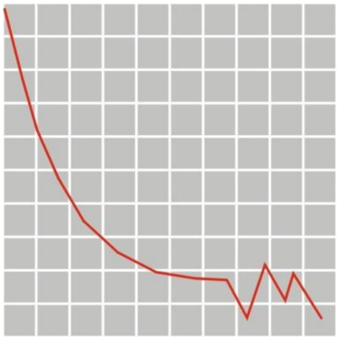
Showersave®



The performance of WWHRS in domestic heat pump installations:

Design of laboratory tests and data analysis

Report commissioned by Showersave

Prepared by: Chris Martin

Version 1.0 - June 2021

Chris Martin

CONTENTS

1 Introduction

This report describes a series of laboratory tests carried out for Showersave at the Ulster University Centre for Sustainable Technologies (CST).

The goals of the tests were to provide measured evidence of the contributions which a Showersave Waste Water Heat Recovery System (WWHRS) could make to a hot water system based around a domestic heat pump. These contributions potentially span a very wide range, including reductions in energy consumption and cost, improvements in the quality of hot water service provided such as the maximum number of showers which could be taken and the time taken by the system to recover from such a load, through to a reduction of the overall load on the electricity grid.

2 Background

A simple model had previously been developed of the interaction between heat pump, hot water cylinder and Showersave WWHRS [1]. This used manufacturers' published data on how heat pump output capacity and COP varied with operating temperatures, and laboratory test data on the effectiveness of WWHRS. The model allowed for a choice between two assumptions of how the water inside the storage cylinder behaved:

- perfectly mixed behaviour, in which the contents of the tank were at all times fully mixed to a single uniform temperature. Water is drawn off at this temperature, and the whole tank temperature reduced accordingly. When heat is supplied to the tank it heats the whole volume uniformly.

- perfectly stratified storage. Water is drawn off at the temperature at the top of the tank, and the corresponding cold make up water delivered to the tank stays at the bottom (a so called 'plug flow model'). Any heat introduced into the tank is delivered to the temperature at the height of the delivery point and then moves up until it encounters hotter water at the top.

The main benefit of a stratified tank is that it allows water to be drawn off at full temperature until the tank is exhausted. In this situation three to four standard SAP showers should be available from a typical 200 litre tank. If on the other hand the tank is perfectly mixed the bulk temperature starts to fall with the first shower, and very soon reaches the point where it is no longer possible to obtain a satisfactory shower. The end result is likely to be the householder increasing the tank temperature (which will fix the problem), with all of the accompanying energy penalties. A further benefit of stratification is that the heat pump delivers its replacement energy to a cooler region in the tank, resulting in a slightly higher COP. Overall, the exact behaviour of the storage tank is therefore important.

The understanding of controls also demands a knowledge of how the tank performs. In the case of the fully mixed tank the thermostat was assumed to sense the overall tank temperature. For the stratified model it sensed the temperature at the relevant height. In both cases the thermostat was assumed to have some hysteresis - that is the temperature at which it turned on was somewhat lower than the temperature at which it had previously turned off. This type of behaviour is common in practice, and prevents the system from rapid cycling around the setpoint.

3 Key Questions

Prior to deciding the exact sequence of tests to be carried out Showersave expressed the goals of the work as three sets of questions. The first related to stratification of the hot water storage tank:

- How well does the hot water cylinder stratify during shower operation ?
- If stratification is poor, is the impact on the number of showers that can be delivered as serious as predicted ?
- What effect does the Showersave WWHRS have on this ?

The second set of questions related to the energy (and hence cost) performance of the whole system:

- What is the electrical energy consumed to produce a realistic daily shower requirement ?
- What is the impact of immersion heater operation on this figure ?
- How does the running cost of the heat pump, with and without Showersave WWHRS, compare with the running cost of the current options which it will be replacing, typically combi-boiler based ?

The final questions related to the quality of hot water provision:

- Can the system provide an adequate number of showers in rapid succession ?
- What is the 'recovery time' of the system ?
- Can waste water heat recovery be used to reduce this significantly ?

4 Designing the Test Sequence

The number of tests which could be carried out was, of necessity, limited by the resources available. The choice of the exact sequence of tests was informed from a range of sources:

- the results of the modelling exercises carried out previously;
- the assumptions currently used in SAP calculations, and those proposed for the next release;
- information taken heat pump manufacturers' installation manuals.

The modelling had revealed that the performance of the hot water storage cylinder could be critical, and also that the performance of the thermostat used to control the heat pump was important.

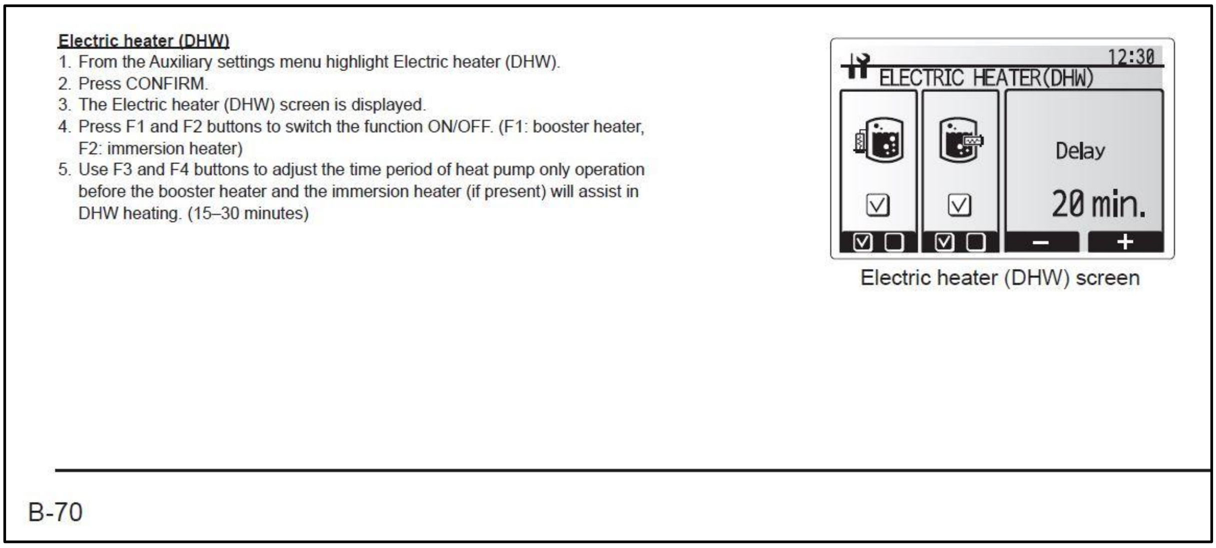
The information taken from SAP included base case shower duration and flow rate. These are currently 6 minutes and 11 litres/minute respectively (66 litres/shower) [2]. This was described as flow rate S. There is, however, continued debate and quite possibly behavioural change in this area, and it was decided to explore further options, bracketing these figures. Two other flow regimes were included, a low user option (6 minutes at 8 litres/minute, or 48 litres/shower, denoted by L) and a more extravagant option with higher flow and increased duration (7 minutes at 12 litres/minute, 84 litres/shower, denoted by H).

Temperature information was also drawn from SAP. It was assumed that the hot water storage temperature was 52°C. The shower temperature was set to 41°C, and it was further assumed that this fell to 35°C as the water passed through the shower, making this the drain temperature at which water was fed to the WWHRS.

It was decided that the shower load on the system should be three showers per day. Using the formulae in Appendix J of the proposed new SAP 10.1 [3] this would correspond to an occupancy level of 3.7 people if there are no baths installed in the property and 5.2 if one or more baths are installed as well as the shower(s). It is important to note that if a bath is present then at this occupancy level the expected number of baths per day is roughly one, and there is the possibility that someone might choose to run this bath while others are showering, which will further impact on the level of service provided by the hot water system. The effect of the use of baths has not been addressed in this trial. The delay between the three showers was set at 5 minutes. This may seem rather short, but it reflects the fact that most houses designed for these sorts of occupancy levels are likely to have at least one en-suite, and the three showers may well be spread between this and the main bathroom.

Hot water cylinders used with heat pumps will generally have an immersion built in to provide a periodic Legionella purging cycle. Typically this heats the water to 60°C or above for a short period once a week. This cycle is not accounted for in our trial and findings.

The key information taken from manufacturers' installation manuals related to the way in which this supplementary electric heating is also used during normal system operation. It seems that the products of at least two major manufacturers (Mitsubishi and Samsung) have potentially heavy use of the built in immersion programmed into them by default. In both cases this takes the form of a time parameter described most clearly by Mitsubishi as 'the time period of heat pump only operation before the booster heater and the immersion heater (if present) will assist in DHW heating'. The Mitsubishi factory default is not known but the picture of the relevant menu in the installers' documentation [4] shows a setting of 20 minutes, and the manual gives the adjustment range as 15-30 minutes, as shown in Figure 4.1 below.



