Boiler System Efficiency

By Thomas H. Durkin, P.E., Member ASHRAE

When natural gas cost $0.40 per therm* (1999), even a poorly designed boiler system would have positive payback. Hurricane Katrina changed that.

According to the Energy Information Administration (www.iea.doe.gov), the cost of natural gas has increased 50% in the U.S. since last fall (due to Hurricane Katrina) and 200% in the last seven years. Electricity has increased only 20% in the same time frame (central Indiana). Winter 2006 natural gas cost as much as $1.40 per therm (100,000 Btu) and electricity costs around $0.07/kWh (3,413 Btu). The electric cost equates to $2.05 per therm.

In the simplest terms, if the boiler cannot deliver heat to the space at an efficiency of at least 68%, then the boiler has zero payback vs. straight resistance electric heat, which is (theoretically) 100% efficient. This represents a large shift in engineers' approach to heating systems.

Some would argue, probably correctly, that the entire national energy picture is in flux, and that the cost of electricity is artificially low compared to natural gas. Conversely, the cost of natural gas may be artificially high because of the hurricane damage to the gas drilling rigs in the Gulf of Mexico. In Indiana, most of the new electric power generation is gas-fired peaking plants, which likely will create a ripple effect on electric costs.

This snapshot makes it seem that gas-fired boilers are a marginal investment, and that boilers burning fuel oil at $2.80 per gallon (139,000 Btu/$2.01 per therm) or propane at $2 per gallon (91,600 Btu/$2.18 per therm) will cost significantly more than straight resistance electric heat. In all fairness, while several

About the Author

Thomas H. Durkin, P.E., is director of engineering at Veazey Parrott Durkin & Shoulders in Indianapolis.

*therm = 105.5 MJ, generally rounded to 100 MBtu, equal to 100 ft^3 of natural gas

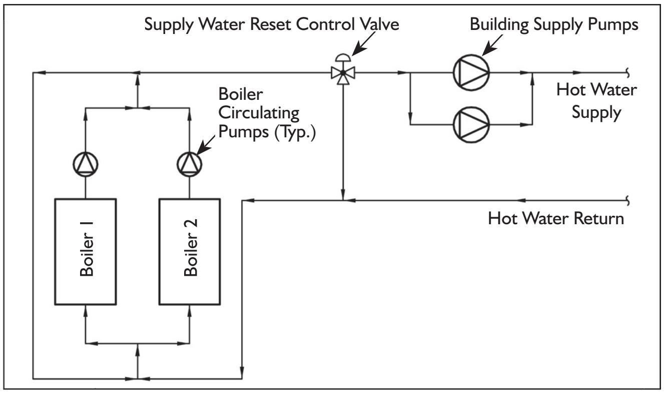


Figure 1: Conventional hot water boiler system.

clients were paying $1.40 per therm in December and January, spot market gas was down to $1.20 per therm by March, and gas bought on contract was still available for $0.95 per therm, including transportation charge.

This article is not advocating a switch from hydronic heating to resistance electric. Since significant regional differences exist in the cost of electricity, that question needs to be evaluated separately. This article is encouraging a thorough look at the way many systems are being designed and operated, and at what boiler efficiency ratings mean. For both economic and environmental reasons, a heating system design using condensing boilers and low-temperature heat (130°F [54°C] maximum) is advocated.

A Typical Heating System

While steam systems have some clear benefits (low distribution energy, many Btu/lb, and higher temperatures suitable for some process requirements), steam systems are more costly to operate, take more operator and maintenance attention and are a little harder to control than hot water heating. For those reasons, most newer institutional projects are hot water heated.

A typical building heating system may not exist, but one possibility might look like *Figure 1* and include:

- Hot water boilers (may be sectional cast-iron, fire tube, water tube, etc.);
- Natural draft or forced draft burners;
- 180°F to 200°F (82°C to 93°C) boiler operating temperature and maximum building supply water temperature;
- Terminal heating equipment, such as VAV boxes, fan coils and unit heaters, are rated at this temperature range and catalogs have correction factors for non-standard temperatures;
- Three-way blending valve to reset supply temperature based on outside air temperature;
- 20°F or 30°F (11°C or 17°C) ΔT; and
- Redundancy (multiple boilers) and spare capacity, i.e., two at 75% of anticipated full load.

