Variable Speed Versus Constant Speed

by **David Carrier (Part 1) and Ryan B. Stickney (Part 2)**

PART 1: DEBUNKING THE MYTHS OF VARIABLE-SPEED PRESSURE BOOSTING

Maybe "myth" isn't the best word to describe the ongoing argument between those who advocate constant-speed and those who support variable-speed pressure control systems. After all, variable-speed domestic water boosters are only now reaching adolescence as an accepted form of pressure control in the plumbing market. Why all the misunderstanding? Does the answer lie in the desire to resist change? Is it due to the lack of information available? Is there a left-wing conspiracy against variable-frequency drives (VFDs)? (Maybe I am being a little paranoid!)

I asked some of these same questions (not the conspiracy-theory thing) while preparing for my presentation on variable-speed boosting for the 2006 ASPE Convention in Tampa, Florida. When properly evaluated, a variable-speed controlled packaged booster system can be very cost-effective if you look at some basic assumptions:

- 80 percent of the time, a typical booster is at 20 percent capacity or less.
- Building load demand is critically important to effective power reduction.
- On the pump curve, both flow and head are significant to effective pressure control.
- Bladder tanks don't store enough water to produce any significant energy savings.
- Variable speed reduces both sides of the electrical formula, yielding greater power reduction.

CONSTANT SPEED

Constant-speed systems are relatively straightforward and simple designs involving the use of a constant-speed pump (the pressure source) with a pressure-regulating valve (PRV) downstream (the regulating device). As the word implies, the pump never changes speed because it is powered by a starter. A starter has two positions: open and closed. Therefore, a constant-speed booster system essentially has two speeds: on and off. This concept has worked very well for many years due to its simple design, which is very common in older plumbing systems. In the past, the need to have some type of pressure system was of primary importance, whereas the integration of the system within the plumbing and piping design took a backseat to pragmatism. Nowadays, you need the practicality of a constant-speed system with the energy efficiency of a system that is not constantly running simply to have water at the end of a fixture when it is opened. In other words, the engineer has had to match the customers' demand for domestic water with the realities of the system load profile. If we match that load profile more closely, only supplying as much power as needed for a particular moment, we have the opportunity to generate substantial energy savings.

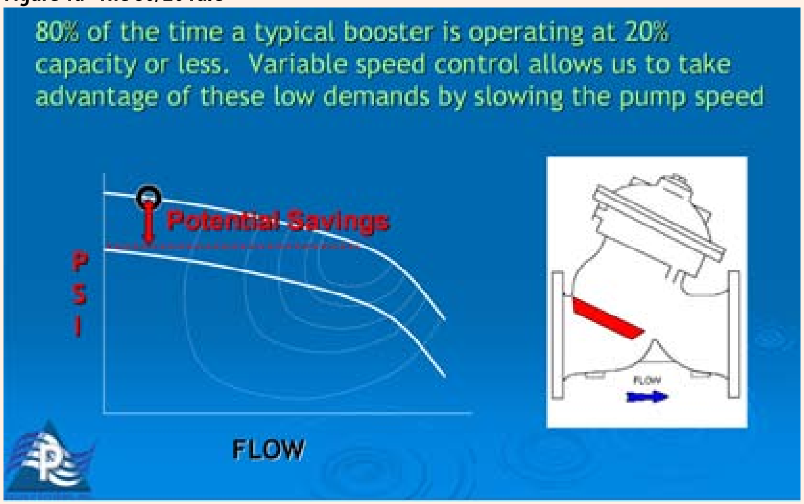
THE 80/20 RULE

Let's face it: All piping systems are different, with numerous and varied applications. A hospital has a different load profile than that of an apartment building. It's very difficult to fit a single, across-the-board constant-speed solution (which never really adapts to the load profile) to piping systems that use water differently. The goal is to match the load profile more precisely, thereby reducing the energy required to run the system when water usage is low. As a rule of thumb, I created what I call the 80/20 rule for boosters (see Figure 1a). This rule states that (on average) 80 percent of the time the booster system is operating at 20 percent capacity or less. Based on this rule, a constant-speed system is not operating efficiently during 80 percent of its operational time, since it is not using much less power when running at 20 percent than when running at 100 percent capacity. In fact, 80 percent of the time it is simply maintaining piping pressure. Ideally, we should use the reality of the 80/20 rule in our favor as an opportunity for power savings.