Electric heater (DHW)

1. From the Auxiliary settings menu highlight Electric heater (DHW).
2. Press CONFIRM.
3. The Electric heater (DHW) screen is displayed.
4. Press F1 and F2 buttons to switch the function ON/OFF. (F1: booster heater, F2: immersion heater)
5. Use F3 and F4 buttons to adjust the time period of heat pump only operation before the booster heater and the immersion heater (if present) will assist in DHW heating. (15–30 minutes)

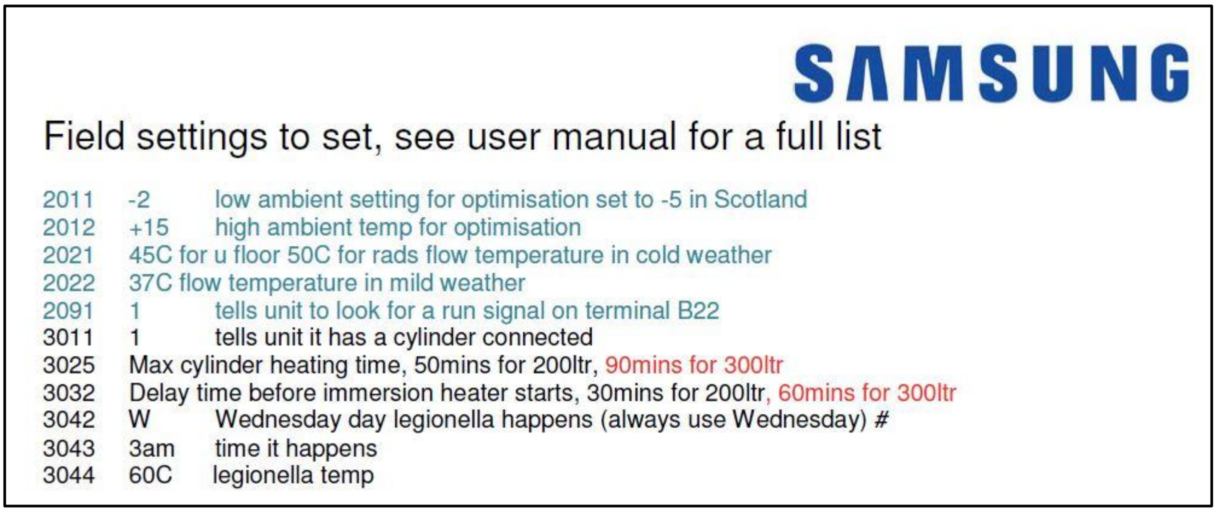
Electric heater (DHW) screen

B-70

Figure 4.1: Mitsubishi DHW supplementary heating settings

The same facility seems to exist for space heating, with a default condition that electrical backup activates after 30 minutes if space heating load is not satisfied by this point. The implications of this, however, are well beyond the scope of this report.

It appears that Samsung set, or at least advise their installers to set [5], the corresponding parameter to a default value of 30 minutes for the cylinder size considered here, as Figure 4.2 shows.



SAMSUNG

Field settings to set, see user manual for a full list

2011	-2	low ambient setting for optimisation set to -5 in Scotland
2012	+15	high ambient temp for optimisation
2021	45C for u floor 50C for rads flow temperature in cold weather	
2022	37C flow temperature in mild weather	
2091	1	tells unit to look for a run signal on terminal B22
3011	1	tells unit it has a cylinder connected
3025	Max cylinder heating time, 50mins for 200ltr, 90mins for 300ltr	
3032	Delay time before immersion heater starts, 30mins for 200ltr, 60mins for 300ltr	
3042	W	Wednesday day legionella happens (always use Wednesday) #
3043	3am	time it happens
3044	60C	legionella temp

Figure 4.2: Samsung DHW supplementary heating settings

This has a large effect on the overall efficiency of the system, and also on the value of the savings delivered by a Showersave WWHRS, which is suddenly displacing direct electric heating as well as heat pump output. In view of this evidence the test schedule included some runs in which the immersion was controlled as follows: if the heat pump has run for more than 25 minutes then the immersion is switched on to speed up reheating of the DHW cylinder - immersion and heat pump operation then continue in parallel until the tank thermostat indicates that hot water storage is back up to temperature.

At various stages in this report we refer to heat pump operation 'without use of the immersion', and also 'reducing immersion use'. These comments relate only to use as part of normal water heating operation. At no stage do we intend to suggest that operation needed to purge Legionella should be reduced.

The testing process was arranged into a series of day long trials. Each of these was preceded by a period during which the tank was held in its fully charged state. This corresponds to the settling period the system would have overnight in a real installation, and ensures that the tank is in a stable state before run offs begin.

One final test was added, in which the tank was artificially mixed using a small pump connected between inlet and output. The goal of this was to provide data from a fully mixed tank to serve as a baseline when comparing degrees of stratification.

Table 4.1 below summarises the final choice of test sequence. It features run offs at each of the three flow rates described, with and without WWHRS and with and without supplementary immersion heating.

TEST	Shower flow	WWHRS	Immersion operation	Artificial tank mixing
1	S	NO	NO	NO
	L			
	H			
2	S	YES	NO	
	L			
	H			
3	S	NO	YES	
	L			
	H			
4	S	YES	YES	
	L			
	H			
5	S	NO	NO	YES
		YES		

Key to shower flow rate codes			
Shower Flow	Flow rate (litres/minute)	Duration (minutes)	Total flow (litres)
S - SAP shower	11	6	66
L - Low user	8	6	48
H - High user	12	7	84

Table 4.1: Test schedule

5 The Test Rig

The hot water cylinder used for the trial was chosen from the Kingspan Aerocyl Heat Pump range. This tank transfers incoming cold water to its base where it is introduced via a diffuser, in order to preserve stratification. The tank is described in detail in [6]. The tests used the thermostat which is provided as part of the cylinder kit. The tank size chosen was 210 litres nominal, with an actual capacity of 205 litres. The Kingspan literature [6] suggests that this size will typically cater for a 4-5 bedroom property with two standard bathrooms. Current MCS guidance [7] is slightly more conservative, and suggests that this cylinder would serve a 3-4 bedroom house, with one or two bathrooms. Finally, the Hot Water Association's on-line tank size calculator [8] suggests that, for average hot water users, this tank should serve up to 6 occupants or 5 bedrooms.

Incoming cold water was temperature controlled to a value close to 11°C . This was fed through the WWHRS (when used) to the cylinder and to one of three mixer valves, preset to deliver water at the required temperature for each of the three flow rates. After passing through the notional shower head, the water was fed through a plate heat exchanger to reduce its temperature to the required drain temperature of 35°C, at which point it entered the WWHRS, if this was in use for the particular test.

Temperatures were measured across the whole test rig, with a great deal of redundancy built in. Temperature distribution inside the hot water cylinder was measured using a rake of seven sensors extending from 100mm above the tank base to 100mm below the tank top. Temperature sensors were checked for consistency before the tests began, using a temperature controlled bath and also by running water at constant temperature past selected sensor sets. The electrical power consumed by the heat pump source fan, the compressor, the circulation pump and the cylinder immersion were all separately measured. Temperature and power data were all recorded at 15 second intervals throughout each test. The experimental rig and data collection are described in much more detail by the University of Ulster in their report on the work [9].

6 Sample Data

Before the tests were carried out a preliminary data file, gathered while the rig was being commissioned, was used to produce software which allowed rapid plotting and preliminary analysis of the data as it was collected. This was used throughout to check on the tests and to consider whether any changes should be made to the schedule as the tests were run.

The sequence of figures below shows the sequence of plots produced after the first set of run-offs in the fourth test using the standard SAP shower run off with a Showersave WWHRS (Test 4-S). This test has been chosen because it incorporates WWHR, heat pump and immersion operation. The first plot, Figure 6.1, shows the performance during shower operation.

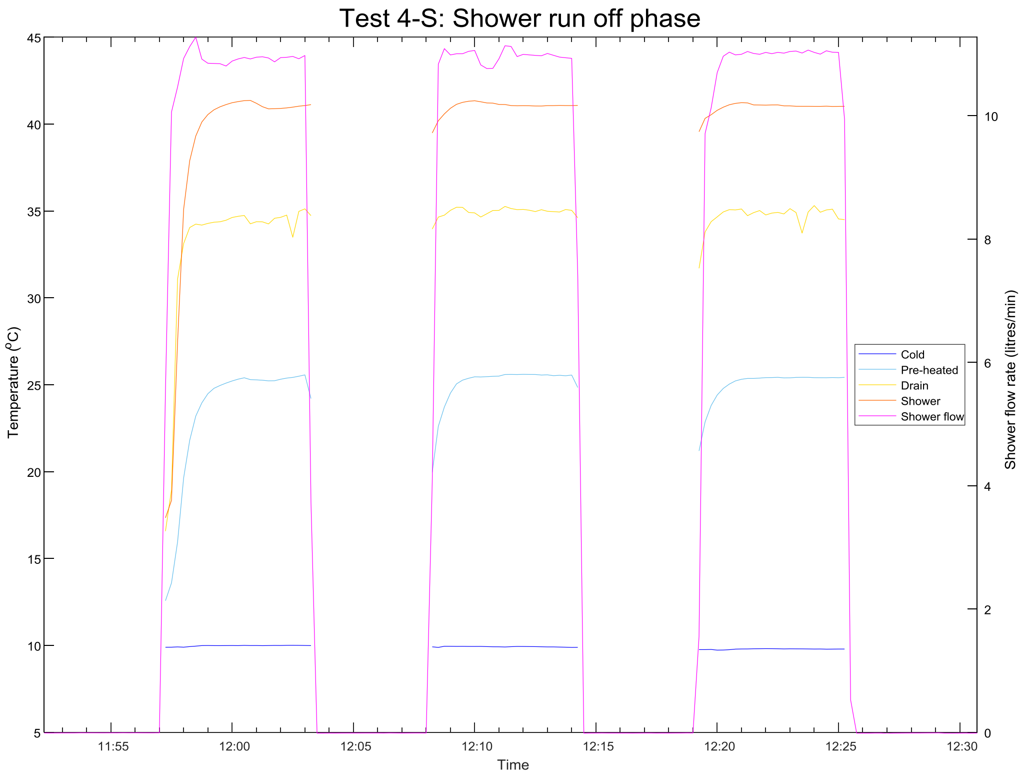


Figure 6.1: Shower temperatures and flow during shower run off (WWHRS +Immersion)

The figure shows clearly the succession of six minute showers, at approximately 11 litres/minute. Interpreting the flow data it is important to remember that the line leaves the x-axis at the point where the flow is last zero, and does not return until the flow is zero again - this makes the duration of the shower look slightly longer than is actually the case. That the test is in line with the specification has been confirmed by shower run times and total volumentric flow. In this case they are six minutes for each shower, and an average of 65.5 litres/shower respectively.