Boiler Ratings

Minimum boiler efficiencies are published in Table 6.2.1F of Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings:* steam or hot water at 75% to 80%, depending on size; and, hot water boilers have a base efficiency of 80%. Boiler manufacturers' catalogs list hot water boilers in the range of 80% (sectional cast-iron or bent tube); mid-efficiency boilers at 83% to 88%; and condensing boilers at 88% to 95%. Mid-efficiency boilers are typically modular with copper fins. Condensing boilers have fire-side metallurgy that is unaffected by the acidic conditions resulting from condensing flue gas, and they are intended for low-temperature operation (entering water temperature less than 140°F [60°C]). Generically, the two types of condensing boilers are true condensing boilers and mid-efficiency boilers equipped with secondary heat exchangers. The secondary heat exchangers typically have an internal circulating pump and blending valve.

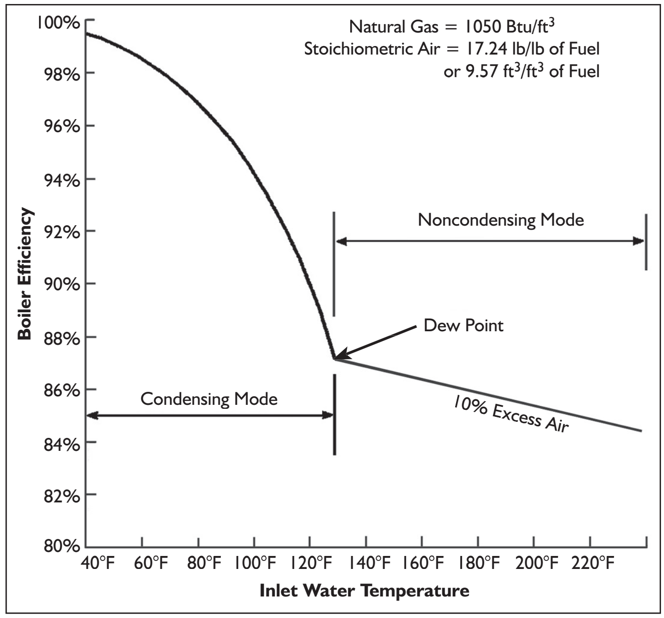
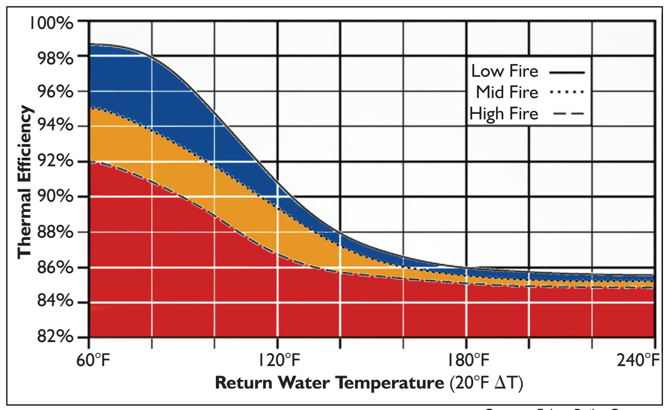


Figure 2: Effect of inlet water temperature.



Courtesy Fulton Boiler Company

Figure 3: Thermal efficiency vs. return water temperature.

All of the published ratings are combustion efficiency as opposed to overall efficiency or seasonal efficiency. The *2004 ASHRAE Handbook—HVAC Systems and Equipment* defines each of these as follows (S27.5):

- **Combustion efficiency:** "Input minus stack (flue gas outlet) loss divided by input."
- **Overall efficiency:** "Gross energy output divided by in-

- put…. Overall efficiency is lower than combustion efficiency by the heat loss from the outside surface of the boiler (radiation or jacket losses) and by off-cycle energy losses where boilers cycle off and on…"
- **Seasonal efficiency:** "Actual operating efficiency that the boiler will achieve during the heating season at various loads…"

It appears that comparisons of boiler styles should be based on seasonal efficiency, but that information is not available. However, a chart in Chapter 27 shows the offset from combustion to overall efficiency, with overall efficiency between 2.5% and 4% lower than combustion efficiency.

As defined by ANSI Z21.13-2000 (the usual test procedure), boilers are rated at steady-state operation, fully loaded and with 80°F (27°C) entering water temperature. This is clearly an artificial rating since most conventional boiler operations manuals contain language similar to this:

> ***WARNING:*** *Inlet water temperatures below 140°F (60°C) can excessively cool the products of combustion in the heat exchanger and flue, resulting in excessive corrosion and premature failure. Operation in that range may void the warranty.*

The proposed ASHRAE Standard 155P, *Method of Test for Rating Commercial Space Heating Boiler Systems,* will reflect actual operating conditions more.

