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INDIVIDUAL APARTMENT SUBSTATION TESTING – DEVELOPMENT OF A TEST AND INITIAL RESULTS

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ABSTRACT

To address poor performance of new DH networks in the UK a substation test procedure for individual dwelling substations was developed from the Swedish District Heating Association Technical Regulation F103-7e test. The test aims to 1) determine the performance of individual substations, 2) to demonstrate the impact of other DH design variables on substation performance and 3) to highlight issues arising from poor commissioning. The test uses volume weighted average return temperature (VWART) as the main performance metric and calculates this for DHW generation, space heating and standby, under conditions representative of typical operation. Other analysis has developed average DHW and space heating demand patterns for a typical UK city centre apartment, which allow an annual substation specific VWART to be calculated. The calculated VWART should represent substation operation in use in a typical new build flat.

This paper discusses the generic issues and observations arising from the substation testing and does not comment on individual manufacture performance.

The results show a wide range of substation performance, with significant variation in DWH, space heat and standby performance between substations. The space heating heat exchangers were oversized, for the small UK required heat outputs, in most the substations causing high return temperatures. The performance variation was greatest for the standby functions with substations having very different standby flow, return temperatures and substation heat losses.

The test results have generated significant discussion within the UK DH community and are being used by suppliers to publicise their products. It is hoped this raising of awareness of substation performance will lead to improved substation and DH specification, installation and performance. It is planned for the test standard to be adopted by an independent body and further developed by a committee of DH operators.

INTRODUCTION

Currently District Heating (DH) in the UK supplies less than 1.5% of properties in the UK [1]. Due to building code requirements new DH is being developed at all large developments in London and this has been the case for nearly 10 years now. DH is being developed in other parts of the UK for both new build and retrofit. Much of this DH has been designed and built by engineers and contractors with insufficient knowledge of DH. As a result, many of the new schemes are oversized and have high heat losses. The growing number of poorly performing DH schemes is gaining the notice of consumer protection organisations, despite the relativity small numbers of customers served, These organisations are reporting, 'Poor design or a lack of insulation can lead to system heat loss, causing unnecessarily high costs and poor thermal comfort for customers' [2]. The 'poor thermal comfort' noted refers to corridors that are uncomfortably hot due to heat losses from DH pipework. The new market opportunity for DH products has led to a large number of substations being offered into the UK market. The problem is that the limited DH knowledge is hampering good substation selection, efficient system design and commissioning to get the best performance from the substation.

The UK Government Department of Energy and Climate Change (DECC) is promoting DH as a route to reduce CO_2 emissions and lower heating costs. DECC has responded to the issues of poor DH performance by offering funds for research into improving DH systems. Using this DECC funding, as part of a larger DH research project, a substation test procedure was developed and 6 of the more popular UK substation substations were tested.

The most common DH setup for new DH schemes in the UK is for individual substations in each residence, the substation having a heat exchanger for instantaneous supply of Domestic Hot Water (DHW) and an indirect connection for the space heating radiators. It is this configuration of substation that the test procedure evaluates.

TEST DEVELOPMENT

There were four aims of the testing:

1) To establish the performance of individual substations

2) To demonstrate the impact of different design decisions e.g. DH flow temperatures and domestic hot water (DHW) temperatures
3) To highlight impacts of other factors that affect overall DH system performance e.g. poorly set up radiators and the scope for some substations to manage this poor setup better
4) Provision of substation performance data for the wider research project.

Points 2 and 3 were included to help develop a wider understanding of the impacts of issues such as choice of DHW flow temperature and the impacts on the overall system efficiency of the operation of substation standby / keep warm functions.

The individual house substation tests from the Svensk Fjärrvärme **(**Swedish District Heating Association) Technical Regulation F103-7e [3] was used as the basis for the test standard. The Swedish test was adapted to more typical UK DH operating conditions and extra tests added to explore and demonstrate issues less well understood in the UK. The main changes being the use of fixed DH flow temperatures, lower space heating loads, higher DHW output and removal of most of the pass/fail criteria – the new test explores substation performance and does not certify the substation in any way. Additional test were included to demonstrate the impacts of poor radiator set up, higher DHW temperatures and scope for the substation to deliver more than rated DHW output.