THE PUMP CURVE

If we reduce the speed of the motor, we take advantage of the pump and fan Affinity Laws, which state that power is reduced as the cube of the speed (see Figure 1b). This is important because on a pump curve, two dynamics are at play from

Figure 1a The 80/20 rule



a demand perspective; typically the flow and head are changing at the same time. Look at a typical pump curve. As the flow increases, pressure capacity drops, and vice versa. In a variable-speed application, as the flow decreases and the potential pump pressure increases, the drive is reducing that speed to match a constant discharge pressure by slowing the pump down. As the pump slows, the Affinity Laws tell us that the energy consumed is being reduced by a factor of eight.

Figure 1b The Affinity Laws

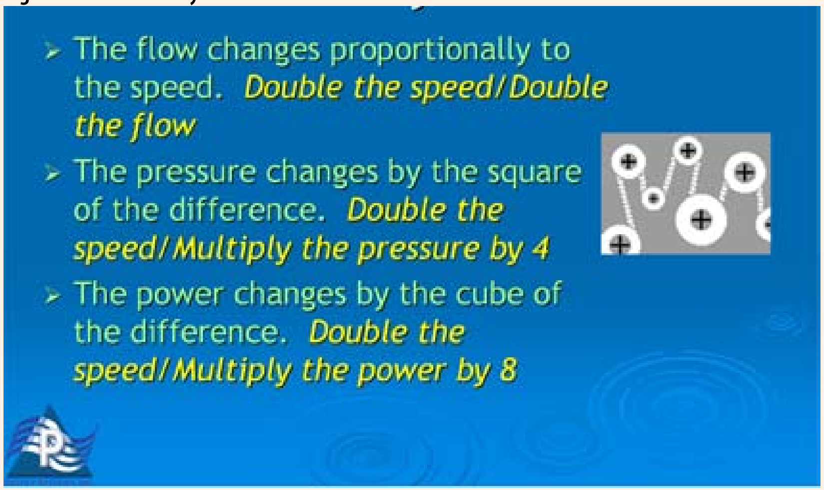


Figure 1c Proper pre-charge for a bladder tank

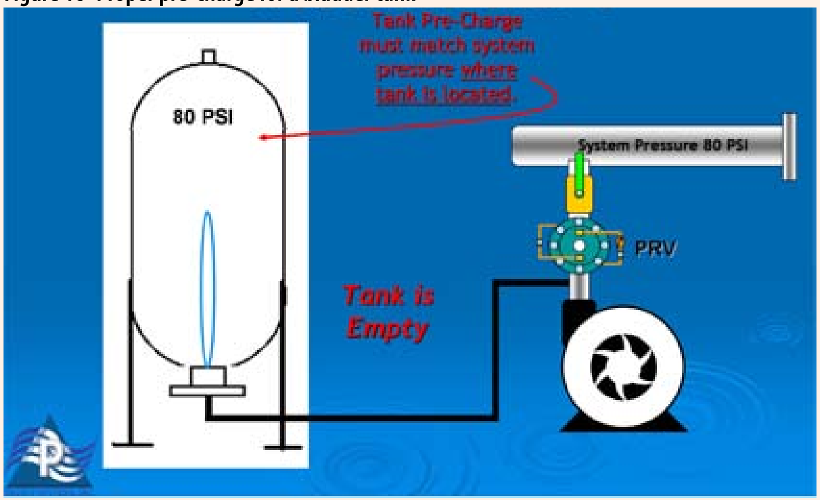
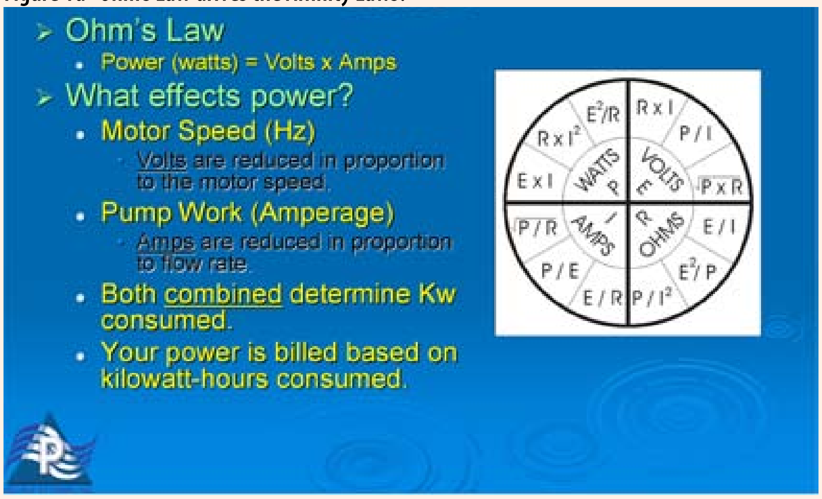


