Distribution Efficiency in Hydronic Systems

by John Siegenthaler , P.E.

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Find out how to improve something that already has an advantage, with this look at how hydronic systems convey heat from the heat source to the heat emitters.

Looking back at the history of residential hydronic heating in North America over the last 25 years, one is amazed at the progress made in the area of thermal efficiency.

For example, I grew up in a 1960s vintage ranch house heated by an oil-fired steel fire tube boiler. The boiler was equipped with a tankless coil for domestic water heating. Upstairs was a single thermostat that controlled the entire 1,500-square-foot house.

When I replaced that boiler in 1989, the fire tube baffles were completely burned away. This helped explain the net stack temperature of about 550°F. Although this boiler kept our house comfortable for over 30 years, its “aged” seasonal efficiency was probably in the range of 50% to 60%.

Today, the house has a boiler with a heat output half that of its predecessor, and a rated AFUE of about 86%. But even 86% AFUE looks mediocre compared to several currently available modulating/condensing boilers capable of efficiencies in the mid-90% range (when operated at low water temperature conditions).

As Good As It Gets?

$$\text{distribution efficiency} = \frac{\text{rate of heat delivery}}{\text{rate of energy use by distribution equipment}}$$

One might conclude that our industry has just about hit the limit of what’s theoretically possible with converting fuel into heat. That little remains to be accomplished in terms of efficiency improvements. But just as an oasis fades away when you’re just about to it, so does this illusion of nearly perfect efficiency.

True, the thermal efficiency of many modern boilers is very high, but a hydronic system is more than a high-performance boiler. The distribution efficiency at which many current hydronic systems convey heat from the heat source to the heat emitters provides plenty of room for improvement.

Let’s define distribution efficiency.

Distribution efficiency describes how many Btus/hr of heat delivery occur for each watt of electrical power used by the distribution system. Just like thermal efficiency, the higher the delivery efficiency, the better.

Here’s an example: Consider a hydronic system that delivers 120,000 Btu/hr at design load conditions using four circulators operating at 85 watts each. The distribution efficiency of that system is listed in the following equation.

$$\text{distribution efficiency} = \frac{120{,}000 \text{ Btu/hr}}{340 \text{ watts}} = 353 \ \frac{\text{Btu/hr}}{\text{watt}}$$

Distribution efficiency can also be expressed by converting the heat delivery rate into watts to match the units of electrical power input.

$$distribution\ efficiency = \frac{(120{,}000\ Btu/hr) \times \left(\frac{1\ watt}{3.413\ Btu/hr}\right)}{340\ watts} = 103.4\ \frac{watt(thermal)}{watt(electrical)}$$

$$distribution\ efficiency = \frac{(80{,}000\ Btu/hr) \times \left(\frac{1\ watt}{3.413\ Btu/hr}\right)}{850\ watts} = 27.6\ \frac{watt(thermal)}{watt(electrical)}$$

The value 103.4 should be interpreted as 103.4 units of heat delivery per unit of electrical power input to operate the distribution system.

It's hard to judge a number for distribution efficiency without something to compare it to. Here's a similar calculation for a furnace with a blower that operates at 850 watts while delivering 80,000 Btu/hr through a forced air ducting system, as shown in the following equation.

For these examples, the hydronic system provides a delivery efficiency about 3.8 times higher than that of the forced air system. This is not uncommon for many current day installations. It's a direct result of water being far superior to air as a media for absorbing and carrying heat.

So, how can we further improve the distribution efficiency of hydronic systems? Here are some things I think will help the North American hydronics industry get more Btu/hr delivered per watt of electrical pump power.

1. Use higher temperature drops: As designers, we have to stop thinking that water "wants" to or needs to drop 20°F as it flows around every hydronic piping loop we design. Instead, we should design for 30° to 40°F temperature drops where appropriate (e.g., in certain primary loops, panel radiators, high mass boilers and air handler coils). Doubling the circuit's temperature drop cuts the flow required for a given rate of heat transfer in half! The Europeans figured this out years ago and routinely use higher circuit temperature drops to reduce tube size, circulator size, and most importantly, pumping power.