Figure 2 is reprinted from Handbook Chapter S27-2004 showing the effect of entering water temperature (EWT) on boiler efficiency, a critical factor. A clear break is on the left side of the chart, where the latent heat of the condensing water vapor in the flue gas is contributing to efficiency rather than being carried up the stack. This chart is for a condensing boiler, rather than a conventional boiler (a comparable chart for conventional boilers is not included in Chapter 27), and if it were accurate to use this information to adjust boiler efficiencies from manufacturers' listings to reflect the minimum 140°F (60°C) EWT required for safe operation, base boilers would be 70% to 73% (vs. 80% to 83% as published); mid-efficiency boilers only would be as high as 78%.

Standard 90.1 says that the heating system should operate at the lowest possible water temperature, which in the conventional scheme would be 140°F (60°C) EWT, dictating the efficiency adjustment addressed previously. However, since condensing boilers can operate at low EWT, the condensing boiler adjustment would be limited by the building heating system design, not a boiler manufacturer's mandated low limit. In other words,

School	Before Therms Steam	After Therms LT/Cond Blr	Therms Saved	Percent Saved
1	69,327	25,171	44,156	64%
2	50,875	16,607	34,268	67%
3	64,513	24,008	40,505	63%
4	96,671	29,933	66,738	69%
5	42,078	12,034	30,044	71%
6	64,780	19,787	44,993	69%
7	61,499	23,496	38,003	62%
8	54,333	17,025	37,308	69%
9	97,257	23,210	74,047	76%
10	77,514	24,623	52,891	68%
			Average	**68%**

Table 1: Steam to condensing boilers.

School	Before Therms 180°F HW	After Therms LT/Cond Blr	Therms Saved	Percent Saved
11	59,246	28,207	31,039	52%
12	67,255	38,689	28,566	42%
13	54,812	24,051	30,761	56%
14	45,262	28,089	17,173	38%
15	49,553	24,636	24,917	50%
16	60,487	24,629	35,858	59%
17	55,109	31,099	24,010	44%
18	57,987	20,804	37,183	64%
19	39,150	26,040	13,110	33%
20	44,651	22,357	22,294	50%
			Average	**49%**

Table 2: Conventional HW boilers to condensing boilers.

a condensing boiler operating on a schedule that could supply 130°F (54°C) during the coldest times (110°F [43°C] boiler EWT), reset down to 100°F (38°C) supply at light heating loads (80°F [27°C] boiler EWT) would be very efficient. Operating a condensing boiler (by definition a low-temperature boiler) at an "industry standard" 180°F/160°F (82°C/7°C) only will be marginally better than a conventional boiler, and create increased first cost for little operating cost benefit.

It is important to note that these efficiency adjustments apply to output as well. For example, a conventional boiler rated at 2.5 million Btu/h (733 kW) input might have a rated output of 2.0 million Btu/h (586 kW), or 80% combustion efficiency. But after applying the adjustment for EWT of 140°F (60°C) minimum, real efficiency would be 70% and the actual capacity would be closer to 1.75 million Btu/h (513 kW).

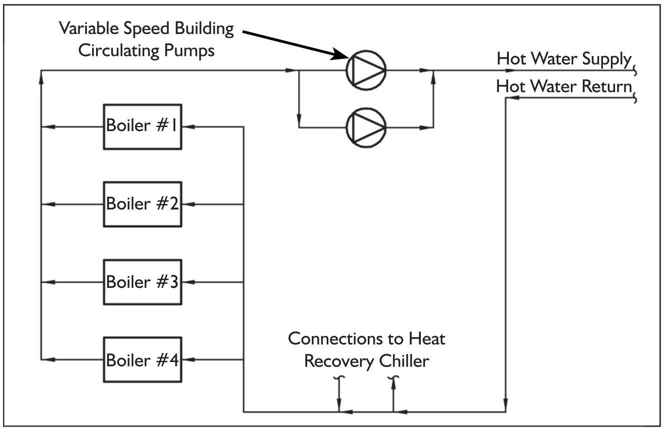


Figure 4: Condensing boiler/low-temperature system.

Other Factors Affecting Efficiency

The boiler is only one piece of the total building system, albeit the most important. Conventional boilers are starting out at a combustion efficiency, as operated, around 70%. Other factors that detract from seasonal efficiency include jacket losses; purge losses at startup, combustion air losses, stand-by losses, pipe system radiant losses, pumping energy, and the part-load effect.

Some of these are very difficult or impossible to model or measure short of a sophisticated research study (see S27.5-2004, definition of "seasonal efficiency"). However, they should be recognized. Some can be anticipated accurately by HVAC designers. Jacket losses are going to be approximately the difference between combustion efficiency and overall efficiency, 2.5% to 4%. Pipe radiant losses can be calculated and are typically around 1% of the total heating load. Pumping energy should not exceed 2.5 hp per 1.0 million Btu/h (0.0064 kW/kW), which equates to about 0.6% net.

