Principals of Condensing Boiler System Design

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ABSTRACT

Condensing boilers can provide significant energy savings due to operating efficiencies as high as 98% as compared to a peak efficiency of 80% for a conventional boiler. However, specifying a condensing boiler does not guarantee achieving anticipated savings; careful attention must be paid to the heating water system as a whole. The first principal is that low boiler entering water temperatures (EWT) are required to realize the advertised efficiency and AFUE performance of condensing boilers. ANSI Standard Z21.13 specifies condensing boiler performance testing with 80˚F (27˚C) EWT and a 100˚F (55˚C) temperature rise (delta-T), a condition not generally achieved with standard design practices. Advantages of high delta-T systems include reduced boiler and pump energy use and reduced pipe sizing and distribution heat loss. A condensing boiler is not a compact fluorescent lamp (CFL); you can't simply plug it into a typical system and expect it to save energy. Selecting a condensing boiler is the easiest and least consequential part of designing a condensing boiler system. This paper provides basic principles for designing a heating system utilizing condensing boilers. The remaining design principals are mostly related to how to achieve a low EWT. The paper presents design principles for heat delivery to the space, coil selection, boiler selection, low mass versus high mass boilers, piping system design, pump and control valve selection, use of buffer tanks, and boiler controls. The paper presents a detailed description of each design principal along with recommendations as to how to achieve it.

INTRODUCTION

Experience over several years of commissioning buildings with condensing boilers is that about 90% of the boilers never operate in the condensing range. Traditional design practices include designing and controlling hydronic heating system to not return water cooler than 140˚F (60˚C) in order to prevent condensation of corrosive flue gases within the boilers. Conversely the focus for condensing boiler system design is to return 80˚F (27˚C) water to the boilers to promote maximum boiler efficiency. Little information could be found on recommended design practices for condensing boiler systems and in discussing design issues with commissioning agents, design engineers, and boiler factory representatives; it was clear there was no consensus on how to design these systems. The ASHRAE Handbook was of little help, but it did encourage design of high delta-T hydronic heating water systems. Internet searches failed to locate any design guidelines focused on optimizing efficiency in condensing boiler systems. Condensing boilers can provide significant energy savings due to operating efficiencies as high as 98% as compared to a peak efficiency of 80% for a conventional boiler. However, installing condensing boiler alone does not guarantee achieving anticipated savings; careful attention must be paid to the boiler heating water system as a whole. Condensing boilers require entering water temperature (EWT) in the 100˚F (55˚C) range to actually condense water out of the exiting flue gas. The onset of condensing is with an EWT of about 130˚F (54˚C), but maximum efficiency occurs at an EWT of 80˚F (27˚C) or lower. This EWT requirement varies with altitude, with condensation starting at 125˚F (54˚C) EWT in Denver. The following design principles were developed for condensing water systems.

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DESIGN PRINCIPALS

Principal-1 - Return Water Temperatures to the Boilers must not Exceed 80˚F (27˚C) to Achieve the Advertised Boiler Efficiency

ANSI Standard Z21.13 tests and rates condensing boiler performance with an 80˚F (27˚C) boiler entering water temperature (EWT) and a 100˚F (55˚C) temperature rise (delta-T) to produce a boiler leaving water temperature (LWT) of 180˚F (82˚C). Condensing boiler performance is dominated by the boiler EWT. Figure 1 below shows a typical condensing boiler efficiency curve from a manufacture and a theoretical performance curve.

Figure 1 Typical Condensing Boiler Efficiency Curves

The boiler starts to condense water out of the combustion gasses when the dewpoint of the combustion gasses is reached; which, at sea level, is about 130˚F (54˚C). As gas temperatures continue to drop, more water is condensed out and the boiler efficiency increases dramatically down to about 80˚F (27˚C), which is the boiler EWT at which the boiler is rated. If the heating water system cannot deliver 80˚F (27˚C) water back to the boiler; the boiler will not operate at it's rated efficiency.

If the system cannot be designed to return water near 80˚F (27˚C) for a good portion of the heating season, a non-condensing boiler should be considered; which can operate with an efficiency of up to 87% with an EWT of 140˚F (60˚C). Typically non-condensing boilers cost about a third of the cost of a condensing boiler.

