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ANALYSIS OF DATA FROM HEAT PUMPS INSTALLED VIA THE RENEWABLE HEAT PREMIUM PAYMENT (RHPP) SCHEME TO THE DEPARTMENT OF ENERGY AND CLIMATE CHANGE (DECC)

RHPP Heat Pump Study - Note on Systematic Errors in Physical Monitoring Data

Issued: March 2016
Revised and re-issued: March 2017

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Nomenclature

PERFORMANCE EFFICIENCY NOMENCLATURE

COP	Heat pump (HP) coefficient of performance
SPF_{Hn}	HP seasonal performance factor (SPF) for heating at SEPEMO boundary Hn

MONITORED VARIABLES

Eb	Electricity for whole system boost only
Edhw	Electricity for domestic hot water (DHW) (typically an immersion heater)
Ehp	Electricity for the heat pump unit (may include a booster heater and circulation pump)
Esp	Electricity for boost to space heating only
Fhp	Flow rate of water from heat pump (may be space heating only)
Fhw	Flow rate of water to DHW cylinder (if separately monitored)
Hhp	Heat from heat pump (may be space heating only)
Hhw	Heat to DHW cylinder (if separately monitored)
Tco	Temperature of water leaving the condenser
Tin	For air source HP (ASHP): Temperature of refrigerant leaving the evaporator For ground source HP (GSHP): Temperature of ground loop water into the heat pump
Tsf	Flow temperature of water to space heating
Twf	Flow temperature of water to cylinder

(Note that external temperature, Tex, was not measured directly. Data from a publicly available database were used in the analysis.)

RHPP ENERGY AND POWER UNITS

Energy	J	Joule	SI unit of energy
Energy	kWh	3.6 MJ	Customary unit of energy for residential energy use
Energy	MWh, GWh	3.6 GJ, 3.6 TJ	
Power	W	Watt, J/s	SI unit of power and heat flow
Power	Wh/2 minutes	30 W	Base unit of energy for monitored data in RHPP trial, limit of resolution of power – note that power and heat have been recorded at 2 minute intervals
Power	kWh/year	3.6 MJ/year 0.11416 W	Customary unit for rate of residential energy use
Power	kW	1000 W	Typical unit for measurement of heating system ratings

KEY ACRONYMS AND ABBREVIATIONS

DECC	The Department of Energy and Climate Change.
EST	Energy Saving Trust
Preliminary Assessment	Preliminary assessment of the RHPP data performed by DECC (Wickins, 2014)
RAPID-HPC	Research and Analysis on Performance and Installation Data – Heat Pump Consortium

MCS	Microgeneration Certification Scheme - a nationally recognised quality assurance scheme, supported by the DECC. MCS certifies microgeneration technologies used to produce electricity and heat from renewable sources.
MIS	Microgeneration installation standards. MIS 3005 set out requirements for MCS contractors undertaking the supply, design, installation, set to work, commissioning and handover of microgeneration HP systems.

Context

The RHPP policy provided subsidies for private householders, Registered Social Landlords and communities to install renewable heat measures in residential properties. Eligible measures included air and ground-source heat pumps, biomass boilers and solar thermal panels.

Around 14,000 heat pumps were installed via this scheme. BEIS[1] funded a detailed monitoring campaign, which covered 700 heat pumps (around 5% of the total). The aim of this monitoring campaign was to provide data to enable an assessment of the efficiencies of the heat pumps and to gain greater insight into their performance. The RHPP scheme was administered by the Energy Savings Trust (EST) who engaged the Buildings Research Establishment (BRE) to run the meter installation and data collection phases of the monitoring program. They collected data from 31 October 2013 to 31 March 2015.

RHPP heat pumps were installed between 2009 and 2014. Since the start of the RHPP Scheme, the installation requirements set by MCS standards and processes have been updated.

BEIS contracted RAPID-HPC to analyse this data. The data provided to RAPID-HPC included physical monitoring data, and metadata describing the features of the heat pump installations and the dwellings in which they were installed.

The work of RAPID-HPC consisted of cleaning the data, selection of sites and data for analysis, analysis, and the development of conclusions and interpretations. The monitoring data and contextual information provided to RAPID-HPC are imperfect and the analyses presented in this report should be considered with this in mind. Discussion of the data limitations is provided in the reports and is essential to the conclusions and interpretations presented. This report does not assess the degree to which the heat pumps assessed are representative of the general sample of domestic heat pumps in the UK. Therefore these results should not be assumed to be representative of any sample of heat pumps other than that described.

[1] The Department of Energy and Climate Change (DECC) merged with the Department for Business, Innovation and Skills (BIS) in July 2016, to create the new Department for Business, Energy & Industrial Strategy (BEIS)

Acknowledgements

The authors gladly acknowledge the inputs to this report of Roger Nordman of SP Technical Research Institute and Tom Garrigan of BSRIA. The work has been supported throughout by colleagues at BEIS, particularly by Penny Dunbabin, Amy Salisbury and Jon Saltmarsh. Additional support for the work has been provided by the RCUK Centre for Energy Epidemiology (EP/K011839/1).

