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Monitoring The Effect Of Gas Boiler Efficiency Modifiers In Field Trials

A low-cost approach using open source hardware

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***Abstract*—This work presents a method of collecting and processing data from a domestic gas boiler that allows the detection of small changes in boiler efficiency even with large changes in usage patterns. It is applicable to both field trials and controlled conditions. It combines unobtrusive data collection with two different methods of assessing the performance of a gas boiler – calorimetry and flue gas temperature.**

It uses low cost open source hardware and software that allows remote monitoring and makes large-scale deployment practical. The impact of key uncontrolled variables is modeled using publicly available data to achieve the required accuracy.

The method presented could be extended to measure the Heat Transfer Coefficient (also called Heat Loss Parameter) of a building using the building's own heating system in lieu of a co-heating test.

Keywords — domestic; gas boiler; efficiency; open source; EN677; Open Energy Monitor; Arduino; Rasberry Pi; field trials; energy monitoring; cost effective; in-situ; heat loss; Heat Loss Parameter (HLP); Heat Transfer Coefficient (HTC); co-heating; performance gap; radiator performance; heat distribution;

I. Introduction

A. Context

In the UK in 2017, natural gas accounted for 74% of final space heating energy and 84% of water heating [1]. In 2018, 85% of UK homes were connected to the gas grid [2] and 77% had a gas boiler [4]. Even small improvements to the efficiency of gas boilers have significant potential to save money and reduce carbon emissions if widely adopted. The typical life of a modern domestic gas boiler is 14 - 15 years [3] [5] so any technology that can improve efficiency without replacing the boiler has the potential to accelerate decarbonisation.

B. Problem Statement

A range of add-on products exist on the market that are claimed to improve heating system performance. Approaches include modifications to the heat transfer fluid (dirt removal, oxygen scavenging, de-aeration, micro-bubble removal [14], substitution of water with other fluids), flue gas heat recovery, cleaning (cleaning solutions, power flushing, filtration, magnetic particle separation) and changes to boiler controls[1]. In some cases the efficiency improvement claimed by the manufacturer has not been independently verified, or is based on anecdotal evidence. Some manufacturers claim efficiency improvements that would result in a thermal efficiency >100% when applied to a modern condensing boiler.

There is a need for a method for independent testing of boiler efficiency modifiers. At present there are no British Standards (BS) or European Standards (EN) standards for this type of testing. The effectiveness of boiler efficiency modifiers often depends on factors such as dirt build-up, scaling, usage patterns, boiler cycling and radiator performance that are difficult to replicate in a laboratory setting.

Field trials comparing gas consumption before and after installation of the performance modifier ensure that these effects are included. Improvements in efficiency caused by the performance modifier are unlikely to exceed 10%, whereas variation in gas consumption caused by changes weather and usage patterns are as much as 30%. Simply comparing gas consumption before and after installation is not a reliable test.

The most basic improvement is to use degree-day data (or thermal modelling and local weather data) to adjust for the effect of weather on space heating energy consumption. A further improvement is metering of hot water consumption. In practice, none of these methods are accurate enough to detect small changes in boiler efficiency.

Another approach [6] is the use of a specialized test house constructed inside an environmental test chamber, such as the Salford University 'Energy House'. This approach is highly accurate but is limited by the cost and availability of specialised testing facilities.

Field trials are also affected by other uncontrolled variables. For example, it's common practice for plumbers to drain and flush the heating system and add a corrosion inhibitor in the course of installing a new device into a central heating system and tests

[1] https://www.energysgroup.com/technologies/boiler-controls/

undertaken by Mayer (2013) [7] suggest that this intervention alone can result in a 5-10% change in gas consumption.

C. Proposed Solution

The gas boiler under test is fitted with a heat meter, a gas meter and temperature probes for flow, return and flue temperatures. Data from these instruments is collected by open-source, web connected energy monitoring hardware from the Open Energy Monitor project[2].

The data is processed to extract a continuous estimation of the operating efficiency of the gas boiler and the performance of the boiler's heat exchanger. Publically available data on the calorific value of the natural gas in the supply network is used to mitigate the effect of variations in gas composition and publically available weather data is used to compensate for changes in barometric pressure.

The result is a multi-dimensional picture of the performance of the boiler across its full operating range that is not affected by changes in the heat demand of the building.