Principal-2 – Select Heating Coils for a 80˚F (27˚C) Leaving Water Temperature

Proper heating coil selection is the most important element of designing a high-performance heating water system. Consider the following example, summarized in Table 1.

Table 1. DHW Coil Selection Example								
Selection	Load Side GPM (L/M)	Load Side EWT ˚F(˚C)	Load Side LWT ˚F(˚C)	Source Side (GPM)	Source Side EWT ˚F(˚C)	Source Side LWT ˚F(˚C)	LxWxH inches (cm)	Weight lbs (kg)

20°F (11.1°C) Delta-T	80 (303)	40 (4.4)	135 (57.2)	195 (90.6)	150 (65.6)	110 (43.3)	38x13x16 (97x33x41)	769 (349)
80°F (44.4°C) Delta-T	80 (303)	40 (4.4)	135 (57.2)	125 (51.7)	160 (71.1)	80 (26.7)	20x10x12 (51x25x30)	156 (71)

A heat exchanger is required to heat 80 gpm (303 lpm) of domestic water from 40°F (4°C) to 135°F (57°C) . The deisgn specified a heat, based on a vendor selection, that used 195 gpm (738 lpm) of 150°F (66°C) boiler water with a design LWT of 110°F. During a design review, the commissioning agent re-selected the heat exchanger assuming EWT=160°F and LWT=80°F (27°C).   The resulting LWT back to the boiler was 80°F (27°C), increasing boiler efficiency, the heating water flow rate dropped about 40%, allowing for a smaller pump, and the heat exchanger weight and cost dropped to 20% of that of the original selection. This is a typical result from sizing the heat exchanger for an appropriate Delta-T rather than staying with a 20°F (27°C) Delta-T dictated by a rule of thumb.

Consider another example, selection of an air heating coil, summarized in **Table** 2. A 20°F (11°C) delta-T on the water side is often used to size heating coils. High-performance systems require coil selection at a much higher delta-T, in the 80°F (45°C) range. A heating coil is required in an AHU to heat 10,000 cfm (4719 lps) of air from 35°F (2°C) to 90°F (32°C) . In an attempt to keep coil LWT at 100°F (38°C), the engineer uses a 120°F (49°C) EWT. He then tries the same selection with a 180°F (82°C) EWT. The difference in the results is that 3 coil rows are required for the 20°F (11°C) delta-T selection along with a 56.4 GPM (213 lpm) flow rate. The 80°F (44°C) delta-T selection results in a 2 coil row and a 14.4 GPM (55 lpm) flow rate.

Table 2. Air Heating Coil Example.		
Selection Run	20F (11C) delta	80F (45C) delta
Face Area ft2 (m2)	20 (1.8)	20 (1.8)
Face Velocity fpm (mps)	500 (2.5)	500 (2.5)
Rows – FPI	**3 – 10**	**2 – 10**
CFM (lps)	10,000 (4,719)	10,000 (4,719)
Entering Air Temp °F (°C)	35 (2)	35 (2)
Leaving Air Temp °F (°C)	93.1 (33.9)	94.2 (34.6)
Fluid	Water	Water
Air Pressure Drop in WG (Pa)	0.28 (70)	0.19 (47)
Water Pressure Drop ft (m)	11.56 (3.5)	13.7 (4.2)
Water Velocity ft/s (m/s)	5.2 (1.6)	4.0 (1.2)
Entering Water Temp °F (°C)	**120 (49)**	**180 (82)**
Leaving Water Temp °F (°C)	**100 (38)**	**100 (38)**
GPM (l/m)	**56.4 (213)**	**14.4 (55)**

 The only other difference is that the 80°F (45°C) delta-T selection has 16 passes of tubing per circuit across the coil face as opposed to 8 passes for the other coil. At lower water flow rates, fewer circuits with longer lengths are required to keep flow in the turbulent range for better heat transfer. The coil selection program used in this example was randomly downloaded from a coil provider web site. The high delta-T coil is very similar to the low delta-T coil, but it provide significant energy savings due to a 75% reduction in pumping energy, lower pressure drop on the air side, and low boiler EWT in a coil that has less rows.