Quantifying substation performance

The key performance criteria are: safe operation, sufficiently fast DHW delivery and low return temperatures back to the network.

1) Safety – the main requirement used, as in the F103-7, was that DHW temperatures should not exceed 65°C for more than 10 seconds.

2) DHW delivery – the substation needs to deliver DHW in a reasonable time and at a reasonably stable temperature. It is difficult to determine what is 'reasonable' for either of these parameters. The DHW response time is affected by DH system upstream of the substation and the time to tap affected by DHW pipework volume – both of these being different for every substation installation. Very few mixer taps are set for the full 55°C DHW temperature so the stability of the DHW the user experiences is affected by both the substation and the thermostatic mixer valve.

3) Low return temperatures – the importance of low return temperatures is not universally understood in the UK, hence this objective has a dual purpose of both raising awareness of the importance of reducing return temperatures and providing a metric for individual substation performance. The annual volume weighted average return temperature (VWART) was chosen as it best represents the temperature of most of the return pipework (and therefore heat losses) and the temperature that returns to the heat source (and therefore impacts upon plant efficiency and capacity of thermal storage).

In the UK, substations for individual domestic connections are commonly referred to as 'HIUs' - Hydraulic or Heating Interface Units. The UK test standard uses the term HIU throughout the document.

This paper refers to version 1 of the test procedure, a simpler version 2 is to be published in June 2016 which removes some of the tests which were included to inform general DH design discussions. The aim of the test now is to provide a measure of substation performance at lowest test cost.

VWART CALCULATION.

The Volume Weighted Average Return Temperature (VWART) is defined as follows:

$$\mathrm{VWART} = \frac{\sum(t_{12,t} \times q_{1,t})}{\sum q_{1,t}} \qquad (1)$$

where t represents each read during the test period (the substation test rig at SP in Sweden records the test data. every second), t_{12} is the primary return temperature and q_1 is the primary flow rate.

The VWART seeks to simulate the return temperature from a typical year of substation operation, for a typical London flat (typical average size of 60 m^2 [4]). The space heating loads assumed for the VWART analysis are 1450 kWh/yr and the DHW load is 1470 kWh/yr. These heat loads are based on Standard Assessment Procedure (SAP) demand estimates. SAP is the UK Government's assessment methodology through which domestic building demonstrate compliance with energy efficiency regulations. Analysis of DH customer heat meter data [4] for new flats in London from shows space heat and DHW typical space heat demands of 1900 kWh/yr and DHW demands of 1030 kWh/yr. The heat meter data demonstrating a similar annual heat demand but a different split between the DHW and space heating. The VWART calculation methodology could be followed for different space and DHW heat loads to give a more representative indication of substation performance where heat loads are known to be different from the VWART calculation base assumptions.

Representative demand pattern were then needed for the DHW and space heating use. The Energy Savings Trust [5] had a database of 120 UK properties where the DHW use was monitored on a one minute basis for a year. From this data a typical pattern of operation could be assessed, and a substation test designed to deliver representative DHW demand conditions. The key issues arising in the DHW demands was the prevalence of short, low flow rate demands. The test rig restricted the number of DHW flow rates to 3 so this imposed an additional constraint. The DHW component of VWART is based on the usage pattern as in Table 1.

Table 1 Composition of DHW demands and durations used for VWART calculation

Flow Rate (litres/min)	Estimated Annual Demand (kWh)	Number of events per year	Average Duration (seconds)
6	729	10,000	30
10	297	660	75
13	444	300	145

The substation test and VWART calculation includes data for the 60 seconds after the DHW draw off ceases as this then incorporates into the data the impacts of any delayed shutting of the DHW control valve.