1 Introduction

The authority on the treatment of measurement errors and uncertainties is the Joint Committee for Guides in Metrology (JCGM). The JCGM produces two main publications, Guide to the Expression of Uncertainty in Measurement (GUM) and the International Vocabulary of Basic and General Terms in Metrology (VIM). The GUM (http://www.iso.org/sites/JCGM/GUM/JCGM100/C045315e-html/C045315e_FILES/MAIN_C045315e/03_e.html) states:

> *'In general, a measurement has imperfections that give rise to an error (B.2.19) in the measurement result. Traditionally, an error is viewed as having two components, namely, a random (B.2.21) component and a systematic (B.2.22) component.*
>
> *NOTE: Error is an idealized concept and errors cannot be known exactly.'*

The treatment of the two categories of errors is necessarily different. In the case of random errors, information to support the estimation of the magnitude of the random error in a given quantity (in the language of the VIM, the measurand) is the set of values returned by repeated attempts to measure that quantity. The magnitude of random error is therefore typically estimated by statistical analysis of such sets. In the case of systematic errors, such information may not be available in repeated measurements of the measurand. Estimation of systematic errors therefore depends on analysis and modelling based on theories of the physical or other processes involved in measurement process, and on the results of other sets of measurements[2] related to these theories. Given that the theoretical description of any system is necessarily incomplete (in general, the more complex the system, the less materially complete the theoretical description), there is a tendency:

- for total systematic errors to divide into an indefinite number of categories, which together constitute the members of an open set;
- for systematic errors to be underestimated, depending on how many members of the open set systematic error mechanisms have been identified;
- for the estimate of total systematic error involved in any given complex system to grow over time as more work is done on that complex system, and as more error mechanisms are identified, characterised and quantified.

The rest of this short paper is an attempt to describe categories of systematic error in the estimation of the performance of the heat pump (HP) systems in the RHPP sample that have been identified to date.

[2] An example of a related set of measurements that is of relevance in this context, is the measurement of heat capacities of different mixtures of water and anti-freeze.

2 Effects of antifreeze and other additives on calibration of heat meters

The measurement of seasonal performance factor (SPF) for a HP depends on being able to measure:

- the heat produced by the HP;
- the electricity consumed to achieve this.

The first of these is measured by heat meters, which themselves consist of three sub-systems:

- a flow-sensing device for measuring the flow of heat transfer fluid through a system;
- a temperature sensing device for measuring the temperature rise produced as the heat transfer fluid flows through the HP and around the primary circulation loop;
- a (typically) micro-processor based system for multiplying the fluid flow rate by the temperature difference, and by any relevant calibration constants (relating among other things, to the density and specific heat capacity of the fluid) to provide an estimate of heat flow.

The primary systematic error in this case arises because the heat meters in the RHPP field trial are calibrated for water, while the relevant heat transfer circuit for most of the systems in the field trial contain an unknown mixture of water and proprietary antifreeze products. This section of the paper attempts to estimate the likely magnitude of the correction that is necessary to ensure that estimates of heat supplied by the HPs are, in this respect, unbiased.

2.1 System boundaries and monitored data parameters

As noted in previous outputs from this project, HP system boundaries are fundamental to the evaluation of annual HP performance using monitored data. The system of boundaries used is that defined by the SEPEMO project (Riviere et al., 2011). The H5 System Boundary, as shown by the outer dotted boundary in Figure 2-1, is not defined by SEPEMO. Instead, it emerged as an extension of the SEPEMO boundary approach (Gleeson & Lowe, 2013:641). Performance based on tapped hot water rather than heat flow into the cylinder, was originally defined as "System efficiency" in the Phase I report of the EST HP Field Trials (Dunbabin & Wickins, 2012).

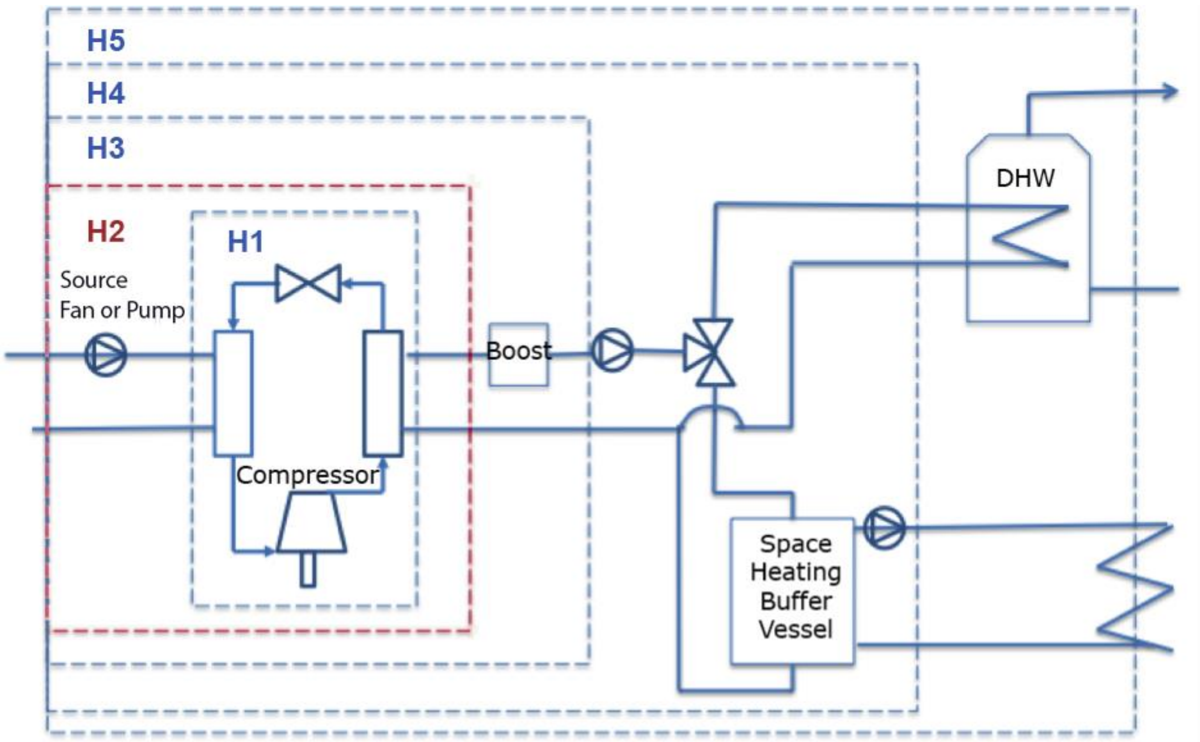

Figure 2-1. SEPEMO system boundaries (derived from Riviere et al., 2011) with the addition of H5 boundary that accounts for heat losses from the hot water cylinder.