Probably the second largest contributor, after combustion efficiency, is the part-load effect. *Figure 3* is reprinted from a condensing boiler manufacturer's literature, and it shows the combined effects of reducing the entering water temperature and running at reduced load. Operating in this mode would

Low-Temperature Boiler is Safer Option

Mike Rawlinson is the director of facilities at Avon Community Schools in suburban Indianapolis. Rawlinson recognizes the economic benefit of the condensing boiler/low-temperature heat scheme but insists on it for another reason. He said, "If there is a leak on one of the older systems, someone could get burned. If there is a leak on a low-temperature system, someone will get wet. As a building operator responsible for several thousand children, there's a big difference." With 180°F (82°C) water, a third-degree burn occurs in one second. With 130°F (54°C) water, a second-degree burn will occur in 17 seconds, and a third-degree burn will occur in 30 seconds (www.shrinerhq.org).

Previous Source	Before Gas, Therms/Year	After Gas, Therms/Year[2]	Payback in Years $0.40/Therm	$0.80/Therm	$1.00/Therm	$1.20/Therm	$1.40/Therm
LP Steam[1]	65,513	24,008	3.6	1.8	1.4	1.2	1.0
180°F HW[1]	45,262	28,089	8.7	4.4	3.5	2.9	2.5

Notes: 1. From previous chart, two comparably sized schools (90,000 ft^2), one originally heated with site generated steam, one with conventional 180°F hot water. 2. Adjusted for heating degree days.

Table 3: Payback for condensing boilers.

mean that the actual overall efficiency would be higher than the published combustion efficiency. In a conventional boiler system, the overall efficiency will never be above the published combustion efficiency.

It appears that one of the most important benefits of condensing boiler/low-temperature hot water heating systems compared to non-condensing high temperature systems is that condensing systems can modulate output temperature lower as heating demand decreases, thereby increasing their benefits. Non-condensing systems have fairly high minimum allowed temperature limits to avoid condensation and cannot be modulated to such low output temperatures. In addition to improved combustion efficiency, condensing low-temperature systems have reduced jacket, distribution system, and cycling losses at part load compared to full-load rated conditions.

All of this is predicated on the boiler being tuned up so that fuel-air mixtures and excess air are properly maintained over the full operating range.

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0	0.007	0.016

Table 4: Fossil fuel emission levels (lbs/billion Btu of energy input).[1]

The Results

After many comparisons of before and after gas use for buildings where the mechanical systems were updated to condensing boilers, the results and the improvement were significant. These case studies didn't quantify all the factors, just the improvement. *Table 1* represents 10 schools that were converted from low-pressure steam to low-temperature hot water, saving an average of 68% of the gas (heating the same space with one-third the energy). Most were high/low fire units started and stopped manually. All of these were site-generated steam, as opposed to a district or campus-wide heating system.

Table 2 represents 10 schools that were converted from a conventional 180°F (82°C) hot water heating system to low-temperature/condensing boiler systems. Average savings was 49% (heating the same space with half the energy). All "before" buildings were equipped with energy management systems, and all were scheduled for occupied/unoccupied operation.

Both comparisons are yearly totals corrected only for heating degree days. Classroom schedules were the same for both study years. The "after" had all spaces ventilated per ANSI/ASHRAE Standard 62.1-2004, *Ventilation for Acceptable Indoor Air Quality*. The before ventilation condition was not measured. In all cases, renovations included minor building envelope improvements, which would decrease heating demand, and lighting upgrades that would theoretically increase heating demand.

The New Standard

If the hurricanes of 2005 cause the industry to redefine the industry standard for heating systems, it would probably look like *Figure 4*, and include the following:

- Multiple modular condensing boilers;
- Maximum operating tem-

perature of 130°F (54°C) reset according to outside air temperature down to 90°F (32°C);
- Modulating firing rate (5 to 1 turndown) to manage temperatures without mixing valves;
- Firing sequence has multiple boilers on at part load most of the time; and
- Direct vent and sealed combustion.

This diagram does not show boiler circulating pumps or boiler isolation valves in a variable speed building pumping scheme. The condensing boiler manufacturers will have their particular recommendations for minimum flow, which will have to be addressed.