The distribution of 1 kW, 2 kW and 4 kW space heating loads are based on analysis of Guru Systems [6] collected consumer heat meter data for a typical modern high-rise residential block in London as in Table 2

Table 2 Composition of space heating demands used for VWART calculation

Space Heating Load (kW)	Estimated Annual Demand (kWh/year)
1	98
2	787
4	565

During those times of the year when no space heating is required, or at times when no domestic hot water is being drawn off, it is common on UK substations that various types of temperature-holding functions come into operation. These functions ensure that domestic hot water will be quickly available and provide a background flow rate on the DH network to keep the network warm. The VWART calculation assumes that for all periods that DHW is not being drawn or the space heating is operating the substation is in standby / keep warm.

The VWART calculations are based on a DH flow temperature of 75°C, DHW at 55°C and the space heating operating at 70°C flow and 40°C return. 70/40°C are the currently recommended maximum operating temperatures for space heating in the UK [7].

The substation test procedure and VWART calculation methodology documents are available at www.fairheat.com via a link from www.carbonalternatives.com

THE TESTS.

The following tests were undertaken. Unless otherwise stated all tests were at 75°C DH flow temperature, space heating secondary at 70°C flow and 40°C return, DHW supply temperature at 55°C and dP across the substation of 0.5 bar.

- Space heating performance at 1, 2, and 4 kW used in VWART calculation
- DHW at flow rates for VWART calculation and at peak 40 kW output
- Standby – the standby test measured the DH temperatures and flowrates for an eight hour standby period
- DHW Response time – how quickly was DHW generated by the substation after the eight hour standby period
- DHW at 50°C and 60°C delivery temperatures
- Performance of DHW and space heating at 65°C DH flow temperatures and secondary system at 60/35°C
- Performance of substation using 2 kW of radiators not commissioned to deliver 40°C return temperatures - a common occurrence in the UK
- Scope for substation to rectify poor radiator setup
- Maximum DHW output, what kW output of DHW can be delivered if DHW temperature is allowed to drop below setpoint
- Low DHW flow – to ensure the substation can control DHW temperatures at low flow rates and not exceed safe DHW delivery temperature
- Combined DHW and space heating demands and the combined demands at higher primary differential pressure.

Not all of the tests undertaken are commented on in this paper.

VWART RESULTS

The results are presented as substations A-E, without the manufacturers being named. The intention of this paper is to discuss the generic issues and observations arising from the substation testing and not comment on individual manufacture performance. The tests are for one particular substation model supplied by each supplier/manufacturer and so are not necessarily representative of all substations from that supplier. The test reports which detail the manufacturer and model of each substation tested are available at www.fairheat.com or via a link from www.carbonalternatives.com

The overall calculated VWARTs for the substations tested are shown in Table 3 and varied between 23°C and 47°C.

Table 3 Overall VWART results

	Overall VWART (°C)
Substation A	47
Substation B	44
Substation C	45
Substation D	35
Substation E	23

To understand the substation VWART it helps to break the VWART down into the DHW, standby and space heat component VWARTs and associated annual volumes. These are shown in Figure 1 and Figure 2.

