Best Practices for Condensing Boilers

BY CATIE VANWORMER, P.E.; DAVID GRASSL, P.E., MEMBER ASHRAE

Boiler systems today are engineered to increase efficiency and reduce operating costs. Condensing boilers are a popular option because they recover energy that otherwise would be discharged out the boiler stack, enabling them to achieve more than 90% efficiency when operated with the proper conditions. Condensing boiler applications are also popular because of their many benefits and ease of system integration; however, they are very different from traditional boilers in their operation and design.

In the past, the industry standard for hot water boilers was based on a non-condensing boiler where the hot water return temperature to the boiler had to stay above the condensing temperature of the flue gases to prevent damage to the boiler. This standard does not hold true for condensing boilers as their heat exchangers are designed and constructed of materials that are able to withstand the effects of condensing. In fact, there is a direct correlation between increasing condensation of the flue gas and boiler efficiency gains, so the goal should be to reduce the water temperature returning to the boiler to condense the flue gas as much as possible.

Due to the increasing condensation of the flue gas in a condensing boiler, the heat exchanger has to be made of robust materials to prevent the acidic condensate from corroding and completely degrading the materials within the boiler and the flue stack. This material is most often stainless steel, although various materials are used depending on the boiler manufacturer. Additionally, a condensing boiler should have an effective design incorporating counter-flow heat exchange to put the coolest flue gases surfaces close to the coolest return water while maintaining a large amount of fireside heating surface area for condensing operation.

The majority of today's hot water boilers use natural gas as a fuel source for the combustion process. In this process, natural gas is combined with combustion air to produce water and other by-products. In a non-condensing boiler, this water remains in a vapor state and is completely removed from the system in the flue gas, whereas in a condensing boiler, the water vapor is encouraged to condense as it is cooled below its dew point. The condensation of the flue gas enables the recovery of 970 Btu/lb (2256 kJ/kg) of latent energy, which is used to increase boiler efficiency. The dew point of the water varies based on many considerations, but generally speaking, flue gases begin to condense when the hot water return temperature is between 120°F to 130°F (49°C to 54°C) as shown in *Figure 1*.

Catie VanWormer, P.E., is product sales manager for ClearFire® boilers at Cleaver-Brooks in Slinger, Wis. David Grassl, P.E., is the founding principal of Dynamic Consulting Engineers LLC based in Milwaukee.

FIGURE 1 Example of flue gas condensation temperature based on the hot water return temperature.

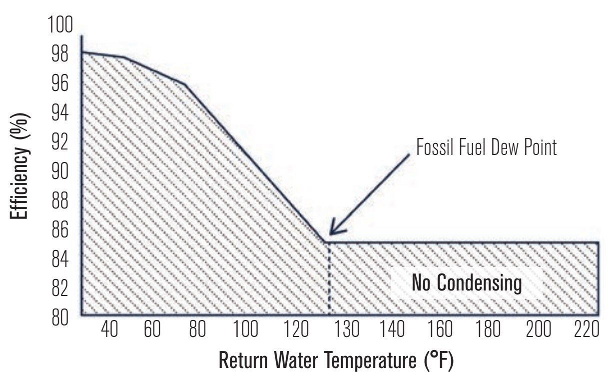
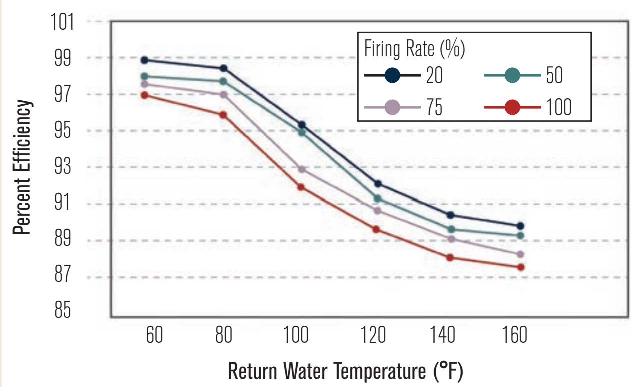


FIGURE 2 Boiler efficiency as a function of hot water return temperature and boiler firing rate.