II. Method

A. Gas Boiler Testing Standards

The European Standards EN677 and the relevant requirements of EN297, EN483 and EN625 define a procedure for full-load efficiency testing of domestic gas boilers under laboratory conditions. This is the method used to produce the Product Characteristics Database (PCDB, formerly 'SEDBUK') efficiency rating of all new boilers for the UK market.

Two types of test are conducted – one with a high flow temperature to avoid condensation, and one in condensing mode with a lower flow temperature. The boilers are run on bottled G39 test gas and extensively instrumented with flue gas analysers, heat and gas metering and weighing of the collected condensate. Both calorimetry and flue gas analysis methods are used to measure thermal efficiency. The results of these two methods are compared in order to estimate the error in the test method.

In order to make the method applicable to field trials some changes from the laboratory method are required.

1. The use of bottled test gas is not practical because this requires re-configuring and re-plumbing the gas supply to the boiler. Mains gas must be used.
2. Flue gas analysis is not practical for long-term monitoring and poses safety problems, so this method of assessing efficiency cannot be used.
3. Continuous weighing of the condensate would require equipment similar to an automatic rain gauge, and this information would not meaningfully improve efficiency estimation without flue-gas analysis.
4. The boiler is not operated under steady state conditions.

[2] https://openenergymonitor.org/

B. Experimental Design

Two partially-independent methods of assessing the performance of a gas boiler are used. If both of these measures show an improvement then it is likely that the performance modifier was effective.

One way to assess the performance of a boiler is its thermal efficiency. This can be expressed by the following equation:

$$\eta = \frac{Q_{\text{in}}}{Q_{out}} = \frac{Q_{gas} + Q_{electricity}}{Q_{water}}$$

Where η is the thermal efficiency, Q_{gas} the chemical energy supplied from natural gas, $Q_{electricity}$ is the electrical energy supplied to operate pumps and fans and Q_{water} is the useful heat delivered to the building. The efficiency of the boiler depends on a range of factors including firing rate, flow and return temperatures and the flow rate of the pump.

Another way is based on the principle that any heat not captured by the boiler heat exchanger leaves as hot flue gasses, reducing efficiency. The relevant parameter is the heat transfer coefficient of the boiler heat exchanger (Boiler HTC). Boiler HTC can be estimated using the log-mean temperature difference (LMTD) method to calculate the average conditions inside the heat exchanger. The equation for the LMTD method is:

$$h = \frac{\dot{Q}(\ln(\Delta T_{flame-return}) - \ln(\Delta T_{exhaust-flow}))}{A(\Delta T_{flame-return} - \Delta T_{exhaust-flow})}$$

Where h is the Boiler HTC, A is the area of the heat exchanger and $\dot{Q}$ is the thermal power output from the boiler.

The key advantage of this method is that it is not affected by changes in GCV. However, it introduces another uncertainty because the temperature of the flame is not measured directly. Modern gas boilers have sophisticated NO_x emission control strategies [8] that use CO, oxygen or ionization sensors to maintain a consistent fuel-air ratio (λ) of 1:1.25 - 1:1.30 and the temperature of a natural gas flame can reasonably assumed to remain constant at around 1950 ± 100 ºC [9].

C. Variables

The independent variables intentionally altered as part of the test are:

- The presence of the performance modifier
- The time water has been circulated
- The pressure that the system is operated at

In this particular case the performance modifier operated on the principle of removing dissolved air, so the dependent variables which change as a result of adding a performance modifier to the circuit are:

- Boiler heat output
- Boiler gas input volume
- Dissolved air content of the circulating water

The controlled variables, which could affect the accuracy of the experiment and which were either kept constant or compensated for are:

- Air pressure
- Air temperature
- Boiler flow temperature
- Boiler return temperature
- Starting air content of the water
- Calorific value of the gas supplied to the boiler

D. Test Sequence

Tests with the boiler performance modifier installed are alternated with control tests, This ensures that errors related to variations in the GCV of gas are randomly distributed and will be reduced by repeated testing. The test rig is fully drained between tests

All the equipment used for testing should be clean; if old equipment with an existing accumulation of dirt is used then it would be important to drain and flush the system before conducting a control test, followed by a test with the boiler performance modifier installed, ideally followed by another control test.

Manual meter readings should be taken before and after each test run so that the accuracy of the automatic meter reading can be checked.

III. Apparatus

Testing can be conducted in summer when there is no heat demand using a specially constructed test stand was to create steady-state conditions which maximizes the accuracy possible from short (4h) test runs. This arrangement allows direct comparison of the behavior of the boiler with and without the performance modifier.