Principal-3 – The Heating Water Design Delta-T for a Heating Coil should equal the Load Design Delta-T

Performance of a hot water heating coil is given by the following equation:

$$Q = Cmin \times \epsilon \times (EWT - EAT) \tag{1}$$

where
Q = Rate of heat transfer (Btuh)
Cmin = Minimum fluid capacitance rate (Btuh/°F)
ϵ = Effectiveness
EWT=Entering water temperature
EAT=Entering air temperature

Fluid capacitance rate is the product of the mass flow rate and the fluid specific heat for both the air and water sides of the coil. Capacitance rate is equal to 500 x GPM on the water side and 1.08 x CFM on the air side, expressed in Btuh/F. Selecting a heating coil with matched capacitance rates on the source and load sides will result in equal Delta-Ts on both side of the heat exchanger. Selecting a delta-T on the source side less than the delta-T on the load side will maximize the heating water delta-T; resulting in cooler return water temperatures to the condensing boilers. In addition, good control with a control vlave requires the source side delta-T to be less than or equal to the load delta-T; given the heat exchanger performance equation above in which the minimum capacitance rate dominates the amount of heat transfer. At part load, the delta-T of the heating water will increase as the control valve pinches down to control coil output. With proper coil sizing, control valves can be significantly smaller and provide much more effective control.

Principal-4 – Select Heating Systems Capable of Returning 80˚F (27˚C) Water to the Boiler

Some HVAC heating systems are more compatible with condensing boilers than other systems. **Error! Reference source not found.** Summarizes typical operating temperatures of common HVAC equipment, the approximate heat exchanger effectiveness appropriate for a condensing boiler system, and achievable hot water return temperatures.

Table 3. Typical Coil Design Temperatures.							
Equipment	DHW Heater	AHU Heating Coil (Single Zone)	AHU Heating Coil (VAV)	VAV Box Reheat Coil	Radiant Slab Heating System	Hot Water Baseboard	Snow Melt System
Entering Load Temp ˚F (˚C)	50 (10)	60 (16)	40 (22)	60 (16)	80 (27)	70 (21)	30 (-1)
Leaving Load Temp ˚F (˚C)	140 (60)	90 (32)	60 (16)	80 (27)	120 (49)	140 (60)	40 (4)
Load Delta-T	90 (50)	30 (17)	20 (11)	20 (11)	40 (22)	70 (39)	10 (5)
Achievable HTX Effectiveness	0.95	0.50	0.40	0.40	0.90	0.60	1.00
Required HW Supply Temp ˚F (˚C)	145 (63)	120 (49)	90 (32)	110 (43)	120 (49)	180 (82)	40 (4)
HW Return Temp ˚F (˚C)	60 (16)	90 (32)	70 (21)	90 (32)	80 (27)	120 (49)	30 (-1)

Ideally the heating coil serves a low temperature load like DHW heating or snow melting or a pre-heat coil in an AHU; which allows a low return water temperature to the boilers. Problem coils include:

- VAV reheat coils, typically 1 and 2 row coils, which require warmer heating water temperatures. Typically a 3 to 4 row coil is required, which is an added-cost option for most manufactures.
- Hot water baseboard heating should be avoided; they require higher temperatures to drive the airflow over the coils. Hot water baseboard can and should be designed with heating water delta-T of 60°F (33°C). The heat output is proportional to the average water temperature for a baseboard circuit.
- Radiant heating slabs work well with condensing boilers, if designed to return water at about the temperature of the slab. The system should include a tertiary pumping loop and optimal tube spacing within the slab.

Table 3 is for typical peak heating load conditions; heating water delta-Ts will increase as flow is throttled down for part loads and the hot water supply temperature can be reset downwards based on decreasing load.

