Heating&Cooling technology

Thermal Shock

"Boiler Thermal Shock" can be loosely defined as sudden thermal change that occurs within the boiler causing rapid and uneven expansion and contraction of a boiler's structure.

The problem of thermally induced stress has been apparent for many years, particularly in hot water heating systems. Several conditions can contribute to boiler stress and eventual cracking. All involve introducing excessively low temperature water or cool water at high flow rates into a hot boiler. The term "shock" suggests a sudden impact type failure, which in the vast majority of cases is far from what actually happens. Most failures of this type occur over a period of time, some-times materializing within as short a time frame as a few weeks, but occasionally a considerably longer time period ensues before damage is detected.

Failures are typically of the iron or metal fatigue type and are caused by thermally induced stress cycling of the boiler structure. Thermally induced cyclic stresses are due to the resistance of the boiler structure to the movement caused by the thermal expansions and contractions within the boiler. The stresses occur during every firing cycle of the burner, a cycle defined as burner on, burner off. Failures of this type appear as leaks from sectional cracking. Malfunctions like this are not catastrophic in nature but are serious in terms of downtime and repair costs. Equipment manufacturers and system designers have devised many approaches over the years to combat this problem. Some have been successful and some have demonstrated a lack of understanding of the nature of these failures.

For their part, manufacturers of cast boilers have learned to pay attention to the shape of the boiler casting. Sharp radius corners and abrupt changes in the thickness of cast metal can amplify stresses encountered during operation. Some advancements such as the development of the wet leg designs seemed to dictate that these shapes and creative approaches were needed to regain the stress relief of the oval section design found in older designs such as Smith's Mills boiler. Fortun-ately, the development of finite element analysis and other computational tools has allowed manufacturers to adjust designs without the trial and error type of development that characterized the 19th century design process.

Manufacturers of cast boilers can also limit the effects of thermal stress by varying their pouring process. The metal mix, addition of trace elements, pour temperature, and cooling times all play a role in producing cast sections that stand up better to challenges in boiler system recogni-tion. It is important to point out that there are 100-year-old cast iron boilers still operating. This undeniable fact indicates that while advances in manufacturing are quite important, what a system demands of a boiler has a lot to do with its longevity.

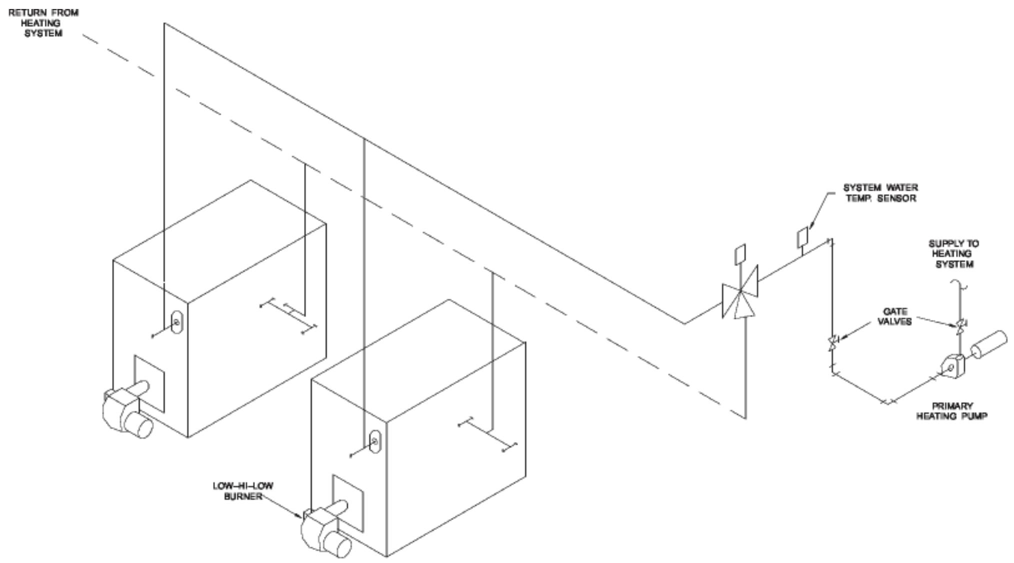
A rule of system design is that boiler supply water temperature and the system return water temperature shall not exceed a 40° F. delta T. This figure is commonly reduced to 20° F. delta T for steel boilers. Boiler protection is frequently ignored when system design is focused heavily on saving energy. Systems incorporating night setback and/or weekend shut-down are designed to save energy by reducing space temperature set points, thus reducing the building's heating requirement. Turning down or shutting down the building's temperature causes the system to become ambient. When the building moves to an occupied mode all the zones at the terminal unit open. The pumps are then enabled, and the ambient system water is injected into a hot boiler. Data from both laboratory stress analysis and field test programs indicate that failure is often the result of an ongoing conflict between the energy conservation requirements imposed on the control system designer and the requirements of the boiler manufacturer to protect the structural integrity of the heating equipment.

