providing insights for today's hvac system designer
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Pressure-Independent Control Valves

and their Role in Comfortable, Efficient Chilled-Water Systems

Somehow we abbreviated the affinity laws to say that load equals flow, or that load is proportional to flow. Neither is inherently true—we find they are neither equal nor proportional when looking at data from operating systems. When pressed about why we don't see a linear relationship in the real world, we shrug and point to system pumping, coil and airside dynamics and something about the so-called low-delta-T syndrome. And this should be cause to investigate!

Upgrading to pressure independence for cooling and heating control valves is the system upgrade that simplifies and restores the flow-load relationship and the focus of this newsletter.

With ASHRAE® now providing consensus guidance for lower and variable hydronic flow rates, different types of coil selections are required and the subject of a past newsletter. Valve upgrades are also key for delivering the intended and expected system performance and cost benefits.

A Valve's Purpose

When a load presents a higher call for cooling, a fan-coil terminal valve opens, responding to the temperature sensor in the room or a discharge air temperature sensor. If a variable speed fan is present, perhaps the fan speed ramps up before the valve opens. Perhaps it is a combination of the two – for example when using single-zone VAV algorithms or sensible-only coils. Regardless, the valve is supposed to open for more cooling and close for less cooling. In heating the inverse is true.

In a centralized system, the air-handler's cooling valve likely responds to a discharge air temperature control loop, while the fan speed responds to a duct pressure setpoint or a critical air valve feedback loop. The discharge air setpoint can reset itself in response to either outdoor air temperature or air valve positions. The hydronic system for chilled and hot water consists of interrelated parts that all must work together.

Both centralized (air-handler) and decentralized (terminal) coil valves are interacting with all other system interconnected valves and pumps. When the pump speed increases, valves serving an unchanged load close in response—otherwise an increased inlet pressure would drive a higher flow through the system. How much they must close depends upon the additional flow the other terminals require.

The ability of the valves to deliver the precise amount of air or water conditioning is usually a function of the omniscience of the designer, or the technology. It's a fairly impossible ask: the system designer must account for system interactions, estimate the loads within reason, select equipment judiciously, and successfully hand off to a team of installers, controls contractors, system balancers, and commissioning agents.

One thing the designer *can* do is specify and insist on better control valves, often with low or no additional first costs. Unfortunately, for many systems, the responsibility falls on the controls contractor to make the valve selecting decisions. In the effort to save cost, the selected valves are generally cheap and the application of the valve is unknown. This is how bad central plants happen.

Definitions Common to Modulating Control Valves

Before we go any further, let's define some basic terminology.

Equal-percentage flow characteristic valves are typically used for hydronic system control. Other valve characteristics (and applications) are quick opening (two-position valves) and linear (steam coils and bypasses).

Authority is the ratio between the valve pressure drop at minimum flow to the pressure drop at maximum flow. Its range is from 0 to 1. High authority leads to excessive valve pressure losses. Authority too low leads to instability—the valve opens too quickly. For cooling coils, a typical authority would be from 0.25 to 0.5. Within this range, authority distortion (in theory) linearizes the valve stroke of an equal-percentage valve when the system is not presenting the valve's design pressure drop.

Flow coefficient (C_V) is the flow capacity of the valve at the fully open position. It is derived from the fluid type and temperature (specific gravity), flow rate, and pressure drop. It is used to select pressure-dependent valves and varies with the location of the valve within the system. Calculating C_V correctly means the designer must know the flow rate and pressure drop at the location where the valve will be installed in the system.

Balancing valve is a type of valve used to minimize the impact of excessive differential pressure in the system. "Circuit setter" is a trade name for a valve introduced by Bell and Gossett for automatic balancing. Differential pressure control valves are a type of balancing valve.

Pressure-dependent (PD) control valves are often selected by choosing a specified or arbitrary pressure drop and calculating the proper flow coefficient (C_V). The location-specific pressure drop across the valve is often unknown or assumed to be constant for large portions of a hydronic system.