System Design–Operating Temperature and Flow Rates

As boiler technology has evolved over time, so has system design. The first notable difference in system design relates to hot water supply and return temperatures. Previously, it was common to design systems with a hot water supply temperature in the range of 180°F to 200°F (82°C to 93°C) assuming that a higher water temperature was always better. To a point, a higher hot water temperature is better as it allows for smaller heat transfer surfaces in heating coils and terminal units, but it limits the efficiency of the system. Conversely, a higher hot water temperature can make it more difficult to control space temperature during periods of low loads when full capacity is not required by the building.

TABLE 1 Comparison of different VAV box selections showing the impact of water temperature and VAV box arrangements on heating capacity.

	STANDARD VAV BOX	STANDARD VAV BOX	STANDARD VAV WITH LOOSE COIL	OVERSIZED VAV BOX
Box Size	10 in.	10 in.	10 in.	12 in.
Inlet Size	10 in.	10 in.	10 in.	10 in.
VAV Box Outlet Size	14 in. × 12 in.	14 in. × 12 in.	14 in. × 12 in.	17 in. × 14 in.
Coil Size	14 in. × 12 in.	14 in. × 12 in.	16 in. × 12 in.	17 in. × 14 in.
Flow Rate	0.6 gpm	0.6 gpm	0.6 gpm	0.8 gpm
Coil Pressure Air Drop	0.22 in. w.g.	0.76 in. w.g.	0.08 in. w.g.	0.30 in. w.g.
Coil Pressure Water Drop	1 ft of water	<1 ft of water	<1 ft of water	<1 ft of water
Heating Capacity	13.6 MBH	14.4 MBH	14.0 MBH	13.8 MBH
Number of Rows	1	4	2	3
Hot Water Supply Temperature	180°F	140°F	140°F	140°F

Systems using condensing boilers should be designed with the lowest hot water supply and return temperature feasible while still adequately heating the space. It should be noted that hot water return temperature is the driving factor that dictates boiler efficiency as shown in *Figure 2*, so optimizing the hot water return temperature with this consideration should be the goal.

A standard hot water supply temperature for a condensing boiler should start at a minimum of 140°F (60°C) with the ability to go lower, provided enough heating capacity is available at a reasonable cost from the heating coils and terminal units. Although a lower water temperature may be possible, there is a point where the increased first cost for additional heat transfer surface area exceeds the benefit of boiler efficiency. For example, most VAV boxes come with one- or two-row coils, which will not provide the required heating capacity at acceptable airside pressure drops with reduced hot water supply temperatures. There are various options available to overcome this, from providing a three- or four-row heating coil to a VAV box that uses a larger, duct-mounted, one- or two-row coil separate from the VAV box. *Table 1* shows the impact of each option available.

Relative to hot water system temperatures are system flow rates. Flow rates for older systems were typically designed for a temperature differential of 20°F (11°C) between the hot water supply and return temperatures at the terminal units, which was above the condensing temperature and caused higher flow rates. The temperature difference between the hot water supply and return temperatures for condensing boilers should be between

30°F and 50°F (17°C to 28°C), which decreases system flow rates, reduces pressure drops through heating coils and terminal units, and results in less system pumping power at full-load and part-load conditions. Because it is common to control the hot water system to the hot water supply temperature, a higher ΔT promotes a lower hot water return temperature to the boiler and leads to more condensing with increased boiler efficiency.

TABLE 2 Comparison of boiler efficiencies, equipment quantities, and pump horsepower for condensing vs. non-condensing boilers.

	TWO 1,500 MBH CONDENSING BOILERS	TWO 1,500 MBH NON-CONDENSING BOILERS	TWO 2,500 MBH CONDENSING BOILERS	TWO 2,500 MBH NON-CONDENSING BOILERS
Boiler and System ΔT	140 to 100°F	180 to 140°F	140 to 100°F	180 to 140°F
Boiler Efficiency	92%+ Depending on HWR Temperature	88%	92%+ Depending on HWR Temperature	88%
Boiler Output	2,760 MBH	2,640 MBH	4,600 MBH	4,400 MBH
Primary Pump Flow Rate	138 gpm	66 gpm	230 gpm	110 gpm
Primary Pump Head	70 ft of water	20 ft of water	70 ft of water	20 ft of water
Primary Pump Power	3.44 bhp 5.00 hp	0.46 bhp × 2 0.75 hp	5.50 bhp 7.50 hp	0.80 bhp × 2 1 hp
Pump Efficiency	72%	75%	76%	71%
Secondary Pump Flow Rate	–	132 gpm	–	220 gpm
Secondary Pump Head	–	65 ft of water	–	65 ft of water
Secondary Pump Power	–	3.01 bhp 5.00 hp	–	4.82 bhp 7.50 hp
Pump Efficiency	–	72%	–	75.5%
Total Pump Power	3.44 bhp 5.00 hp	3.93 bhp 6.50 hp	5.50 bhp 7.50 hp	6.42 bhp 9.50 hp