2. Reduce head loss: Hydronic system designers make daily "trade-off" decisions between tube size and circulator power (i.e., should I stick with 1-inch copper for this circuit and use the 1/12 hp circulator, or go to 1.25 copper and drop down to a 1/25 hp circulator?).

The answer depends on what yields the lowest life-cycle cost, which includes not only installation cost but also the operating cost over an assumed design life. You'll spend more for the 1.25-inch copper, and somewhat less for the smaller circulator, but few of us bother to factor in the savings in operating cost over the life of the system. The latter is where the big savings potential exists.

3. Avoid overpumping: moving water through heat emitters at high flow rates does very little to

improve thermal performance, yet greatly affects the power requirements of the circulator.

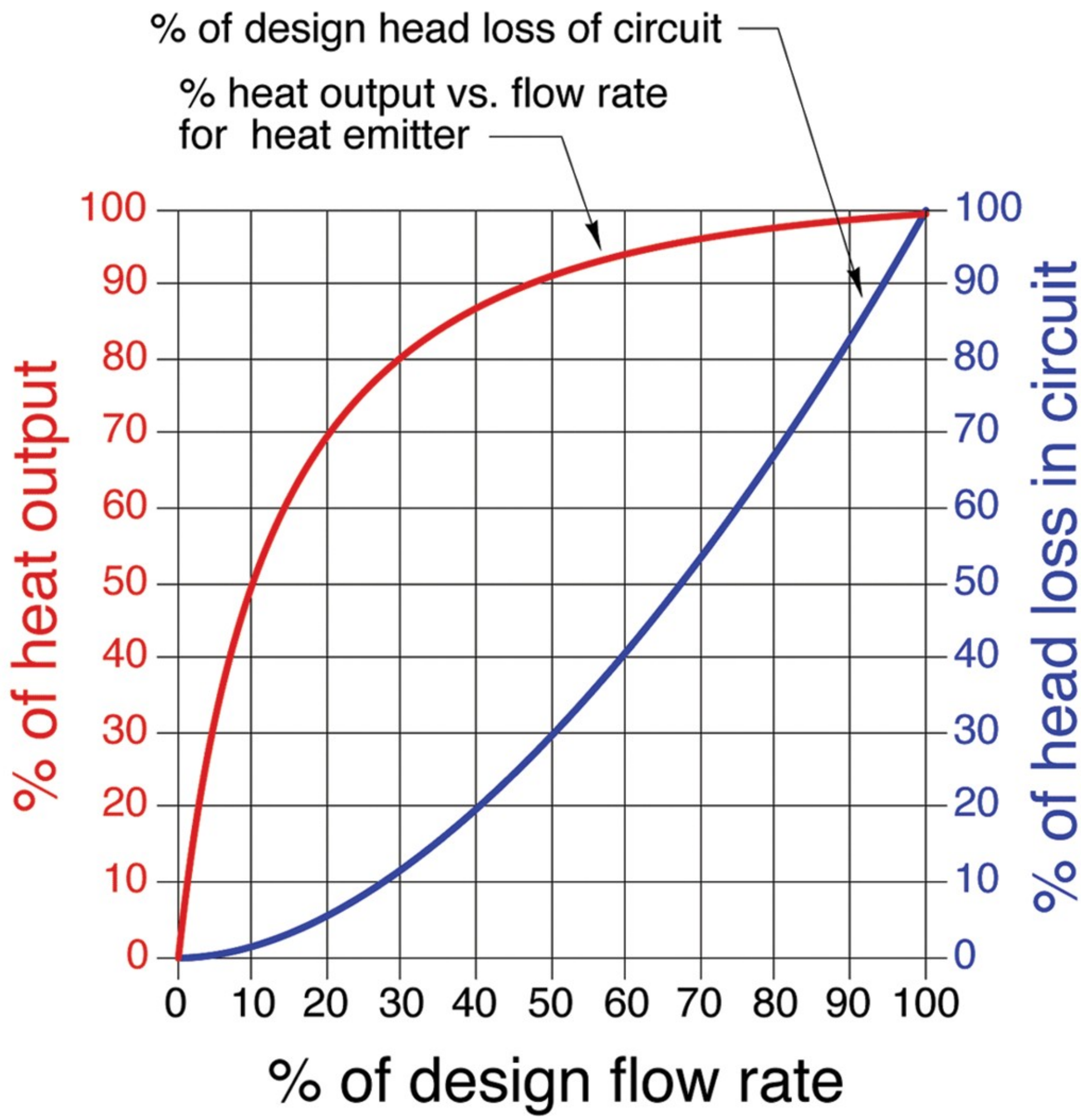


Figure 1

For example, the graph in Figure 1 shows that a typical hydronic heat emitter, such as a radiant floor circuit or fin tube convector, achieves about 90% of its "design" heat output at only 50% of design flow rate. The nominal 10% loss in thermal performance due to reduced flow is usually within the typical thermal oversizing "safety factor" used in many systems. Operating at 50% of design flow also decreases head losses to about 30% of design head loss.

$$P_2 = P_1\left(\frac{f_2}{f_1}\right)^3$$

Perhaps the most impressive savings associated with reduced flow rate are those in pumping power. One of the pump affinity laws states that pumping power is proportional to the cube of flow rate, as shown in Equation 1.
Where:

P_1 = power required at flow rate f_1

P_2 = power required at flow rate f_2

According to this equation, operating a circulator at 50% of design flow would (in theory) require only 12.5% of design load power input. Actual savings will be less due to non-proportional losses in bearings, motor windings, etc., but very significant savings are still waiting for those who recognize the physics of moving water through piping systems, and take advantage of it in their designs.

Figure 2
Example of a Smart Circulator

Smarter Than the Average Pump
Another way to increase distribution efficiency is to improve the way the "head source" (e.g., the circulator) is built and operated. Here are some of those improvements, many of which already exist in small circulators sold in Europe.

1. Replacement of traditional PSC (Permanent Split Capacitor) motors with ECM (Electronically Commutated Motor) motors in small- to medium-size wet rotor circulators.

2. Variable speed operation controlled by a microprocessor that allows several "smart" modes of operation.

3. Improved "3D" impeller design based on computational fluid dynamic modeling.

4. Improved flow characteristics within the volute and minimal internal recirculation losses.

An example of a smart circulator with all these features is shown in Figure 2.