Note: Valve authority is rarely noted in a project specification or manufacturer's valve selection table.

Pressure-independent control valves (PICVs) eliminate variability from pressure fluctuations within the system. This can be done mechanically with a dynamic pressure regulator or electronically with integrated software and measurements. **Mechanical PICVs** consist of a pressure-regulating section and a flow-control section. **Electronic PICVs** consist of a flow-measurement section and a flow-control section. These valves serve as both the control valve and the balancing valve.

Modulating Valves Counteract the Flow Characteristics of a Cooling Coil

Now let's discuss the interaction between the valve and the cooling coil. A sequence of figures from the Valves chapter from the 2020 version of the ASHRAE® *Handbook of Fundamentals* illustrates that coil flow has an exponential relationship with heat output (see Figure 1). As flow increases, the rate of change of the heat output decreases. To counteract this, the valve actuator performs the opposite exponential relationship (image B). The result is a linearization of the valve position-heat output relationship (image C). This assumes that there is a constant pressure drop across the valve—a bad assumption that we'll circle back to later.

Valves are often oversized. The effect of oversizing means that the coil output is not as desired (Figure 2).

Figure 1. Heat output, flow, and stem travel characteristics of equal-percentage valve

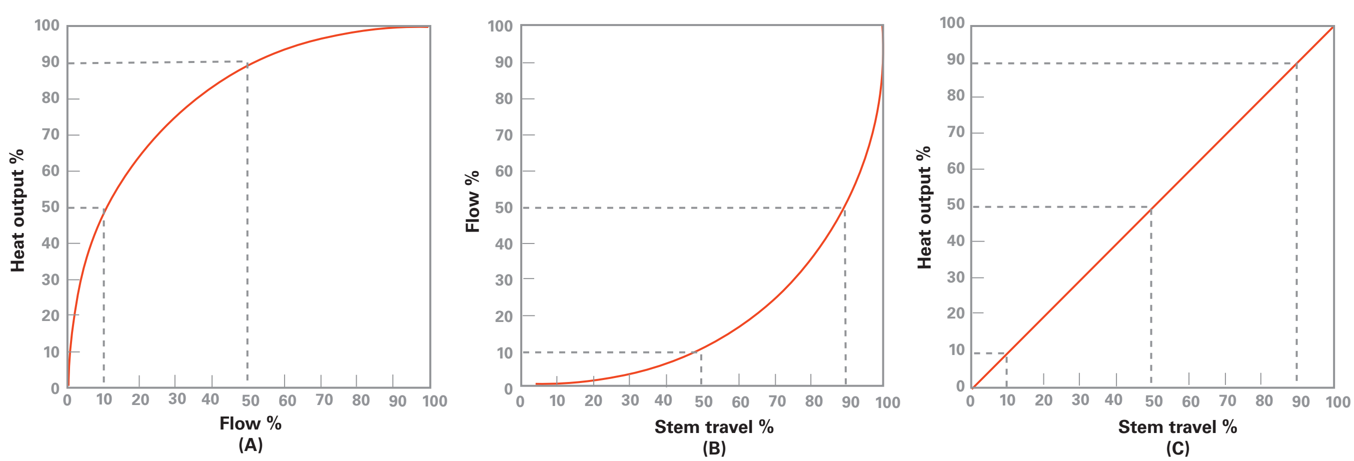


Image source: 2020 ASHRAE *Handbook of Fundamentals*

Hydronic Modeling

If assuming a constant pressure drop across the valve is bad, how can it be determined? Steady-state hydronic calculation tools such as Trane® Pipe Designer determine flows and pressures at the design point. Comfort applications in buildings are unlikely to have all terminals at design load at the same time, so there is some diversity embedded in these calculations. While we size pipes for full load, the pressure at any point in the system will vary throughout operation. Dynamic hydronic modeling tools simulate how the system might operate at other conditions. If this sounds complicated, that's because it is. To avoid these complexities, many designers default to rules of thumb, such as 4 to 5 psid across all control valves in the system, regardless of location or valve type. These shortcuts often lead to poor system performance, such as valve hunting, actuator and valve failures, limited system capacity, starved coils, hot and cold spots, low delta-T syndrome, and energy waste.

