RC25481 (IRE1406-021) June 26, 2014
Other

IBM Research Report

An Effective Method for the Characterisation of Smart Building Hot Water Provisioning Systems through Analysis of Loop Return Temperature at High Temporal Resolution

Niall Brady
IBM Research
Smarter Cities Technology Centre
Mulhuddart
Dublin 15, Ireland

An Effective Method for the Characterisation of Smart Building Hot Water Provisioning Systems through Analysis of Loop Return Temperature at High Temporal Resolution

Niall Brady bradynl@ie.ibm.com
1st June 2014

Abstract — *Most campus type building environments operate large boiler estates either centrally or individually within buildings, in the provisioning of Low Pressure Hot Water (LPHW) services to their sites. And despite the fact that boilers occupy one of the top significant energy users in any building estate listing, it is contended that in general the level of understanding within the Facilities Management communities around boiler operation and their control is less well understood than their electricity related energy user counterparts, due to a number of reasons. This paper presents a pragmatic efficient data driven approach to address this deficiency, through the presentation of a simplified data analysis approach, using high resolution sampling (periods of one minute) of a single control point, that of LPHW Loop Return temperature (T_{return}) to adequately characterise hot water provisioning systems. A subsequent set of time series T_{return} profiles are presented and discussed that demonstrate the effectiveness and value of such an approach. Also one example of how this insight can be converted into an actual savings opportunity is presented where the leveraging of zero heating demand event signatures can achieve savings of the order of 100 MWh in one building alone during a summer season. The paper also contends that such an approach could become an important element of Smart Building hot water provisioning optimisation in the future, where the development and use a library of such time series T_{return} profiles could help identify realtime anomalous control behaviour, and allow for automatic dynamic demand response control strategies to be implemented.*

Keywords : Smart, Building, Gas, Energy Boiler, Hot, Water, Return, Temperature, Demand

1. Introduction

Commercial office buildings account for nearly 40% of all worldwide energy consumption **[1] [2]**. Within this percentage, the use of natural gas in boiler systems contributes significantly to this building usage percentage. In the UK for example about a third of the country's energy consumption is in the provisioning of hot water services (and an even higher percentages in the winter heating season) **[3]**. Yet, in many large campus environments operating sizable boiler estates in the provisioning of LPHW services, levels of awareness of boiler operations, and their performance, among the facilities support teams tended in general to be less well understood than their electricity based significant energy users counterparts. This is understandable, for a variety of reasons but is mainly due to the high reliability levels associated with the gas boiler operations, where boiler rooms were managed as lights out operations, and visits to boiler rooms tended to be limited to biannual PM's or in response to occasional boiler trip alarms. As a result the level of experience and subsequent understanding of boiler operational efficiencies for many companies, not having onsite domain expertise, is generally not as high as it could be. And this coupled with the relatively low comparative pricing of natural gas versus electricity has made gas saving project opportunities less attractive and as a consequence have been somewhat overlooked as a significant contributor to an organisation's overall energy conservation programs.

Lack of available usable meter and sensor data, including basic realtime gas usage reporting is also a contributory factor to this problem, where it is a quite common experience for Energy Managers to be faced with unexplained "after the fact" usage peaks, or unawareness of impending breaches or actual exceeding daily capacity limits which incur additional charges, issues that do not become apparent until the next billing cycle, which can be several months after the event, and obviously too late for any cost avoidance interventions.

So this paper attempts to help address this understanding deficit by presenting a pragmatic and efficient approach to assist Facilities Management teams better understand their boilers and hot water provisioning estates, with the view to improve their management and a subsequent lowering of their natural gas energy usage.

2. General Boiler Control Elements Review

While there are obviously a combination of both high pressure and low pressure systems in use in the provisioning of hot water services in commercial buildings today, the approach presented here is based on the authors experiences with LPHW systems, but the approach is also considered relevant to Low High Pressure systems.

2.1 Boiler Controls Strategy

All boilers, high pressure or low pressure operate around controlling to a temperature setpoint. As a result all boilers will have a thermostat controlling boiler temperature (in addition mechanical thermostat safety interlocked in case of electronic failure that would cause unsafe over temperature scenarios).

The older boiler controller types tended to operate either as single stage (“burner 100% on or off”) arrangements, or use a two stage control strategy where the burner operated in two stages, high flame and low flame, and where there was a second thermostat to switch the burner between a low fire (typically 40%) and a high fire position (100%) **[4]**.
This arrangement suits good matching of baseloads to boiler system capacities particularly during high demand winter months where there are very significant baseloads but becomes very inefficient when working on very low baseloads, during the summer months which can lead to very high incidences of short cycling **[5]**.