High ΔT Systems

Systems that operate with a high temperature differential between the hot water supply and return temperature are also candidates for condensing boiler systems since the hot water return temperature directly relates to boiler efficiency. An example of a high ΔT system would be designing at a typical hot water supply temperature of 180°F (82°C), however, instead of using a 20°F (11°C) temperature differential between the hot water supply and return temperatures, using a 30° to 50°F temperature differential. Although high-mass boilers are capable of handling higher ΔTs without damaging the pressure vessel, the 30°F to 50°F (17°C to 28°C) ΔT range offers the ideal mix of high ΔT and good operational control.

As demonstrated below, system flow rate and ΔT are both factors in determining the total heat load based on the following heat transfer equation for water.

$$Q = 500 \times \text{gpm} \times \Delta T$$

where

Q = Total heat load (Btu/h)

gpm = Flow rate (gpm)

ΔT = Supply and return piping temperature difference (°F)

Using the energy equation above, and maintaining a constant Btu/h value, one can see the effect varying the ΔT has on the flow rate. If we use 1,000,000 Btu/h (293 071 W), with a 20°F (11°C) ΔT, the flow rate equals 100 gpm (6 L/s). However, with a 40°F (22°C) ΔT, the flow rate is cut in half to 50 gpm (3 L/s). This often means that a wider ΔT will keep the boilers in a condensing mode more often, increasing system efficiency.

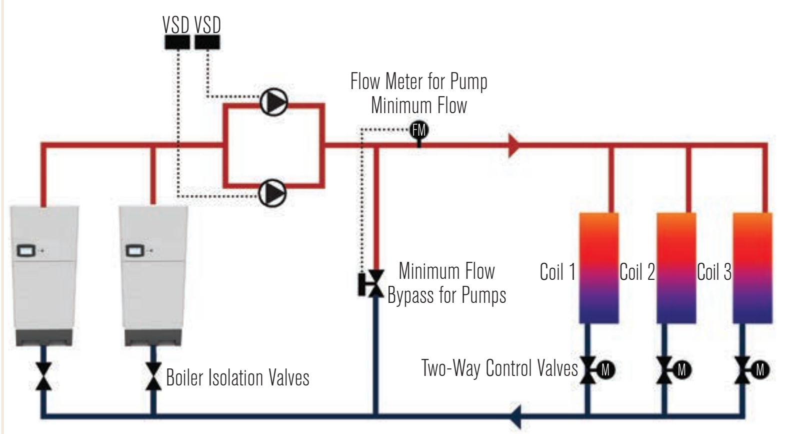
Table 2 shows the comparison of boiler efficiencies, equipment quantities, and pump horsepower for condensing vs. non-condensing boilers.

System Distribution

In the past, non-condensing boilers were known for not being able to accept variation in system flow, primarily to maintain the hot water return temperature to the boiler above condensing operation. However, some condensing boilers are capable of handling variable flow in the system as well as through the boiler. In all cases, be sure to confirm this with the boiler manufacturer as different manufacturers have different requirements for their respective boiler.

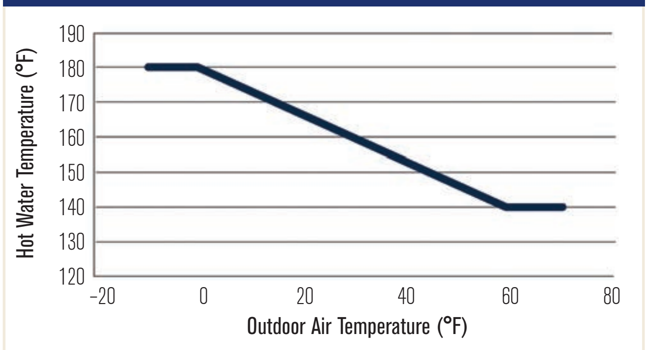
Variable flow primary has emerged as a system design option for hot water systems and operates based on the principle that one set of pumps will distribute water to the entire system, including the boilers and all heating coils. In this scenario, the entire system is exposed to variable flow, enabling it to benefit from lower flow rates and energy savings at reduced loads with two-way control valves at the coils. In addition to the control valves at the heating coils, two-way isolation control valves should be provided at the boilers to eliminate flow through a boiler when the boiler is not in operation to avoid unnecessary mixing in the supply header. An example of a variable flow primary hot water system can be seen in *Figure 3*.

