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Design Tips to Avoid Boiler Short-Cycling

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Boiler short-cycling occurs when a boiler quickly satisfies the load and reaches the cycle off limit setting in the boiler controls and cycles off, or the high-temperature limit safety. This becomes a problem when there is heating demand and the boiler will quickly need to come back online. This problem has grown more prevalent due to the modern light–mass boiler design—to reduce costs and improve efficiency, modern boilers have less stored water volume and lower mass heat transfer area due to enhanced tube designs. This contrasts with the old fire-tube designs that had large water volume and old water-tube designs with high mass of straight tubes.

The design decisions made in selecting and sizing heating boilers and their components as well as the control sequence have a direct impact on the performance of the overall heating hot water plant. This month, I provide some design tips in boiler selection and the design of heating hot water systems to avoid boiler short-cycling. These problems can impede the system's ability to perform reliably and efficiently.

Short-Cycling Issues

Short-cycling is not good for any type of gas-fired boiler system. It causes excessive wear and tear on the boiler and substantially decreases efficiency. In many cases, the boiler cannot reliably deliver heat to the loads. The mechanical problem comes from the effects of rapid cycling on boiler components. The burner material, for instance, rapidly heats and cools, and sometimes cannot run long enough to dry out from condensed combustion products. This can create stress and corrosion failures. Gas valves can experience 20 years of use in a few short months. There also tends to be nuisance shutdowns and unexplained flame failures with flame fault codes that have no easily identifiable cause.

A boiler cycle consists of a pre-purge, a firing interval, a post-purge, an idle period, and a return to firing. Boiler efficiency is the useful heat provided by the boiler divided by the energy input (useful heat plus losses) over the cycle duration. This efficiency can substantially decrease when short-cycling occurs.

This decrease in efficiency occurs, in part, because fixed losses are magnified under lightly loaded conditions. For example, if the radiation loss from the boiler enclosure is 1% of the total heat input at full-load, at half-load the losses increase to 2%, while at one-quarter load the loss is 4%.[1] In addition to radiation losses, pre- and post-purge losses occur. In the pre-purge, the fan operates to force air through the boiler to flush out any combustible gas mixture that may have accumulated. The post-purge performs a similar function. During purging, heat is removed from the boiler as the purged air is heated.

Short-cycling can have a dramatic effect on boiler fuel consumption. There is an old rule-of-thumb that says that a short-cycling boiler achieves 15 efficiency points

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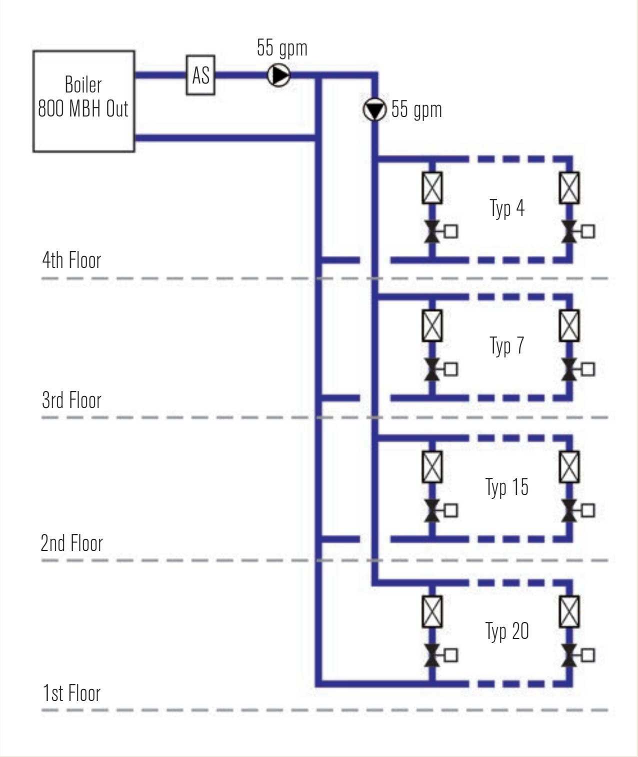
less than the lowest efficiency achieved in non-short-cycling low fire. An atmospheric flex-tube boiler, for instance, that achieves 72% efficiency at low fire will see 57% efficiency in short-cycling mode. The loss of fuel efficiency is staggering. If you want an energy-efficient boiler plant design, there is often more to be gained from short-cycle prevention than from choosing an ultra-high efficiency boiler.[2]

The Challenge

When energy is put into a system, it must be carried away from the point of input at least as fast as it is being introduced. This means that the designer must consider the relationship between the boiler's minimum heat output and the system's ability to use or absorb this energy. Boilers used for space heating loads are often oversized, with their capacity chosen to meet total building heat losses plus heating of ventilation and infiltration air under design-basis temperature conditions. Often no credit is taken for thermal contributions from lights, equipment, or people. Excess capacity is also sometimes added for morning warm-up after night setback. It is not uncommon for some buildings to see a mild day heating load that is only 5% of the design day heating load. These small loads also can occur mid-summer when attempting to provide a small amount of heat for a VAV reheat system.