Figure 1d Ohm's Law drives the Affinity Laws?



In a constant-speed system, this does not happen because the pump does not change speed. Instead, the PRV becomes a throttle that reduces potential head pressure by adding friction and resistance through the closure of the regulator. Since this overpressure condition is a reality in the constant-speed world, manufacturers over the years have sought to take advantage of this "free" pressure by adding storage tanks in the hope that energy consumption could be mitigated by simply shutting off the power to the system. It is a good idea, but unfortunately this application collides headlong into the realities of Boyle's Law, which states that the volume of a confined gas at a fixed temperature is inversely proportional to the pressure exerted on the gas.

THE BLADDER TANK

The bladder tank was added to the system to save energy consumed by the constant-speed pump, which was only running to maintain piping pressure. It involved using the excess pressure created by the pump at shutoff to charge a pressure tank, allowing water to be stored so the system did not have to restart to meet small loads. In fact, the idea caught on so well that it became an industry standard. Unfortunately, only half of the story was told. To charge a bladder tank, you need a pre-charge equal to the system pressure before you add even a drop of water (see Figure 1c).

This means that the only advantage in storage is when the pump generates more pressure than it requires for maintaining system pressure. After this pre-charge, little room is left in the tank for water. If you want to calculate how much water a typical bladder tank holds, a simple rule of thumb is to figure about 10 percent of the tank volume. If your client buys a 200-gallon tank, he'll have only about 20 gallons of water available for shutdown periods. It can be more cost-effective to run the variable-speed system 80 percent of the time at a reduced speed than to run the constant-speed/bladder system 70 percent of the time (if that's even plausible) at full voltage. In cases of high demand, such as flush valves, the demand is so quick that the pump will typically start before the tank can even begin to satisfy the rapid demand of the valve. I have seen bladder tanks on variable-speed systems. As mentioned before, the pressure must change for the tank to receive any storage. The VFD must increase its speed, thereby changing its purpose to a variable-pressure system. Without increasing the speed and system pressure for the purpose of charging the tank, the tank will never be charged with any water.

THE SAVINGS

At the end of the day, the most important aspect of these decisions is the cost to operate the machinery. How does the owner get operational efficiency from the system? This is where the engineer earns his paycheck. The key element to operational efficiency is clearly stated on the energy bill. The owner is billed in kilowatts. What impacts the reduction of watts? In electrical terms, this can be summarized by a single electrical law known as Ohm's Law (see Figure 1d). Ohm's Law states simply that volts multiplied by amps equals watts.

In the case of the constant-speed pump, as the flow is reduced, the amount of amperage consumed is reduced, but the voltage remains the same. A typical squirrel-cage induction motor has a reduction in amperage draw from full load to zero load of about 60 percent, thereby reducing amperage at low flows, which is only one variable of Ohm's equation. If the same motor is attached to a variable-speed pump, the amperage is reduced the same; however, the voltage is reduced at an equal percentage to the reduction in speed. This means that a 460-volt motor running at half speed while connected to a drive will be pulling only 230 volts at its rated amperage for the pump capacity. In the variable-speed application, both variables of the Ohm's Law equation are impacted, versus the constant-speed application in which voltage remains constant at all capacities. This is the primary reason that variable-speed pressure control has become an industry standard.