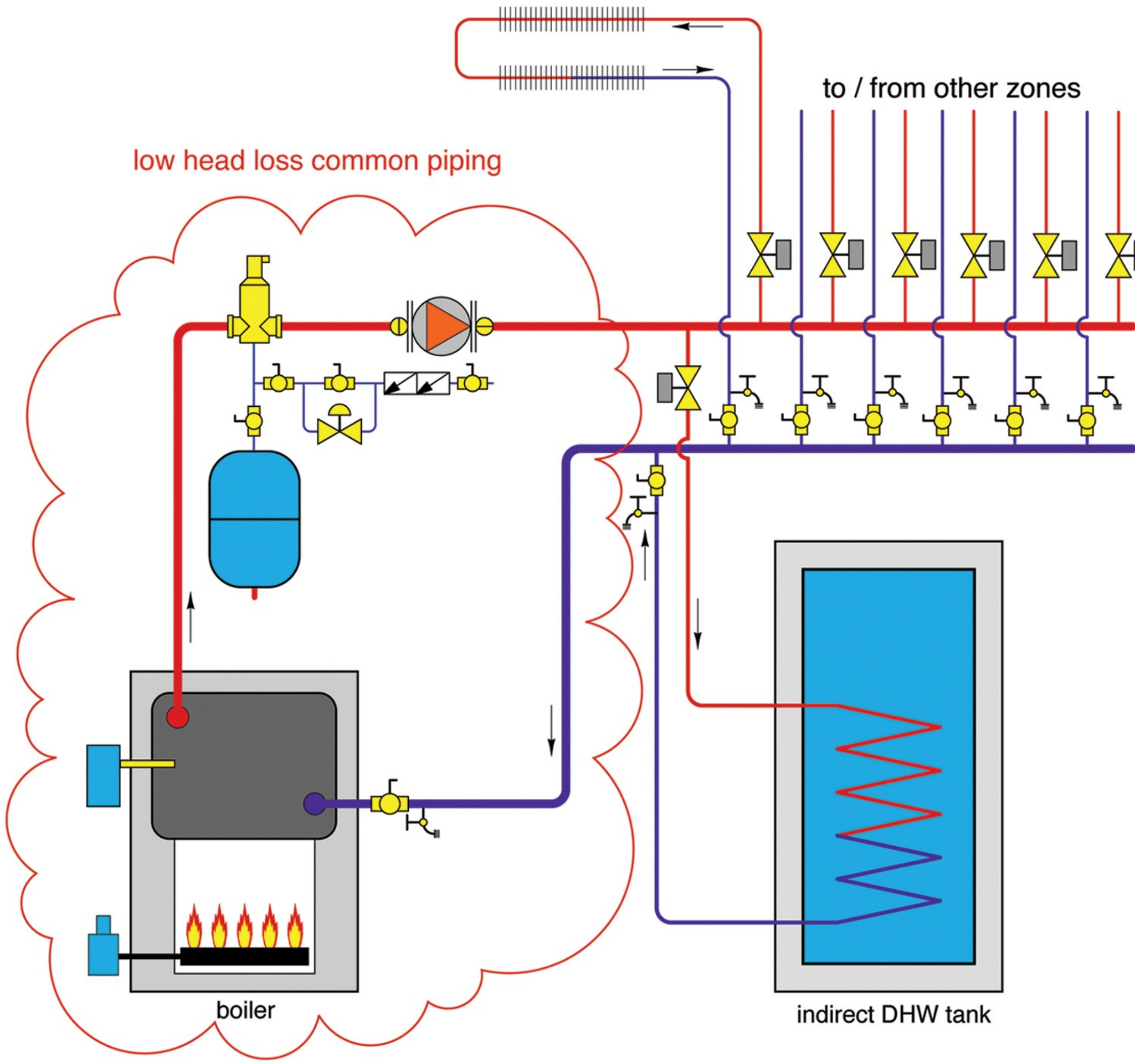