This method is also applicable to field trials of domestic boilers installed in domestic buildings conducted over winter during normal operation. This approach requires a longer period of operation to achieve an equivalent precision and would generate a multi-dimensional measurement of boiler efficiency in relation to return water temperature.

In this particular case the test stand consisted of a Vaillant ecoTEC 832 domestic gas boiler connected to a heat dump. A 100l buffer tank was used to provide thermal inertia. The heat dump consisted of a stacked-plate heat exchanger with one side connected to the boiler's primary circulation loop and the other connected to cold mains water which passed through the heat exchanger and flowed to waste. The mains water flow rate was controlled to achieve a constant return temperature to the boiler. A schematic of this arrangement is shown in Fig. 1

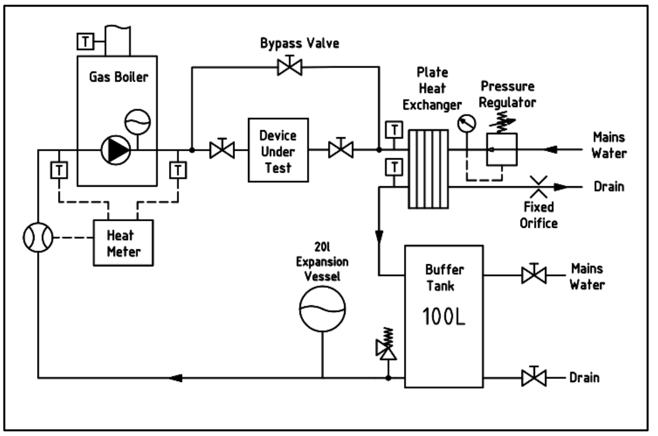

Fig. 1. *Steady-state test schematic*

A. Instrumentation

Thermal power output was measured by a Sontex Superstatic 449 Class II heat meter. The heat meter was specially re-programmed by the manufacturer to produce an electrical pulse for every 0.01 kWh of heat and every 0.01 m^3 of water. The meter was placed in the boiler return pipework well away from any sources of turbulence that could affect the flow meter.

A mechanical gas meter that included a magnet in the dial was read automatically by using a reed switch to generate electrical pulses. This is preferred to optical reading which is prone to missing pulses [10].

Temperature probes based on the DS18B20 temperature measurement device were used to measure the pipework, flue gas and ambient temperature. The DS18B20 is a factory-calibrated temperature measurement IC made by Maxim that has an accuracy of ±0.5C in the range -10°C to 85°C and a precision of 0.0625°C. This makes it much more accurate in practice than other methods of temperature measurement (e.g. platinum resistance or thermocouples) and costs a fraction of the price.

A temperature probe was placed in the gas meter cabinet to allow temperature compensation of gas meter readings.

Some boiler modifiers work on the principle of removing dissolved air, and it is possible to extend the stand to measure dissolved oxygen. In this particular case the dependent variable was measured using a Mettler Toledo InPro 6860i polariographic dissolved oxygen meter connected to a Mettler Toledo M400 Multi-Parameter Transmitter.

Fig. 2. *EmonTX (front left), EmonHub (front right), Dissolved Oxygen Sensor (rear left),2x EmonTH (rear right)*

B. *Data Collection*

Data collection was achieved using the Open Energy Monitor[3] hardware platform. The devices are based on open source hardware, firmware and software so it is possible to adapt them to many situations. A photo of the main equipment used is shown in Fig. 2 above.

A web-connected 'Emonhub' base station based on the 'RasberryPi' single board computer was used to collect data from measurement nodes via a 434 MHz ISM band radio link and log it at 20s intervals.

The 'Emon TX' measurement node is able to measure up to four clamp-on current meters and, when powered by a 9V AC adapter, allows separate measurement of real and reactive power; this was used to monitor boiler electrical power. The EmonTX also includes an RJ45 port that can read up to six DS18B20 temperature probes; this feature was used to measure temperatures within the boiler pipework and flue gas temperature.

'EmonTH' devices are based on the 'Arduino' microcontroller platform. They run off AA batteries and have a radio range of around 50m. This allows them to be freely positioned in order to collect data from multiple locations simultaneously. In this application they were used to collect temperature and pulse data from the gas meter and transmit it to the base station.