Constant-speed systems have served the industry well for many years, but technological enhancements increase just like your client's power bill. With the pressure on the consultant to optimize the system for energy efficiency, the variable-speed system has become an appealing option in the 21st Century economy. Perhaps the constant speed system will be relegated to the history books, just like those old myths of the past.

PART 2: GAINING ENERGY SAVINGS WITH DOMESTIC WATER BOOSTER PUMPS

Variable-speed operation is now a standard in most of our specifications, but how many of us can really explain its operation? What are the dynamics? What is the operating cost? How much energy can we save? Such questions are presented to the consultant on almost every domestic water booster application. The proper response to these questions is especially critical due to the increasing desire of consultants, owners, and consumers to be environmentally responsible. The following will answer these questions and provide a path to quantifying energy savings for our clients.

First things first: Domestic water pumping is a variable torque application. Pumps are machines that have the benefit of the Affinity Laws. This allows us to reduce the motor torque, which yields the highest energy savings.

As mentioned in Part 1, the Affinity Laws state the following:

- Law #1: The flow varies directly with the speed or impeller size.
- Law #2: The head varies by the square of the speed or impeller size.

Figure 2a Single-speed pump curve

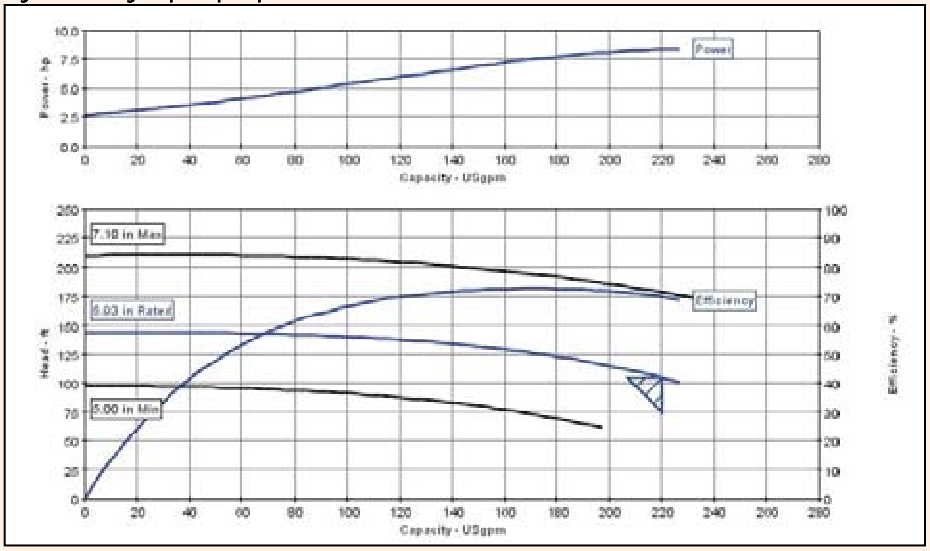


Figure 2b Multi-speed pump curve

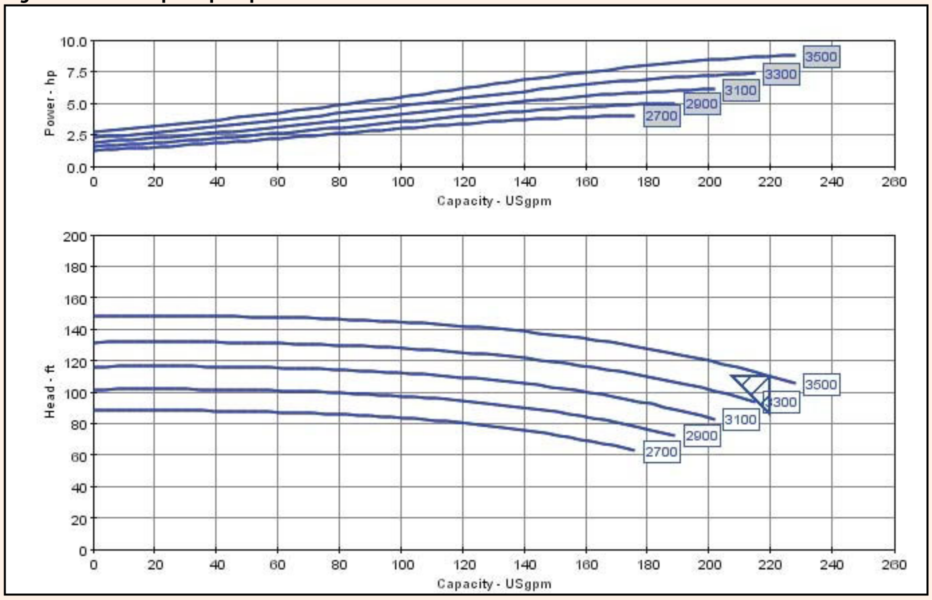
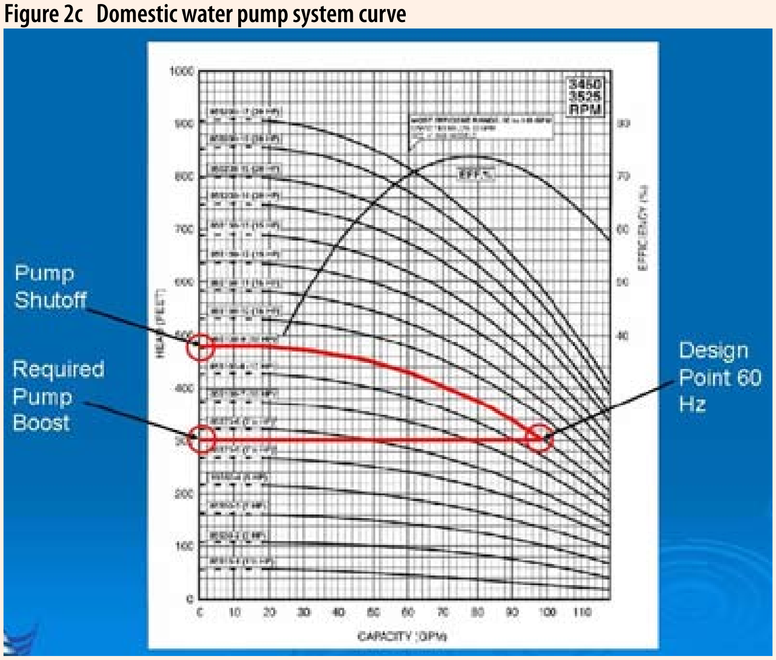


Figure 2c Domestic water pump system curve



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- Law #3: The power varies by the cube of the speed or impeller size.