A common scenario has the Building Automation System (BAS) control bring the system up to operating temperature after a night or weekend setback. Systems incorporating night setback and/or weekend shutdown are designed to save energy by turning down or shutting off the building's temperature. This, however, causes problems when all the zone valves and pumps come back on, delivering room temperature water to a hot boiler. Once the set point has been reached the BAS calls for all the zones to be energized simultaneously. The large reservoir of cold (ambient) water in the system is immediately brought back to the boiler at a high flow rate, resulting in a temperature differential greater than the boiler can endure.

Heating systems that have boilers maintaining temperature without flow are susceptible to thermal shock by sudden changes in flow due to pump operation. Controlling the load imposed on the boiler can prevent waterside thermal shock. Boiler load is a function of flow rate and temperature difference. One of the most effective methods known to prevent thermal shock is to create a boiler loop separate from the system and pump it with its own circulator. Since the flow rate is constant, the temperature difference across the boiler becomes the measurement of the boiler's load, and if the boiler is maintaining temperature, the return water's temperature will determine the boiler load. Control against "boiler shock" involves control of the incoming cold water flow rate so that the boiler's temperature is changed slowly.

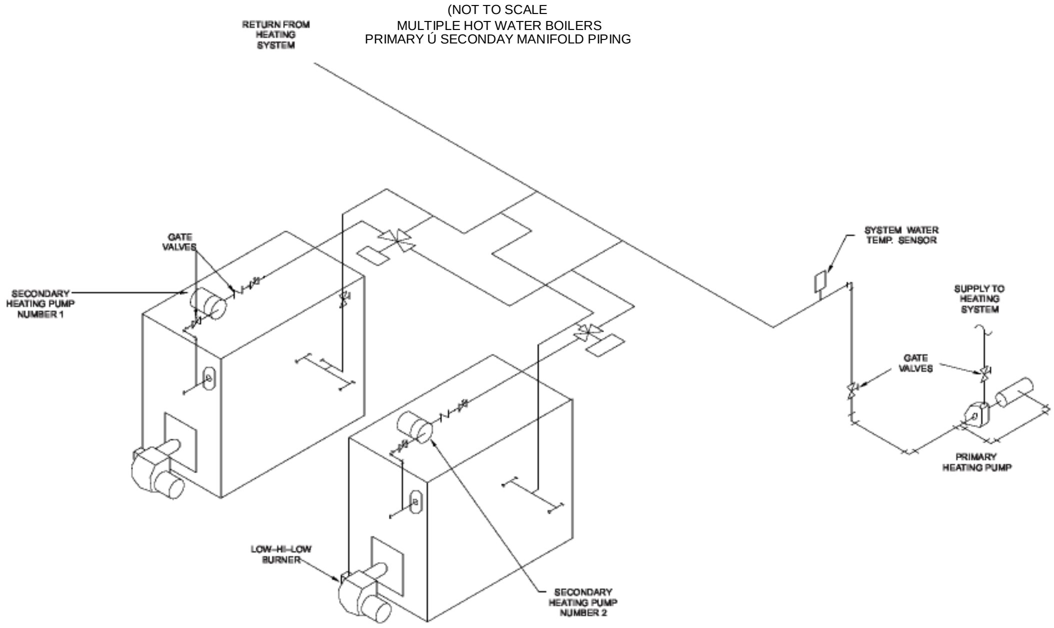
Additionally, a common cause of thermal shock is a system that incorporates outdoor reset with 3-way valves while the boiler maintains temperature, see Figure I. The boiler is set at 180° F, but based on outdoor temperature the system may require only 100° F. (60° F. outside air). The return temperature can be as low as 90° F., which can cause a 90° F. differential across the boiler. Most cast iron boiler manufacturers would like to see no more than a 40° F. temperature difference between the boiler's return and leaving temperature.