The water temperatures are measured using pocketed probes inserted into the pipework. When there is no flow in the pipe the stationary water within it, sensor pocket and finally the probe drift steadily towards ambient temperature. The resulting reading is no longer representative of any meaningful temperature, and for this reason these values have not been shown on the graph. With these warnings in place, the plot confirms that during run off the shower temperature is close to the value specified (41°C) . The temperature of the incoming cold water is close to 11°C. It also shows that by the time the shower water reaches the drain and enters the WWHRS it is close to 35°C as required. Finally, the Showersave WWHRS can be seen doing its job, by pre-heating the incoming cold water from 11°C to about 25°C. Since the system here is running in 'balanced mode', with equal flows on both sides of the heat exchanger, the WWHRS effectiveness can be calculated from these temperatures alone. The net figure, which includes the effect of the temperature drop between the shower head and the drain is in this case 48%. The gross value, which is more appropriate for comparison with laboratory measurements of heat exchanger effectiveness, is 60%.

The next graph shows the temperatures inside the hot water cylinder during shower operation.

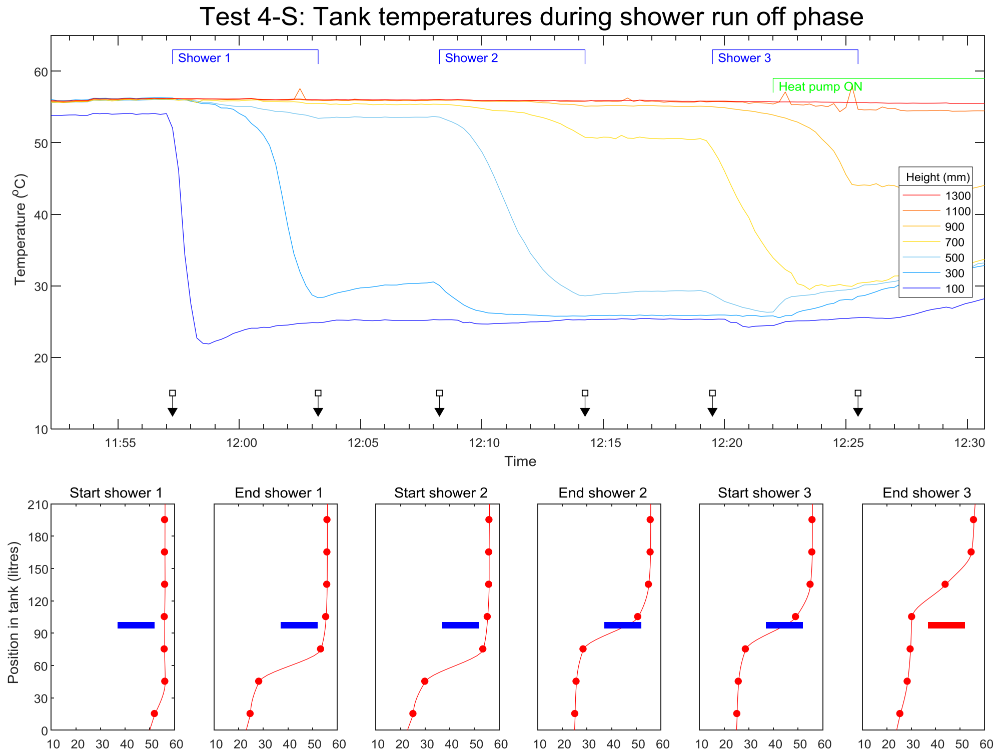
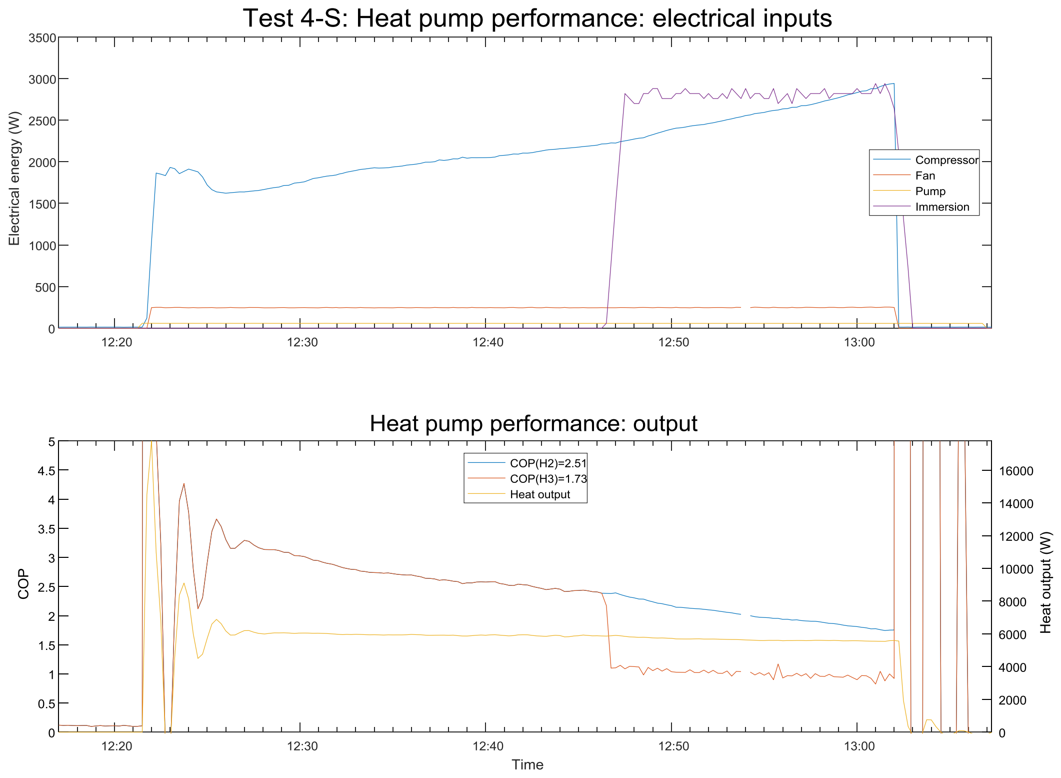


Figure 6.2: Tank temperatures and flow during shower run off (WWHRS +Immersion)

Figure 6.2 shows that the tank starts off quite well mixed, with only the temperature at the very lowest level (below the heat pump coil) differing significantly from the remainder. As water is drawn off for each shower the hot water at the base of the tank is replaced by incoming cold, and a clearly defined temperature boundary moves steadily up the cylinder, in a way very similar the perfect stratification model described earlier. The set of smaller graphs at the bottom show this profile at the start and finish of each shower and confirm this. They show the cold front progressively smearing out due to natural mixing, but being largely maintained as it moves up the tank. The curves shown fitted to the measured points have been fitted using pchip interpolation. Extrapolation to values beyond the ends of the sensor rake has been done by a simple linear fit to the last two points.

The horizontal bar on each of these plots is placed at the level of the thermostat, and its left and right hand edges represent the turn on and turn off points respectively. These have been determined by detailed inspection of the data on thermostat operation and the surrounding temperatures in the cylinder. The thermostat was seen to turn off at around 52°C (as specified) but did not turn on until its temperature fell below 35°C. This hysteresis serves the valuable purpose of preventing the system from short cycling, but the fact that it is so large for this particular thermostat increases the response time quite significantly. As expected, the heat pump is not turned on (denoted by the thermostat bar turning red) until the rising cold front has passed the thermostat location. One unforeseen consequence of the stratification is that preserving higher temperatures in the top part of the tank has the effect of further delaying the point at which the thermostat operates. Taken together with the relatively wide hysteresis band this means that the heat pump does not start until the middle of the third shower.

Figure 6.3 shows the performance of the heat pump during the period for which it runs to return the hot water cylinder to its fully charged state.


Test 4-S: Heat pump performance: electrical inputs

Heat pump performance: output

Figure 6.3: Heat pump energy flows during recovery (WWHRS +Immersion)

The vee-shaped power consumption detected in the modelling study for un-stratified storage remains just about evident on the graph. This arises from the fact that the COP decreases as the tank temperature rises. The immersion heater power on this plot has been measured using a pulse output, and this results in a rather spiky appearance when plotting raw 15 second data. For this reason the plot shown has been lightly smoothed (using a moving average of length four data points). This explains the slightly slow transitions during power on and power off. The raw data has been used unsmoothed throughout the rest of the analysis.

