CC® Retrofits and Optimal Controls for Hot Water Systems

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ABSTRACT

Boilers account for about 42% of space heating energy consumption in commercial and multifamily buildings in the U.S. Boilers are typically designed to be oversized, with redundant safety factors and without consideration of internal heat gains. Significant energy savings could be achieved by optimizing the selection of commercial boiler systems and utilizing proper operation and optimal controls. This paper presents a case study in which the boilers are significantly oversized. After implementing Continuous Commissioning (CC) technologies, three old boilers (13.39 MMBH each) were replaced by three new boilers (1.675 MMBH each) and hot water pumps. Optimal controls for the hot water systems included optimal hot water temperature reset, hot water pump speed decoupled control, and optimal enable/disable. Heating load and heating capacity were calculated based on EMCS recorded data and hourly measured water flow data. The measured hourly utility data show reductions in annual gas consumption and cost by 36% and 43%, respectively.

1. INTRODUCTION

Boilers account for about 42% of space heating energy consumption in the commercial and multifamily building sectors in the U.S. [1] Hot water systems, including boilers and hot water pumps, should be sized optimally to meet the maximum demand required by the facility through the heating season. In addition, most boilers are designed to operate at maximum efficiency when they generate the design output capacity in BTH. However, the boilers are usually sized with up to 50%~100% safety factors. The oversized boilers have short cycling which ultimately shortens the life of the system. Second, boiler efficiency decreases when short cycling occurs, because heat demand is smaller than the boiler output. Third, the overall seasonal efficiency is lower [2]. In terms of cost effectiveness, the maintenance and repair costs are higher due to the short cycling [3]. Fuel cost is also higher compared to the properly sized boilers since the radiation loss and standby loss are higher.

In addition to ensuring a properly sized boiler installed with high efficiency and maintained in good condition, optimal control strategies could also make the heating plant serve the facility energy efficiently. Liu et al. developed a series of CC measures for central heating plants. The primary CC measures include optimal supply water temperature and steam pressure, optimal feed water pump operation, optimal airside operation, optimal boiler staging and improved multiple heat exchanger operation [4~6].

The original building peak load for the case study building was 11 MMBH when the outside air temperature is -20 ºF. The building has three boilers installed (13.39 MMBH each) that have a safety factor of 1.15. The annual boiler gas energy cost is $105,778, which is twice the energy usage expected by the Continuous Commissioning team. The old and oversized boiler plant contributes to the high O&M costs. The temperature differential of the hot water supply and return temperatures was only 4.4 ºF at the time of the site visit. This indicates that significant pump energy is wasted.

This paper demonstrates the energy efficiency and cost effectiveness using a CC case study. First, the building information and control upgrades are introduced. Then, the optimal controls are presented for hot water systems including optimal hot water temperature reset, and hot water pump speed decoupled control and optimal staging. In addition, the implementation results are presented. The measured hourly utility data show that annual gas consumption is reduced by 36% and energy savings of 43% is realized.

2. SYSTEM DESCRIPTION

The case study building is located in Omaha, NE. The total gross floor area of the two-story shopping mall and office building is 231,333 ft^2.

A total of ten single fan dual-duct variable volume (VAV) air handling units (AHUs), with inlet guide vane installed, supply conditioned air to the entire building. The AHUs and central plants are shut down when the building is unoccupied based on the schedule. Both dual-duct CAV and VAV pressure independent terminal boxes serve the conditioned interior and exterior zones. Each AHU has design airflow of 45,000 CFM. The high gas usage is caused by a dual-duct system with CAV boxes, which is an outdated and inefficient technology. Pneumatic controls make the operation and maintenance more difficult and do not have sufficient capability to implement advanced higher efficiency control technologies.

The central hot water plant consists of three gas-fired fire-tube boilers (13.39 MMBH each), and three constant speed booster pumps. The central hot water plant supplies hot water to the heating coils for the AHUs. All hot water valves at the coils are three-way control valves.

The old central heating plant used to serve the case study building and an adjacent facility. The old boilers were sized as 13.39 MMBH each based on a peak heating load calculation of 11MMBH. There are three circulation hot water pumps and three secondary hot water pumps with design water flow rate of 1200 GPM. However, only two boilers had been used. After the adjacent part was removed, the old central plant wasted significant gas and electricity. The old and oversized boiler plant also contributes to the high O&M costs.