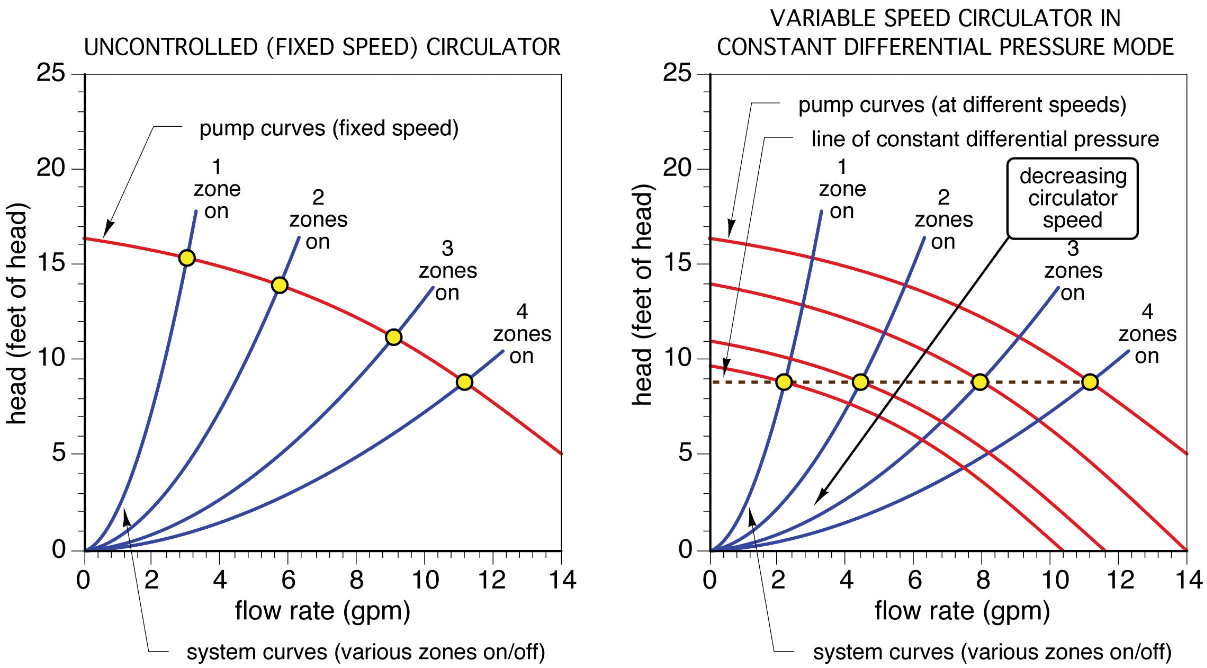