Principal-5 – Use Primary-Only Heating Water Distribution Systems

A problem we've seen the field with condensing water systems is the use of primary-secondary distribution systems, which are designed to provide constant water flow through the boilers and variable flow through the heating coils. This arrangement results in mixing of supply and return water, if boiler and load flow rates are not exactly the same. Mixing will result in either elevated return water temperatures to the boilers or reduced supply water temperatures to the coils; both of which degrade condensing boiler efficiency. The recommended primary-only boiler system is indicated by the Figure 2 and has the following elements:

- A single variable-speed pump sends return water to the boilers and on to the heating coils. The boilers are equipped with isolation valves and the coils with 2-way control valves. Pump speed is controlled to maintain a differential pressure (DP) setpoint between coil supply water and return water piping in the vicinity of the coils. The DP setpoint may be reset based on valve positions.
- A recirculation control (system bypass) valve operates at low load to maintain the required minimum flow rate setpoint through the operating boiler. A flow meter (not shown) is required in the boiler loop. Boiler sequencing is controlled to avoid operation of the recirculation valve.
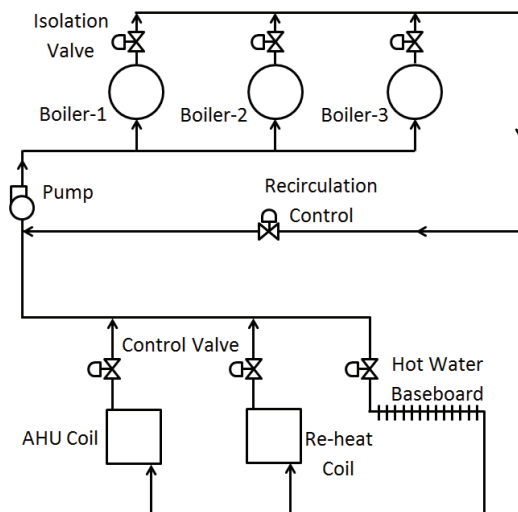

Figure 2 Primary-Only Heating System Schematic.

Principal-6 – Select Boilers with Low Burner Turn-Down Ratios

Condensing boilers are typically designed with a low burner turn-down ratio to 20% or lower. Some of the better boilers have turn-down ratios as low as 5%. If loads drop below the turn-down ratio, the boilers must cycle on and off to meet the load, which can significantly reduce the efficiency of the boiler. When boilers cycle, a pre and post purge of the combustion air in the burner and heat exchanger is required. As a result, every time a boiler is started, cold combustion air is blown through the heat exchanger at the maximum airflow rate for a minute or two; pulling heat out of the boiler and exhausting it. Purge losses are insignificant if boiler cycling is limited to 20 minutes or more, but are significant for fast boiler cycling, like every 5 minutes. We've seen boiler cycling as fast as every 2 minutes with a minute of operation and a minute of purge.

Boiler mass is essentially the amount of water inside the boiler and has a direct impact on boiler cycling at low load. Most condensing boilers are "low-mass" meaning they could have as little as 2 quarts (liters) of water in the boiler. The problem is low-mass boilers are subject to fast cycling at low loads, which aggravates the performance during cycling. External water storage (buffer) tanks can be piped into the system to reduce or eliminate short-cycling. Low-mass boilers are compact and can be wheeled through a doorway and arranged in modular banks; adding a large buffer tank defeats the space-saving advantage of low-mass boilers.

Principal-7 - Select Boilers with Low Minimum Water Flow Requirements

Minimum operating boiler water flow rates are usually more important to system performance than the burner turn-down ratio. Minimum flow turndowns range from zero to as high as 80%, depending on the boiler selected. High-mass condensing boilers generally have low or no minimum flow requirements. Most primary-only distribution systems utilize a system flow meter and bypass valve to maintain the minimum flow rate through the operating boilers. The bypass valve directs boiler exiting supply water directly back into the boiler return, which greatly increase boiler entering water temperatures, generally taking the boiler out of the condensing range. The minimum boiler flow requirement is generally the most critical factor in boiler selection. The minimum allowable boiler flow is often not immediately apparent in boiler design and installation manuals, but it is almost always stated somewhere. Operation below this limit can damage the boiler and void the warranty.

Principal-8 – Vary the Size of Boilers to lower System Turn-Down Ratio and Minimum Water Flow Requirements

For instance, for a total system capacity of 100%, consider two boilers sized at 20% and 80% rather than two boilers both sized at 50%. Assuming the minimum burner turn-down and flow rate is 20% of peak for each boiler, the system minimum of unequally sized boilers is 4% versus 10% for equally sized boilers.