The dissolved oxygen sensor produced a 0-20mA signal that was read using an EmonTH running a customized firmware. This is a good example of how the use of open source hardware is helpful in a research context as it can easily be adapted to new applications.

1) *EmonCMS Setup*

The EmonHub data-logging base station has a web interface called EmonCMS that allows processing of incoming data, logging of processed data 'feeds' to a database and visualisation of that data. It is specifically designed for energy monitoring applications and includes a variety of dedicated functions that make working with energy data easier.

[3] https://openenergymonitor.org/

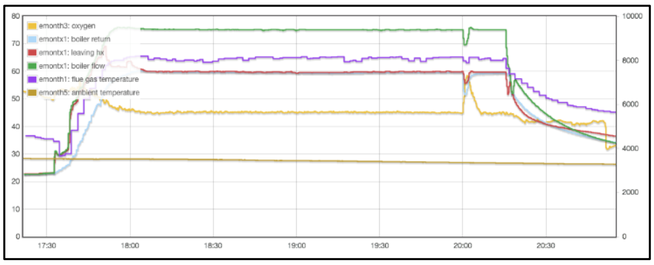

Fig. 3. *Example graph of a typical test run from EmonCMS*

EmonCMS offers a flexible ability to generate live graphs to monitor the behavior of the heating system in real time. This facilitates fault finding and investigation of the causes of anomalous data. An example of the live graph of a typical boiler test is shown in Fig. 3 above.

C. *Data Processing*

Raw data is downloaded from Open Energy Monitor as a .csv file and processed using the 'R' statistical programming language.

The number of gas pulses recorded is checked against manual meter reading in order to detect missing or duplicated pulses. It was found that the two methods usually agreed to within 1%, indicating that automatic pulse counting was reliable.

Pulses measured by the gas meter were converted to standard cubic meters of natural gas using the relationship [11] shown in Fig. 4

Hourly barometric pressure data is obtained from a local weather station and resampled to 20s intervals using a smoothed local regression. An air temperature probe located in the gas meter cupboard is used to estimate the temperature of the gas passing through the meter.

Daily data on the gross calorific value (GCV) of the gas in the main high pressure gas network is published online by National Grid[4] for each region of the UK. This data was used to improve the estimate the GCV of supplied gas.

Assumptions

Gross Calorific Value	39.60MJ/m^3	(GCV)
Standard Temperature (sT)	288 ºK	(T1)
Standard Pressure (sP)	1.01325 bar	(P1)

Calculations

Gas Relationship states:

$$\frac{P1 \times V1}{T1} = \frac{P2 \times V2}{T2}$$

Therefore:

$$V1 = V2 \left(\frac{P2}{P1} \times \frac{T1}{T2} \right)$$

Energy Content (kWh):

$$V1 = \frac{V2 \left(\frac{P2}{P1} \times \frac{T1}{T2} \right)}{3.6} \times GCV$$

Fig. 4. *Temperature and pressure compensation formula for energy content of natural gas*

[4] https://www.nationalgridgas.com/data-and-operations/calorific-value-cv

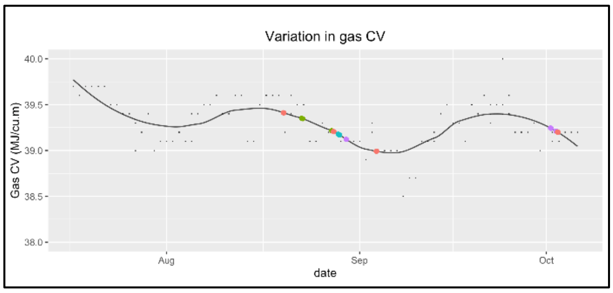

Fig. 5. *Smoothed GCV estimate (solid line) and underlying daily GCV data (black points)*

It cannot be assumed that the GCV of the gas in the high pressure gas network is the same composition as the gas burned in the boiler. It may take several days for gas from the high pressure network to reach the consumer, and it is likely that some mixing of gas from different days occurs as part of this process. To account for these effects a local regression smoothing function is applied to the daily gas data to remove daily fluctuations while preserving weekly trends.

An example of the smoothed GCV estimated from daily data is shown in Fig. 5 above.

D. *Thermal Efficiency Calculation*

Gas consumption and heat meter readings are transmitted to the base station every 60s using the RF data link. These reading are logged by the base station every 20s. This means that an increment on a gas meter or heat meter can be recorded up to 80s after it occurred, creating uncertainty when comparing gas and heat meter readings.