Figure 3

So what exactly does a “smart circulator” do? Well, like many microprocessor-controlled devices, they offer multiple, user-selectable operating modes.

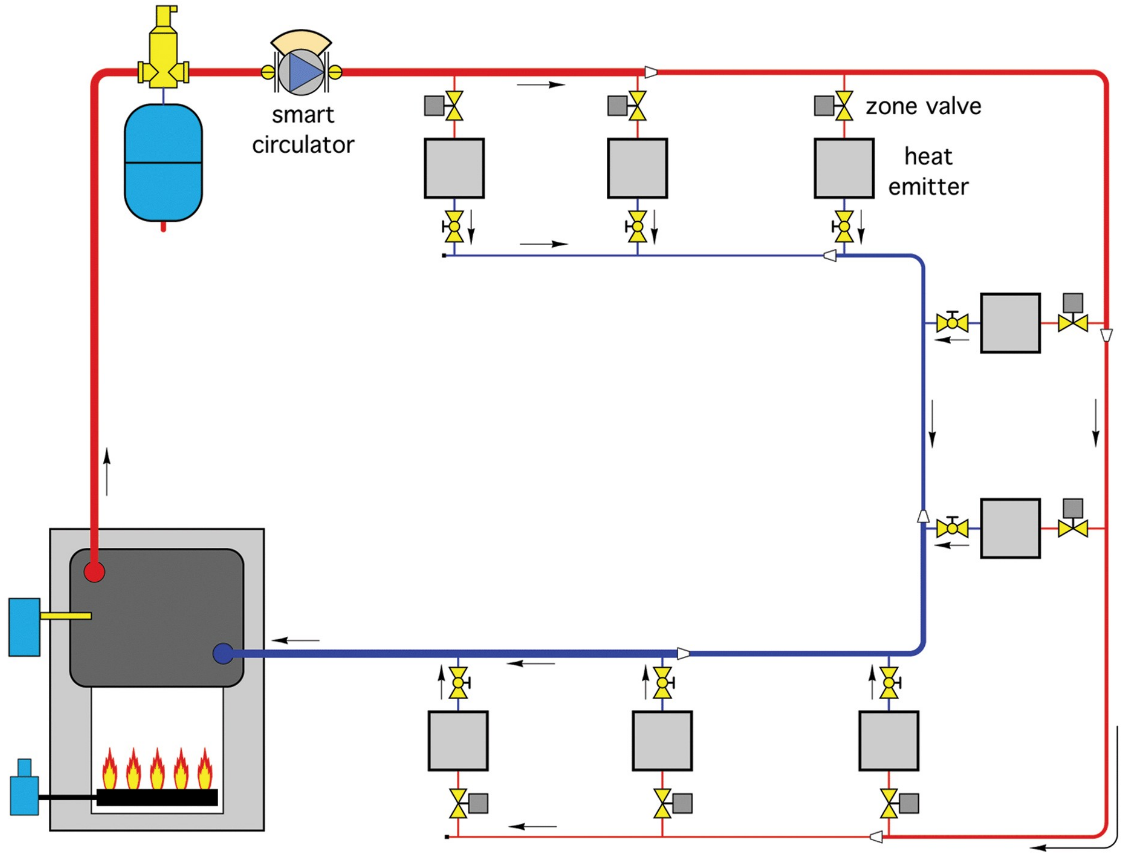
One of those modes is constant differential pressure. This mode is well suited to distribution systems where the head loss of the common piping (see Figure 3) is relatively small compared to the head loss of distribution circuits controlled by zone valves or thermostatic radiator valves.