Control Valve Response to Changing Loads

When loads change, control valve stem positions also change based upon a measured variable. The degree of change to control that variable depends on the type of valve and its set up. The frequency of these adjustments is dependent on multiple factors, such as the type of control loop, and could be the subject of a future newsletter.

A pressure-dependent valve has a non-linear valve-stem-position to flow relationship. If the pressure drop across the valve is relatively small, the valve will have to move more than for a larger pressure drop, in order to obtain the same impact on flow. For this reason, pressure-dependent valves are selected for a specific pressure drop (Figure 3).

A pressure-independent valve has a linear valve-stem-position to flow relationship across 85 percent or more of its throttling range. For every percent change in valve stem position, the same amount of change in flow rate is created (Figure 4).

Figure 2. Effect of oversized valve on coil output

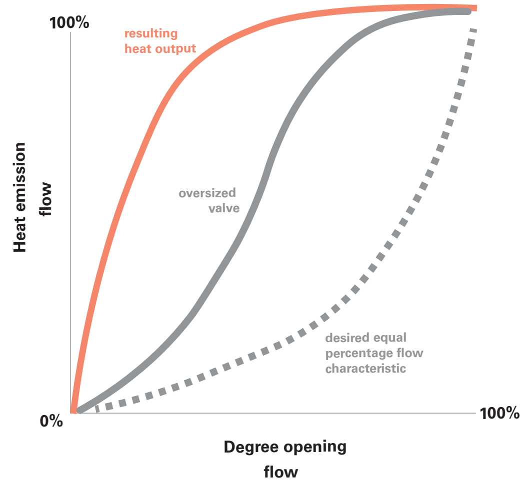
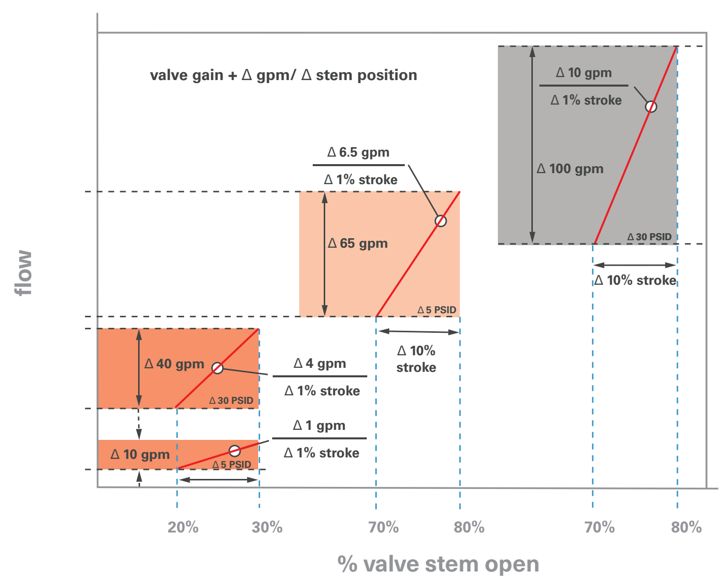