Table 2-1 shows the complete set of parameters in the monitored data used to calculate the SPFs, though it should be noted that different sites had different combinations of parameters according to the schematic (or monitoring layout) that was applicable to that installation and plumbing arrangement. Figure 2-2 and Figure 2-3 provide examples of two simple schematic diagrams (for an air source and ground source HP) that illustrate the location of monitoring points corresponding to the monitored parameters in any given HP system. Full details of the monitoring programme, including the overall monitoring philosophy and considerations of sensor resolution, can be found in the Preliminary Assessment report (Wickins, 2014); a summary of this report will be published at the end of the project. Further information about heat metering in general is provided by Butler et al. (2015) and further details of the heat metering arrangements for the RHPP field trial have been provided in the form of private communications by Chris Martin.

Table 2-1. The complete set of parameters included in the monitored data

Parameter	Description
Eb	Electricity meter for whole system boost only
Edhw	Electricity meter for domestic hot water (typically an immersion heater)
Ehp	Electricity meter for the HP unit (may include a booster heater and circulation pump)
Esp	Electricity meter for boost to space heating only
Fhp	Flow rate of water from HP (may be space heating only)
Fhw	Flow rate of water to DHW cylinder
Hhp	Heat meter from HP (may be space heating only)
Hhw	Heat meter to DHW cylinder
Tco	Temperature of refrigerant leaving the condenser
Tin	For ASHP: Temperature of refrigerant leaving the evaporator For GSHP: Temperature of ground loop water into the HP
Tsf	Flow temperature of water to space heating
Twf	Flow temperature of water to cylinder

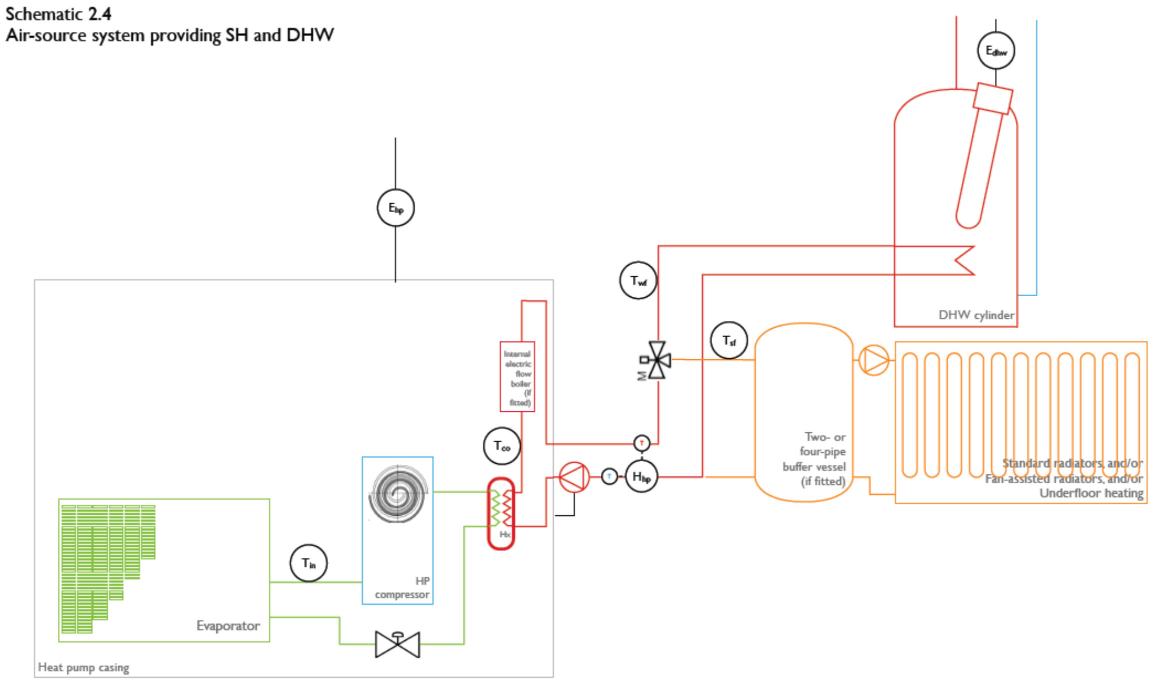

Figure 2-2. An example simplified schematic of the metering arrangement for a monobloc ASHP that provides heat to space heating and a domestic hot water cylinder with an immersion element.