3. CONTROL UPGRADE

The Continuous Commissioning efforts were applied to a luxury shopping mall and office building from May 2006 to February 2007. A detailed energy study evaluation and calculation was done before the project. Comfort and energy consumption issues were identified and advanced technologies were developed as solutions based on comprehensive measurement and evaluation. To realize optimal control and better building energy operation and energy performance, a series of CC retrofits were done as described below.

First, after consideration of the downsizing of the serving area of the central hot water plant and implementation of innovative CC technologies, the design load was reduced to 4.5 MMBTH. The three old boilers were replaced by a network of three smaller packaged steel fire-tube Modular hot water boilers with 1.675 MMBTH each. The new boilers are designed at 167 GPM water flow, 200 ºF supply water temperature and 135 ºF return water temperature. Modular boilers can be fired independently, and each module could be fired on demand at full capacity with load fluctuations being met by firing more or fewer burners. If the first burner cannot keep up with the heat demand, a second burner will be kicked on to take care of the extra heating load. Also, modular boilers have low thermal inertia which provides rapid response and low heat-up and cool-down losses. Outdoor temperature fluctuations during the heating season reduce the seasonal efficiency of even optimally sized boilers and boiler systems. There are relatively few periods during the heating season when it will be running at its rated output or point of maximum efficiency.

Second, the old hot water pumps were replaced by two new booster pumps with VFDs installed. The design water flow for the booster pump is 510 GPM. In addition, there were three circulation pumps attached to the three boilers. One differential pressure sensor was installed between the supply and return hot water pipes. All hot water valves at the heating coils were converted from three-way valves to two-way valves.

The air side CC retrofits is referenced in another paper [7]. The main CC measures related to gas usage reduction are a main hot air damper in the hot duct to isolate hot air in summer, a VFD on the supply and return fans, supply air temperature reset and commissioning of terminal boxes.

4. OPTIMAL CC CONTROL STRATEGY AND IMPLEMENTATION RESULTS

Fig. 1 shows the schematic diagram of the hot water system. The hot water system includes three gas-fired fire-tube boilers with one constant speed circulation hot water pump each, and two booster pumps with VFD installed after CC retrofits. Since the boilers, pumps and control are all upgraded, only the control algorithm after CC is presented here.

4.1 Optimal CC Measures

Boiler enable/disable.

For each AHU, the hot deck is enabled when the outside air temperature is lower than the enable set point, which is typically 60 ºF but different based on the serving area orientation. When the AHU is enabled based on the occupancy schedule and the hot deck is enabled, the AHU sends out a heating call for the hot water system. The hot water system is enabled when at least one AHU heating call is on. Disable the boilers when none of the AHU heating calls is on. Turn off the hot water pumps when the boilers are off.

Hot water supply temperature set point reset.

Hot water temperature is one of the most important safety parameters for a central heating plant. The hot water supply temperature is reset based on the outside air temperature. Under partial load when the outside air temperature is lower, there are numerous benefits in lowering the supply water temperature reset: 1) Improve plant safety, 2) Increase boiler efficiency and decrease source energy consumption, and 3) Reduce hot water leakage though the malfunctioning valves. Fig. 2 shows the optimized hot water supply temperature reset schedule based on the outside air temperature.