FIGURE 3 A variable flow primary distribution system.



When implementing a variable flow primary system, it is important to take into account minimum flow requirements of the system pumps and boilers. Depending on the pump and boiler selections, either can drive the minimum flow requirement. With high-mass condensing boilers, often the pumps will dictate the minimum flow rates required. One method is to use a minimum flow bypass pipe somewhere in the system with a two-way temperature control valve in the bypass piping. This requires a flow meter to provide means for modulating the bypass valve when the minimum flow cannot be maintained in the system. A second method is to replace a select amount of two-way control valves with three-way control valves in the system. This allows for constant flow through the three-way valves, maintaining the minimum flow without the use of a flow meter. However, with this method, the return water temperature back to the boilers can be raised, affecting the operating efficiency of the condensing boilers.

FIGURE 4 Condensing boiler reset curve.



Control Strategies

In traditional boiler systems, it is common practice to operate boilers in a lead-lag staging configuration to maintain the hot water supply setpoint. In modern condensing applications, boilers typically operate in parallel, regardless of the system load. Contrary to the traditional method of control, system efficiency with condensing boilers improves at part-load condition as more surface area is available for condensing. Similarly, a consistent hot water supply temperature can be produced from each boiler in parallel to the distribution system. With the condensing boilers operating in a true parallel configuration at similar loads, control strategies can be used to further maximize system efficiency.

For example, systems that require high hot water supply temperatures based on a traditional design can operate with an aggressive hot water reset schedule based on outside air to promote condensing during the summer or periods when there are low loads in the system. The theory behind resetting the hot water supply temperature is that as the outside air temperature increases from the design condition, the amount of heat required to satisfy the space load decreases as shown in *Figure 4*.

Similarly, as the space load decreases, it is also possible to heat the space with a hot water supply temperature less than the design condition, which uses less energy to heat the water to a lower setpoint. Hot water reset can be combined with a night setback schedule to promote the use of lower hot water supply temperatures when there may not be any occupants in the space. Per ASHRAE/IES Standard 90.1-2016 hot water temperature reset is required for systems larger than 300,000 Btu/h (87 921 W), supplying hot water to comfort heating systems. These controls must automatically reset the supply water temperature based on building load or outside air temperature.

Adding variable speed drives, either in a variable primary flow configuration as described above, or in a primary-secondary configuration, requires control strategies to provide variable speed pumping. This can be accomplished in a variety of ways with the most common method being to control the pump speed based on the differential pressure at a defined location in the system. As the system pressure changes based on the terminal devices' control valve position at any given time, the pump speed modulates to provide only the required pressure and flow the system needs, saving pumping energy. Per Standard 90.1, variable speed pumping is required when the pumping system has a total pump horsepower exceeding 10 hp that includes control valves designed to modulate or step open as a function of the load.

Because condensing boilers are more efficient at lower firing rates, it is advantageous to run multiple boilers at low firing rates to improve overall system efficiency. Since the return water temperature directly impacts a boiler's efficiency, maintaining the design ΔT and keeping the return water temperature as cool as possible are important to maximize overall system efficiency with condensing boilers.

Integration Into System Designs

Condensing boilers can be incorporated into most hydronic systems where a standard boiler is used, but it is important to know the design modifications required to achieve system efficiency gains for a holistic solution. The following are design options for incorporating condensing boilers into traditional designs.