Principal-9 – Select Control Valves Capable of Accurately Controlling less than 1% of Peak Flow

Control valves can negatively affect the ability of the system to maintain a high delta-T at low loads. Restricting water flow with a modulating control valve, results in a higher water delta-T. However, operating a control valve in an open/closed mode, results in a low delta-T. Open/closed control of a modulating valve will occur at low flow through the valve, typically starting at about 5% of design flow for an inexpensive control valve. Characterized valves and multi-port valves can decrease the advent of open/closed cycling down to 1% or less. It is recommended that all high-performance systems be equipped with modern pressure independent control (PIC) valves. PIC valves can provide accurate control down to the range of 0.5% load.

Principal-10 – Optimize Heating Water System Controls

Optimizing hydronic system controls is focused on reducing boiler entering water temperature (EWT) to maximize boiler condensing time and efficiency. Control strategies include system enable control, optimal boiler sequencing, outside air reset, and load reset.

System Enable Control is an important consideration for both condensing and conventional boiler operation. Most systems, we encounter in commissioning, use an outside air temperature (OAT) lockout strategy, which enables the heating water system when temperatures drop below a setpoint, typically 60˚F (15˚C) . This is a very poor strategy, resulting in hundreds of operating hours at no load other than pipe heat loss. A better strategy is a dual boiler enable setpoint strategy. An example of a dual setpoint strategy is to keep the system off when the OAT is above 60˚F (15˚C) and enable the system when OAT is below 40˚F (4˚C). When OAT is between these setpoint limits, the system enables upon a call for heating by one or more coils. During a retro-commissioning effort on two identical buildings, one enabled the hot water system on OAT and the other on coil demand between the two setpoints; the single OAT strategy had double the annual natural gas use as the one with the recommended strategy.

Optimal Boiler Sequencing can be complex given multiple boiler sizes, varying burner and minimum flow turn-down ratios, boiler performance characteristics, and temperature reset strategies. Operating multiple boilers in parallel at low loads is often recommended; condensing boilers are most efficient when operated at middle part load conditions in the 20% to 60% range. However, the minimum boiler flow ratio must be considered to avoid excessive hot water flow through the bypass valve, and subsequent increase in boiler entering water temperature, which is the dominant factor in the boiler efficiency equation.

Outside Air Temperature (OAT) Reset, which reduces boiler LWT in response to OAT, is common boiler control strategy. Traditionally OAT reset is focused on reducing control valve cycling at low flow, but will also reduce boiler EWT and thus increase condensing boiler efficiency.

Load Reset is like OAT reset, except boiler LWT is reset in response to zone temperatures or control valve position. With the feedback from the loads, load reset is much more effective than OAT reset.

Principal-11 – Use a Robust Design Tool to Design Condensing Boiler Systems

There are many variables to consider in designing a high performance condensing boiler system, too many for the human mind to consider simultaneously. A design tool is required to evaluate the result of applying the nine principals of condensing boiler system design. **Error! Reference source not found.** below is from a spreadsheet based tool and shows the results of a particular schematic design. Boiler LWT is automatically reset to meets the loads on two air heating coils, some hot water baseboard, and a radiant slab. At high loads, the hot water baseboard LWT pushes the Boiler EWT up close to 130˚F (54˚C) , the edge of the condensing range. But overall, Boiler EWT is mostly in the 80˚F (27˚C) range at mid and low loads, where the majority of load hours occur.

A design tool must include calculation of several components of the system including:
- The boiler efficiency curve,
- Boiler operating characteristics including the minimum burner turndown ratio, the performance with short cycling boilers, the minimum flow ratio, the sequencing of the boilers, and other control strategies,
- The heat exchange characteristics of several types of heat coils including air heating coils, hot water baseboard, radiant slabs, and DHW heaters,