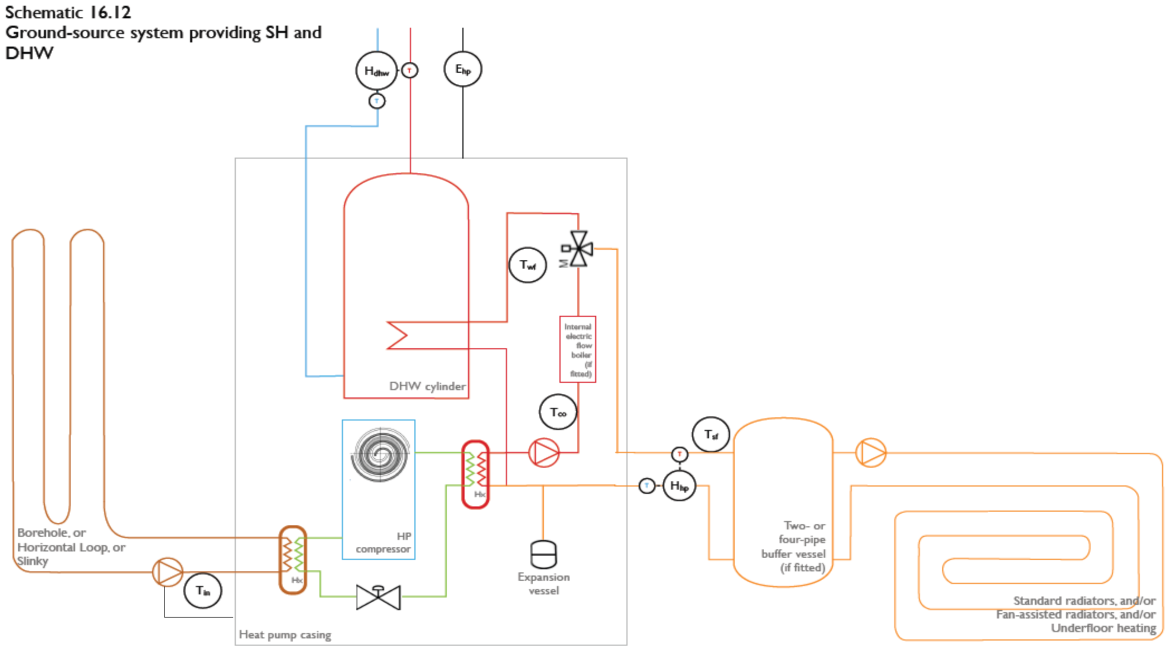

Figure 2-3. An example of a GSHP with an integrated domestic hot water cylinder.

In each of the above cases, the heat meter is shown as a cluster of three components just outside and to the right of the HP casing, thus:

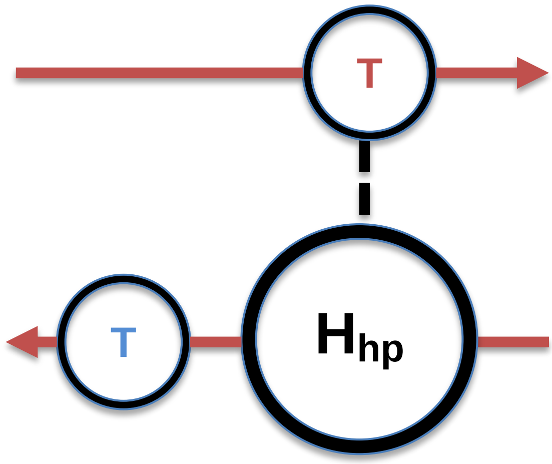

Figure 2-4. Layout of main components of heat flow meter.

In Figure 2-4:

- the heat meter flow sensor is labelled "H_{hp}"
- the return temperature sensor, is labelled "T" in blue, and is shown positioned in the return flow from the dwelling back to the HP
- the flow temperature sensor is labelled "T" in red, and is shown positioned in the flow from the HP to the dwelling.

The heat meter used in all installations in the RHPP field trial consisted of a Sontex Superstatic 440 Qp2.5 ¾" flow sensor, with Sontex 531 energy integrator and temperature sensors. The return temperature sensor low sensor is normally supplied integrated into the flow sensor, but for the RHPP field trial, both temperature sensors were supplied separately, to allow more flexibility in installation. The heat meter flow sensor is shown in Figure 2-5 below.

Figure 2-5. Image of Sontext Superstatic 440 heat meter used in the RHPP field trial.

The flow sensor in this heat meter measures volume flow (litres of liquid per second). The Sontex 531 energy integrator can be programmed for known mixtures of antifreeze and water, but Wickins (2014) notes that the heat meters used in the RHPP trial were calibrated for pure water:

> *'Furthermore, it should eventually be possible to adjust the heat meter reading to take account of the fact that a lot of air source HP (ASHP) systems have antifreeze in their primary circuit but this exercise has not been completed. Using heat meters calibrated for water in primary circuits containing antifreeze is suspected to result in an over-estimate of heat output for those sites of up to approximately 5%.'*

Although Wickins (2014) implies that ground source HPs (GSHPs) may not have anti-freeze in their primary circuits, we believe that many such systems – essentially, all those in which the HP is sited outside the heated envelope of the dwelling - may have also have antifreeze. Moreover, given that it is possible for freezing to occur in any dwelling following a heating system failure, it is possible for almost any HP to be judged to be at risk of freezing, and therefore to contain antifreeze in the primary circuit. Split systems, in which the condenser is indoors, are probably the least likely to contain antifreeze, but the term "indoors" may in practice be interpreted widely, and could include unheated basements, integral or attached garages or outbuildings.

Our understanding is that where a heating system in most of the UK is protected by antifreeze, the concentration of antifreeze will be sufficient to prevent freezing down to a temperature of around -10°C. Higher levels of protection may be needed in upland areas, e.g. in the Scottish Highlands.

2.2 Chemical content of the fluid in primary heating circuits

Antifreeze is typically provided by mixing ethylene[3] or propylene glycol (ethane 1,2 diol, or propane 1,2 diol) with water. Primary heating circuits that contain antifreeze will also contain substances to suppress bio-fouling. Furthermore, many systems will require protection against corrosion. In practice, all of these functions are likely to be combined into one proprietary water treatment product. The RHPP metadata refer to three proprietary water treatment products - Fernox, Sentinel and Tyfocor (the last was recorded in just three systems).

