distance} = 2\pi \text{ Radius} \times \text{rpm} \times \text{time}$$

$$\text{Work} = (\text{Torque} / \text{Radius}) \times 2\pi \text{ Radius} \times \text{rpm} \times \text{time}$$

$$\text{Work per min.} = 2\pi \times \text{torque} \times \text{rpm}$$

$$\text{Brake HP} = (2\pi \times \text{torque} \times \text{rpm}) / 33,000$$

$$\text{Brake HP} = (\text{torque} \times \text{rpm}) / 5,250$$

Since instruments to measure torque at shaft couplings are expensive and rarely available except in test facilities, brake horsepower is frequently approximated by measuring the energy consumption of the

driver. For a steam turbine, this would be the steam flow; for an electric motor, the amps, and for an engine or gas turbine, the fuel consumption.

Efficiency

Efficiency is the ratio of the hydraulic horsepower to the brake horsepower.

Efficiency (η) = hydraulic HP / brake HP, therefore:

Brake horsepower BHP = (sg x gpm x head) / 3,690 x η

Specific Speed

It is obviously not possible to discuss this concept in great depth. For our purposes, we will assume that natural phenomena do not affect it, then it should be possible to define a concept of dimensionless specific speed based on differential head and performance. One could argue that this is not a We will therefore recognize that there are many parameters which result in similar machines. The performance is calculated as follows:

$$N_s = N Q^{1/2} / H^{3/4}$$

Where

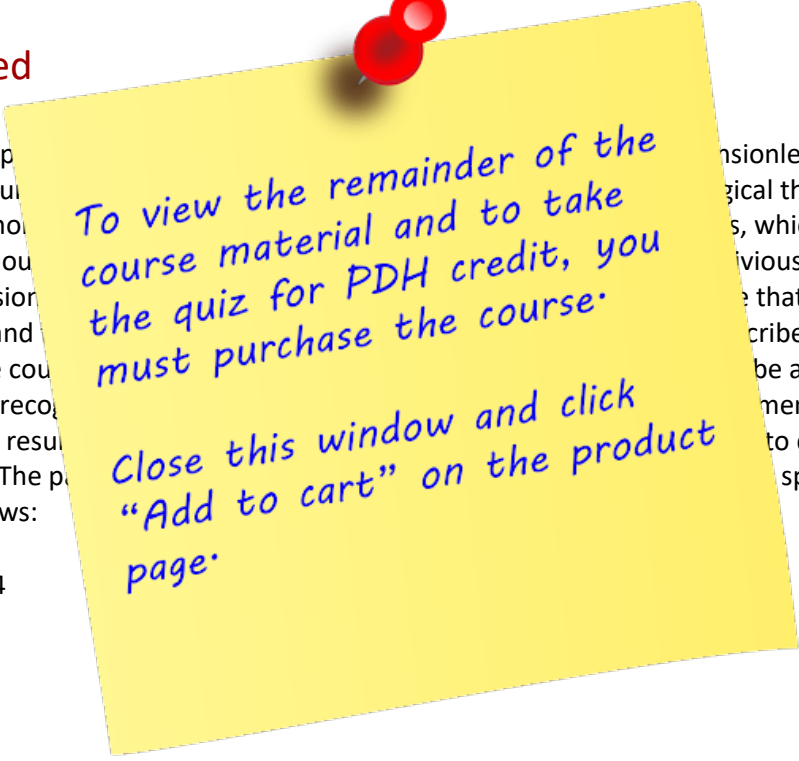
Q = flow in gpm

H = head in feet

N = pump speed

The number that results from this formula is not the same number which would result if the dimensions were consistent. In order to make the dimensions consistent, we would multiply by the appropriate constants. Therefore, the conclusions drawn from specific speed calculated with standard parameters and inconsistent units would be the same as if the dimensions were consistent. Follow that? Words can be tricky as well as math!

The concept of specific speed was originally defined as the speed which is required to produce a head of one foot at a flow of one gallon per minute in a machine that is dimensionally similar, but smaller. The concept is extended to state that at a given value of specific speed, the operating conditions are such that similar flow conditions can exist in geometrically similar machines. This is analogous to the concept of using the Reynolds number to predict fluid flow characteristics. As a result of empirical tests which have been performed on a number of pumps, the curves shown in Figure 2 have developed. These curves show a plot of efficiency versus specific speed for various types of centrifugal pumps.



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dimensionless parameters in... logical that if any complex... s, which could logically... ivious to the man made... e that the flow, the... rscribe pump... be added to this list... dimensionless... to dimensionally... specific speed and is