So today most modern boilers operate with some form of automatic flame controller which typically consists of a physically coupled (through the use of mechanical linkage rod arrangement) gas control valve and an air butterfly valve, both driven by a servomotor that modulates the firing output as per a predefined control strategy that is aimed at ideally continually matching boiler output to meet the current loop heat demand.

The burner is designed to operate to a control set point and achievement of that setpoint is managed in normal scenarios by an industry standard controller which uses standard proportional/ integral/derivative PID **[6]** controller hardware and controller settings to maintain an output around a designated setpoint.

While it is possible to optimise these PID settings to best match likely building demand profiles, and to minimise possible boiler starts, and subsequently reduce natural gas energy usage **[7]**, detailed investigation into this energy saving opportunity was considered outside the scope of this paper.

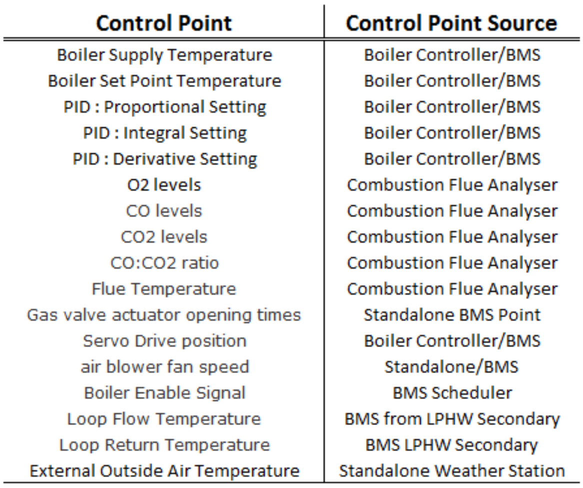
2.2 LPHW Control Strategy Datapoint Availability

While the basic boiler control strategy of controlling to a temperature setpoint as outlined above is relatively straightforward to understand, extracting or making this fundamental boiler control data visible, and available for analysis may not be straightforward. This is due to the fact that either the controls are purely mechanical or subject to proprietary non open control systems that make it difficult to extract the actual temperature data. Or, as is the case in many cases facilities operating Building

Management Systems, while such boiler control data is available, many do have additional data historian capabilities or see the need to apply such capabilities to record such historical boiler performance.

There are many additional control data points that are provided and are used to improve boiler control and improve boiler efficiency, and ultimately natural gas energy usage, and a non exhaustive list of these control points are summarised in Table 1 below.

Table 1 : LPHW Provisioning Control Point Listing



Control Point	Control Point Source
Boiler Supply Temperature	Boiler Controller/BMS
Boiler Set Point Temperature	Boiler Controller/BMS
PID : Proportional Setting	Boiler Controller/BMS
PID : Integral Setting	Boiler Controller/BMS
PID : Derivative Setting	Boiler Controller/BMS
O2 levels	Combustion Flue Analyser
CO levels	Combustion Flue Analyser
CO2 levels	Combustion Flue Analyser
CO:CO2 ratio	Combustion Flue Analyser
Flue Temperature	Combustion Flue Analyser
Gas valve actuator opening times	Standalone BMS Point
Servo Drive position	Boiler Controller/BMS
air blower fan speed	Standalone/BMS
Boiler Enable Signal	BMS Scheduler
Loop Flow Temperature	BMS from LPHW Secondary
Loop Return Temperature	BMS LPHW Secondary
External Outside Air Temperature	Standalone Weather Station

2.3 LPHW Loop Return Temperature Control Point : Energy Demand Proxy

Inline heat metering is the known preferred method for calculating the actual heat energy provided to the LPHW loop on an ongoing basis, where with a combination of delta T information $(T_{flow} - T_{return})$ and water flow, rates q, the Kwh energy usage can be calculated as per formula 1 presented below.

However the cost of installing heat meters can be expensive, disruptive and time consuming (installing the inline flow meter can be disruptive requiring the pipe cutting and possible loop drain down) although the availability now of ultrasonic meters is making this less of a problem.