To minimise the effect of temporal uncertainty a local regression model (from R 'stats' package) is used to smooth out short term variations in gas and heat meter readings.

```
library(stats)

localRegression <- function(x){
## Smooth gas meter readings, filling missing data
gasModel <- loess(gasWhRecal~elapsedTime, data=x,
span=0.1)
x$gasWhSmoothed <- predict(object=gasModel,
newdata=x)
return(x)
}
```

The data is then divided into 15-minute intervals and a rolling least squares regression on heat output as a function of gas energy input was performed to find thermal efficiency.

```
library(rollapplyr)
rollingRegression <- function(x){
efficiencyCalc <- function(x)
coef(lm(heatPulses20s ~ gasWhRecal,
as.data.frame(x)), na.action = na.omit)[[2]]

x$thermalEfficiency <- rollapply(x, 45,
efficiencyCalc, by.column = FALSE, fill = NA,
align = "center")
return(x)
}
```

A similar approach is used to process the accumulated pulses from the flow meter and calculate flow rate. After processing, data is plotted using the ggplot2 package.

IV. RESULTS

The result is a complete minute-by-minute picture of the key operational parameters of the boiler -- thermal power input; thermal power output; thermal efficiency; electrical power consumption; primary loop flow rate and the heat transfer coefficient in the boiler heat exchanger. Some example outputs are shown in Fig. 6 – 9 below.

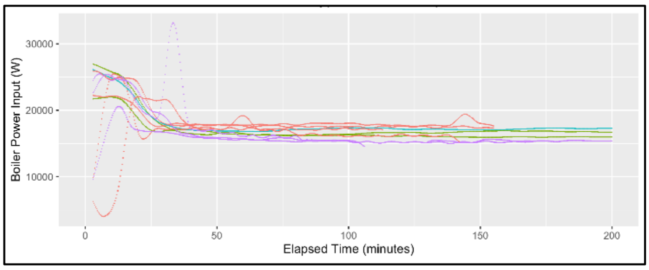

Fig. 6. *Gas power input to the boiler in relation to elaped time for multiple test runs.*

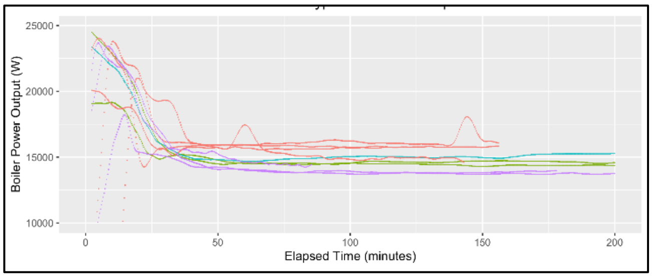

Fig. 7. *Thermal power output from the boiler in relation to elapsed time for multiple test runs.*

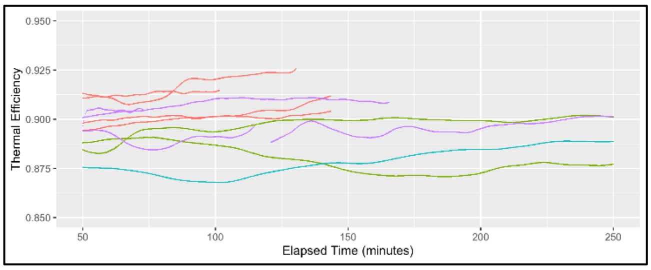

Fig. 8. *Thermal efficiency in relation to elaped time for multiple test runs.*

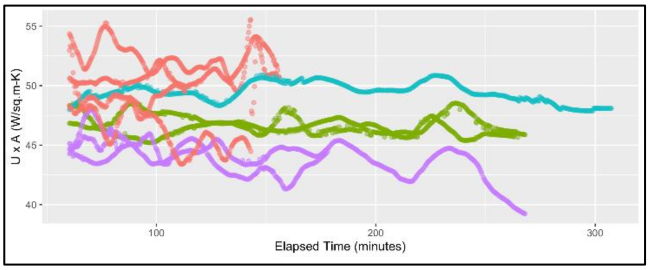

Fig. 9. *Heat Transfer Coefficienct in relation to elaped time for multiple test runs.*

Each test run generates hundreds of instantaneous efficiency data-points which can be used to generate a multi-dimensional plot of boiler efficiency across its operating range. Relationships between the operation of the boiler and experimental variables can be examined in detail. Some examples of this approach are shown in Fig. 10 and Fig. 11 below. The colour coding relates to different experimental conditions.

