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WHITE PAPER

PUMP AFFINITY LAWS FOR CENTRIFUGAL PUMPS

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The "Affinity Laws" for centrifugal pumps describe the impact of changes in speed or impeller diameter on pump flow, head, and HP. They are useful tools in predicting pump performance changes when speed or impeller diameter are changed, such as might be experienced when

- variable speed drives are employed,
- impellers are trimmed, and
- pump curves, which are plotted at 60 Hz speeds, are to be used across international borders at 50 Hz speeds (and vice versa).

However, as explained in this White Paper, care must be taken in their application. Several "watch outs" will be discussed.

THE AFFINITY LAWS

The Affinity Laws state that (1) flow will change directly when there is a change in speed or diameter, (2) heads will change as the square of a change in speed or diameter, and (3) HP will change as the cube of a change in speed or diameter. As formulae, Affinity Laws are expressed as follows in *Table 1*.

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \quad \text{OR} \quad \frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{H_1}{H_2} = \left(\frac{D_1}{D_2}\right)^2 \quad \text{OR} \quad \frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

$$\frac{BHP_1}{BHP_2} = \left(\frac{D_1}{D_2}\right)^3 \quad \text{OR} \quad \frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3$$

Where:

Q = Flow
D = Impeller Diameter
N = Speed
H = Head (TDH)
BHP = Brake Horsepower

The subscript 1 indicates "existing conditions"; the subscript 2 indicates "new" conditions.

Table 1. *Formulaic Representation of Affinity Laws*

Using these calculations, we could then predict the impact a 10 percent drop in speed would have on the performance of a pump that is delivering a flow of 100 gpm against a head of 100 ft., operating at a speed of 3,550 rpm, and having a BHP requirement of 3.53 (*Table 2*). This pump would now deliver 90 gpm at 81 ft. TDH and require 2.574 BHP.

DISCUSSION AND "WATCH OUT'S"

The understanding of how centrifugal pumps work is vitally necessary. Energy is added to the fluid in the form of velocity in the impeller. This velocity increases as it travels out the vanes of the impeller.

As the fluid exits the impeller, the fluid enters the pump body (volute), thereby reducing velocity and increasing pressure. The increase in velocity is directly related to the shape of the impeller vanes, the impeller discharge angle (specific speed), the diameter of the impeller, and the speed at which the impeller is rotating.

The relationship between the impeller and the volute is important in this conversion to pressure as recirculation losses, turbulence, shock, and friction inside the pump will detract from the conversion.

When the shape of the vane inside the impeller changes, prediction of the impact of impeller trim becomes difficult. The Affinity Laws, in regard to their use in impeller trim, work better for radial-vaned impellers (impellers with low specific speed) while very poorly for Axial Flow impellers (impellers with high specific speeds).

As the specific speed increases, the accuracy of Affinity Law decreases. When coupled with the impact of increases in shock, recirculation, and turbulence, it is recommended that Affinity Laws, in general, not be used for ascertaining a change in impeller trim unless the manufacturer is contacted and approves the use.

Superior results will be obtained by using empirical data that is available from the pump manufacturer for performance at various trims and interpolating, as required.

Regarding changes in speed, great care must also be taken. The Affinity Laws are very useful in "small" changes to speed, but they have become predictive tools for VFD operation where changes may be more dramatic. Since BHP is a function of the amount of work being done (GPM x TDH) and the efficiency of the pump (3,960 x Eff), it is obvious that changes in efficiency will impact BHP.

At "shutoff," the efficiency is zero (0) (power is going in, but no work is being done). Using the logical extreme to illustrate the point, what would happen to the efficiency of a pump designed for 1,750 rpm operation with 85 percent efficiency when the speed is reduced to 1 rpm?

$$Q_1 = 100$$

$$H_1 = 100$$

$$N_1 = 3{,}550$$

$$BHP_1 = 3.53$$

$$N_2 = (3{,}550 \text{ x } .9) = 3{,}195$$

$$Q_2 = [100 \text{ x } (3{,}195/3{,}550)] = (100 \text{ x } .9) = 90$$

$$H_2 = [100 \text{ x } (3{,}195/3{,}550)^2] = [100 \text{ x } (.9 \text{ x } .9)] = (100 \text{ x } .81) = 81$$

$$BHP_2 = [3.53 \text{ x } (3{,}195/3{,}550)^3] = [3.53 \text{ x } (.9 \text{ x } .9 \text{ x } .9)] = (3.53 \text{ x } .729) = 2.574$$

Table 2. *Performance Impact*

Using the Affinity Laws would allow us to calculate flow, head, and BHP – but that calculation would be based on keeping efficiency constant. It is apparent that efficiency will not stay at 85 percent and then suddenly become zero (0) with a 1 rpm change in speed.

A prediction cannot be made – other than the pump most likely will not work – when there is not enough energy being added to the fluid. The Affinity Laws must therefore not be used when speed change is extreme.

How is "extreme" determined? One useful tool provided by most manufacturers is minimum continuous stable flow. It is plotted on many curves and represents the manufacturer's recommendations for a stable operating range. Of course, this will vary by both manufacturer and pump.

If in doubt or when the reduction in speed could violate MCSF, the manufacturer's engineering department should be contacted to ascertain suitability. Since most VSDs are being employed as energy-saving devices, and energy use will be directly linked to pump efficiency, the efficiency of the pump at those reduced speeds must be taken into consideration. Actual BHP should be calculated from empirical data rather than by using pump Affinity Laws.

In general, most manufacturers will place a lower limit on speed reduction to approximately 40 to 50 percent of full speed before considering speed reduction as extreme, and, beyond that, Affinity Laws may be used for predictive purposes.

CONCLUSIONS

Affinity Laws are useful tools for the majority of centrifugal pumps. When properly used, they will allow prediction of performance when speeds or impeller trims are employed. Used improperly, Affinity Laws may yield false predictions.