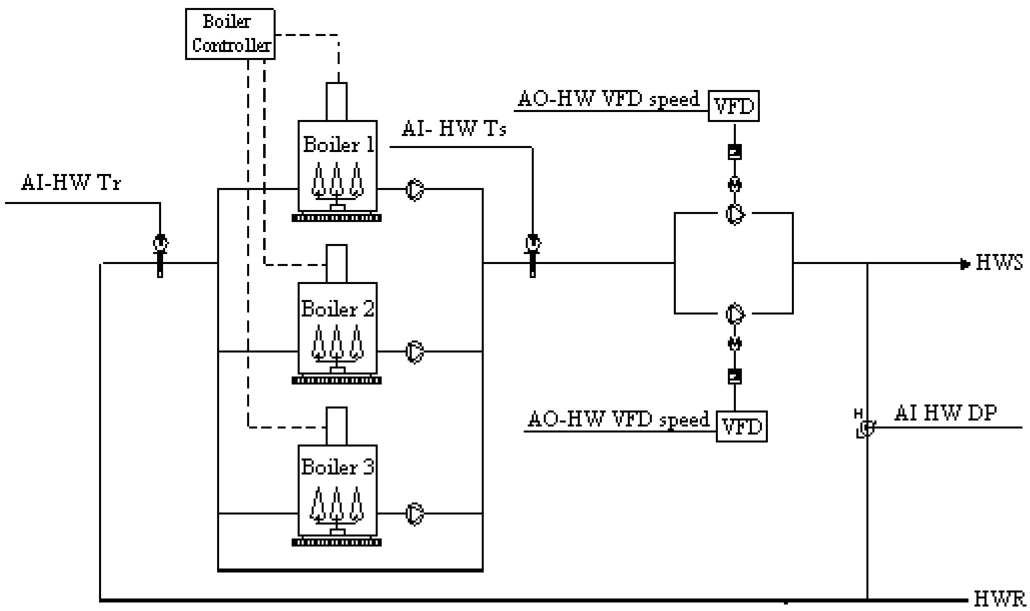

Fig. 1 Schematic Diagram of the Hot Water System

Optimize booster pump operation.

In a variable water volume system, it is typical to modulate booster pump speed to maintain the loop differential pressure. The maximum set point is the summation of the total pressure loss along the whole pipe downstream and the pressure loss through the control valves at the end of the run. However, under partial load conditions, the heating control valves have to be closed more since the required water flow is less than the design water flow. According to the affinity law, the pressure loss is proportional to the square of the water flow ratio at the similarity point. So the constant differential pressure set point could lead to more pump power consumption due to higher pump head, and more actual water flow. The increased actual water flow also results in more cooling energy consumption since the dual-duct systems will compensate for each other. Therefore, the differential pressure should be reset lower.

The goal of the pump optimization control is also to reduce the pressure loss through the heating control valve while providing enough water flow to the building, coil or other end user.

In this case, the optimization of the pump speed is done as follows:

1) Inspect the heating control valves at the coils. Convert all three-way valves to two-way valves by cutting the bypass line.

2) Identify the coil that calls for the highest differential pressure to deliver the required flow. Open all manual valves between this coil and the building pump. Check the coil supply air temperature set point. If the set point is lower than the design value, reset it back to the normal value.

3) Reset the differential pressure of the loop to let at least one hot water valve be 95%

open. It should be noted that the worse case is not necessarily at the end of the loop due to the load diversity.

Optimized Boiler Staging.

Boiler staging involves boiler shut-off, start-up and standby. Since there are large thermal inertia and temperature changes between shut-off, standby and normal operation, one should avoid running the boiler at a load ratio less than 40% or higher than 90%. The standby loss is small in comparison to useful output when boilers operate at or near their rated capacity, but it can be significant when boilers operate frequently at low loads [2].

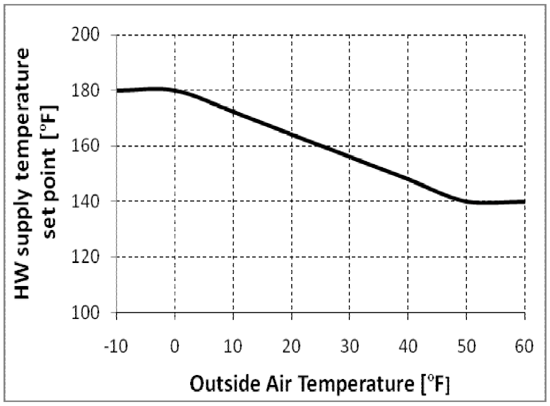

Fig. 2 Hot Water Supply Temperature Reset Schedule

The optimal control logic is as follows:

When the hot water system is enabled, turn on the lead hot water pump,

1) Enable the leading boiler.

a. Set the pump speed low limit at 35%. Reset hot water supply temperature based on outside air temperature as shown in Fig.2. Modulate the hot water valve to maintain hot deck supply temperature at AHU. Reset hot water loop differential pressure based on valve position. The goal is to open the hot water valve as more as possible. Then modulate the pump speed to maintain the differential pressure at its set point. If the hot water temperature is higher than 180 ºF, go to step 1b.

b. Maintain the supply water temperature at 180 ºF and modulate the pump speed to maintain the differential pressure set point which is reset to ensure at least one hot water valve is at least 90% open. If the pump speed is below 30% go to step 1a. If the pump speed is higher than 40% for 10 minutes, go to step 2.