Work has been done by the heat meter manufacturer, Sontex, in Switzerland, to characterise the physical properties of proprietary water treatment products. But for clarity and transparency, what follows is an analysis based on the assumption that the only additive in primary circuits is either ethylene or propylene glycol. This analysis is based on data on the physical properties of mixtures of water and the two common glycols provided in tabular form in the ASHRAE Guide, and assumes that the presence of antifreeze only affects the specific heat capacity of the fluid in the primary circuit, and not the calibration of the flow sensor with respect to volume flow.

2.3 Variation of physical properties of water with concentration of antifreeze

The density and heat capacity of water are functions of temperature. The properties of water-antifreeze mixtures, including the depression of the freezing point, are also functions of the ratio of water to antifreeze.

The relationship between glycol concentration and freezing point depression is shown below:

[3] Given that ethylene glycol is poisonous, it is likely that domestic installations use mostly propylene glycol. We understand that the two main commercial products, Fernox and Sentinel, are propylene glycol-based. Tycofor is manufactured in two forms, Tyfocor and Tyforcor-L which are ethylene and propylene based respectively.

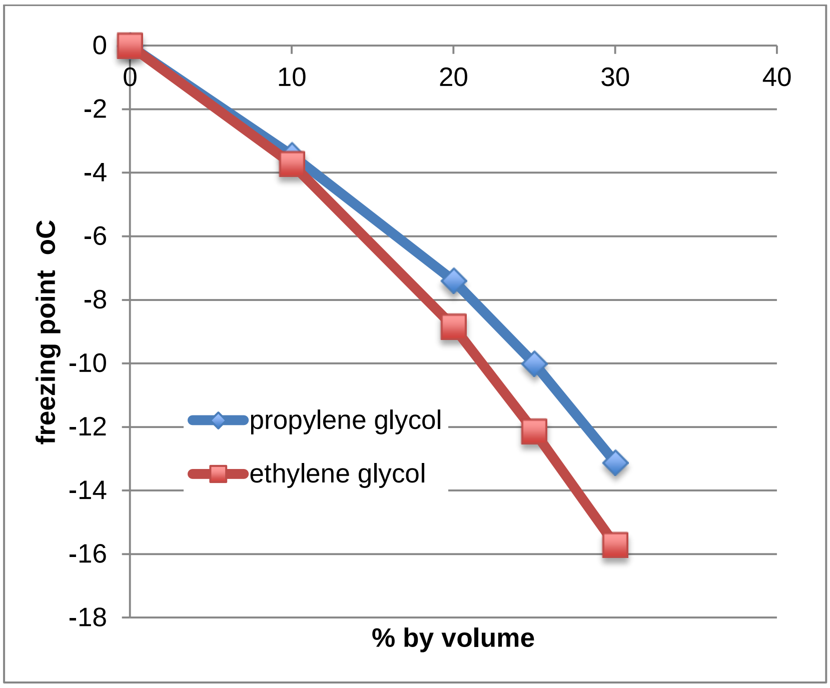

Figure 2-6. Variation of freezing point depression with concentration of antifreeze. Note that the points for 25% concentration are interpolated from data for 20% and 30%.

Figure 2-6 shows that to provide protection to -10°C, would require just over 20% of ethylene glycol or approximately 25% of propylene glycol.

Figure 2-7 and figure 2.8 below show the corresponding corrections to the heat capacity of water that would be required to offset the addition of glycol antifreeze, at temperatures of 40°C and 50°C (measured at the heat meter flow sensor). Note that the data markers on the two graphs correspond to concentrations of 10%, 20%, 25% and 30% of glycol by volume. Note also that the Sontex 531 energy integrator automatically adjusts the calibration for the actual temperature of water flowing through the heat meter body.

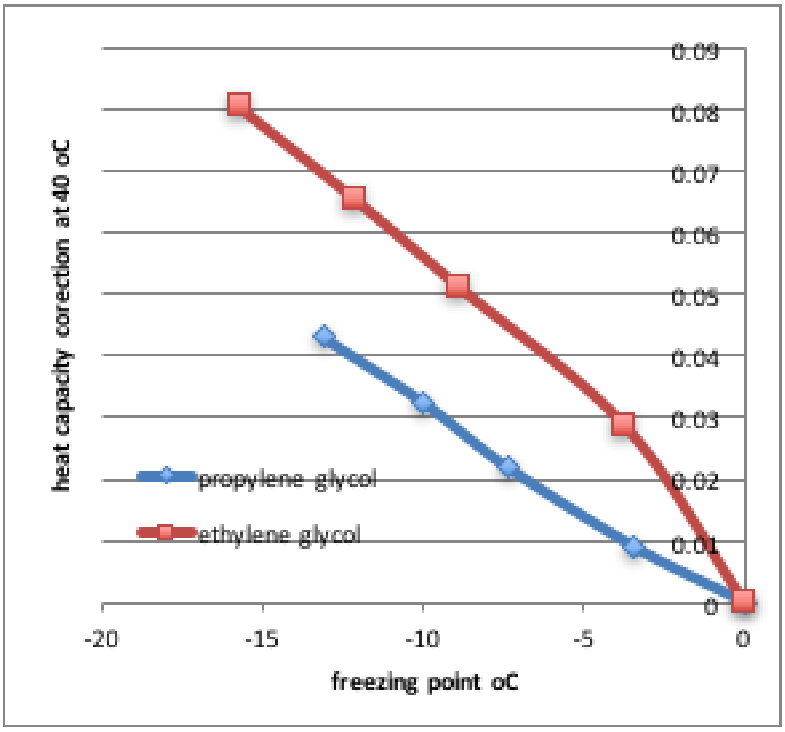

Figure 2-7. Heat capacity correction versus level of frost protection for ethylene and propylene glycol – flow temperature 40°C.