The two values of COP shown are calculated according to the SEPEMO definitions [10]. COP(H2) includes the electricity to the heat pump compressor, and also the power used to drive the fan which moves air across the evaporator. COP(H3) adds the electricity used for built-in suplementary heating, in this case the immersion.

The 'instantaneous' COPs shown on the lower chart confirms that performance decreases as tank temperature increases, and also show the COP (H3) reducing suddenly as the immersion operates after the first 25 minutes of heat pump operation. The overall COP values shown with the plot legend are calculated from the sums of the relevant energies over the whole period shown on the graph (not as the average of the instantaneous COP values !).

The next figure shows the temperatures within the tank during the recovery period, and reveals how the tank which was highly stratified at the start of the recovery phase comes to be almost fully mixed in time for the next for the next set of showers.

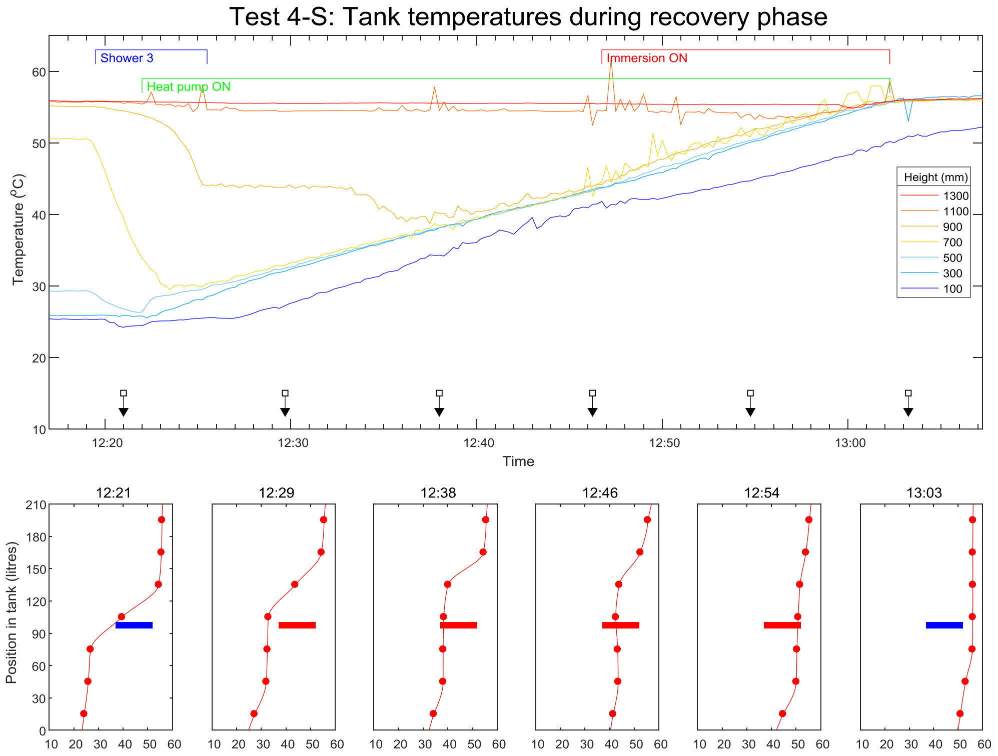


Figure 6.4: Tank temperatures during recovery (WWHRS +Immersion)

It appears from the profiles that the behaviour assumed by the perfectly stratified model, in which heat introduced moves up the tank to to effectively push the cold front back down, is not what is happening. Instead the heat first mixes into the region around the heat exchanger, and progressively increases the temperature at that level. This water then mixes with the cold layer above it, until the whole tank is back at the required temperature.

Finally, Figure 6.5 attempts to show the overall stratification picture a little more intuitively. It was originally produced with the aim of providing a pictorial way of comparing the measured conditions in the tank with the predictions of a range of stratified tank models. That task remains ongoing.

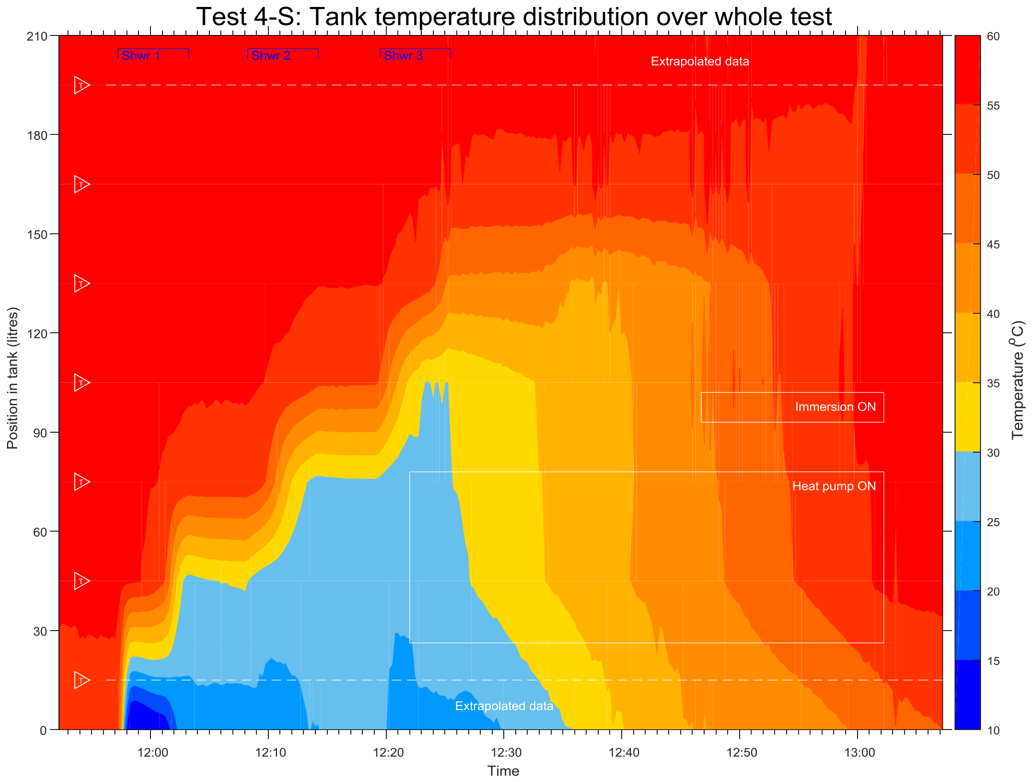


Figure 6.5: Evolution of tank temperature distribution (WWHRS +Immersion)

In looking at this plot it is important to remember that while there is no shortage of resolution on the time axis (measurements were made at 15 second intervals) the vertical temperature distribution was measured at only seven points, marked on the left hand side of the plot. Therefore a lot of the vertical detail has been filled in by the same routine used to generate the contours. In particular, the temperature sensors do not extend completely to the top or bottom of the tank, and so in these regions the data are being extrapolated. These regions are marked on the plot.

The operating periods of both the heat pump and immersion are also shown on the plot. The width of each rectangle shows the operation time, and the height shows the position in the tank at which the energy is being injected.

For this particular figure the x-axis has been scaled to allow the maximum amount of detail to be seen. In subsequent sections these plots with WWHRS have their x-axes adjusted to match the non-WWHRS cases in order to allow more direct comparisons.

Copies of these graphs for all the tests carried out are available from Showersave on request.

7 Data Analysis

Much of the data analysis described here had already been carried out as part of the process of producing the graphs shown above for preliminary data checking. For example placing markers on plots of when the shower, heat pump or immersion is operating requires finding the relevant start and finish times, and the corresponding run times were then calculated for checking purposes. With these operations in place calculating the corresponding energy flows is easily accomplished.

Using this information, the table below shows the results of the first two tests, featuring operation with no immersion with and without WWHRS.

	ELECTRICITY USE (kWh/shower) (No immersion)		
	S	L	H
No WWHRS	0.930	0.747	1.252
WWHRS	0.666	0.512	0.822
Change	-0.264	-0.235	-0.430
	-28%	-32%	-34%

Table7.1: Measured electricity use (No immersion)

7.1 Normalisation of results

Inevitably, there are small differences in the conditions during each test. The causes of these include variations in incoming cold water temperature, small differences in shower water delivery temperature and variations in shower durations and flow rates. Although these variations have been kept sufficiently small to avoid any major changes in system operating point they can still be large enough to affect the savings generated when two test results are compared. Because of this it is desirable to correct for them, or to 'normalise' the results.

There are two possible approaches to the normalisation process. The first is to identify the sensitivities of the measured energy consumptions to each of the key factors. For example, the amount of energy used is directly proportional to the volume of water run off. The shower run off volume (equal to the integral of the flow rate over the shower duration) has been denoted by V_{shower} and if the value that we wish to normalise to is designated V_{shower}^{NORM} then multiplying the measured data by the factor:

$$\frac{V_{shower}^{NORM}}{V_{shower}}$$

will provide at least an approximate estimate of what the energy use would have been had the actual run off volume been the same. The corresponding factor for cold water inlet and shower delivery temperatures is:

$$\frac{T_{shower}^{NORM} - T_{cold}^{NORM}}{T_{shower} - T_{cold}}$$

The second way to look at the problem is to simply calculate what the actual shower energy requirement would be operating under normalised conditions, and scale the results to bring the measured energy requirement into line with this value. This gives a single correction factor of:

$$\frac{4180 \times V_{shower}^{NORM} \times (T_{shower}^{NORM} - T_{cold}^{NORM})}{4180 \times V_{shower} \times (T_{shower} - T_{cold})}$$

This is exactly the same as applying the two factors derived above. As expected, both approaches give exactly the same result.