The relationship between delivered kilowatts of heating energy to system flow rates and loop flow and return temperature is given as follows

$$h = q * c_p * \rho * (T_{flow} - T_{return}) \quad \ldots\ldots.(1)$$

where

h = heat flow rate (Kw)
c_p = specific heat capacity (kJ/kg ^oC)
ρ = density (kg/m^{3})
q = flow rate (m^3/s)

However if one considers that for the most part the T_{flow} will remain relatively constant and in normal steady state operation the flow rates q, remain stable within a relatively narrow range, the only truly moving variable, and as such would be considered a good proxy for LPWH demand, h, would be T_{return} alone, so formula 1 simplified becomes

$$h \sim T_{return} \quad \ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

So it is contended, as the following examples will confirm, that the effectivity of using T_{return} alone as a good proxy for building heating demand, and sampled at high enough frequency (at 1 minute intervals), is sufficient to characterise a building’s hot water provisioning system.

Furthermore, the additional benefit of using just T_{return} approach, is the fact that this control point is relatively easy to monitor, completely independently, and external to existing control systems, be it boiler or building management. Simply by using a standalone data logger and by just attaching a single channel pipe temperature probe to an appropriate location on the LPHW return loop piping, set up to measure one minute intervals, it is possible within one week to establish a good understanding of the LPHW loop and boiler operation and control performance. In fact there are now very effective low cost wireless data logging solutions , like one such system from Episensor **[8]** that allow this logging solution to be deployed (and without the need for any additional electrical installation works), to have live data visible on a remote

web based interface within minutes. A week’s volume of data logs is sufficient to establish a significant level of insight into boiler and LPHW loop system performance.
And as will be outlined in the following section this simplified approach to the new founded understanding will allow the Facilities management community the ability to quickly and efficiently, and without the need for additional domain expertise input, efficiently identify significant saving opportunities on systems that have until now for the most part have remained untapped for the reasons outlined in the earlier section.

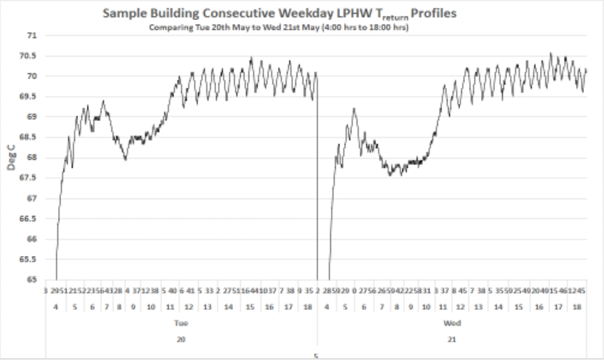
3.0 Building LPHW Characterisation through T_{return} Analysis

The following section presents the time series T_{return} data profiles and followon commentary from data taken from the sample building

3.1 General T_{return} Time Series Profile Review

Figure 1 below shows time series samples of two consecutive LPHW T_{return} daily profiles from one of the case study buildings, from data acquired using an line North Commander **[9]** connected into the building’s BMS network.

Figure 1 : Consecutive weekday T_{return} profiles examples



Taking the simplicity of the approach one can quite quickly establish from just the visualisation of this two day snapshot alone, a number of key observations around the LPHW system performance within this sample building.

So the T_{return} time series plots for this sample system at first pass provides;

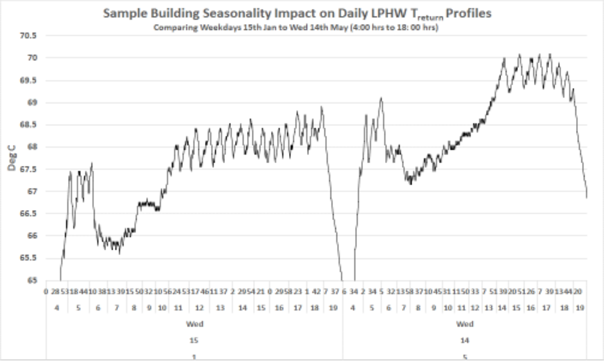
1. An estimate of the duty boiler temperature control point – in this sample building where the setpoint is close to 71 deg C – this information can be used effectively in ensuring that all site based boilers setpoints are appropriately benchmarked – this may represent a savings opportunity in certain buildings or generally if setpoints are set too high **[10]**.
2. The relative building operation schedule information - this is clearly visible from the sample profile, with system starting at 4am and running through to 6pm in the evening.
   And although not apparent in this example, any unexpected out of hours operation of the system could be picked up here – e.g. validation of proper frost and fabric protection system activation during sub zero winter month nights.
3. Ability to highlight schedule discrepancies – in thi example there is a clear mismatch in the enabling of the system at 4am and the beginning of the heat load centre startup (likely to be the main AHU’s) at 7am – this represents a savings opportunity in this building
4. Visiblity of system demand events – there is a clear morning demand load period from 7am in the plots, and probably relates to the main AHU’s starting up and high heating valve % events where the level of demand is high, and the T_{return} drops significantly as the AHU heating valves open to meet morning load.
5. Ability to identify burner stop start events, by identifying peaks in the time series profile as the burner kicksin to achieve boiler control setpoint