We are often asked by clients to determine why their boiler system does not operate properly and many cases it is due to short-cycling. *Figure 1* shows a primary-secondary boiler system arrangement that is similar to others we have encountered from various designers on different projects. These arrangements work well in constant flow applications. ASHRAE/IES Standard 90.1-2016[3] requires *"Chilled- and hot-water distribution systems that include three or more control valves designed to modulate or step open and close as a function of load shall be designed for variable fluid flow and shall be capable of and configured to reduce pump flow rates to no more than the larger of 25% of the design flow rate or the minimum flow required by the heating/cooling equipment manufacturer for the proper operation of equipment"*. Variable flow secondary can result in very low minimum heating loads to the boiler without the ability to use the system volume to store heat.

FIGURE 1 Boiler short-cycling piping diagram example.



In the above example, the 800 MBH (234 kW) output boiler had a 5:1 turndown ratio, allowing the boiler to operate at minimum 20% load, or 160 MBH (47 kW). The boiler was designed to provide 150°F (66°C) supply water. The boiler was provided with a constant speed 55 gpm (12.5 m^3/h) boiler pump while the system was provided with a variable speed 55 gpm (12.5 m^3/h) circulating pump. The heating loads consisted of 46 terminal reheat coils with two-way valves ranging from 2.5 MBH to 50 MBH (0.75 kW to 15 kW) with a median load of 12.4 MBH (3.6 kW). The designer's sequence called for the boiler to be enabled whenever there was a call for heating from *any of the zones.* The high temperature high limit safety was set at 210°F (99°C). The volume of the boiler and its loop was only 14 gallons (53 L) while the volume of the distribution mains, not including terminal device runouts, was 70 gallons (265 L). The sequence enabled the pump and boiler to run with only one zone calling for heating, meaning that the boiler would be enabled even if only the smallest terminal unit called for heat.

There are several issues in this example. First, the boiler's minimum energy output is too large for the minimum load and is more than is required to raise the temperature of the system water to its setpoint. Since the sensor for the boiler control is in the boiler, it doesn't take long for the excess heat to reach the sensor and cycle off the boiler. When this happens, the sensor sees immediate loss of heat and calls for more heat but the boiler anti-cycle timer will prevent the boiler from firing until it has timed out. Second, the system flow is reduced by the action of terminal unit 2-way valves and the secondary pump's speed controller making the boiler primary pump's flow rate far exceed the system flow rate at minimum load. Boiler loop flow overwhelms the secondary loop flow in the common piping between the two primary-secondary connections. This rapidly raises the boiler's entering water temperature and can trip the boiler's high temperature operating limit on low load. In this case, the boiler would trip on high temperature less than 1 minute after firing.

The excessive short-cycling could have been avoided if the designer evaluated how the system would perform at low load to ensure the boiler would stay on for at least 10 minutes at minimum system load. A system with all two-way valves does not allow the thermal mass of the secondary loop water volume to be used to load the boiler.

Design Tips To Avoid Short-Cycling

Attention to the following system parameters can help designs avoid short-cycling.

Determine System Minimum Heat Load

It is important to determine the system minimum heat load, Q_{min}, expected when the boiler is enabled. This is a function of the minimum heating load expected and potential heat loss from the operating system. While each project is unique, in the author's experience, buildings with zone heating can produce system minimum loads that are only 5% of peak system loads. Examples would include fan coil units and zone heating through terminal reheat or radiant heating.

Determine System Circulating Water Volume Required

The system circulating water volume, V_c, when the boiler is operating provides capacity to store heat. Every Btu of heat that is added to a pound of water will increase its temperature by 1°F (0.56°C). Since there are 8.33 lbs (3.78 kg) in 1 gallon (3.78 L) of water, 8.33 Btus (8.79 kJ) will raise the temperature of 1 gallon of water by 1°F (0.56°C). There is flexibility in design to increase system storage capacity. The system circulating water volume can include the secondary loop volume only when the secondary minimum flow is adequate to remove the heat put in from the boiler loop.