2) Enable the second boiler.

a. Set the pump speed at 55% and modulate the hot water valve to maintain the hot air temperature. Modulate the hot water pump speed to maintain the differential pressure at its set point which is reset based on the valve position. If the hot water temperature is maintained at 180 ºF and the remote resistant hot air temperature is 3 ºF below the set point for 5 minutes, go to step 2b. If the hot water temperature is below 140 ºF, disable this boiler. Set the pump speed at 35%, and go to step 1b.

b. Maintain the supply water temperature at 180 ºF and modulate the pump speed to maintain the differential pressure set point. If the pump speed is below 50%, go to step 2a. If the pump speed is above 60% for 10 minutes and the remote resistant hot air temperature is 3 ºF below the set point, go to step3.

3) Enable the third boiler.

a. Set the pump speed at 75% and modulate the hot water valve to maintain the hot air temperature. Modulate the hot water pump speed to maintain the differential pressure at its set point which is reset based on the valve position. If the hot water temperature is maintained at 180 ºF and the remote resistant hot air temperature is 3 ºF below the set point for 5 minutes, go to step 3b. If the hot water temperature is below 140 ºF, disable this boiler. Set the pump speed at 55%, and go to step2a.

b. Maintain the supply water temperature at 180 ºF and modulate the pump seed to maintain the differential pressure set point. If the pump speed is below 70% go to step 3a.

4.2 Implementation Results

Hot water flow.

The hot water flow rate was trended using an ultrasonic flow meter from January 25 to February 12 to verify the central hot water plan capacity. Fig. 3 shows the hot water flow trending data from Feb. 1 to Feb. 3, 2007.

With room thermal comfort maintained, the pump power is reduced significantly under partial load due to the reduced water flow.

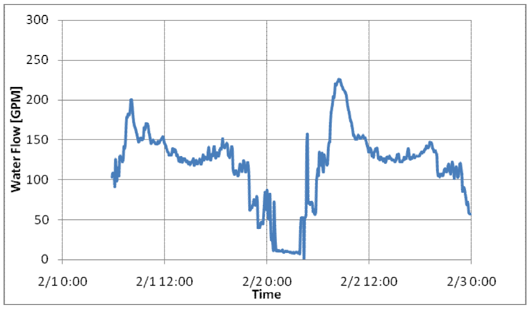

Fig. 3 Hot Water Flow Trending Data from 02/01 to 02/03

Hot water temperature.

The supply and return hot water temperature was logged for several weeks. Fig. 4 shows the hot water supply and return temperature on Nov. 29, 2006. It should be noted that the temperature was measured at the surface of the hot water pipe. The actual hot water supply temperature low limit is 140 ºF.

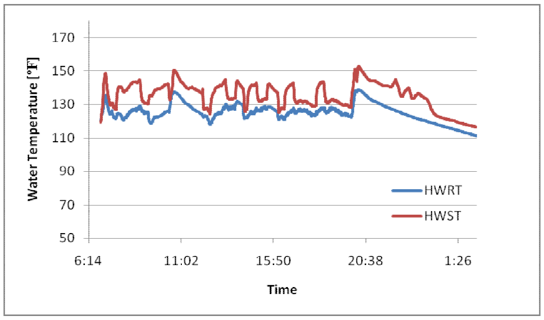

Fig. 4 Hot Water Supply and Return Temperature Data on 11/29/06

Hot deck supply air temperature.

The air side is integrated with the water side. The detailed control strategy of the hot deck air is described in another paper [7]. After the replacement of the new boilers, all AHU hot deck air temperatures could be well maintained well. Fig. 5 shows the hot deck supply air temperature on Dec. 27, 2006.