6. Ability to identify short cycling events - there are short cycling events present in the plots represented by the high frequency oscillations post midday onwards from both days. It is estimated that there are 17 daily starts in evidence in the sample plot within the day which would be considered excessive **[11]** – this is due to low or no load events and is discussed in more depth in the Section 3.3 below.
7. Pattern recognition – comparative similarity in profiles is observable between the consecutive days and similarity within day characteristics are also in evidence. For example there is a shift in demand pattern post midday as the building warms up and the AHU heating demand reduces – exploitation of this effect will form the basis of major energy savings opportunity discussed later in Section 3.3 below.

3.2 Seasonal Effects T_{return} Time Series Profile Review

Broadening out this analysis to cover weekly, monthly or seasonal considerations is the logical next step as the data logfile builds over time to give further insight as to the longer term effects on LPHW loop performance due to things like average ambient air changes impacting building demand. Here, the summer seasonal effect of lower building demand correlating strongly with increasing average outside air temperatures should be apparent **[12]**, as is the case with this sample building as seen in Figure 2 below.

Figure 2 : Seasonality Impacts on T_{return} profiles examples



In Figure 2 one can see the heavier demand being in evidence as represented by an overall shift downwards in the T_{return} profile, as a result of the greater AHU morning loads in the winter where more heat is needed to heat the building during the colder winter months.

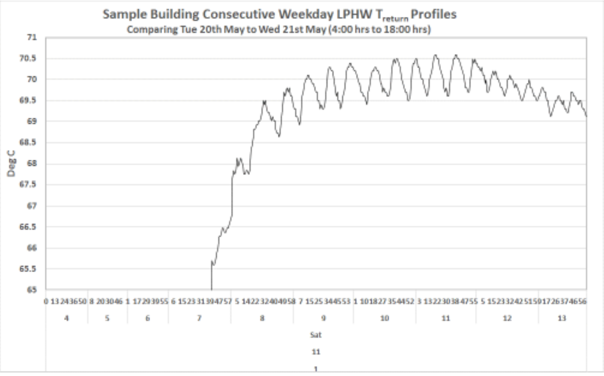
In fact failure to demonstrate this seasonality in the T return is an indicator of either incorrect LPHW system control strategy, or possible presence of a continuous rogue demand source like a faulty or passing heating valve on an AHU which causes additional unnecessary heating demand during expected lower demand periods, like in the summer months.

3.3. Building No Load T_{return} Time Series Profile Review

One of the key requirements in relation to proper use of this T_{return} profiling approach to identify the significant energy saving opportunities, is the requirement to establish the building no load signature i.e. to be able to determine from the T_{return} profiles when the building is approaching or has reached zero demand conditions.

While it is possible to extract the zero no load signature from the existing data set, and has probably already been identified in the observations from Figure 1 discussed above, it is probably best to attain this information through offline experimentation, where one would continue to run the building’s LPHW systems beyond normal office hours or weekends, when there is known to be no scheduled load on the system, while continuing to log T_{return} . The no load T_{return} time series for the sample building is presented in Figure 3 below.

Figure 3 : Building No Load T_{return} Signature

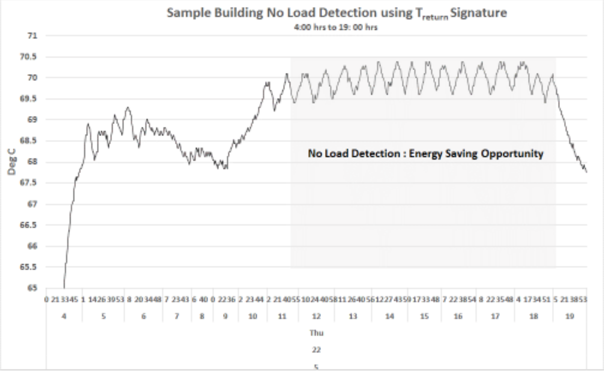


In Figure 3 one can see that the resultant zero load signature for this building is characterised as an oscillating T_{return} signal temperature (from 9am), with a periodicity of 20 minutes, and a one degree peak-to-peak amplitude, above 69.5 deg C, this is due to the boiler short cycling brought about the low demand conditions, manifested as a series of increased frequency of boiler starts during the no load period.