Table 7.2 shows the resulting normalisation factors, which are generally small.

Test	Correction	Impact
1-S	1.002	0%
1-L	0.995	-1%
1-H	0.980	-2%
2-S	0.962	-4%
2-L	0.968	-3%
2-H	0.957	-4%
3-S	0.970	-3%
3-L	0.970	-3%
3-H	0.982	-2%
4-S	0.997	0%
4-L	0.979	-2%
4-H	0.973	-3%
5-S	1.013	1%
5-SWWHRS	0.973	-3%

Table 7.2: Factors required to normalise actual run off energies to specified temperatures and flows

For the normalisation process to work accurately it is important that the corrections are small, but also that the quantity being normalised is at least roughly linear in the variable being used to normalise. The table indicates that the corrections are generally small. In the situation where energy comes just from the heat pump it is also likely that the linearity requirement is met: increasing the shower load by, say, 5% will also increase the electrical input by about 5% (leaving aside small variations in COP) and also the recovery time. However, once the immersion is used the situation changes, as a small increase in load has the effect of increasing heat pump electricity consumption, but also of disproportionately increasing immersion consumption.

The graphs show how total electricity use varies with shower energy load, for the first four tests.

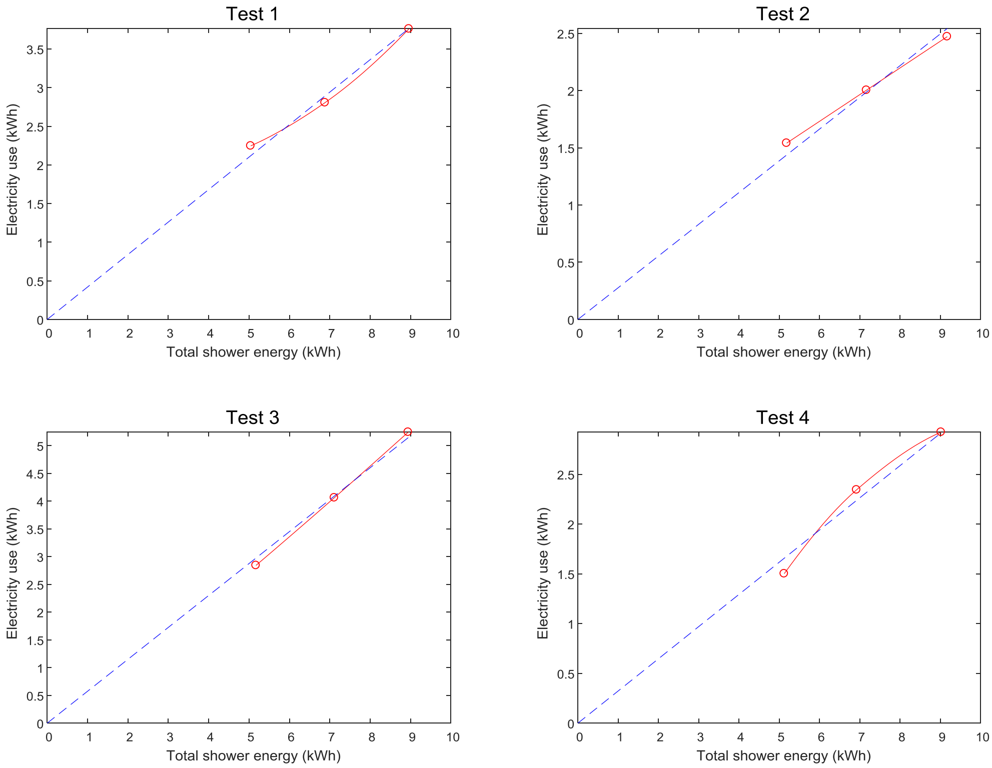


Figure 7.1: Linearity of electricity use in shower energy requirement

When it comes to heat pump running time (which we will later choose as our definition of recovery time) the situation is again confused by the operation of the immersion. If the total running time is less than 25 minutes the the running time is linear in the load applied (it is simply the load divided by the output capability of the heat pump). Beyond 25 minutes the immersion operates, and the divisor becomes the combined output of the heat pump and immersion. At this point the line becomes less steep. Figure 7.2 shows the recovery time plotted against total energy requirement.

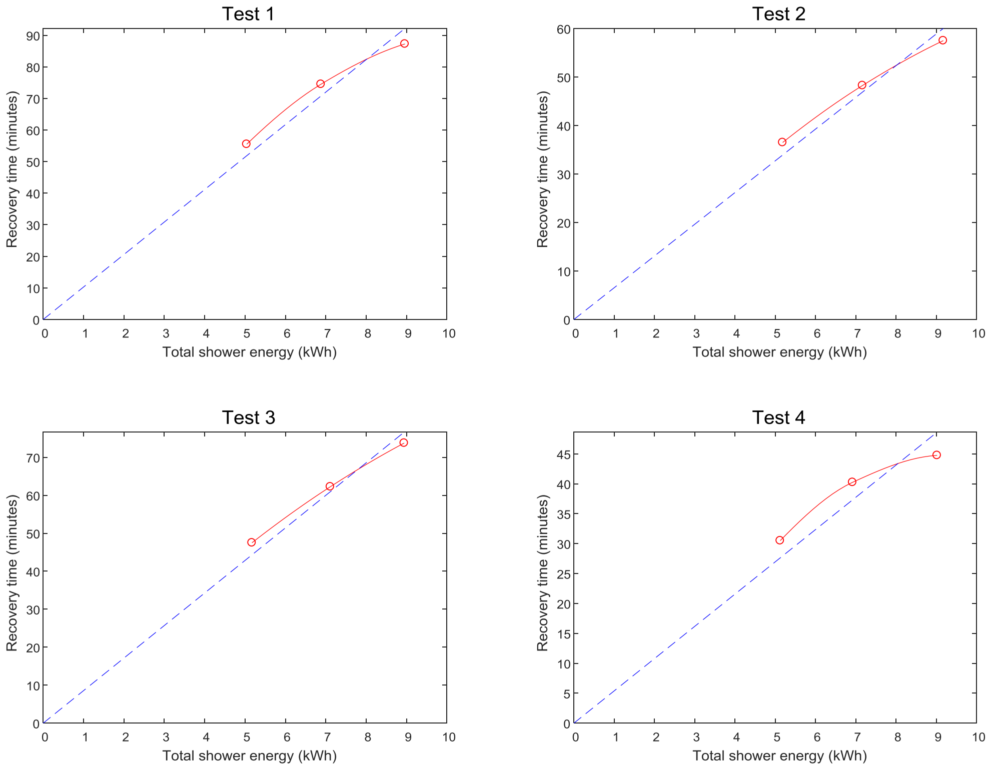


Figure 7.2: Linearity of recovery time in shower energy requirement

These graphs do seem to indicate the sort of non-linearity expected at higher loads, and indicate that the accuracy of run time normalisation may fall off at higher flows. However, it is at least still operating in the right direction, and has therefore been retained.

8 Results

In the introduction to this report three groups of key questions were raised and this section attempts to address each of those in turn from the measured results.

8.1 Hot water cylinder stratification

The graphs already presented have demonstrated that the hot water cylinder stratifies very well during shower run off. For a standard SAP shower (flow regime S) the volume of hot water required is given by:

$$V_{hot} = V_{shower} \frac{T_{shower} - T_{cold}}{T_{hot} - T_{cold}} = 66 \times \frac{41 - 11}{52 - 11} = 48 \; litres$$

This is approximately one quarter of a tankful and Figures 6.2 and 6.5 confirm that the cold front created by stratification moves up the cylinder by this much for each shower, corresponding exactly to the 'plug flow' model of the tank assumed in the perfectly stratified tank model.

During tank replenishment however the picture changes. When the heat pump operates its effect is to mix the whole region below the cold front, and the heat that is then transferred is moved uniformly into this mixed volume. The next figure shows the tank behaviour over Test 5-S, during which a mixing pump connected from tank outlet to inlet was used to destroy stratification.