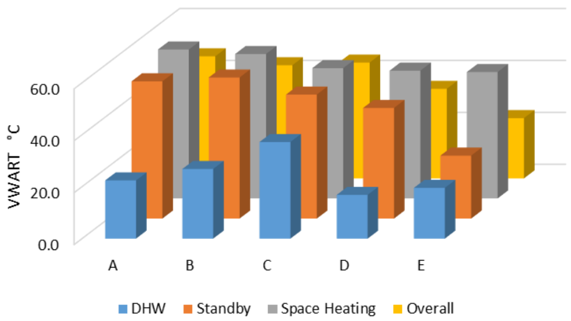

Figure 1 Components of VWART and overall VWART

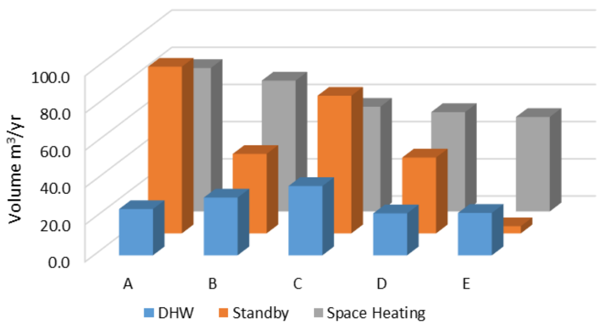

Figure 2 Annual component volumes for an individual substations

DISCUSSION

Standby

To those less experienced with this type of substation the magnitude of the impacts of the standby operation is a surprise. In the author's experience it is rare for a UK substation procurement specification to detail substation performance during standby. It follows that the designers are unlikely to be considering the DH system performance during periods when the substations on standby are the predominant system load. The standby performance is also the component that varies most between substations, with a wide variation in the volume weighted return temperatures (24 to 52°C), the annual volume of primary flow (4 to 90 m^3/yr) and the heat loss as shown in Table 4. It is hoped the substation testing will raise the designers' and specifiers' awareness of the importance of substation standby operation.

The keep warm operation varied between the substations with two of the substations tested pulsing the DH flow to keep the substation hot with cycle time ranging from 30 minutes to 3 hours. The other substations settled down to a constant steady trickle DH flow.

Table 4 Standby performance

Substation standby	Average DH return (°C)	Flow rate (l/hr)	Heat loss (Watts)	Average DH flow (°C)
Substation A	54	11.5	79	58
Substation B	49	7.3	25	51
Substation C	48	10.1	96	58
Substation D	42	6.2	53	53
Substation E	25	3.9	33	39

The standby/keep warm performance should be considered along with the DHW response times as reported in Table 5. The response time is the number of seconds the substation takes to deliver DHW to the substation DHW outlet after the substation has been standing by / idling for 8 hours.

It could be expected that warmer standby temperatures would increase the speed of delivery of the DHW, but increase heat losses from DH network and substation. The test results in Figure 3 show this is not necessarily the case. The DHW response time, the return temperature and the standby flow rate all need to be considered to optimise the standby design and DHW delivery speed. There are clearly substations with better standby configurations. There also is a range in the DHW delivery times and this also varies for different target DHW temperatures, so it is important to consider what DHW temperature it is best to use in any response time performance assessment – e.g. Substation D is the fastest to deliver 42°C but the slowest to 55°C.

Table 5 DHW response time test DHW at 55°C set point

Time to DHW flow temperature	Seconds to 42°C	Seconds 50°C	Seconds to 55°C
Substation A	22	30	48
Substation B	41	76	85
Substation C	11	17	28
Substation D	3	23	91
Substation E	22	27	29