- The ability to convert coil selection data into a coil performance model,
- The flow characteristics of control valves and their performance when cycling at low load conditions,
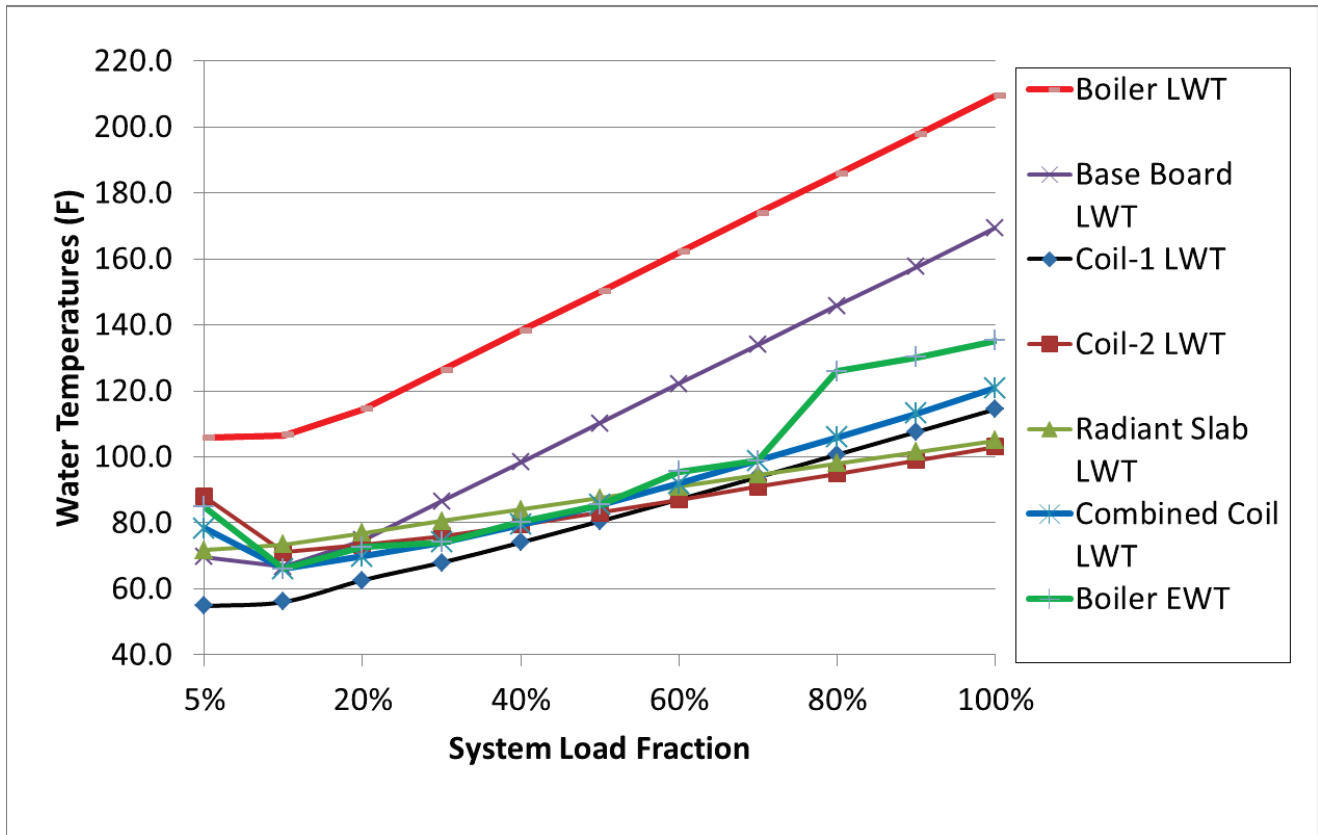- And finally the tool must output results in a meaningful manner.

Figure 3 Condensing Boiler System Energy Model Output Graphic.

CONCLUSION

Designing an energy-efficient design for a heating system using condensing boilers is completely different than designing a conventional boiler system. The goal in a conventional system design is to keep the boiler return water temperature above 140˚F (60˚C) . The goal for a condensing boiler system is to return 80˚F (27˚C) to the boilers to maximize efficiency. This difference in the optimal boiler EWT results in significant differences in systems including distribution piping design, operating system delta-T, coil selection, boiler sequencing, and system control. Given the cost premium of a condensing boiler, the designer's goal is to make the system operate as efficiently as possible.