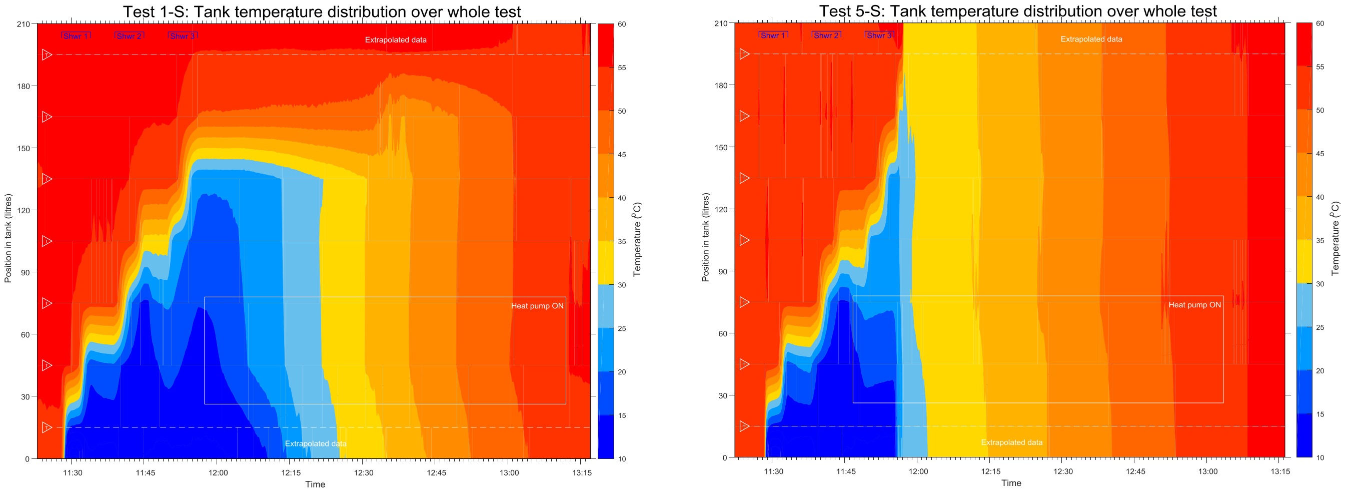


Figure 8.1: Impact of mixing pump on tank temperature distribution
(x-axes matched to facilitate comparison)

This indicates how robust the stratification during run off is - even with the mixing pump running the tank tends to maintain the step like movement of the cold front seen before in normal operation, albeit slightly less distinct. There is no doubt that even with the pump running the required showers are available, possibly even with the option of a potential fourth. However, once the stratification driving force of hot water draw off and cold water input ends the pump quickly mixes the whole cylinder. Comparing the resulting recovery time to the corresponding test without the mixing pump indicates that, with or without WWHRS, the mixing pump is having little effect during this phase, as the next table shows.

	RECOVERY TIME (minutes) (Normalised - No immersion)	
	No WWHRS	WWHRS
Unmixed	75	46
Mixed	78	43
Change	3	-3
	4%	-7%

Table 8.1 : Normalised electricity use (No immersion)

The results confirm that, as expected, neither of the two previously developed models of hot water cylinder performance is exactly correct. However, the way in which the measured performance differs is a little unexpected. When developing the models of perfectly mixed and perfectly stratified storage the assumption was that the real performance would be some sort of mixture between the two, due to hot water rising while natural diffusion caused a certain amount of stirring along the way. In fact, it appears that the perfectly stratified model is adequate during high run off periods, but that during heat input the mixed model represents the performance well, at least for the part of the tank below the cold front. This is in direct contradiction to the assumption in [7] where tank sizing is done under the assumption that the tank stratifies perfectly at all times. Actual operation is still a mixture of the two models explored previously, just not in quite the way expected. The model described in [1] is now being refined in the light of this new information.

8.2 Energy inputs

The table below shows total electricity consumption, normalised using the factors from the previous section, without immersion operation.

	ELECTRICITY USE (kWh/shower) (Normalised - No immersion)		
	S	L	H
No WWHRS	0.932	0.743	1.227
WWHRS	0.641	0.495	0.787
Change	-0.292	-0.248	-0.440
	-31%	-33%	-36%

Table 8.2 : Normalised electricity use (No immersion)

The savings shown are as expected and the measurements confirm the current understanding of how they are achieved. Figure 6.1 showed the Showersave pre-heating incoming cold water to around 25°C. Without the WWHRS this water would enter the shower directly from the incoming main, at around 10°C. This water is fed both to the cylinder or boiler inlet, where it has the effect of reducing the energy required to heat it to the hot water setpoint, and to the cold inlet of the shower mixer, where it reduces the amount of hot water required in the mix. These two effects impact separately on the distribution in the hot water storage tank. The pre-heated incoming water results in a higher temperature at the base of the tank, and the reduced volume of hot water required reduces the rate at which the cold front moves up. These effects together produce the energy savings shown in the table.

These effects are both clearly visible in the temperatures recorded in the tank during run off. Figure 8.2 shows the plots without and with the Showersave WWHRS. The resulting increases in both the intensity of the cold front and the rate at which it moves up the tank are clear.

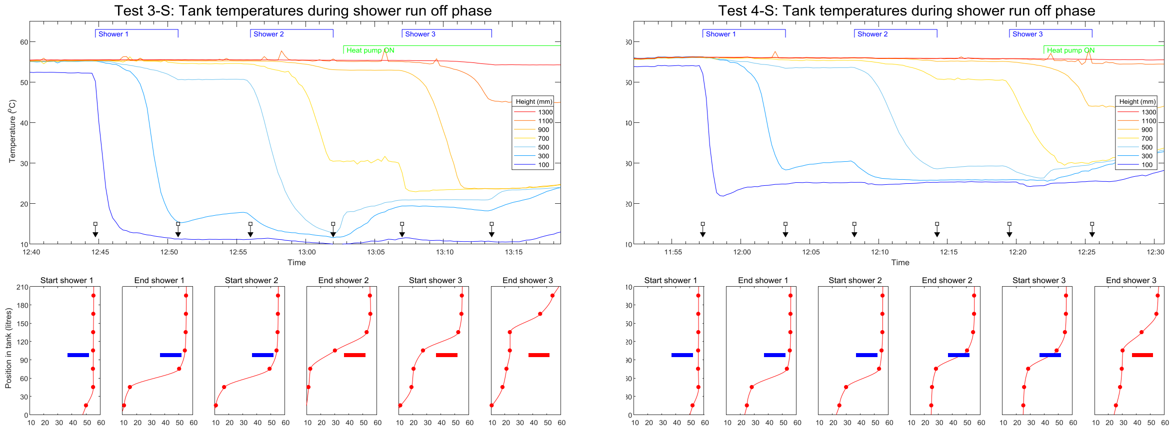


Figure 8.2: Impact of WWHRS on tank temperatures during run off

For a more comprehensive graphical demonstration of these effects, Figure 8.3 shows the whole tank temperature distribution, and provides a direct demonstration of the impact of WWHRS.

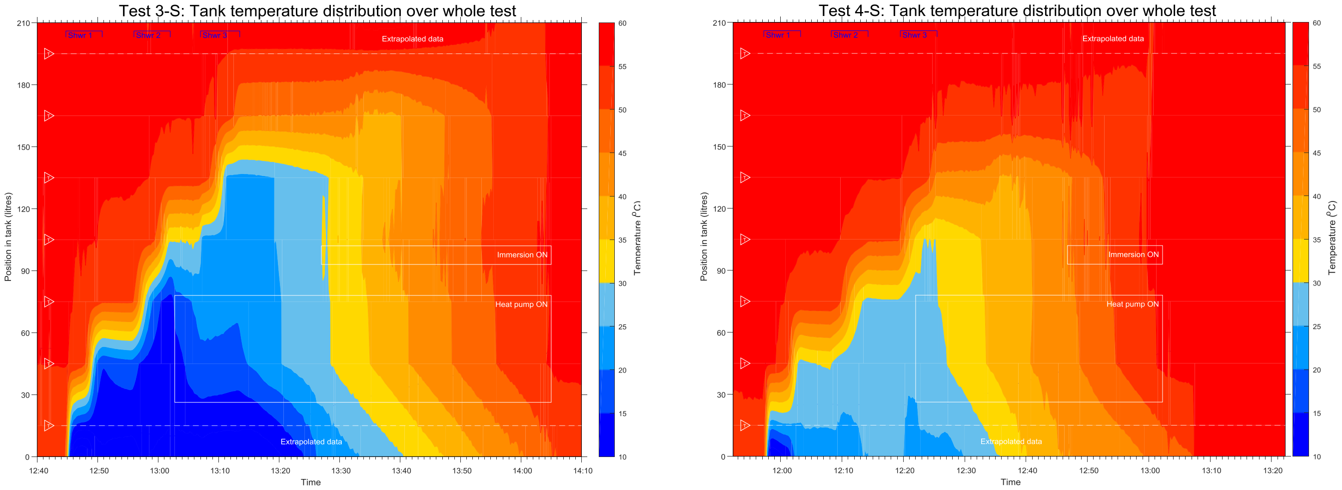


Figure 8.3: Evolution of tank temperature distribution without and with WWHRS (Immersion) (x-axes matched to facilitate comparison)

This comparison clearly shows both of the effects described above, and also starts to give some insight into how immersion operation is impacted by a Showersave WWHRS. Table 8.3 shows the effect on the total electricity used by the system.

	ELECTRICITY USE (kWh/shower) (Normalised - Immersion in use)		
	S	L	H
No WWHRS	1.312	0.917	1.715
WWHRS	0.777	0.488	0.947
Change	-0.534	-0.448	-0.768
	-41%	-47%	-45%

Table 8.3 : Normalised electricity use (Immersion in use)

The WWHRS now produces a much larger saving in electricity use, because as well as electricity supplied to the heat pump (COP≈3) it is displacing immersion electricity (COP=1). In effect, as well as reducing the hot water load it simultaneously increases the efficiency of the hot water heating system. This is reflected by the fact that without immersion heating the Showersave reduces electricity consumption by between 31% and 36% (Table 8.2), but with the immersion enabled this rises to a 41% to 47% saving (Table 8.3). The current SAP treatment of heat pumps used for hot water production [11] incorporates supplementary heating energy by using a single COP(H4) calculated at the time the heat pump is tested. It therefore predicts an electricity consumption proportional to hot water load, and so does not reflect this effect.