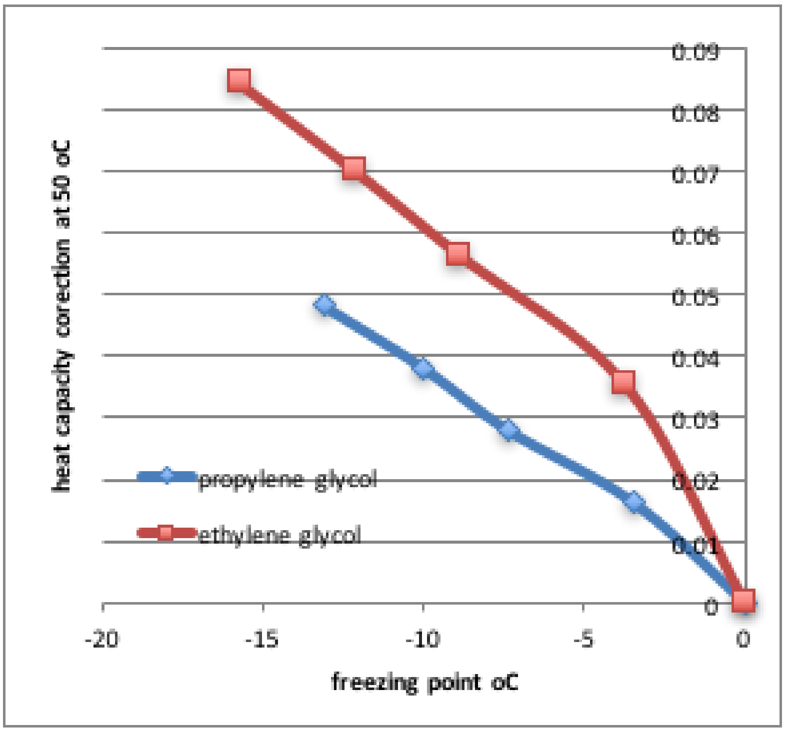

Figure 2-8. Heat capacity correction versus level of frost protection for ethylene and propylene glycol – flow temperature 50°C.

These two figures have been interpreted as follows:

- no data point corresponds precisely to -10°C of protection (though the 25% points for **propylene** come close);

- this means that to precisely achieve -10°C of frost protection with ethylene glycol, an installer would have to add about 22% by volume;
- such precision is unlikely in the field; installers are more likely to aim for the first round number that exceeded -10°C of protection; for **ethylene glycol,** this would be a concentration of 25% by volume, which would give corrections of about 6.5% at 40°C and about 7% at 50°C;
- some systems will operate at 60°C flow temperature for at least some of the time (e.g. during hot water heating) – this would give a slightly higher correction for such periods.

To sum up, with propylene glycol and automatic temperature correction of heat meters, heat meters would over-read by about 4% at a temperature of 50°C measured at the flow sensor, and SPFs would be reduced by the same amount. If ethylene glycol were used, heat meters would over-read by about 7%.

The most immediately important question that the RHPP field trial was set up to determine, is the proportion of HPs with SPF_{H2} > 2.5. The median SPF_{H2} for ASHPs in the cropped B2 sample is 2.65 and that for GSHP is 2.81. A 4% over-read would mean that the median SPF_{H2} for both ASHPs and GSHPs would have been overestimated by approximately 0.1. In other words, the nominal median values of 2.65 and 2.81 should have been around 2.55 and 2.71 respectively.

2.4 Additional issues and uncertainties associated with anti-freeze

Practical problems may arise with accurate dosing on site. These may include difficulty in assessing primary circuit water volume[4], lack of equipment on site for confirming correct levels of antifreeze protection, and time and cost pressures, versus the risk of an expensive failure caused by under-dosing. Hence we would expect there is the possibility of both under and overdosing. Further uncertainties for the present field trial are likely to be introduced by the difficulty associated with identifying actual brands of proprietary water treatment products used in each installation.

Ideally, this problem would be addressed by undertaking a systematic survey of a sample of installations drawn from either sample B or C, including the collection of samples of liquid from the primary circuit of each for subsequent laboratory analysis. This may not be practically possible, but we suspect that the nature of the underlying problem is unlikely to change quickly. A separate survey would therefore almost certainly be valuable.

[4] Determining this volume is in principle straightforward, but is likely to be perceived as an additional burden on installers in new build. It is likely to be more problematic still in retrofit, where radiators maybe up to 30 years old and no longer available commercially, and radiator specifications may not be available on-line.

3 Other possible bias errors

3.1 Possible misreading of heat production due to temperature offsets.

Detailed analysis of time series of physical data for individual installations that has taken place in the first quarter of 2016, has begun to reveal the possibility that some of the heat meters may be misreading the heat produced by HPs, H_{hp}. The primary observation is of prolonged periods where the HP is off, but heat production continues to be reported by the heat meter – see Figure 3-1 below, taken from a companion report, *RHPP Performance Variations Report*[5].