How would the new standard differ from the old one? Surprisingly, it would not differ very much outside of the boiler room. Since both the old and new are designed around 20°F (11°C) ΔT, the pumps, valves and piping are the same. Coils have to be deeper, typically going from one or two rows in the old to three rows typically in the new. This equates to about $300 first cost increase on a size 30 air-handling unit (AHU), and $30 per 1,000 cfm ($63.60 per 1000 L/s) VAV box (Currently, a limited number of VAV manufacturers make heating coils for low-temperature water). There will be slight increases in AHU internal and downstream static. Radiation and convection will require fan assist. And obviously, the new standard has limited application in retrofits on existing buildings originally designed around traditional 180°F (82°C) heating temperatures. The biggest change will have to be in engineers' and manufacturers' attitudes.

Some might question the validity of heating with water at those relatively low temperatures. But, the objective of hydronic heating is to warm air up to about 100°F (38°C), and that could be theoretically accomplished with 100°F (38°C) water if there were enough of it.

Some might question the freeze potential of l30°F (54°C) water vs. 180°F (82°C) water. Consider this duty: a face/bypass coil handling outside air at 0°F (–18°C) to be preheated to 55°F (13°C). A coil sized for 180°F (82°C) and 20°F (11°C) ΔT will be half the coil rows and have half the water volume that a 130°F (54°C) coil will have. The lower temperature coil actually will contain more total Btus. Neither situation bodes well if water flow is lost, however, with freeze-up occurring in a short time.

Payback

According to R.S. Means 2006 Mechanical Cost Data, condensing boilers are about 60% more expensive than conventional boilers of comparable output. The author feels that the real premium is higher, and recommends budgeting $10,000 per million Btu/h (293 100 kW) (output) for conventional boilers and $24,000 per million Btu/h (293 100 kW) (output) for condensing boilers, a 140% premium. *Table 3* shows payback vs. steam at 1.2 years, and payback vs. conventional hot water boilers at 2.9 years based on gas at $1.20 per therm.

Other Benefits

The ability to integrate a heat recovery chiller into a condensing boiler/low-temperature heat scheme is one benefit. *Dedicated Heat Recovery*[2] explains the economic and technical benefits of using recovered heat at any time there are concurrent heating and cooling loads. The combining of heat recovery device (the heat recovery chiller) that can make 130°F (54°C) water with a heating system that operates at 130°F (54°C) maximum means that low-cost recovered heat, which will be about one quarter the cost of the most efficient boiler heat (at Indiana electric rates), is available year-round.

The pragmatic engineer tends to look at issues like this in purely economic terms, i.e., payback. The environmentalist would encourage looking at how much less carbon dioxide is being released by improving the efficiency of our heating systems, thereby decreasing greenhouse gases (*Table 4*). (Conversion note: one billion Btus equals 10,000 therms of natural gas.) The gas savings from the 20 school buildings included in *Tables 1* and *2* equate to 4,260 tons (4328 Mg) of carbon dioxide per year that is no longer released into the atmosphere. This has a compounding effect in that the stack temperatures from condensing boilers typically will be in the 120°F to130°F (49°C to 54°C) range, as opposed to the 250°F (121°C) typically seen from a conventional hot water boiler, or 300°F (149°C) from a steam boiler.

The Dark Side?

Condensing boilers are a relatively recent advancement, going back about 18 years in the United States but considerably longer in Europe. Condensing boilers have become more popular in the last four or five years, but they do not have the long track record that that the "old standards" have. Will condensing boilers enjoy the same 40- or 50-year life expectancies that engineers and owners have come to anticipate from the "old standards?" It is too soon to tell, but the initial results are encouraging.

However, on the other side of the longevity question is the concern about thermal shock in conventional boiler systems, especially fire-tube boilers. Thermal shock is arguably the largest cause of shortening the life of conventional boilers but will not be a concern in a condensing boiler heating system.

Recent information on low-temperature heating systems indicates that biocides should be part of the water treatment regimen to prevent the propagation of *Legionella*. Even though these are closed loop systems, the biocide is recommended for protection of maintenance personnel.

Conclusion

The case studies of heating systems did not quantify all of the many parameters that contribute to inefficiency, but it did identify that they exist and are significantly larger than the author had imagined. An installed system only can approach the theoretical best case overall efficiency. The condensing boiler system demonstrated here comes closer to the theoretical than any other boiler type, but even those do not reach it. The conclusion to be drawn is that the old standard can be improved significantly. Whether energy prices keep tracking the same or they settle out at some new point, no obvious answers exist for building heating systems, other than to say that if the building is to be heated hydronically, use low-temperature water from condensing boilers.

Reference

1. Energy Information Administration. 1998. "Natural Gas 1998: Issues and Trends." http://tinyurl.com/rpnxj and www.naturalgas.org/environment/naturalgas.asp.

2. Durkin, T.H. and J.B. Rishel. 2003. "Dedicated heat recovery." *ASHRAE Journal* 45(10):18–24.