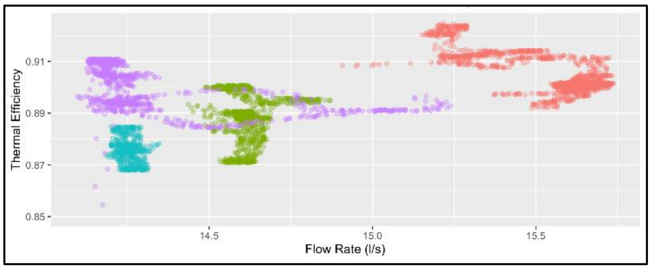

Fig. 10. *The relationship between primary flow rate and thermal efficiency for four experimental conditions*

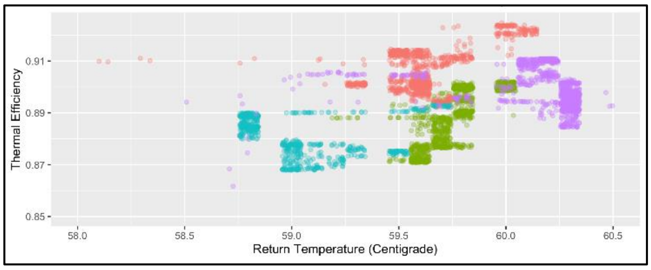

Fig. 11. *The relationship between return water temperature and boiler efficiency for four experimental conditions*

A. *Error Analysis*

Even under laboratory conditions it is challenging to accurately measure the efficiency of a boiler. De Paepe (2013) [12] compared the results of different European labs testing the same boiler. It was found that the overall relative uncertainty for comparable test method in a laboratory setting was around 2% for full-load tests and 4% for part load tests. The main sources of uncertainty were the temperature differential used to estimate power output and the GCV of the gas. One laboratory used the GCV data provided by the gas utility, one used their own measurements of GCV and another used bottled test gas.

In order to better understand the limitations of this method the random and systematic errors of this test method were quantified and combined in accordance with the procedure proposed by Taylor (1997) [13].

1) *Random Error*

a) *Thermal Efficiency*

For tests of 4h duration or more the main source of random error in estimation of boiler thermal efficiency is the calorific value of the supplied gas. If it is assumed that the GCV of supplied gas is anywhere within its legally allowable range the overall random error in this measurement is around ±7%. This is too high to adequately distinguish the effects of a boiler performance modifier and a better estimation of GCV is needed.

TABLE I. RANDOM ERROR IN BOILER EFFICIENCY ESTIMATION, NO GCV ESTIMATION

Measurement	**Unit**	**Abs. Unc'ty**	**Ref. Value**	**Rel. Unc'ty (%)**
Gas meter temperature	°C	0.1000	288	0.03
Gas calorific value (legal max.)	MJ/cu-m	2.7500	39.6	6.94
Barometric Pressure	N/sq.m	3.0000	1000	0.30
Heat Meter dT	°C	0.0003	0.9	0.03
Heat Meter Flow Rate	Cu-m/h	0.0006	0.9	0.07
Natural Gas Volume	Cu-m	0.0100	6	0.17
			Total Uncertainty	**6.95**

TABLE II. RANDOM ERROR IN BOILER EFFICIENCY ESTIMATION, WITH IMPROVED GCV ESTIMATION.

Measurement	**Unit**	**Abs. Unc'ty**	**Ref. Value**	**Rel. Unc'ty (%)**
Gas meter temperature	°C	0.1000	288	0.03
Gas calorific value (corrected)	MJ/cu-m	0.4400	39.6	1.11
Barometric Pressure	N/sq.m	3.0000	1000	0.30
Heat Meter dT	°C	0.0003	0.9	0.03
Heat Meter Flow Rate	Cu-m/h	0.0006	0.9	0.07
Natural Gas Volume	Cu-m	0.0100	6	0.17
			Total Uncertainty	**1.17**

If daily data published by the gas supplier is used to improve the estimation of GCV then the situation is considerably improved, as shown in Table 2 above. The main uncertainty is now the time delay between the measurement of the GCV in the high pressure transmission network and the gas arriving at the boiler.