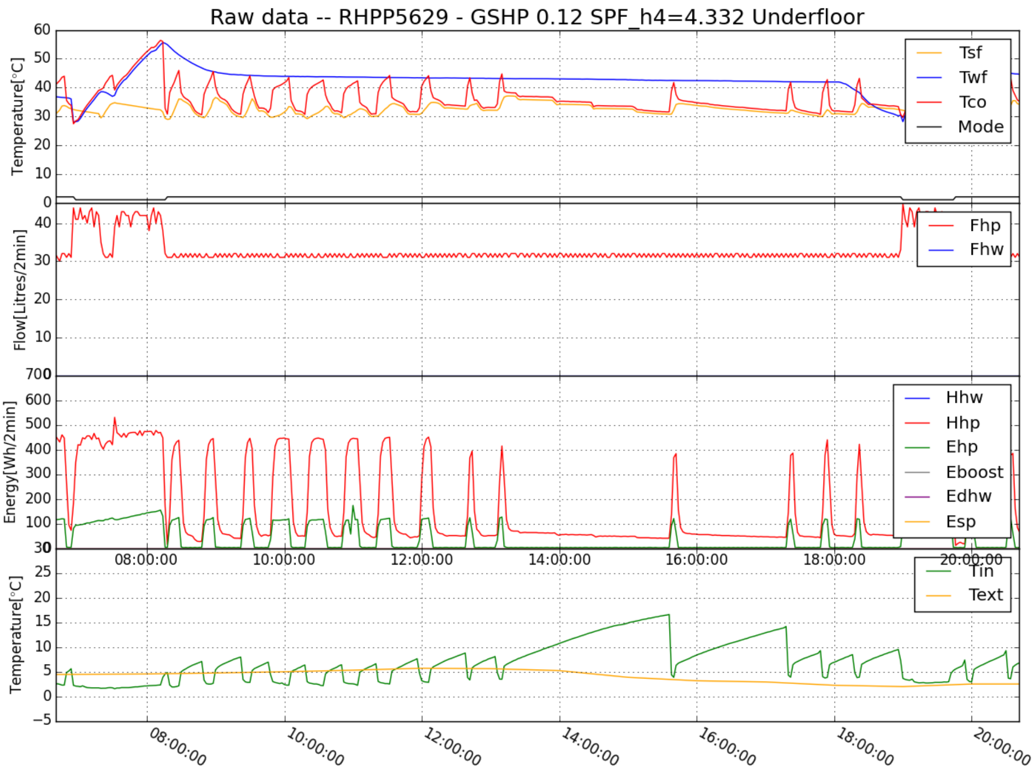

Figure 3-1. Time series from multiple sensors, showing potentially anomalous heat output from a GSHP.

Key observations in the above time series are:

- the heat meter records volume flow in the primary circuit for the whole period shown;

[5] The present report is accompanied by four parallel reports, the abbreviated titles of which are: *RHPP Performance Variations Report* (RAPID-HPC, 2017a), *RHPP MCS Compliance Report* (RAPID-HPC, 2017b), *RHPP Case Studies Report* (RAPID-HPC, 2017c) and *Final Report on Data From the RHPP Scheme* (RAPID-HPC, 2017d).

- the heat meter shows heat output persisting at levels above 1 kW (50 Wh/2 minutes) for up to two hours during periods when the electrical input to the HP is zero – this is most obvious for the period from around 13:15 to around 15:15.

One possible explanation for this is that the continued heat flow is caused by electric resistance heating in which the electrical feed to the resistance heater bypasses the electricity meter that supplies the heat pump compressor (E_{hp}) and is unmonitored. From examination of the monitoring schematics, up to 23 sites within the cropped B2 sample could potentially be affected (21 ASHP and 2 GSHP). Considerable effort has been put into exploring this possibility, but the evidence for it is so far at best ambiguous. If it is the case, the implication is that SPF in the RHPP sample as a whole is being slightly overestimated, because of unreported consumption of some of the electricity used in <=23 installations (around 5% of the cropped B2 sample).

An alternative explanation is that at least a portion of the heat detected and reported by the heat meter following the switching off of the HP is an artefact of continued flow in the primary circuit, coupled with an offset in the effective calibration of the two temperature sensors attached to the Sontex 531 energy integrator. In principle, the two temperature sensors are matched, but it is possible that local environments of the two sensors are sufficiently different for them to record significantly different temperatures. Environmental differences could e.g. be caused by a combination of poor thermal contact between one or both temperature sensors and the flow (despite efforts to detect this and eliminate affected installations from the analysis dataset, some sensors may be strapped on, rather than being fitted into pockets), with temperature gradients in the space housing the HP. The case that we are considering here is where:

$$T_{flow}' - T_{return}' = T_{flow} - T_{return} + T_{offset}$$

where unprimed quantities are "true" values, and prime ' denotes "as reported to the energy integrator by the temperature probes". T_{offset} is assumed to be positive in the above.

At a volume flow rate of 0.25 l/s (30 litres per 2 minutes), a temperature offset of 0.96 K between the two temperature sensors would be sufficient to cause the energy integrator to report a heat flow of 1 kW. If the offset between the two temperature sensors is approximately constant, the H_{hp} time series would be subject to a positive offset of approximately 1 kW across the whole 15 hour period shown.

The implication is that SPF in the RHPP sample as a whole may be being overestimated, because of erroneous reporting of heat flow in some installations. It is perhaps worth observing that regardless of its effect on SPF, continuous running of the primary circulation pump through the whole of the 15 hour period shown in Figure 3-1 is probably unjustifiable in energy terms. Modification to the control system to shorten primary circulation pump overrun to 10 or 15 minutes would reduce electricity consumption for the period shown by approximately 0.5 kWh. It would also reduce, but not eliminate, the overreporting of H_{hp}.

Induced calibration offsets between the matched temperature probes, if the sign of the temperature offset were reversed ($T_{offset} < 0$), would lead to underreporting of heat output by the heat meter. But such cases would be harder to detect from the data. The temperature probes are in their correct positions, but the sign of the calibration offset is reversed; this would mean that when:

$$T_{flow} \approx T_{return}$$

$$T_{flow}' - T_{return}' = T_{flow} - T_{return} + T_{offset} < 0$$

and the heat meter would read zero. But when the HP was running:

$$T_{flow} >> T_{return}$$

and therefore

$$T_{flow}' - T_{return}' = T_{flow} - T_{return} + T_{offset} > 0$$

and the heat meter would provide non-zero output, but with values understated by:

$$T_{offset} / (T_{flow} - T_{return})$$

which we think, in practice, could be by as much as 10% in those systems affected.