Figure 4



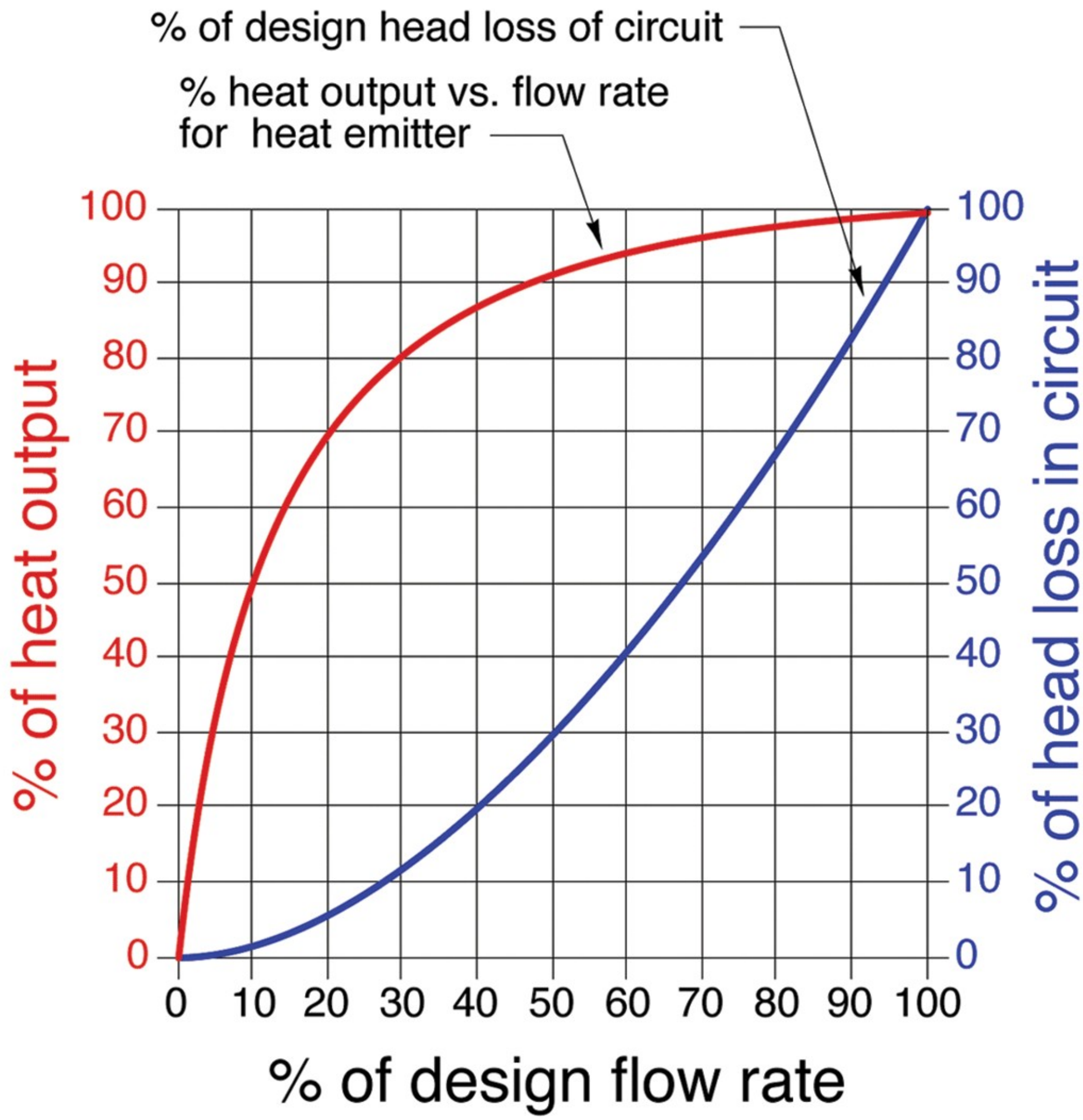
Constant differential pressure mode allows the differential pressure across the branch circuits to remain steady regardless of what zones are on or off at a given time. It's accomplished by varying the speed of the impeller such that the intersection of the pump curve and system operating curve remain at a constant head (e.g., constant differential pressure). As soon as the system curve steepens or flattens in response to a zone valve closing or opening, the circulator electronically senses the attempted change in differential pressure and instantly responds with a speed adjustment to nullify that change. This is shown in Figure 4, along with a comparison of what happens in systems using an uncontrolled fixed speed circulator.