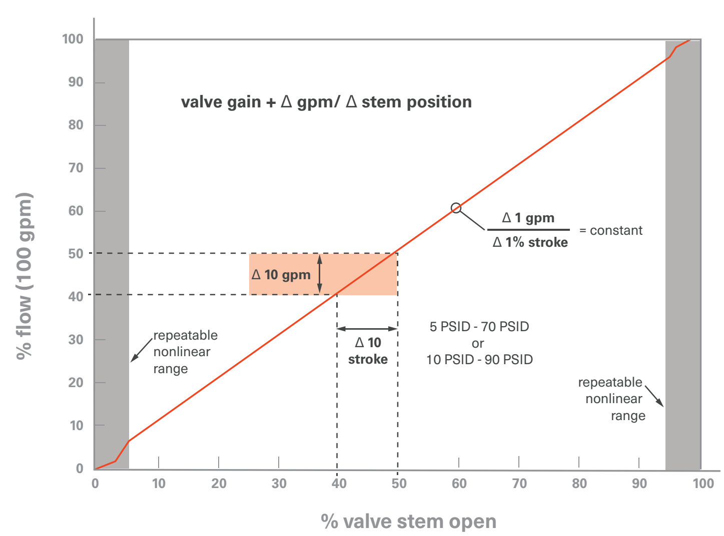
Image source: Belimo Aircontrols (USA), www.belimo.us

Figure 3. Pressure-dependent control valve gain



Process gain of pressure-dependent control valves changes by an order of magnitude with stem position and with pressure differential

Figure 4. Pressure-independent control valve gain vs. stem position



Process gain of pressure-independent control valves is constant over >85 percent of stem travel and pressure differential (5 to 70 PSID or 10 to 90 PSID)

Pandemic responsive designs

In response to renewed concerns about pathogen transmission through HVAC systems, designers are developing air-conditioning systems with a much broader range of airflow and loads. A mode of operation could deliver 100 percent outdoor air for the dilution and relocation of airborne pathogens, while normal modes would bring in less outdoor air and recirculate the rest. Air-handlers designed for this mode will have a dramatic difference in air- and water-flow rates in this mode versus a normal mode of operation. This is an excellent application for industrial-quality, pressure-independent control valves that offer 100:1 turndown while maintaining +/- 0.1°F off the coil.

Not only the flow, but also the pressure in the system is going to change dramatically in these different operating modes. The old standby design for this sort of challenge (1/3 – 2/3rd valves) won't work very well.

And, it's not just the coil in the dual-mode air-handling unit that's affected. There is a case to be made that ALL control valves in such a chilled water system need to be PICVs—the valves on the normal AHUs would benefit even more than those associated with the ventilation system.

When in the high ventilation mode, the AHUs will want substantially more flow, which means they will need significantly more pressure to produce that flow. With proper pump control, the "dual mode" AHUs will only see increased pressure when they need it. If a standard pressure-dependent valve had sufficient turndown capability, it could have a *chance* to work. The problem lies in the remainder of the system. For those times when high pressure is created for high ventilation mode units, all valves in the system will be subjected to this increase in pressure—even though they don't need or want it. The increased differential pressure will destroy their flow control—they need pressure independence.

Energy and Cost Implications of More Precise Control

Operational differences exist between pressure-dependent and pressure-independent valves. We can quantify the impact in terms of energy and first costs.

With a pressure-dependent valve, as the pressure in the system changes, the flow through the valve changes. By incorporating an integral automatic balancing component, pressure-independent valves compensate for pressure changes and maintain a constant flow over a wide range of pressures. Pressure-independent valves essentially create perfect valve authority and have valve action that is proportional to flow (see Figure 5). This means that control corrections for under and overflowing the load (hunting) are unlikely. Instability from hunting alters coil performance, as the coil moves away from steady-state, tested conditions. It undoubtedly leads to less comfort, as the loads are subsequently over- and under-served.

Energy

To quantify the potential energy benefit of precise flow control, consider an example coil designed to produce a 55°F dry-bulb leaving air temperature. With pressure-dependent valves, flow is often erratic. Reasons for erratic control include over-sized valves, poorly tuned gains, dirty coils, and higher-than-design inlet pressures. As a result, discharge air temperature deviates from setpoint. Figure 6 shows a simplified view of discharge air temperature over time. If this cycle held through for an entire day, the average discharge air temperature would be 55°F.