- Law #4: The torque varies by the square of the speed or impeller size.

The pump Affinity Laws work two ways: We may vary the speed or vary the size of the pump impeller. We only get one impeller size, so herein lays the benefit of varying the speed of the motor. Figure 2a is an example of a single-speed pump curve and Figure 2b is an example of a multi-speed pump curve. The multi-speed curve gives us a precise look at the behavior of a pump when the speed is reduced.

The system curve of a domestic water pump is flat, running from the design point horizontally back to shutoff (see Figure 2c). You should be concerned with three areas of the curve: the design point, the 60-hertz (Hz) shutoff pressure, and the system curve (the system curve pressure is the same as the pump's required boost). As the 60-Hz or constant-speed curve rides toward shutoff, it rises, increasing the pump's capable pressure. The difference between the pump's capable pressure and the pump's required boost determines the pump's speed and its potential energy savings.

A minimum speed exists in this application. We must maintain a minimum pressure in a domestic water system to maintain proper pressure at the top of the building. Since the speed varies as the square of the head, we are limited in our ability to reduce it. The difference between the pump's capable shutoff and the pump's required boost determines its minimum speed. Minimum speed is critical in determining variable-speed operation and potential energy savings. In Figure 2d, the pump's capable shutoff is 300 feet, and the pump's required boost is 200 feet. The second Affinity Law is used to determine the minimum speed. Following is the equation used to solve for variable torque speed in the Figure 2d example:

3,500 revolutions per minute/(300-foot shutoff/200-foot pump required boost)^(½) = Minimum speed

Thus, the minimum speed is 2,860 rpm.