A system with all two-way valves and no end-of-loop bypass is not be able to use much of the system volume since the closed valves will not allow flow in their corresponding circuits, and thus limits its ability to store energy. Storage capacity can be increased through bypass, typically provided by a three-way valve, on main branch piping circuits. This allows the system to use the thermal mass of the distribution loop on the lowest boiler output. The following formula could be used to estimate the minimum secondary flow rate:

$$Secondary\ gpm_{min} = \frac{Boiler_{min\ out}}{\Delta T \times 8.33\frac{\text{lbs}}{\text{gal}} \times C_p \times 60\frac{\text{min}}{\text{hr}}} \qquad (1)$$

where

$Boiler_{min\ out}$ = boiler heat rate delivered at minimum firing rate of smallest boiler, Btuh

C_p = specific heat of fluid, Btu/lb$_m$·°F

ΔT = expected system ΔT at minimum load during low-load condition, °F

The ΔT used in the above equation should be the ΔT anticipated during low-load conditions. At worst case, this could be the difference between the hot water supply temperature when the boiler turns off and turn on. For instance, if the boiler turns off at 152°F (67°F) and turns on at 140°F (60°F), the minimum ΔT would be 12°F (7°C) with no load. The hot water load coil ΔT cannot be used if the system has bypass since the ΔT coming back to the boiler plant will be less with the bypass at low load.

Buffer tanks provide additional system volume and thermal mass between the hydronic heat source and a zone distribution system when the secondary loop cannot provide adequate system flow or volume. When the heat source is operating, the buffer tank absorbs the difference between the rate of heat production and the rate of heat dissipation to the load. Buffer tanks can be piped several ways but are commonly either in a two-pipe or four-pipe configuration as shown in *Figure 2* and *Figure 3*. In both configurations, the tank serves as the common leg between the primary and secondary loops. Siegenthaler[4] explains the differences between the two alternative piping configurations.

The minimum boiler cycle time can be calculated by adding the minimum boiler runtime to the minimum boiler off time. The runtime is a relationship between boiler minimum output, circulating system heat capacity, and the system minimum load. The recommended minimum runtime can be provided by the boiler manufacturer. In the author's experience, a runtime of at least 10 minutes and an off time of at least 15 minutes are good design targets.

The required system circulating water volume can be calculated using the following formula:

$$V_c = \frac{Runtime \times \left(Boiler_{min\ out} - Q_{min}\right)}{\Delta T \times 8.33\frac{\text{lbs}}{\text{gal}} \times C_P \times 60\frac{\text{min}}{\text{hr}}} \tag{2}$$

where

V_c = circulating system water volume, gallons

Runtime = boiler minimum runtime, minutes

Q_{min} = system minimum heat load, Btu/h

ΔT = expected system ΔT at minimum load during low-load condition, °F

The above equation can be rearranged to calculate the minimum runtime as follows:

$$Runtime = \frac{V_c \times \Delta T \times 8.33\frac{\text{lbs}}{\text{gal}} \times C_P \times 60\frac{\text{min}}{\text{hr}}}{\left(Boiler_{min\ out} - Q_{min}\right)} \tag{3}$$

The minimum off time can be calculated with the following equation:

$$Off\ Time = \frac{V_c \times \Delta T \times 8.33\frac{\text{lbs}}{\text{gal}} \times C_P \times 60\frac{\text{min}}{\text{hr}}}{Q_{min}} \tag{4}$$

Using these equations designers have various options in selecting boiler sizes, boiler turndown ratio, and designing the system circulating volume in order to ensure the design allows for minimum boiler runtime at low-load conditions.

Revisiting the Example Project

In the previous example:

The circulating water volume required to provide a minimum runtime of 10 minutes at low load can be calculated as shown below.

$$V_c = \frac{10\ \text{min} \times (160{,}000\ \text{Btu/h} - 2{,}500\ \text{Btu/h})}{30°\text{F} \times 8.33\frac{\text{lbs}}{\text{gal}} \times 1.0 \times 60\frac{\text{min}}{\text{hr}}} = 105\ \text{gallons} \tag{5}$$

The above equation uses the load design ΔT because the system did not have secondary bypass. The original system volume in the boiler loop and the distribution to the first load was approximately 30 gallons (114 L). There were several design options that could have been evaluated to help ensure the boiler would not short cycle. These include the following options.

FIGURE 2 Two-pipe buffer tank piping.