Initially, this average discharge air temperature looks good, however, more flow is used during the periods below setpoint than is saved when making warmer temperature air. This is due to the non-linear relationship between coil flow and heat output (Figure 1). To fully compensate for the coil non-linear relationship, as well as the pressure drop, the control gains need to be programmed specifically to

Figure 5. Pressure-independent versus conventional valve

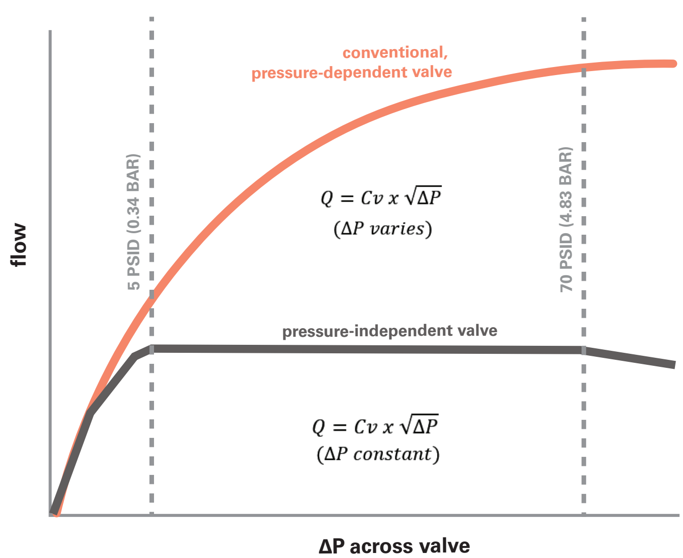


Image source: Flow Control Industries, Inc., www.flowcontrol.com the pressure differentials. What typically happens is the coil over and undershoots the desired capacity and the valve "hunts" around the controlled variable— whether that's discharge air temperature in VAV, or room temperature in constant volume or on-off control air systems.

Because of the exponential effect that higher flow has on coil output, it is important to remember that at higher flow rates there will be more overcooling accomplished than will be saved by undercooling at lower flow rates. Said another way, additional latent energy will be removed from the space, even though the average discharge air dry-bulb temperature is at setpoint.

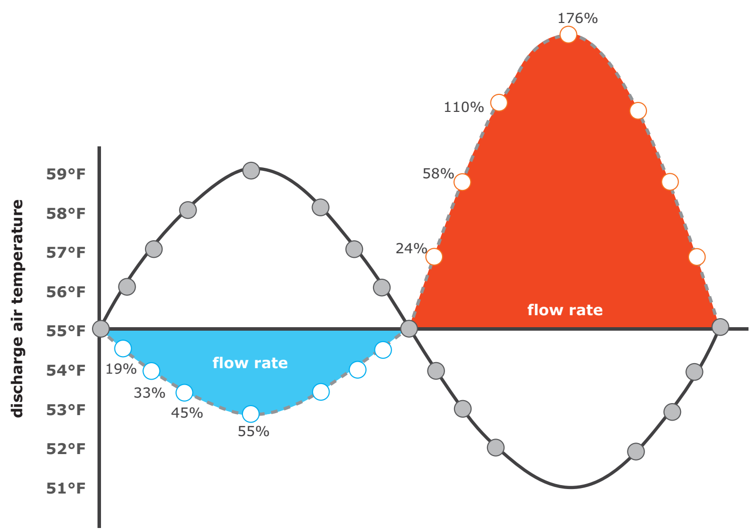
Reducing latent overcooling does more than just reduce required flow and pump energy. It also reduces the total cooling consumption and peak cooling load. Having a low average delta-T is an indicator of overcooling, and loads throughout the entire cooling profile are often inflated. This can have an impact much larger than the pump energy reduction alone. After removing the over-cooling, the chiller loads are lower, and less energy is consumed. We'll come back to this later.