Traditional Condensing and Non-Condensing Systems

The traditional hot water system design includes a non-condensing boiler for space heating needs. The simplest solution for using condensing technology is to substitute a condensing boiler in place of the standard, non-condensing boiler. Depending on the system temperatures, efficiency gains may be small because to achieve the highest efficiency, the system must operate in condensing mode. Regardless of the boiler type, a condensing boiler will operate near the same efficiency point of a standard non-condensing boiler during conditions when the hot water return temperature is above the condensing temperature threshold. Despite this, in a standard system design, it is still beneficial to operate condensing boilers given the ability to operate hot water reset strategies during periods of low-load or summer conditions, assuming that in the summer lower water temperatures can be used to meet the building loads. While a traditional, non-condensing boiler system would require a three-way mixing valve for supply temperature reset in order to protect the boiler, condensing boilers allow for a simpler system design since the supply temperature reset can occur (and is encouraged) at the boiler. During these conditions, careful consideration must be taken to avoid operating the hot water system at too high of a flow rate and trading boiler energy for pumping energy, but optimized appropriately, hot water reset can offer system efficiency gains.

FIGURE 5 Piping configuration for condensing vs. non-condensing boilers in a heat-pump system.

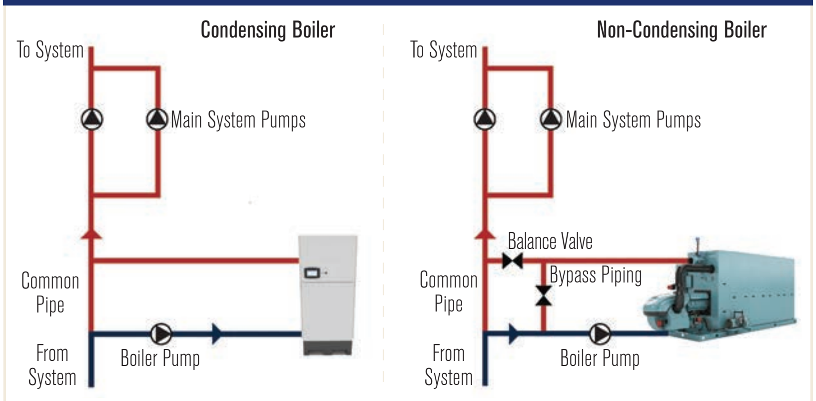
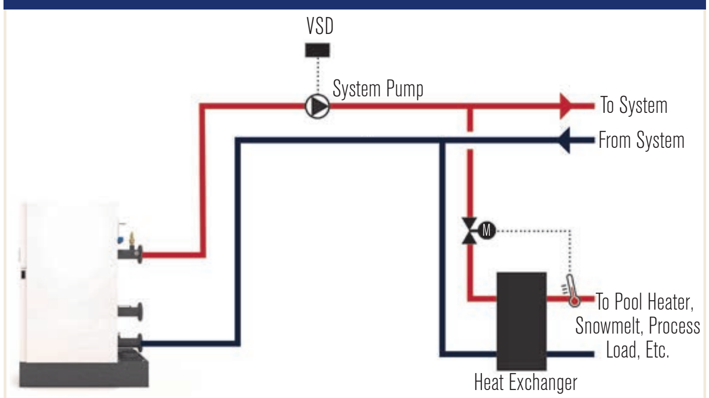


FIGURE 6 Basic heat exchanger used for pool heating, snowmelt, or other process load.



Non-Traditional Systems

Traditional hot water systems work well with condensing boilers as do several non-traditional systems. In general, any system that operates at a hot water return temperature below the condensing point is a perfect application. Among the options are water-source heat pumps, geothermal heat pump systems, in-floor hydronic radiant heating systems, snow-melt systems, domestic water heating and pool heating systems.

Condensing boilers do not require mixing valves to maintain the hot water temperature above the condensing temperature of the flue gases as required for non-condensing boilers, making them a good fit with less complexity. A comparison of the piping requirements for a condensing and non-condensing boiler in a water-source, heat-pump system can be viewed in *Figure 5*.

In-floor hydronic radiant heating is a relatively cost-effective way to provide heat that can be concealed architecturally within a space. In-floor heating requires a low hot water supply temperature in the range of 100°F to 120°F (38°C to 49°C), an excellent condition for condensing boilers. Although hot water return temperatures naturally will be low, the temperatures will remain low by keeping the tubing spaced closely together, reducing the floor resistance, installing the tubing near the top of the slab, and providing insulation below the tubing. In addition to boiler-efficiency improvements, in-floor heating embeds the tubing within the slab, which conceals it from any damage. It also eliminates finned heat exchangers or enclosures that can corrode, become physically damaged, or need to be replaced over time.