The minimum speed will fluctuate if there is a variance in suction pressure. If the suction pressure increases, the pump works less, and vice versa. Remember: We size boosters based on the minimum city suction pressure available. This minimum city suction is not always realistic. In many cases, the city guarantees a lower pressure than actually exists.

Pump selection is critical to variable-speed operation. The curve in Figure 2d is relatively steep. Let's compare this steep curve to a flat curve (see Figure 2e). We apply the same formula using the second Affinity Law:

3,500 rpm/(240-foot shutoff/200-foot pump required boost)^(½)

Thus, the minimum speed is 3,195 rpm. (Again, the minimum speed will fluctuate if there is a variance in suction pressure. If the suction pressure increases, the pump works less, and vice versa.)

In comparison, the minimum speed is reduced as the curve gets steeper. Therefore, selecting a steep curve versus a flat curve yields greater energy efficiency. With either curve, your selection should be as far right on the

Figure 2d Steep curve

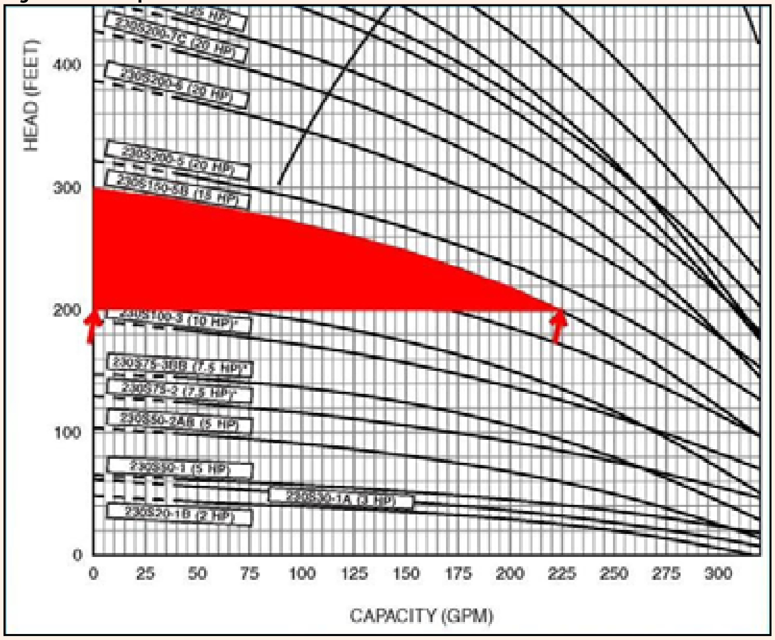


Figure 2e Flat curve

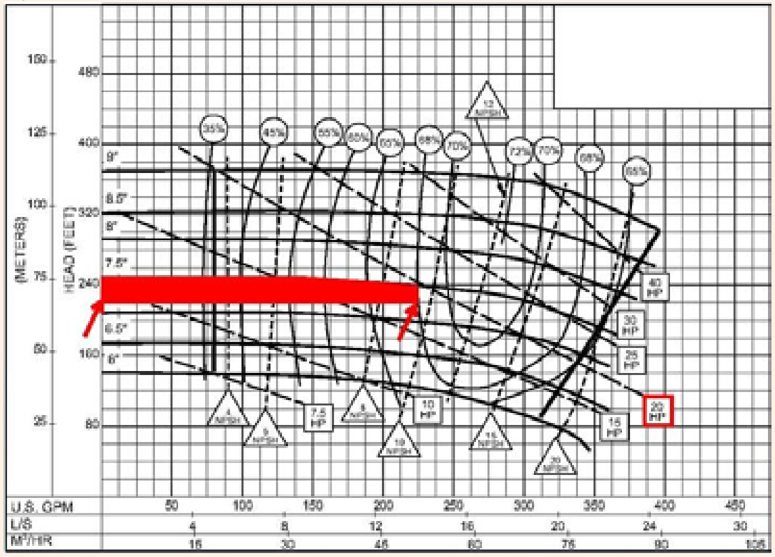
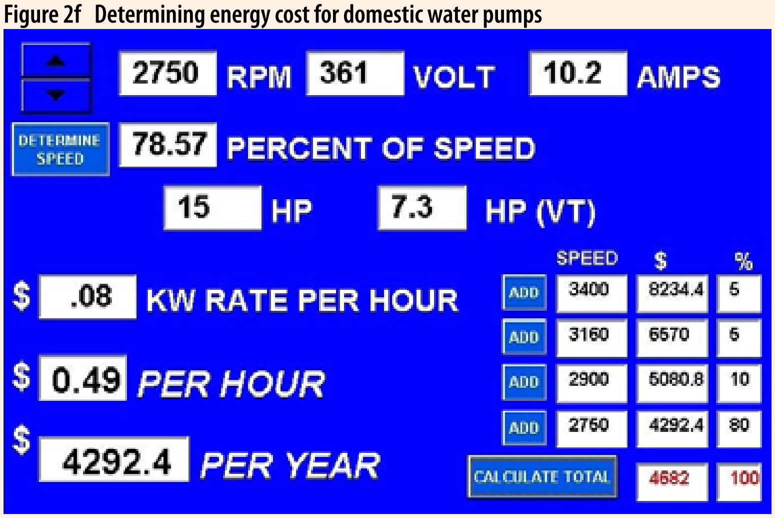