8.3 Fuel use and cost implications

The results presented so far have compared heat pump electricity use with and without WWHRS and with and without the supplementary immersion heating which some manufacturers appears to provide by default. As the drive towards reducing the emissions associated with domestic heating continues many of these installations will be replacing existing gas boilers. For the size of house considered here these are most likely to have been in the form of a combi boiler.

In this section we will attempt to estimate the change in running cost which is likely to be incurred by making this change. If the system did not have a WWHRS to begin with we will also look at the impact that installing one at the same time as the change from combi boiler to heat pump. Of course, any reduction in annual running cost can only be assessed in the light of the capital cost associated with acheiving that saving. This section finishes with a short discussion of the impact that the use of WWHRS can have on capital cost for a properly designed system. The problem here is that for some housing types the capital costs may not be met by the same individual as the running cost.

To calculate the total fuel consumption associated with a given hot water load SAP first takes account of three potential sources of heat loss from the hot water system. These are:

- the loss from the primary pipework connectcting the heat source to the storage tank;
- the standing heat loss from the storage cylinder;
- the losses from the secondary pipework.

The SAP calculation of combi boiler performance is well established. There are no losses from primary pipework or from a cylinder. The secondary pipework losses are fixed in SAP at 15% of the load. It is therefore simple to attribute this to the portion of the load used for showering.
A boiler efficiency to is applied to the total hot water load. Here we will carry out the same calculation, using just the shower hot water load. The combi boiler calculation is therefore:

$$Fuel\ used\ (gas) = \frac{Normalised\ shower\ hot\ water\ energy \times 1.15}{Boiler\ efficiency}$$

SAP also accounts for the electricity used by the boiler flue fan, estimated as 45 kWh/annum, or about £7 per year. Once the fraction of this attributable to showering (as opposed to other hot water use and space heating) has been evaluated the result is small, and has not been included here. The calculation for the heat pump is slightly more complicated. The measurements made on the heat pump system here do not include pipework losses (the instrumentation is all relatively close to the heat pump and storage vessel) or the majority of the tank losses (the energy inputs have been calculated over only the time taken for the cylinder to first recover). Thus the SAP estimates of each have to be calculated. Furthermore, only the portion of primary and tank loss attributable to shower hot water must be added in to the overall electricity costs:

- primary pipework losses for insulated pipework are estimated (using SAP Table 3) at 0.75 kWh/day. This loss occurs when the heat pump is recharging the cylinder, thus if an immersion is in use it will be also used to satisfy part of this load. The relevant COP is therefore H3;

- manufacturers generally quote tank loss in kWh/day (for the particular cylinder used here it is 1.76 kWh/day), and SAP applies a temperature factor of 0.6 × 0.9 = 0.54 (from Table 2b [2]) to this to account for the fact that the cylinder is not at full temperature all the time. We have assumed that, because they are spread over the whole day, the tank losses will be satisfied without the assistance of the immersion heater, and that the appropriate COP to use is therefore H2;

- finally the 15% secondary pipework losses described above mostly occur at the same time as the shower run off itself and so these have been incorporated simply by increasing the electricity consumption of each shower by 15%. The previous discussion of linearity is as relevant to this as it is to the normalisation process.

For the first two of these the energy included in our calculation must be adjusted by the fraction of total hot water use which is being used for showering. To evaluate this we have turned to the much more comprehensive treatment of hot water use proposed for SAP 10.1 [3]. It is convenient to calculate the fraction first. It typically evaluates to between 0.65 (generally cases without WWHRS) and 0.35 (generally cases with WWHRS).

$$Sfrac =$$

$$\frac{Normalised\ shower\ hot\ water\ energy}{Normalised\ shower\ hot\ water\ energy + SAP\ estimate\ of\ other\ hot\ water\ energy}$$

For the heat pump the final SAP fuel calculation (carried out entirely in electricity) is therefore:

$$Fuel\ use\ (electricity) = Normalised\ shower\ electricity$$

$$+ \frac{Sfrac \times\ Primary\ pipework\ loss}{COP(H3)}$$

$$+ \frac{Sfrac \times Daily\ tank\ loss\ \times Temperature\ factor}{COP(H2)}$$

$$0.15\ \times Normalised\ shower\ electricity\ (secondary\ pipe\ loss)$$

Note that these calculations treat only the hot water used for showering - they do not include hot water for other purposes. They also do not include the additional cost associated with the weekly Legionella purge cycle, or of any defrosting required. Table 8.4 shows the results of the two calculations for all of the tests carried out without artificial mixing.

Normalised cost of producing hot water for showering using Gas combi boiler and Electric heat pump (£\annum)					
Immersion	WWHRS	Flow	Gas combi	Electric heat pump	Change
NO	NO	S	161	196	36
		L	117	159	42
		H	205	256	51
	YES	S	78	137	59
		L	59	107	48
		H	98	167	69
YES	NO	S	161	274	113
		L	117	195	78
		H	205	354	150
	YES	S	78	165	87
		L	60	107	46
		H	99	201	101

Table 8.4 : Comparative costs of gas combi and electric heat pump hot water systems

One slightly anaomalous feature of the results shown in the table is that in some cases the predicted cost of gas heating varies with whether or not the corresponding heat pump system uses its immersion. The costs of gas in cases with WWHRS varies slightly for flows L and H with and without the immersion heater in the heat pump case. The reason for this is that the results shown are calculated from the net hot water requirement. Although the total shower energy demands have been normalised to be identical, these cases include heat recovery and the measured benefits of this have varied very slightly between tests. However, to preserve consistency and accuracy when comparing between the two fuels these results have been retained.

The table shows that the increases in running cost can be quite large, particularly when supplementary electricity heating is in use, which we believe to be the norm. To assess the possible contribution that a Showersave WWHRS can make it is helpful to arrange the figures slightly differently. The next two tables show the changes for systems without WWHRS, and for cases where the Showersave is added as part of the changeover package.

	Cost change (£/annum) No Immersion	
	No WWHRS (before or after)	WWHRS (added on upgrade)
S	36	-24
L	42	-10
H	51	-38

Table 8.5 : Normalised fuel cost (No immersion)

The key message here is that without WWHRS even a householder who opts to turn off the supplementary heating option is likely to see an increase in their annual fuel bill. If WWHRS is fitted at the time of upgrade then this increase can be turned into a decrease.

	Cost change (£/annum) Immersion in use	
	No WWHRS (before or after)	WWHRS (added on upgrade)
S	113	4
L	78	-10
H	150	-4

Table 8.6 : Normalised fuel cost (Immersion in use)

When supplementary heating is used the cost increases become much more significant. However, because WWHRS displaces a large part of this, it is again very effective in reducing the running cost of the change.

The capital cost of installing a WWHRS is well known. However, the option of roughly halving the volume of hot water used for showering opens up the possibility of reducing the cost of other items. If the demand for showers remains the same, reducing hot water load opens up the possibility of using a smaller cylinder. Even using the current SAP assumption that only about half of the house hot water load is for showering this still allows a 25% reduction in hot water cylinder size (in our case from 210 to 150 litres). A more significant capital saving comes from the potential to reduce heat pump capacity by 25%. However, in a dwelling where capital and running costs are paid by by the same person it could be argued that this should only be done after the householder had dispensed with operating the immersion. Otherwise the option of eliminating immersion use is probably a much better first step before moving to a smaller heat pump, which could result in even more immersion use.

A final issue associated with fuel use, which was mentioned briefly in the introduction, is the total load on the grid. This is particularly marked for requirements such as hot water production for showering, since the use pattern tends to be highly concentrated at certain times of day. As previously outlined, most systems heat water by diverting the output of the heat pump from space heating. This makes little difference to the electrical load profile. However, if the use of hot water is associated with the addition of supplementary heating loads will increase (here from 7kW to 10kW) at this time of day.

8.4 Quality of hot water provision: Shower availablity and recovery time

The 'Quality' of hot water provision is likely to be judged on multiple criteria. In terms of showers the first of these is how many showers can be taken before the hot water runs out. In the previous modelling study [1] it was seen that if the hot water storage was fully mixed even the first shower could reduce the temperature of the tank to a point where it was not possible to provide a further shower at the desired delivery temperature. The behaviour measured here has shown that, due to stratification, this worst case does not happen in practice. However, even with the cylinder size used here, which is deemed suitable for a house with up to six occupants, and nobody taking a bath when others are showering, only three SAP standard showers in succession can be guaranteed.

By reducing domestic hot water load, a WWHRS can help to increase this capacity. The two figures below use data from the high user shower run-offs, without immersion, to demonstrate this.