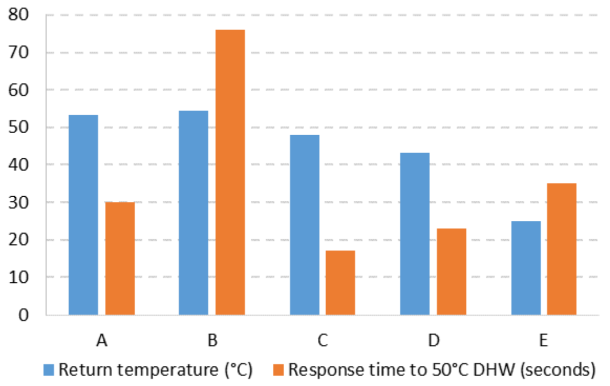

Figure 3 Comparison of average return temperatures and DHW response time

The testing shows a wide variation in the substation heat losses. Clearly the lower the substation standby heat losses are the better as this will reduce unwanted heat gains and reduce the customers' bills – the heat meters in the substation will be recording a significant proportion of these losses. The heat losses are a function of the temperature of the DH water in the substation and the effectiveness of the substation insulation. To be effective the insulation needs to totally surround the hot components, this is where the pipe insulation approach fails as all the joints, elbows, valves, strainers etc are not insulated – only the relatively short elements of pipe in between all the fittings tend to get insulated. For this reason some manufacturers have moved to insulating the substation outer casing, so the air inside the substation warms up and then the heat losses from the components is minimised, but for this to work the case needs to be air tight – which is not the case for some of the substations as shown in Figure 4. Additionally on this substation the back half was an uninsulated steel box which also supported the incoming pipework with no thermal break incorporated between hot pipework and case. These details will also increase the heat losses from the substation.

Figure 4 Non airtight 'insulating' substation cover, top in upper photo, underside in lower photo

SPACE HEATING

Figure 1 and Figure 2 show the space heating VWARTs to be higher than expected based on a 40°C secondary return temperature with the primary return ranging from 49 to 57°C.

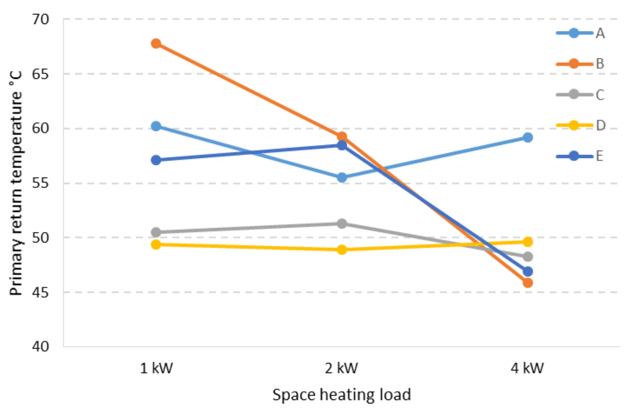

Figure 5 Substation space heat performance based on 40°C secondary return temperature

Figure 5 shows the data from the 1, 2 and 4 kW space heating load tests which are used in the VWART calculation. For this test the DH flow temperature was 75°C, the secondary flow temperature 70°C and secondary return 40°C. The space heating performance of the substations was poor as many of the substations showed large temperature differences between the secondary and primary return temperatures. Analysis of the heat exchangers sizes using manufacturers' heat exchanger performance software shows the heat exchangers to be over sized for the low flow rates of these low heat demands and 30°C temperature differences. The author suggests three issues are driving this oversizing – overestimation of peak space heat loads, insufficient awareness of the poor performance of significantly oversized heat exchangers and the lack of rigorous monitoring of the performance of installed substations.

DHW TESTS

VWART results

There are a range of VWARTs arising from DHW production too. In particular Substation C stands out in Figure 1, the control of the DHW heating in this substation is primarily based on the DHW flow rate – but the valve design is optimised for a specific DH flow temperature and DHW temperature, not the 75°C DH flow and 55°C DHW temperatures of the test. Under the test conditions the DHW was overheated and then reduced in temperature by a thermostatic mixing valve in the substation. Substation C generated lower return temperatures during DHW production at lower DH flow temperatures – which is counter to heat exchanger theory, because the lower DH temperatures were closer to those the valve control was designed for. Another observation from Substation B is shown in Figure 6, which is part of the dynamic test that is used to provide the VWART calculation. the substation performance during DHW generation is good, delivering a sub 20°C return temperature, but when the DHW demand stops at 200 seconds the control valve takes 40 seconds to close and during this period the return temperatures rises, as the primary continues to flow lifting the overall DHW VWART to 27°C

