4

The Affinity Laws

Introduction

The Affinity Laws are a group of rules that govern your pumps. Sometimes they're called the Laws of Similarity. In years gone by, these laws served to predict a pump's operation when exported to a country with different electricity. The electricity in the United States is 60 hertz (Hz). This means that the electricity moves in waves with a frequency of 60 cycles per second. Some other countries in the world have electricity moving at a frequency of 50 Hz., or 50 cycles per second. A change in frequency brings about a change in running speed (rpm). Upon exporting a pump into a country and connecting it to an electric motor running at different speeds, the pump has different operational characteristics. Those characteristics change by the Affinity Laws. Now, with the arrival of the variable speed electric motor, called Variable Frequency Drive (VFD), the Affinity Laws will become increasingly important with industrial pumps.

The Laws

When a pump's velocity changes, measured in revolutions per minute (rpm), the operational characteristics also change. These changes can be calculated using the Affinity Laws. Before continuing, let's define some terms we'll be using:

1. Flow = Capacity = Q: Liquid volume measured in gallons per minute (gpm) or liters per minute, cubic meters per hour, or some other rate.
2. Head = H: Liquid force measured in feet of elevation. H can be converted into pounds per square inch (psi). This is discussed in Chapter 2.

3. Brake Horsepower = BHP: Energy needed to pump a liquid.
4. Speed = Velocity = N: Shaft speed measured in revolutions per minute (rpm).

Stated simply, the Affinity Laws indicate:

- Flow, Q, changes directly proportional to a change in velocity. $Q \alpha N$.
- Head, H, changes directly proportional with the **square** of the change in velocity, $H \alpha N^2$.
- Power, BHP, changes directly proportional with the **cube** of the change in velocity, $BHP \alpha N^3$.
- α means 'directly proportional to'.

In the form of equations:

Summary

$$\text{New Flow} = \text{Initial Flow} \times \left(\frac{\text{r.p.m. New}}{\text{r.p.m. initial}}\right) \qquad \frac{Q1}{Q2} = \frac{N1}{N2}$$

$$\text{New Head} = \text{Initial Head} \times \left(\frac{\text{r.p.m. New}}{\text{r.p.m. initial}}\right)^2 \qquad \frac{H1}{N2} = \left(\frac{H1}{N2}\right)^2$$

$$\text{New BHp} = \text{Initial BHp} \times \left(\frac{\text{r.p.m. New}}{\text{r.p.m. initial}}\right)^3 \qquad \frac{BHp1}{BHp2} = \left(\frac{N1}{N2}\right)^3$$

With a small change in velocity (say 20 or 50 rpm), the pump's efficiency would not be affected. But with a velocity change of say twice the speed, or one half the speed, you could expect a small change in the pump's efficiency of maybe 2 or 3%. The pump's efficiency would tend to increase by a couple of points at twice the speed, and the efficiency would tend to decrease a couple of points at one half the speed. In a practical situation, a process engineer or operator might double the speed of the electric motor because the plant is undergoing an expansion and needs twice the production. That engineer or operator should know that:

$$\begin{aligned} 2 \times \text{velocity} &= 2 \times \text{flow} \\ &= 2 \times \text{capacity} \\ &= 2 \times \text{gpm} \\ &= 2 \times \text{production} \end{aligned}$$

$2 \times$ velocity $= 2^2 = 4 \times$ Head
$= 2^2 = 4 \times$ Pressure (psi)
$= 2^2 = 4 \times$ NPSHr
$= 2^2 = 4 \times$ Misalignment in the bearings.
$2 \times$ velocity $= 2^3 = 8 \times$ (BHp) requirements
$= 2^3 = 8 \times$ maintenance costs
$= 2^3 = 8 \times$ downtime
$= 2^3 = 8 \times$ erosion in pipes and elbows
$= 2^3 = 8 \times$ impeller wear
$= 2^3 = 8 \times$ wear in wear rings
$= 2^3 = 8 \times$ other close tolerance wear
$= 2^3 = 8 \times$ friction losses (Hf) in pipes
$= 2^3 = 8 \times$ Hf in fittings, valves, etc.

Consequently, if the pump and motor speed were reduced by 50%:

- The flow would be divided by 2.
- The head would be divided by 4 ($2^2\times$)
- The BHP would be divided by 8 ($2^3\times$)

The relationship between velocity and horsepower requirement (BHp) presents some good arguments in favor of variable speed motors, VFDs. When normal manufacturing plant operations don't depend on time (for example, if you have all night to drain a tank) the pump operator can perform this function at 50% speed, while consuming one-eighth the BHp. VFDs are practical in manufacturing plants because they permit the pumps and other equipment to work at their best efficiency. Controlling pump flow with a VFD is better than using a constant speed motor and controlling the flow by opening and closing valves.