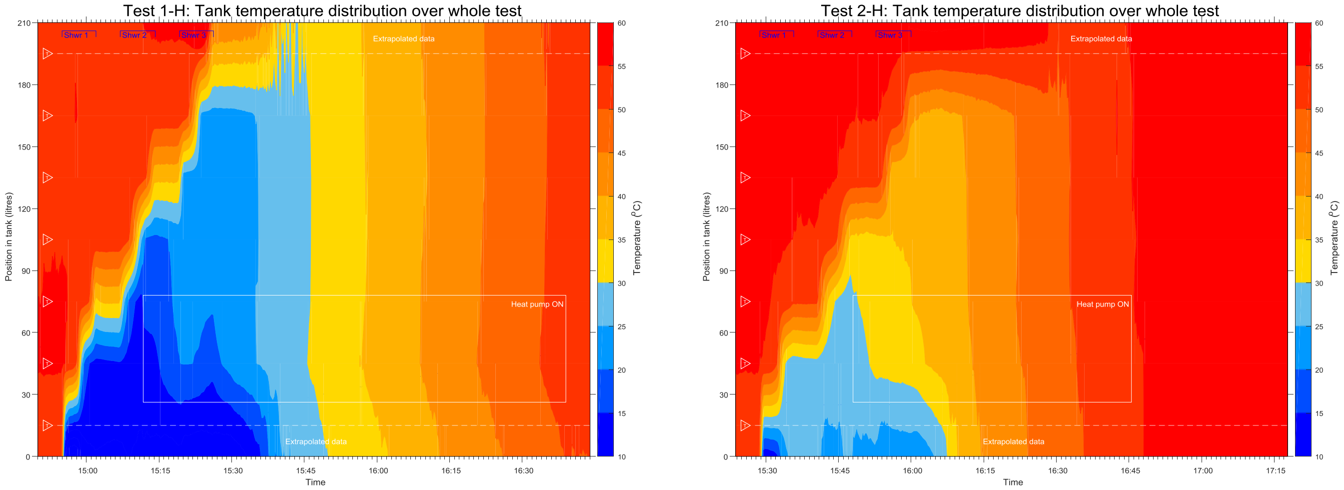


Figure 8.4: Evolution of tank temperature distribution without and with Showersave WWHRS (x-axes matched to facilitate comparison)

From this figure it is clear that at this flow rate three showers is the practical limit of the system - the next shower will start out with a delivery temperature between 45 and 50°C and will quickly have access only to water below 40°C, from which it will no longer be possible to provide an adequate shower. Given that this size of cylinder is deemed to be adequate for a household of five to six people this could obviously be a source of problems. By contrast the system fitted with the Showersave WWHRS has ample capacity remaining for at least one further shower.

A second measure of the quality of provision is the recovery time of the system. This can be defined in at least two ways. The first is how soon another shower can be taken after the system runs out of hot water. Heat pumps typically divert their entire output towards hot water production when this is required. As a result, the house is without space heating for a period. A second measure of recovery time is how long this interruption lasts. In the case of the tests carried out here this is given simply by the heat pump run time. For the combi boiler based systems considered in the previous section this recovery time is simply the duration of any showers (during which time the boiler diverts its output away from space heating to produce hot water).

The table below shows these times, with and without a Showersave WWHRS, when the immersion heater is not in use.

	RECOVERY TIME (minutes) (No immersion)		
	S	L	H
No WWHRS	75	56	87
WWHRS	48	37	58
Change	-26	-19	-30
	-35%	-34%	-34%

Table 8.7 : System recovery times (No immersion)

As before the percentage reduction is consistent across the range of flow schemes. Applying the normalisation factors again makes only a small difference, and provides the results shown in Table 8.8.

	RECOVERY TIME (minutes) (Normalised - No immersion)		
	S	L	H
No WWHRS	75	55	86
WWHRS	46	35	55
Change	-28	-20	-30
	-38%	-36%	-36%

Table 8.8 : System recovery times (No immersion)

These results are as expected. The cylinder is being recharged by a heat source with an essentially constant output, and therefore reducing the initial load by a given factor reduces the recovery time by roughly the same amount. The next table shows how the immersion acts to reduce these recovery times, again with and without the Showersave WWHRS.

	RECOVERY TIME (minutes) (Normalised - Immersion in use)		
	S	L	H
No WWHRS	60	46	72
WWHRS	40	30	44
Change	-20	-16	-29
	-34%	-35%	-40%

Table 8.9 : System recovery times (Immersion in use)

Once again, these results are as expected, and the reduction provided by the Showersave WWHRS is consistent across all run off schedules. The numbers in these tables become more interesting if WWHRS is considered as an alternative way of reducing recovery time to the use of an immersion heater. Table 8.10 shows the reductions in recovery time achieved when the two measures are applied separately.

	RECOVERY TIME (minutes) (Normalised)		
	S	L	H
No Immersion No WWHRS	75	55	86
Immersion No WWHRS	60	46	72
Change	-14	-9	13
	-19%	-17%	-15%
No Immersion WWHRS	46	35	55
Change	-28	-20	-30
	-38%	-36%	-34%

Table 8.10 : Impact of Showersave WWHRS on system recovery times

The actual reduction achieved by the addition of the immersion alone is modest. For the SAP standard shower it is only 19% (17% and 15% for the other two flow regimes). By constrast, omitting the immersion heater and instead adding WWHRS reduces the recovery time by between 34% and 38%. Thus the energy saving WWHRS solution is more than twice as effective at reducing recovery time as the energy consumption increasing immersion solution.

9 Conclusions and Further Work

This work set out to answer three groups of questions about the performance of heat pump based domestic hot water systems, and to appraise the value of any benefits that a Showersave WWHRS could bring to such a system.

The first group of questions related to stratification of the hot water storage tank. This had already been identified as a key issue when determining how many showers would be available in rapid succession, given the relatively low hot water setpoints favoured in heat pump systems. The measurements we have presented have shown that during hot water run off poor stratification is not an issue, and even with a small mixing pump running the cylinder still stratifies robustly. The number of showers available is as predicted by the stratified model, as is the increase in the number of showers predicted when a WWHRS is installed. During cylinder recharging however the picture changes. When the heat pump starts injecting heat into the cylinder that heat quickly mixes into the tank. This results in a small, and probably insignificant, deterioration in COP. It also calls into question the basis of the MCS sizing calculation [7], which is based on the assumption of perfect stratification at this stage. Work to incorporate these new observations into a model of tank stratification is already underway.

The next set of questions addressed the energy (and subsequently cost) performance of the heat pump based hot water system, with and without WWHRS and with and without supplementary heating from an immersion. The measured energy consumptions have tied in well with expectations, because both the heat pump and Showersave have performed in line with previous determinations of COP and efficiency respectively.

In looking at cost implications the new factor introduced was the calculation, using mainly existing or proposed SAP assumptions, of the cost of producing equivalent shower performance from a gas fuelled combi boiler. If a system is being upgraded this has direct relevance: the end user will experience an immediate change in running cost. For a system installed in a new building it may be more difficult for the householder to perceive the increased costs, and they may be disguised by reductions in the cost of space heating fuel that are provided by ever improving insulation standards.

Without immersion use, the cost of producing hot water for showering in a house without WWHRS rises by between £36 and £51 per year, depending on shower use. When supplementary immersion heating is introduced the results become more startling, with increases in the cost of showering alone ranging from £80 to £150 per year. In all cases, the addition of WWHRS when the heat pump is installed provides very useful reductions in these costs. If the system is operated without supplementary heating it turns the cost increases described into cost decreases. With immersion heating in use the increased benefits that the WWHRS provides just manage to offset the increased costs and achieve cost neutrality.

The final questions related to the quality of hot water provision. Given that the system has been seen to stratify during run off, the number of showers available is exactly as predicted by the stratified model. In this case the more meaningful definition of system 'recovery time' is the amount of time for which the system diverts its output from the task of providing space heating. The measurements have shown that without an immersion or a WWHRS this can be as much as 1 to 1½ hours. Using supplementary electric heating to speed recovery, which seems to be the approach of at least two heat pump manufacturers, is one possible solution to this. It has been demonstrated that this dramatically increases energy costs. By contrast, a WWHRS reduces recovery time by twice as much, while at the same time also reducing energy cost.

Due to limitations in the resources available for this work all of these conclusions are based on a relatively small amount of measured data. Future work could address a much larger range of use profiles, and could also examine the impact of other hot water run offs (for example to baths). As hot water accounts for a larger and larger fraction of overall domestic heat requirement it will become increasingly important that these results are then supported by measurements in real dwellings.

REFERENCES

[1] Performance of heat pumps for domestic hot water production: Potential contributions of WWHRS. Chris Martin. April 2021.

[2] The Government's Standard Assessment Procedure for Energy Rating of Dwellings. 2012 Edition. Building Research Establishment. Last revised June 2014.

[3] The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Version 10.1. Consultation document. 2019.

[4] Mitsubishi Ecodan Data Book. Volume 5.3, R32. December 2020.

[5] Samsung Air Source Heat Pump Installation and Maintenance Manual. Model Numbers: RC090-120-140 and 160MHXEA.

[6] Kingspan Albion. Ultrasteel and Aerocyl Product Guide. 2018. https://www.kingspan.com/gb/en-gb/products/hot-water-cylinders/resources/kingspan-albion-stainless-unvented-cylinder-guide

[7] MCS Domestic HW cylinder selection guide. https://mcscertified.com/wp-content/uploads/2019/08/Domestic_HW_cyl_selection_guide.pdf

[8] Hot Water Association on-line tank size calculator: https://www.hotwater.org.uk/hot-water-cylinder-calculator/

[9] Invest Northern Ireland Innovation Voucher Programme.
Project Title: Benefits of integrating of waste water heat recovery and heat pumps in a domestic environment. Dr. Christopher Wilson and Dr. Nikhilkumar Shah. University of Ulster. June 2021.

[10] System Boundaries for SPF calculation. Andreas Zottl, Roger Nordman, Marek Miara and Heinrich Huber. 10th IEA Heat Pump Conference. 2011.

[11] SAP SUPPORTING DOCUMENT Calculation Method: CALCM:01 SAP REVISED HEAT PUMP PERFORMANCE METHOD. Issue 1.2. Building Research Establishment.