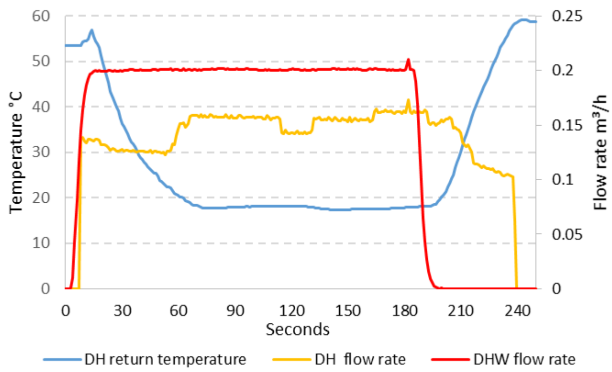

Figure 6 Substation B DHW production

Peak Load DHW test

The DHW tests done at the peak load of 40kW, detailed in Table 6, showed a range in return temperatures and resultant primary delta T (dT). At 55°C DHW temperature and a cold water supply temperature of 10°C, the best substation has a primary dT of over 55°C the worst 43°C, so the flowrate is 32% higher at the lower dT. Typically reducing a pipe by one size reduces capacity by 36%, so in many cases the best performing substation could potentially be supplied with a service pipe one size smaller than the worst performing substation (the peak DHW load is the dominating pipe sizing factor for the pipework close to the substation). Typically a pipe one size smaller at the same temperature loses 10% less heat [8].

Table 6 Primary return temperatures from DHW generation

40kW DHW at 55°C	Primary return temperatures (°C)	DH dT (°C)
Substation A	27	48
Substation B	26	49
Substation C	32	43
Substation D	19	56
Substation E	27	48

Maximum DHW output

In the UK a DH specification commonly requires over 50 kW of DHW from the substation. This is excessive, there are millions of UK homes with instantaneous gas water heaters [9] which have a DHW output of under 35kW and it is common in countries where DH is widespread for the required DHW to be below 35 kW. For example the Swedish F103-7 certification and the standard for Arhus in Denmark is for the substation to deliver 32.5 kW DHW [10]. The 40 kW test point was a conscious decision to try to reduce the size of the peak DHW output mainly to allow reduced service pipe size.

The physics of heat exchangers will allow higher heat transfer if the return temperature is allowed to rise, so a test was included to explore how much DHW could be drawn from the substation by increasing the differential pressure across the substation, allowing the DHW temperature to drop and the return temperature to rise. Analysis of heat meter data shows very few demands over 40kW [6]. This should give confidence to specifiers to lower the peak DHW requirements for substations, safe in the knowledge that if the DHW demands did exceed 40kW they would be supplied with little impact on the customer.

The test aim was to increase the DHW flow rate until the DHW supplied dropped to 10°C below the DHW set point of 55°C. The logic behind this is that most DHW outlets are thermostatically limited to lower than 50°C or the mixer tap is set to lower than the maximum DHW temperature so the end users would be unaware that the DHW temperature had dropped. The results are shown in Table 7. Unfortunately despite increasing the cold water supply pressure the pressure drop on the test rig was too high to enable sufficient flow to get the DHW temperatures to drop by 10°C. But the results still demonstrate that all of the substations can significantly over deliver on the DHW output with very limited reduction in DHW temperature – indicating that actually a far higher flowrate could be delivered at a 45°C DHW temperature.

Table 7 Maximum DHW output from substations

Max DHW output	Output kW	DHW temperature °C	Increase in return temperature °C
Substation A	68	54	3.8
Substation B	65	54	4.4
Substation C	52	49	-9.8
Substation D	71	51	1.7
Substation E	51	55	2.4

CONCLUSIONS

The testing clearly shows performance differences between substations. The simplicity of the VWART as a benchmark of substation performance is having an impact – with manufacturers starting to publicise the VWART figure for their substations. Most of the manufacturers have made or brought forward planned substation improvements as a result of the testing. The hope is that the VWART may become part of the specification of substations, but time will tell if this occurs.

The testing is bring into focus the requirement for and design of standby / keep warm systems.

Substations A, B and E had electronic controls and substations C and D were purely mechanical. The tests undertaken shows that both approaches can perform well.

It is planned that the management of the test procedure will move to a suitable independent organisation within the UK and then be further reviewed and developed by a representative body of DH system operators.

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