Natural gas moves through the distribution network at speeds of 5 – 20 m/s[5]. In this case the distance from the boiler to the gas terminal is 150km. This means that it takes at least 8h for the gas to get to the boiler, but the exact time is uncertain. Taking the very conservative view that the gas received by the boiler could be delayed by up to 7d the maximum error on the estimation of GCV is around ±1.1% -- this was

5 https://www.quora.com/How-fast-does-natural-gas-travel-through-pipelines

calculated by taking a year of gas GCV data and finding the maximum variation in GCV that occurred within a single week.

With the help of this improved estimate the overall random error is reduced to ±1.2%, making this method suitable for assessing the effect of boiler performance modifiers

b) Heat Transfer Coefficient

A similar analysis of errors in the estimation of the boiler heat transfer co-efficient was performed and the random error was found to be around ±5%, as shown in Table 3 below. This means that it is more repeatable than thermal efficiency if the GCV of the gas is not known, but less repeatable if a corrected GCV is used.

Readers should note that although the error in the flame temperature is large it makes a relatively small contribution to overall error because of the way heat transfer coefficient is calculated.

In practice the boiler heat transfer coefficient is mainly useful as a cross-check to establish whether a measured change in thermal efficiency could be attributable to short-term variations in the GCV of supplied gas. If the thermal efficiency changes, but the boiler heat transfer coefficient does not, the cause may well be a variation in the GCV. It is occasionally possible for GCV to change by 7% across timescales of a few minutes [15] so this check is useful in identifying unreliable measurements.

TABLE III. RANDOM ERROR IN HEAT TRANSFER COEFFICIENT ESTIMATION

Measurement	Unit	Abs. Unc'ty	Ref. Val.	Rel. Unc'ty (%)
Heat Meter dT	K	0.107	20	0.53
Heat Meter Flow Rate	kg/s	0.005	0.25	2.07
Flame Temperature	K	200	1950	10.26
Flue gas temperature	K	0.100	70	0.14
Flow Temperature	K	0.100	60	0.17
Return Temperature	K	0.100	50	0.20
		Total Random Error		**4.69**

2) *Systematic Error*

a) Thermal Efficiency

TABLE IV. SYSTEMATIC ERROR IN BOILER EFFICIENCY ESTIMATION, NO GCV ESTIMATION

Measurement	Unit	Abs. Unc'ty	Ref. Value	Rel. Unc'ty
Gas meter temperature	°C	0.500	288	0.17%
Gas calorific value (published data)	MJ/cu-m	0.165	39.6	0.42%
Barometric Pressure	N/sq.m	3.000	1000	0.30%
Heat Meter dT	°C	0.005	0.9	0.53%
Heat Meter Flow Rate	Cu-m/h	0.019	0.9	2.07%
Natural Gas Volume	Cu-m			2.00%
		Total Systematic Error		**2.97%**

Systematic errors mean that the measured value of the efficiency will deviate consistently from the 'true' value. If a Class II heat meter and a gas meter approved for billing use are used then the overall systematic error is ±3% as shown in Table 4 above.

b) Boiler Heat Transfer Coefficient

The estimation of the boiler heat transfer co-efficient depends on the area of the boiler's heat exchanger, which is not usually known. This means that it cannot be compared with any reference value and systematic errors are of no importance.

3) *Discriminatory Power*

The smallest change in boiler efficiency that can be reliably detected depends on the test duration, test sequence, the number of repeat tests and how closely the system achieves steady-state conditions. A Student's T-test can be performed to assess how likely a difference could have occurred by chance. Since the expectation is that the performance modifier will *improve* efficiency a one-tailed test should be used.

For steady state tests of 4h duration using three control tests and three experimental condition tests the standard deviation of the thermal efficiency measurement was around 0.75% and the mean was around 85%. Under these circumstances, if the mean thermal efficiency improves by >1.3% with the addition of the performance modifier there is a <5% chance that that this is caused by random variations.

Most performance modifiers are expected to improve efficiency by more than 1.3%, so six 4-hour steady-state tests are sufficient to test the claim that the performance modifier improves efficiency. To quantify the effect on thermal efficiency, or for dynamic tests using in-situ monitoring longer test durations would be required.

V. Discussion

A. Cost Effectiveness

The total cost of the heat meter, temperature probes, gas meter pulse detector and data-logging equipment required for this testing was £775 + VAT, with the heat meter accounting for roughly half the cost at £360 + VAT. This compares favorably with proprietary datalogging hardware. A comparable datalogger costs around £2000 + VAT (Omega OM-240) and requires all sensors to be wired.