Such a configuration would be hard, but maybe not impossible to detect. It would have the effect of shutting off the heat flow prematurely, following the HP being turned off, provided that the control system allowed the circulation pump to overrun. It is just possible that by looking at the time taken for heat flow to reach zero after the HP turned off, one might hazard a guess at which installations were affected. Confirmation would require site visits.

If induced calibration offsets occur, they are as likely to be positive as negative, so systematic underreporting of H_{hp} would be statistically as likely as overreporting. The difference would be that positive temperature offsets would lead to overreporting both when HPs were on, and when they were off but circulation pumps were still running. But negative temperature offsets would lead to underreporting only when HPs were on.

3.2 Possible degradation of heat flow meters

Appendix A to a companion report, *DECC RHPP Detailed Analysis Report*, presents evidence of a long term decline in volume flow rate reported by some heat meters. This is shown for one particular installation shown in Figure 3-2 below.

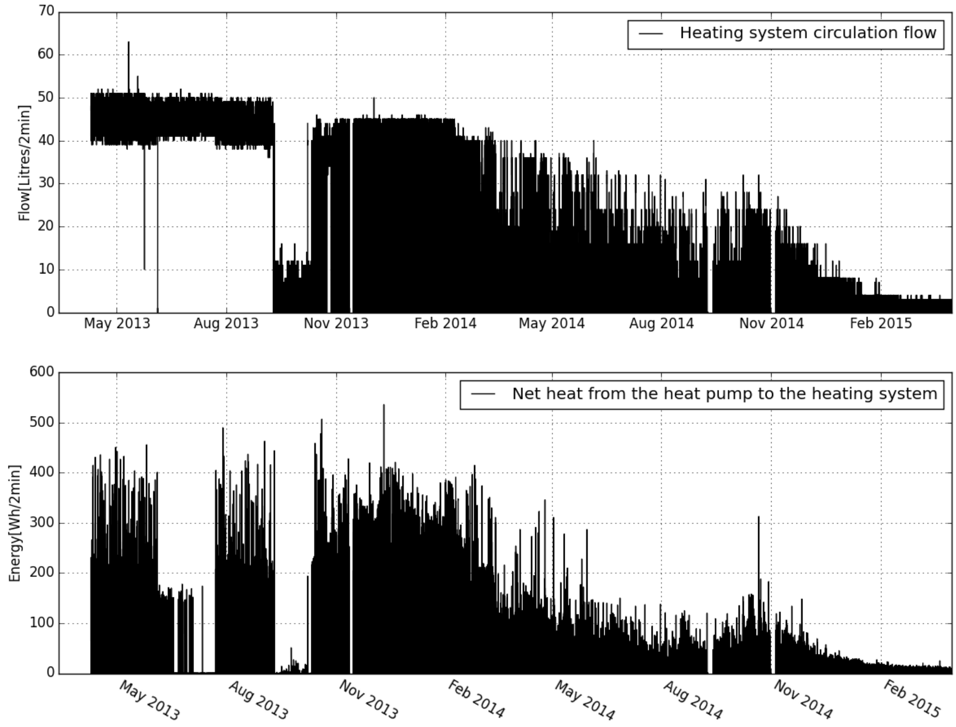

Figure 3-2. An example site where the circulation flow rate progressively declined over the monitoring period.

The decline in volume flow, and consequently measured heat flow, H_{hp}, in this installation is so large that it is difficult to believe that, had it been real, it would not have been noticed by the dwelling occupants and reported. It is easier to believe that the flow sensor and heat meter are underreporting real heat output, but unfortunately, we do not know of a physical mechanism that would cause this effect.

Most of the RHPP sites show smaller decay rates than that shown above. The median decay over a year over the whole of Sample B2 (cropped) is 1.5%. The implication is that SPF in the RHPP sample as a whole may be being underestimated by a small amount, because of under reporting of heat flow in some installations.

4 Discussion and implications

This short addendum has considered three possible sources of systematic error that would lead to bias in estimates of SPF. All affect heat meter output. Two of the three would lead to SPF being overestimated, the third to its being underestimated.

The first of these sources of systematic error arises from a well-understood mechanism – the dosing of primary circuits with proprietary additives containing antifreeze. Although the presence of antifreeze on heat meter calibration has not been measured directly, we have circumstantial evidence – the observation of an empty container of additive at a GSHP installation - which is in accordance with prior knowledge and expectations of industry practice. The implication of modelling based on published properties of glycol based additives, is that SPF may be being overestimated across much or most of the sample, perhaps by 0.1.

The other two possible sources of bias error are the effects on heat meter output of temperature offsets, and of declining heat meter output. These two mechanisms are not as well understood as the effect of glycol based additives, and further work is needed to determine whether our interpretation of the data is correct, and to estimate the magnitude of any resulting bias. The effects of temperature offsets on heat meter output would be detectable only under certain circumstances. And we do not know in detail how they arise. It appears that they are unlikely to be as widespread in the RHPP sample of installations as the effect of proprietary additives. The effect of declining heat meter output is very clear. At present we do not have a physical mechanism to explain it. The median decay over a year over the whole of Sample B2 (cropped) is 1.5%, which would imply a corresponding underestimation of median SPF in the RHPP sample.

To sum up, of the three sources of bias error reviewed in this report, the effect on heat meter calibration of glycol based additives to water in primary circulation circuits appears likely to be the largest, but we have no direct evidence of its magnitude in the RHPP sample. Refining estimates of all three sources of possible bias error would require on-site investigations in a sample of domestic HP installations.

The list of sources of bias described in this report is not necessarily exhaustive.

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