In fact this in itself highlights an issue with regard to the current low/no load control strategy deployed within this system, and warrants further investigation to reduce the number of these excessive boiler starts.

Having this no load signature information now allows the user to detect no demand scenarios through analysis of the T return profile alone, and establish opportunities for significant energy savings as is shown in Figure 4 below.

Figure 4 : Building No Load Savings Opportunity



Here, in Figure 4 it is clear, that from midday on the sample day in May, that the no load signature was clearly in evidence in the time series plot. Detecting the presence of this zero demand condition allows for intervention to realise this 6 hour energy saving opportunity. This saving can be realised by either, disabling the boiler completely, or setting back the boiler to a predetermined zero demand alternative control strategy. Using actual gas usage readings it is possible to directly quantify these energy savings which for the target building in question turned out to be very significant. In this case the boiler was actually disabled during the no load conditions, which resulted in savings of between 1Mwh and 2Mwh per day, which equated to over 100 MWh alone over a complete summer season which is substantial.

In time, it is expected that these no load scenarios can be detected automatically and built into the control strategies so that they can be dynamically adjusted throughout the day, or minimally manually switched between summer and winter seasons, to maximise these very substantial energy savings opportunities.

4.0 Conclusion

It is contended that through making use of a single data control point, that of T_{return} , the Loop Return Temperature alone, sampled at a high resolution of 1 minute, that characterisation of building hot water provision systems can be effectively and efficiently achieved.

The presented approach which works with both directly acquired data through the building management or boiler control systems, or indirectly through readily available single channel dataloggers, is considered both a pragmatic and cost effective means for the Facilities or Energy Managers to begin to quickly gain the insight required to achieve very significant energy savings opportunities through system control and demand anomaly detection.

Furthermore, within a Smart Building environment, the notion of the further development of a future library of these time series T_{return} profiles, and by applying existing and future signal processing analysis techniques to these profiles, could enable scenarios for automated dynamic demand response, efficient system benchmarking across estates, and the concept of a system diagnoser that could be deployed on a temporary basis to diagnose non normal control behaviour by analysis of historical logged T_{return} data. In whatever mode, the value and analysis of T_{return} will allow the Facilities Management community to fully exploit the savings opportunities quicker and easier to achieve greater insight, thus redressing the balance between the understanding levels of electricity and gas usage within buildings.

5.0 References

1. IEA Report, "Energy Efficiency Requirements in Building Codes" P10, March 2010
2. Lombard, L., Ortiz, J, Pout, C., "A Review on Buildings energy consumption information", Energy and Buildings Journal, Elsevier, Jan 2007
3. Carbon Trust Best Practice, "Low Temperature Hot Water Boilers Guide" P4, March 2012
4. M Bora, S. Nakkeeran, " Performance Analysis From The Efficiency Estimation of Coal Fired Boiler", International Journal of Advanced Research (2014), Volume 2, Issue 5, 561-574
5. US Department of Energy "Minimize Boiler Short Cycling Losses", Advanced Manufacturing Office, Steam Tip Sheet 16, Jan 2012
6. "PID Theory Explained", National Instruments White Paper, March 2011, http://www.ni.com/white-paper/3782/en/
7. www.facilitiesnet.com, "Boilers Focus on Efficiency", February 2008, http://www.facilitiesnet.com/energyefficiency/article/Boilers-Focus-on-Efficiency--8263#
8. Cowan, J., "M2M smart services management platform acts as new gateway to energy monitoring system", M2M Website Episensor NGR 30 Wireless Gateway reference, October 2013
9. Archetech Magazine, "Heating and Cooling Fight" - Issue 14 P54 and the North Commander solution reference, March 2014, http://issuu.com/archetechmagazine/docs/archetech_issue14
10. Tabrizi, D. "Boiler systems: Economics and Efficiencies", June 2012, http://www.csemag.com/home/single-article/boiler-systems-economics-and-efficiencies/882702317f45aa774eb70b797efe75bd.html
11. Baldwin, J. Eureko Controls "Ascon Boiler Controller Setup and Optimisation conversation", December 2012
12. Cox, Drews, Rode, "Simple future weather files for estimating heating and cooling demand", Build and Environment Journal, Elsevier, April 2014