FIGURE I
TYPICAL PIPING DETAIL
(NOT TO SCALE)
MULTIPLE HOT WATER BOILERS
THREE WAY VALVE



By installing the 3-way valve in the boiler loop, see Figure II, the outdoor reset can control the amount of hot water that is introduced into the system based upon a reset schedule. More importantly, the reset controller can measure the return temperature entering the boiler. If water temperature becomes too low for the boiler manufacturer's recommendations the 3-way valve will close off the system loop. Hot water from the boiler will then be pumped right back into the return, raising the water temperature entering the boiler. The 3-way valve and controller will float back and forth, resetting the supply water to the system while protecting the boiler from cold water.

FIGURE II
TYPICAL PIPING DETAIL
(NOT TO SCALE
MULTIPLE HOT WATER BOILERS
PRIMARY Ú SECONDAY MANIFOLD PIPING



Dual temperature changeover systems can experience boiler problems when the system tries to change over from a cooling demand to heating. The piping system and terminal units are filled with water at temperatures of 50 - 60° F; however, the boiler may contain 180° F. water.

Heat pump loop systems typically require some form of supplementary heat to maintain supply water loop temperatures when the outdoor temperature approaches design conditions. Boilers are the common source for this additional heat, but design loop temperatures are as low as 70 - 85° F., while non-condensing commercial cast iron boilers do not operate below 140° F.

A dependable method for interconnecting this boiler loop with the system loop is through primary/secondary pumping techniques. By keeping the supply and return tees close together the pressure drops in the common piping are kept to a minimum. This allows different size pumps to coexist in the system without affecting each other as well as preventing ghost flows from occurring from one loop into the other.

BAS or Building Automation Systems are becoming the norm in most new construction or building renovation design. These systems control HVAC operation and equipment. The benefits of BAS include simplified wiring and piping in addition to energy-efficient operation, flexibility in meeting diverse building use, and increased occupant comfort. These benefits cannot be achieved unless the BAS and the personnel operating them properly understand the heating equipment and its controls. All phases and modes of operation must be anticipated prior to putting the heating system on line.

The capabilities and operating limitations of the equipment, regardless of the material of construction, must be understood and accounted for to avoid risks of equipment damage. Cast iron is a very convenient material to use in heating equipment. It offers longevity and excellent heat transfer characteristics at a reasonable price. However, it is a brittle material and cannot withstand significant abrupt temperature changes. Steel boilers are built from different grades of material. Welds expand and contract at rates different from the metal they join. Copper boilers, particularly operating with hard water conditions, must operate with minimum and maximum flow rates for long life.

BAS management personnel seem to understand the philosophy and operational sequence for loading and unloading chillers. However, when it comes to heating equipment, these units are treated as on/off appliances. For example, a boiler with an input rate of 4000 MBH is similar to a chiller rated 333 tons. No control program would allow the enabling and disabling of a 333-ton chiller to be controlled on/off. The chiller must be staged on and staged off. This is mandatory for boilers as well to insure safe and efficient operating equipment.

Following are some typical findings from projects where thermal stress has been suspected:

1. All systems had a reset schedule for the building system temperature based on the outdoors-ambient temperature. This resulted in boiler return temperatures that were lower than manufacturers' recommendations. Return temperatures as low as 90 degrees F. were tolerated in mild weather.

2. Boilers were oversized for the load, especially during the mild weather of spring and fall. This resulted in excess cyclic operation of the boiler, one of the key ingredients for a fatigue failure.

3. Burners' operating and modulating controls were improperly set in relation to one another, resulting in high burner cycling rates to high firing rates. Operation of the same boiler at the same outdoor temperature when the burner controls had been properly set showed that cyclic operation had been eliminated for the outdoor temperature in question. Burner firing rate, and hence stress level, was also reduced considerably. In this particular case, no further failures were experienced.

4. Electrical load shedding is a factor to be considered in systems where air handling units are shut down for many hours, allowing large volumes of water to cool down. On system restart, large volumes of relatively cold water can enter the boiler in a short period of time unless the proper preventive measures are taken.

PROTECTIVE MEASURES AGAINST THERMALLY INDUCED STRESS CYCLING (THERMAL SHOCK)

It may not always be possible to design a boiler structure within the confines of boiler design codes and at the same time encompass thermally induced operating stresses that fall below the fatigue limit of the materials of construction. This is especially true when one considers that heating system operating parameters controlled by the BAS are most often unknown to the boiler manufacturer. It then becomes necessary for the boiler manufacturer to set guidelines for the system-and-controls designers to use, in order to minimize these effects.