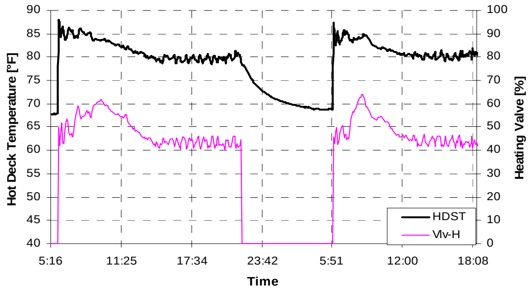

Fig. 5 Hot Deck Supply Air Temperature Data on 12/27/06

Gas savings.

The measured hourly utility data show that annual gas consumption is reduced by up to 36% and gas expenses are reduced by as much as 43%, as shown in Figs. 6 and 7, even including the control upgrade period. For the months considered, the gas consumption savings is 52,000 therms while the gas cost savings is $45,738 in total.

It should be pointed out that the gas savings are not only from the optimal CC measures but also from the CC retrofits.

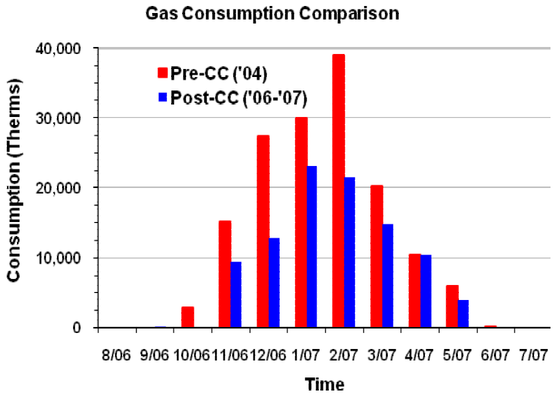

Fig. 6 Gas Consumption Comparison Before and After CC

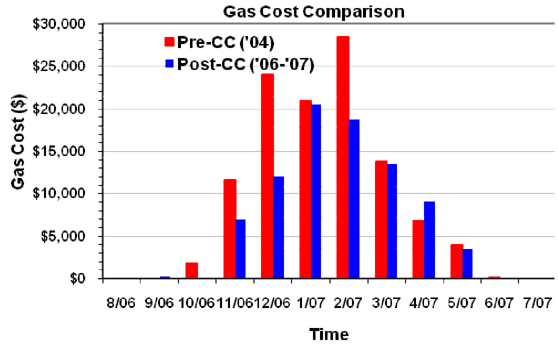

Fig. 7 Gas Cost Comparison Before and After CC

The post-CC gas rate is higher than the pre-CC gas rate. For example, the pre-CC gas rate in January 2004 was 0.7 \$/therm while the post-CC gas rate in January 2007 was 0.89 \$/therm. The pre-CC gas rate in December 2004 was 0.88 \$/therm while the post-CC gas rate in January 2006 was 0.94 \$/therm.

It also needs to be pointed out that the outdoor average temperature in the winter after CC is lower than the baseline case, as shown in Fig. 8.

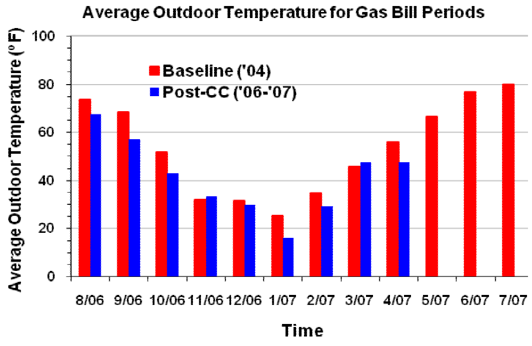

Fig. 8 Average Outdoor Temperature Before and After CC

CONCLUSIONS

This paper demonstrates the energy efficiency and cost effectiveness using a CC case study. Significant energy savings can be achieved by optimizing the selection of commercial boiler systems at the time of boiler replacement and utilizing optimal hot water control measures.

After the CC evaluation and retrofits, the three old hot water boilers (13.39 MMBH each) of the facility were replaced by three new boilers (1.675 MMBH each), with the hot water pumps replaced accordingly. The optimal controls for hot water systems include optimal hot water temperature reset, hot water pump speed decoupled control and boiler optimal staging. The measured hourly utility data show that annual gas consumption is reduced by 36% and gas expenses are reduced by 43%.

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