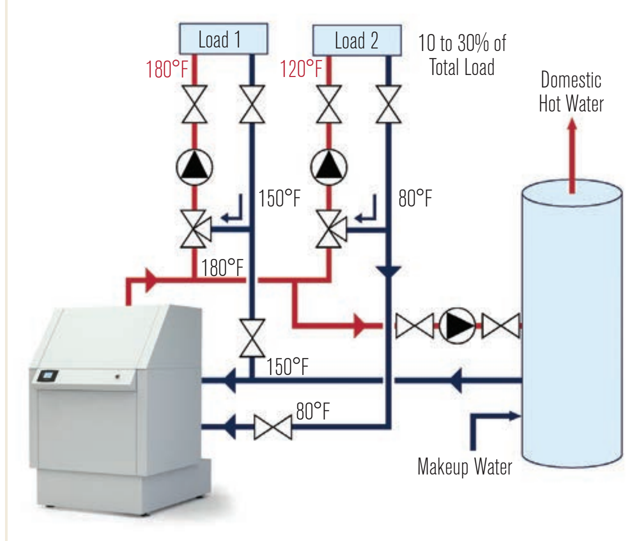
Snow-melt systems are similar to in-floor hydronic radiant systems in that hot water supply and return temperatures are very similar, but the tubing is used in exterior applications, and glycol often is used to prevent freezing within the piping system. Depending on the building's heating system, a plate-and-frame heat exchanger can be used to separate the snow-melt system loop from the main building heating system loop, or a dedicated boiler to the snow-melt system can be provided.

Pool heating requires only low-grade heat to maintain the pool water temperature below 90°F (32°C) as shown in *Figure 6*. Again, the low water temperature is a perfect application to use condensing equipment to recover the energy that would otherwise be wasted in the flue gases. Hot water for pool heating can be provided either with a condensing, domestic water heater or a condensing boiler with heat exchangers. Another good application for pool heating is to use a dual-return condensing boiler as described below.

Some condensing boilers are equipped with a dual-return capability that allows hot water return from two sources within the building as shown in *Figure 7*. With a dual-return system, if there are applications that use low hot water temperatures, this loop can be kept separate from the higher hot water return temperature loop back to the boiler. Then, the two return loops are piped to the boiler separately with the lower hot water return loop piped into the boiler where it will come in contact with the higher temperature flue gases, and the warmer hot water return loop is piped to the connection that comes in contact with the cooler flue gases to extend the condensing conditions.

Although this approach may use additional piping, the design strategy maximizes the condensing zone prior to blending the lower and higher return water temperatures within the boiler. In order to effectively use this piping setup, it is critical to keep the water loops separated and ensure that at least 10% of the flow be provided

FIGURE 7 Dual return system with two temperature zones and domestic hot water.



to the low-temperature connection for condensing efficiencies to be achieved.

In closing, understanding the principles of condensing boiler technology is required to properly apply it in a new or retrofit application. When designing systems with condensing boilers, it is important to focus on a few key items to maximize the system operating efficiencies:

1. The entire system needs to be designed for condensing applications:
   - Boiler heat exchanger;
   - Stack;
   - System operating temperatures; and
   - Terminal devices.
2. Minimize mixing within the hydronic system to keep the return water temperature to the boilers as low as possible.
   - Reduce the number of three-way valves in the system, considering the minimum flow bypass with flow meter approach for minimum flow requirements.
   - Pipe the system variable flow primary instead of primary-secondary to eliminate the mixing seen in the decoupler between the boiler and system loops.
3. Design hydronic systems with wider ΔTs – consider 30°F to 50°F (17°C to 28°C) ΔTs instead of the traditional 20°F (11°C).
4. Lower the system temperature in both traditional and non-traditional systems.
   - Either reduce both the supply and return temperatures; or
   - Widen the system ΔT.
5. Be cautious with reducing the system temperature due to its effect on terminal unit selection. Lowering the system temperature often results in larger terminal equipment.
6. Always consult the boiler manufacturer. Rarely are two equal, even when one is substituted for the other.

Condensing boilers, when properly applied in both traditional and non-traditional system applications, offer the ability to greatly improve the system operating efficiencies over a non-condensing boilers. They also allow for simpler system designs with easier to implement controls, pumping, and piping strategies over most non-condensing boilers. ■