Figure 5



Another smart pump algorithm is called “Proportional Pressure Control.” This is appropriate for distribution systems where the head loss along the mains and heat source is significant relative to the head loss through the branch circuits. An example would be a two-pipe reverse return distribution system, such as shown in Figure 5.

Figure 6



The manner in which the pressure/flow characteristic is modified accounts for head losses along the mains, so that the differential pressure across individual zone valves remains almost constant, as shown in Figure 6.

Both constant differential pressure and proportional pressure control modes eliminate the need for a differential pressure bypass valve. Such valves are currently regarded as the standard approach to controlling the symptoms of fluctuating differential pressure in zoned systems with fixed speed circulators. Smart circulators address the cause rather than the symptoms of the problem (excessive head input under partial load conditions). In doing so, the symptoms of excessive differential pressure (flow noise, erosion corrosion, and valve stem lift) are eliminated, while considerable energy savings are also achieved. The cost savings from not having to purchase and install a differential pressure bypass valve obviously reduces the incrementally higher cost of the smart circulator.

Some smart pumps can also compensate for changes in water temperature associated with outdoor reset control, and even nighttime setback. The circulator contains an internal temperature sensor that constantly measures water temperature to (or in some cases from) the distribution system.

The Bottom Line

Estimated energy savings vary according to the specifics of the load as well as the operating mode of the circulator. Simulations done in Europe project savings in electrical usage of 50% to 80% relative to an uncontrolled fixed speed circulator of equivalent performance.

One manufacturer estimates that converting all small circulators (under 250 watts peak) in the European Union to current generation smart circulators has the potential for saving 10 billion kilowatt-hours per year! Although similar projections for the North American market are yet to be made, there is little doubt that savings in both new and retrofit installations will be profound. Payback periods of four years or less are likely, with a projected 20-year life-cycle cost of a smart circulator approaching half that of an uncontrolled fixed speed circulator.

Several manufacturers currently offer small smart circulators in the European market, and this is finally being noticed in North America. Just as the concept of smaller modulating boilers made its way from Europe to North America, it's inevitable that smart circulators will capture the attention of cutting edge hydronic designers, as well as their clients who are presented with the economic advantages.

Current generation wet rotor circulators will surely remain in the market for the foreseeable future, but will decline in market share as our industry and its customers grasp the energy-saving implications of the next generation of smart circulators. The eventual impact these circulators will make on the North American market will likely rival that of modern high-performance boilers versus their predecessors. Get ready, because big changes in small circulators lie just ahead. Together with careful refinements in piping design, these new circulators will greatly improve the distribution efficiency of present day hydronic systems.

John Siegenthaler , P.E.
john@hydronicpros.com
John Siegenthaler, P.E., is principal of Appropriate Designs, a consulting engineering firm in Holland Patent, NY, and author of Modern Hydronic Heating. Visit www.hydronicpros.com for information on his recently released second edition, as well as the new Hydronics Design Studio software. E-mail John at john@hydronicpros.com.