Typically these guidelines may include:

1. Maximum Delta T across the boiler.
2. A minimum water return temperature to the boiler.
3. A minimum water flow rate through the boiler.
4. Recommendations as to how to set burner controls to maximize the boiler shell temperature for a given operating pressure and minimize the number of operating cycles and the burner firing rate for a given load condition.

In designing a system, there are two key points to keep in mind. First, prolonged periods of low firing rates are preferred to a series of on-off cycles to high firing rates. Secondly, an attempt should be made to isolate the boiler as much as possible from system temperature changes.

These targets can be achieved in two steps:

1. Correctly setting the burner operating control in relationship to the boiler operating pressure and limiting the temperature of the water returning to the boiler below which the burner would be held at low fire to reduce stress levels. It should be noted that in some systems, design or operating parameters might preclude the use of low-fire hold devices, whether they are time delays or aquastats. This is due to the fact that the system will be unable to attain its design operating temperature without the burner being allowed to achieve higher firing rates. In this case a manually supervised start-up should be employed.
2. The common method of minimizing the effect of heating system temperature changes on boiler bulk water temperature is to use a two-loop system. One loop of the two-loop system is the boiler loop, which is operated at a constant temperature set in accordance with the guidelines referenced above.

Typically, this loop would have a minimum flow requirement imposed by the boiler manufacturer. (In the absence of a detailed knowledge of system operating parameters, a rule of thumb is 0.5 to 1.0 GPM per BHP, depending upon the boiler manufacturer.) This sabotages any tendency for temperature stratification within the boiler, as well as attempting to achieve the desired level of shell temperature.

The second loop is the building system(s) loop in which the temperature will vary in response to an outdoor temperature reset schedule, and in which flow rate may vary to meet energy conservation criteria. The interface between these two loops is usually either a three- or four-way valve, to which the building system temperature reset schedule is applied. This allows sufficient water from the hot boiler loop to blend with the cooler water returning from the building heating system to achieve the temperature requirements prevailing at any given time. Obviously, many system configurations will meet this basic concept.

Reducing the number of stress cycles is achieved first by correctly setting the burner operating and modulating controls in relation to one another. This means that the modulating control must not send the burner to the high fire position immediately after the operating control has initiated the firing sequence and the main flame is established.

When a BAS system is used to sequence the boilers and directly reset water temperature in relation to outdoor air temperature the three-way valve that can be a source of thermal stress may be eliminated.

With the BAS providing direct hot water reset the control designer needs to remember that he must not only reset the “enable” point of the boiler but also should reset the firing rate control to a set point slightly below the “enable” point. This step will prevent the burner from immediately driving to High Fire and the short-cycling and undue thermal stress consequence.

The second method of reducing the number of stress cycles is to carefully select boiler size and burner turndown rates (high-fire fuel flow/low-fire fuel flow) for a given boiler room. The heating season load profile must be matched, paying particular attention to the low-load segments in the spring and fall, as it is in these periods when there will be an inclination for the boiler/burner to cycle on and off more frequently. Selecting the number and size of boilers to suit a seasonal load profile may mean that the boilers will not all be of equal size, but rather a smaller boiler will be used in the spring and fall with larger boilers handling the high load of the winter months. Alternatively, a large number of smaller boilers may be used with a lead/lag control system (the modular approach). Properly selecting boiler sizes for a seasonal load profile has the added benefit of energy savings in terms of reduced heat loss from the boiler shell. It is always possible that financial constraints will preclude the ideal size selection of boilers and their numbers for a given installation. However, if this is kept in mind as a goal a better system will result.

CONCLUSION

Failures caused by what is commonly called thermal shock are actually fatigue malfunctions originated by thermally induced stress cycling. They are not an indication of boiler design or manufacturing deficiencies, as has been inferred on occasion, but are rather due to the manner in which the heating system has been designed, controlled or operated. In some cases, a lack of knowledge may be an explanation, while in others financial constraints may play a part.

Remember that a boiler is not a light bulb to be turned on and off in an effort to conserve energy. It is an engine that when warmed up and driven first at moderate speeds will provide both economy and long life.

ANDREW L. WOLF
AND THOMAS E. NEILL
APPLICATION ENGINEERING/
TECHNICAL SERVICES