The higher the deviation, the more excess flow and the more wasted energy. In addition, there will likely be flow-starved coils in hydraulically remote locations. The problem is made worse if higher deviations from temperature setpoint are allowed.

Pumping Power

We can quantify the effect of precise flow control in terms of pumping power, though it also affects the amount of load and run time experienced by the chillers. The relationship between the waterside flow rate and power can be calculated at each terminal. However, the effect of all the terminals together is what ultimately determines the pump's

Figure 6. Effect of erratic valve control on deficit/surplus flow



power consumption. We often use system delta-T as an indication of system "health", as it is directly related to the coil flow rates throughout the distribution system.

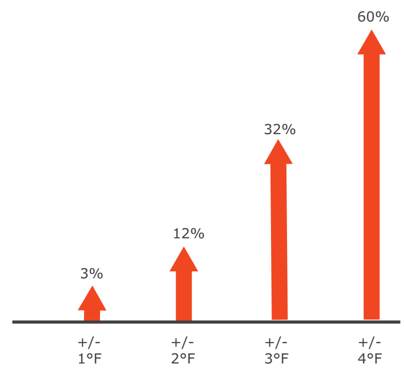
hp = gpm x 8.33 lb/gal x pd / (33,000 ft lb/hp min x pump eff.)

kW = 746 x hp / motor eff.

Having good delta-T at all load conditions adds up, especially when looking at overall system performance. For an 800-ton chilled-water system with a 10°F delta-T, the flow rate would be 1920 gpm. For an assumed pump head of 110 feet, pump power would be 52 kW, or 0.06 kW per ton. Contrast that with a system operating with a 16°F delta-T. The revised system is now only pumping 1200 gpm of water and the pump head of the same system (pipes unchanged) would drop to 49 feet. By reselecting the pump and motor to retain the same efficiencies, 80 and 95 percent, the resulting pump power is now 16 kW, or 0.02 kW per ton.

How much is 0.04 kW per ton worth? Pump energy occurs for the whole cooling season. But, from a first cost perspective, in an 800-ton chiller selection, that 0.04 kW/ton efficiency difference is equivalent to eight to seventeen percent of the purchase price of the chiller.

Figure 7. Percent over design flow



Overall System Power

Besides minimizing the required pump energy for a given load, achieving higher coil delta-T through stable flow and temperature control can actually reduce the total system load. The same 800-ton chilled water system may only peak at 720-tons when achieving a 16°F system delta-T, due to the reduction in latent overcooling. The total flow reduction also allows better chiller utilization. Additional latent energy removal by not overshooting the desired flow and improving operational delta-T allows better chiller utilization. In a primary-secondary system, chillers are staged based on flow, not based on capacity. When delta-T falls below design, more chillers than necessary will operate for portions of the cooling season. And in the case of a water-cooled system, adding a chiller also typically means an additional condenser water pump and cooling tower.

Stability Essential for High Delta-T Systems

As systems push for higher delta-T designs, the coils become more sensitive to changes in flow. A 16°F delta-T coil uses 25 percent less flow than a 12°F delta-T coil to move the same amount of heat. That means every gallon becomes more important, and stability becomes more critical.

Installation Cost Differences

One of the perceived drawbacks of pressure-independent control valves is the upfront cost difference compared to traditional pressure-dependent valves. The valve alone will likely be more expensive than a traditional control valve; however, pressure-independent valves eliminate most balancing valves and the need for system balancing. Some manufacturers of pressure-independent valves do not require strainers upstream of the valve, though strainers somewhere in the system are needed to protect the coils and other components.

Also consider the ability to design for and deliver systems with higher delta-T. As the system design delta-T increases, equipment to accommodate the distribution flow can be downsized, including the control valves, piping, insulation, structural steel (pipe hangars, etc.), pumps, VFDs and electrical service. This opportunity is directly related to the ability to achieve or exceed the required delta-T. As coils are designed with increased delta-T, they are more sensitive to changes in flow, thus increasing the importance of providing stable flow to each device.