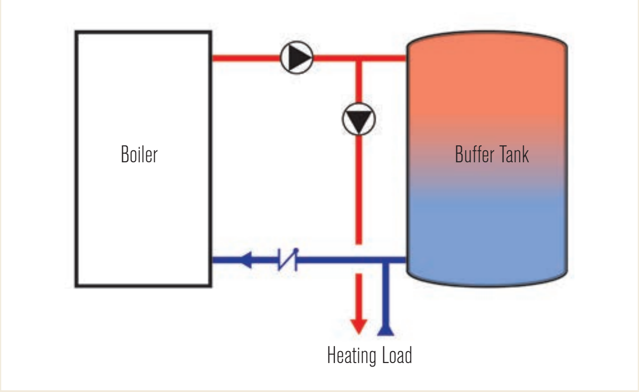
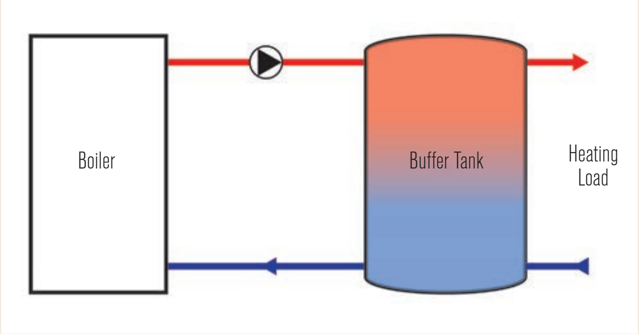


FIGURE 3 Four-pipe buffer tank piping.



Option 1 – Provide Bypass to Use Secondary Loop Volume

Secondary loop bypass could have been used to provide minimum flow in order to use the secondary system volume as heat storage for the boiler minimum heat output. The minimum secondary flow rate required would be:

$$Secondary\ gpm_{min} = \frac{160{,}000\ \text{Btu/h}}{(152°\text{F} - 140°\text{F}) \times 8.33\frac{\text{lbs}}{\text{gal}} \times C_P \times 60\frac{\text{min}}{\text{hr}}} = 27\ \text{gpm} \tag{6}$$

The system in the example had 84 gallons of system volume that could have been used bypass flow was provided on the secondary system. This would have resulted in a runtime of 3.2 minutes, which is too short to prevent the boiler from short-cycling.

Option 2 – Provide Required Circulating Water Volume

The minimum circulating water system volume could have been met in the original design by providing a buffer tank or oversized boiler loop headers sized to provide adequate heat storage to allow the boiler to fire on low load for the minimum runtime. The minimum system volume required would be:

$$V_c = \frac{10\,\text{min} \times (160{,}000\,\text{Btu/h} - 2{,}500\,\text{Btu/h})}{(152°\text{F} - 140°\text{F}) \times 8.33\,\dfrac{\text{lbs}}{\text{gal}} \times 1.0 \times 60\,\dfrac{\text{min}}{\text{hr}}} = 263\,\text{gal} \qquad (7)$$

With this option, additional system volume of roughly 250 gallons (946 L) would need to be added to allow a minimum runtime of 10 minutes. Option 1 and Option 2 could be combined requiring an additional system volume of roughly 180 gallons (681 L) for the same runtime. The advantage of Option 1 is lower system heat loss, assuming the buffer tank is fully insulated. Heat loss from circulating distribution systems can be significant over time since most low temperature hot water valve assemblies and hot water coil tube bends are not insulated.

Option 3 – Provide Lower Minimum Boiler Output

This option would require the designer to evaluate using a greater turndown ratio for the selected size boiler or using multiple boilers that in both cases would provide a lower minimum boiler output. Reducing the minimum boiler output would reduce the amount of secondary loop bypass flow required and the amount of circulating water volume required. Typical modulating boilers have a turndown of 5:1 but many manufacturers claim turndowns of as much as 15- or 20-to-1. In our example, using two boilers with 20-to-1 turndown would provide a total turndown of 40-to-1, low enough that the 30 gallons (114 L) of circulating water in the system would be sufficient without additional storage tanks to provide a runtime of 10.2 minutes.

Control Thoughts for Low Load

Many times, there is flexibility on when a boiler is enabled under these low-load conditions. The sequence does not always have to enable the boiler when only one zone is calling for heat. The circulating pump can be enabled first to provide whatever heat is in the loop and the boiler can be enabled after the hot water supply drops below setpoint. The control system hot water supply temperature setpoint to enable the boiler could be set lower at lower loads to provide a higher ΔT between the start setpoint and stop setpoint.

Concluding Remarks

Boiler energy performance and operation are a function of both good boiler selection and system design and controls for the heating hot water system. Boiler short-cycling causes excessive wear and tear on the boiler and has a tremendous penalty on boiler efficiency. I hope these tips can help designers improve heating hot water system performance.

References

1. DOE. 2012. "Steam Tip Sheet #16." DOE/GO-102012-3407. U.S. Department of Energy.

2. McKeegan, J. 2005. "Short-cycle prevention." Patterson-Kelley White Paper #3 Rev. 1.

3. ASHRAE/IES Standard 90.1-2016, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

4. Siegenthaler, J. 2014. "Alternate methods to pipe a buffer tank." *Radiant & Hydronics* (10). ■