VFDs work well on most PD pumps, and also centrifugal pumps performing a flow service. Remember that some centrifugal pumps are required to comply with head, pressure and elevation applications. An example of this would be a boiler feed water pump, or a pump pushing a fluid through a filter. In these applications, the VFD may only be effective at 85% to 100% maximum speed. Incorrect use of the VFD or lack of understanding of the affinity laws could prejudice these applications because running the VFD and pump at 50% speed would only generate one-fourth the head, pressure, or elevation.

The Affinity Laws and the impeller diameter

If the velocity should remain fixed, the flow, head and BHP will change when the impeller diameter changes. With a change in the impeller diameter (this is called an impeller 'trim'), the affinity laws indicate:

- The Flow changes directly proportional to the change in diameter, $Q \alpha D$.
- The Head changes directly proportional with the square of the change in the impeller diameter, $H \alpha D^2$.
- The BHp changes directly proportional with the cube of the change in the impeller diameter, $BHp \alpha D^3$.

In the form of Equations:

$$\text{New Flow} = \text{Initial Flow} \times \left(\frac{\text{New Diameter}}{\text{Initial Diameter}}\right) \qquad \frac{Q1}{Q2} = \frac{D1}{D2}$$

$$\text{New Head} = \text{Initial Head} \times \left(\frac{\text{New Diameter}}{\text{Initial Diameter}}\right)^2 \qquad \frac{H1}{H2} = \left(\frac{D1}{D2}\right)^2$$

$$\text{New BHp} = \text{Initial BHp} \times \left(\frac{\text{New Diameter}}{\text{Initial Diameter}}\right)^3 \qquad \frac{BHp1}{BHp2} = \left(\frac{D1}{D2}\right)^3$$

What's the practical application of these laws?

The pump curve, the H-Q curve, is in a descending profile. This means that with an increase in flow 'Q', gpm, the Head 'H', or pressure falls. And if flow is reduced, the pressure rises. At times, in normal industrial production, the flow must rise and fall, but the pressure or head must remain a constant.

Many industrial processes experience seasonal rises and falls. This means that flow varies. For example, we consume more cough syrup and aspirin in the flu season and less of these products in other seasons.

(This chapter is written with the authors suffering this ailment.) Normally we buy more ice cream in summer, and less in winter.

The pasteurization process for milk and ice cream requires heating the milk to a specified temperature and pressure for a specified time to kill all germs and bacteria in the milk. This pressure is constant although the production of milk and ice cream goes up and down with consumption and the seasonal changes. It is the same with the treatment of potable water, sterile pharmaceuticals, and petroleum refining.

Let's consider sterile water, used in the preparation of medications for injection. A typical process to sterilize water would require boiling the water at 35 psi, and pumping the water at 40 gpm to 70 gpm, according to consumption. The 35 psi is a constant for the water to pass through the heat exchanger, and a bank of filters. To compensate for the change in demand for sterile water, the affinity laws are used, varying the diameter of the impeller, so that the pump can pump 40 gpm at 35 psi, or 50 gpm at 35 psi, or 70 gpm at 35 psi. This allows the operator to use the same pump and motor, and only change the impeller diameter depending on the needs of production. This precise manipulation of pumping parameters could not be obtained by opening and closing valves, or by simply controlling the pump speed with a VFD.

AUTHOR'S NOTE

Most people change their wardrobe and clothes as the weather changes. Most people would change their cars if their transportation needs change. As the authors of this book, it has always seemed strange to us that most pumps are sold with only one impeller. There is absolutely nothing wrong in selling (or buying) a pump with various impellers of different diameters, ready to be changed when the needs of production change seasonally, or with an advertising campaign. This is the reason that back pullout pumps exist.

Many clients specify and buy pumps with the back pullout option, and they never take advantage of the option. This is like buying a car with an air conditioner and never turning it on. Many engineers, operators, and even pump salesmen believe that the back pullout feature is designed to facilitate maintenance. This is wrong. The back pullout pump exists to facilitate the rapid and frequent impeller change, adapting the pump to the ever-changing needs of production. The back pullout pump exists to facilitate production.

Manipulating flow and controlling pressure by varying the impeller diameter conserves kilowatts of energy, and this is the third affinity law in this group. A pump consuming 10 BHP with a 10 inch impeller, would only consume 7.3 horses with a 9 inch impeller.

This means a 10% reduction in the impeller diameter, would bring about almost 30% reduction in energy. These energy savings will easily cover the cost of multiple impellers and the manpower to change them frequently.