The cost of a plumber to install the equipment is not included. A breakdown costs and a complete equipment list is given in Table 5 and Table 6 below.

The equipment can log data locally without an internet connection. Remote access requires an internet connection, either via a local wireless network or a cellular modem (around £80).

If all data is stored on the built in memory of the device there is no ongoing cost associated with datalogging, and a typical memory card can store several years of data. If a backup of the data is stored on the emoncms.org website there is a charge of £1+VAT per data feed per year. Monitoring all parameters of a boiler requires 22 data feeds, so would cost £22+VAT per year.

TABLE V. Metering Equipment Costs

Metering	Cost
Sontex Superstatic 449 Heat Meter	£360.00
Heat Meter programming	£30.00
Gas meter with magnetic dial	£65.00
TOTAL	**£455.00**

TABLE VI. Datalogging Hardware Costs

Datalogging	Cost Ea.	Qty	Sub-Total
Emon Base	£47.50	1	£47.50
Power Adapter	£7.70	1	£7.70
Case	£7.95	1	£7.95
Micro USB cable	£2.70	1	£2.70
EmonTX v3	£50.00	1	£50.00
100A CT Sensor	£8.00	1	£8.00
AC Power Supply	£8.89	1	£8.89
DS18B20 Sensor	£6.80	8	£54.40
RJ45 Expander	£9.75	3	£29.25
emonTH v2	£31.30	3	£93.90
Reed switch	£3.00	1	£3.00
USB Programmer	£5.83	1	£5.83
		TOTAL	**£319.12**

B. Accuracy Improvements

It was found that the temperature of the air in the meter cupboard did not accurately predict the temperature of the supplied gas. If this work were repeated it would be better to attach the temperature probe to the gas meter pipework using thermally conductive glue.

When setting up the datalogging in EmonCMS it is preferable to record all data at 10s intervals to minimize the time between a meter pulse occurring at it being recorded. The additional memory required for higher frequency measurement is not a problem in practice.

The higher the pulse rate of the heat meter outputs the more precisely they are logged. There was a concern that if the pulse rate was too high that the logging equipment might fail to register pulses correctly. In practice the logging equipment can cope with hundreds of pulses per second and it would have been better to program the heat meter to produce pulses at its maximum rate for both heat and water flow.

C. Further Applications

Multiple EmonTH nodes can be used to measure the temperature of each room in a building, and each EmonTH can monitor up to five other temperatures. If these additional inputs were used to measure flow and return temperature for radiators located in that room then changes in the effectiveness of the heat distribution system (radiators etc.) could also be assessed using a method similar to that used to find the heat transfer coefficient in the heat exchanger – a lower return temperature for a given combination of input power and room temperature would indicate improved heat dissipation.

Another way to use the additional inputs on the EmonTH is to measure guarded dry-bulb air temperature using the internal sensor, and an external temperature sensor placed inside a ping-pong ball that is painted black [17] to measure globe temperature. The combination of these two measurements allows comfort temperature to be estimated which is useful when comparing conditions inside super-insulated and conventional dwellings – in winter, super insulated dwellings have a higher globe temperature and feel warmer for a given air temperature.

If the instrumentation were further extended to include local weather measurements, or if local weather data were purchased then there would be sufficient information to calculate the in-use heat transfer coefficient of the dwelling (Dwelling HTC), also called the heat loss parameter (HLP). This is of particular interest in investigating the performance gap between in-use and as-designed thermal performance, and assessing the effectiveness of insulation measures. HLPs are usually obtained either by thermal modeling which ignores the possibility of construction defects, or by 3-5 week co-heating tests, which are expensive in terms of energy and equipment, and require vacant possession.

Another potential refinement that would be useful for field trials involving combi-boilers would be monitoring a water meter placed on the the incoming cold water supply, as well as the temperature of the hot and cold water pipework. This would permit disaggregation of space and water heating demand without the need for a second heat meter.

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VII. References

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VIII. Abbreviations

BS: British Standard

EN: EuroNorm

GCV: Gross calorific value

HLP: Heat Loss Parameter

HTC: Heat Transfer Coefficient

ISM: Industrial, Scientific and Medical

IC: Integrated Circuit

LMTD: Log-mean temperature difference

PCDB: Product Characteristics Database

SEDBUK: Seasonal efficiency of domestic boilers in the UK

VAT: Value-added Tax