Costs for characterized ball valves

- valve
- balancing valve
- balancing contractor
- strainer
- commissioning

Costs for pressure-independent valves

- valve
- limited commissioning

Electronic versus Mechanical Pressure-Independent Control Valves

Table 1 summarizes some of the differences between the leading electronic and mechanical valves.

Table 1. Electronic versus mechanical pressure-independent control (PIC) valves

mechanical PIC valves		electronic PIC valves	
benefits	*considerations*	*benefits*	*considerations*
easier selection	optional support for BACnet communications	BACnet communication typically standard	software and programming for setup
near perfect authority	variability in robustness of design between manufacturers	load measurement	straight pipe upstream of flow meter—can split flow meter section from valve if there are installation constraints
no additional control power, programming or software	load measurement with optional temperature sensors	flow limiting and delta-T limiting operating modes	potential comfort issues when operating in a flow-limiting or delta-T limiting modes
no balancing devices or system balancing, limited commissioning required	some field setup required depending on manufacturer	supply temperature and pressure setpoints can be independently reset	control portion reacts after a flow change is measured, leading to a slower response

Summary

Hydronic systems perform better with pressure-independent control valves and unlock opportunities to reduce first costs through comprehensive system design.

Designing for (and achieving) high delta-T systems with pressure-independent control is what should be expected from chilled-water systems. The lower flow rates mean much of the equipment can be downsized, with better system energy performance. Systems that operate well need fewer or smaller chillers and lower flows mean smaller control valves, pipe sizes, insulation, structural steel (hangars, supports, etc.), pump sizes, VFDs and electrical service.

Designing this way requires a system approach, but it extends far beyond the basic "valve to valve" comparison. When designers can take advantage of the available technology, it allows for a much larger savings opportunity. Careful consideration of the costs of the entire system installation should make their inclusion in hydronic systems first cost neutral. If there is any additional cost, the benefits to system performance are significant enough to make the case for using pressure independence. It's difficult to overstate the value of having a properly operating system at all load conditions, and pressure-independent control valves are key for successful system operation.

By Susanna Hanson, Trane. To subscribe or view previous issues of the Engineers Newsletter visit trane.com. Send comments to ENL@trane.com.

Resources

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2021 Engineers Newsletter *Live!* program schedule

MARCH

State-of-the-Art Chilled-Water Systems. When designed using today's industry guidance, chilled water systems provide building owners and operators with flexibility to meet first cost and efficiency objectives, simplify maintenance and operation, and exceed energy code minimum requirements. Design principles that right-size equipment and minimize system power draw are inherently simpler to control, and lead to high efficiency and reduced utility costs.

MAY

ASHRAE Standard 62.1-2019. The 2019 version of ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, was published in late 2019. This ENL will overview the standard, discuss several key changes implemented in the 2019 version, explain the three allowed procedures for determining ventilation airflows (Ventilation Rate Procedure, IAQ Procedure, and Natural Ventilation Procedure), and walk through calculation steps using an example office building.

SEPTEMBER

Air Cleaning Devices for IEQ. A building's indoor environmental quality is key to the safety, health, and comfort of its occupants as we move forward in a post-pandemic future. This ENL will cover what Indoor Environmental Quality is, how to create resilient systems, and discuss air cleaning device testing in order to construct healthy and efficient spaces.

NOVEMBER

ASHRAE Standard 15. ASHRAE Standard 15, Safety Standard for Refrigeration Systems, focuses on the safe design, construction, installation, and operating of refrigerating systems. This ENL will overview the 2019 version of this standard and explain how its requirements apply to various types of refrigerating systems, including new requirements for systems with Class A2L (lower flammability) refrigerants.

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