Figure 2f Determining energy cost for domestic water pumps



curve as possible, which ensures the greatest operating bandwidth. Decreased axial and radial loads on the bearings and seals are additional benefits to operating at a lower speed.

The next step in determining your operating cost is to determine the building's load profile. The 80/20 rule is very helpful when determining the building's load profile. The 80/20 rule is not a substitute for an accurate load profile. It is simply the average of most system types. This rule does not apply to every application, and the only way to precisely quantify the operating cost of a pump is to use a meter while it is operating. However, we can give our clients a fairly close representation of operating cost using this rule in many building types. We should be realistic when determining the building's load profile. A typical load profile would state: 80 percent of the time the flow is 20 percent of the design point; 10 percent of the time the flow is 50 percent of the design point; 5 percent of the time the flow is 80 percent of the design point; and 5 percent of the time the flow is 90 percent of the design point. An energy calculation must be performed during each stage of operation (see Figure 2f).

Once determining the load profile, you can begin to quantify the operating cost. We begin with the minimum speed, so we look back to our example in Figure 2d. Remember that the first Affinity Law states that the speed directly changes the flow. To define your operating bandwidth, subtract the minimum speed from the rated speed. In the following example, the operating bandwidth is 640 rpm. The minimum speed plus 20 percent satisfies the 80/20 rule; therefore, this system will operate at 2,980 rpm 80 percent of the time. Repeat this step for each portion of the load profile.

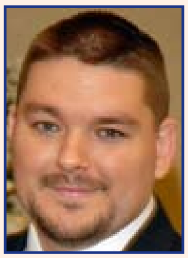
- 3,500 rpm – 2,860 rpm = 640 rpm
- 640 rpm * 20 percent = 120 rpm
- 2,860 rpm minimum + 20 percent = 2,980 rpm

Next, determine the variable torque horsepower (HP), amps, and kilowatts (KW) for each portion of the load profile. Change the hours of operation for each portion based on the percentage of operation.

- HP (variable torque) = Rated HP * (Speed variable torque/Rated speed)^3
- Amps = (746 * HP)/(1.732 * Volts * Efficiency * Power factor)
- KW = (Volts * Amps * Power factor * 1.732)/1,000
- KW * Hours (8,760 hours/year) * Energy rate (Average $0.08 per KWh) = Operating cost

We have an obligation to provide our clients with the most environmentally efficient systems available. This will become increasingly important as energy costs rise (24 percent in Illinois as of January 1) and resources are depleted. By accurately determining building load profiles and selecting energy-efficient pumps, we are well on our way to providing our clients with environmentally efficient domestic water pump systems. PSD

DAVID CARRIER is the executive vice president of Delta P. Systems Inc. in Ormond Beach, Florida, a packaged systems manufacturer and pioneer in the use of variable-speed controls in the plumbing market.



RYAN B. STICKNEY is the general manager of Mechanical Room Inc. in Chicago. Ryan specializes in plumbing and HVAC pumping systems and variable-frequency drives. He is also the author of engineering software that assists engineer with domestic water pumping operating costs when using variable-frequency drives.

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