Vapour Compression Heat Pump Technologies for Domestic Hot Water Heating

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Abstract

Decarbonising space heating in domestic buildings has advanced through combinations of building insulation and lifestyle changes e.g. Passive House, integration of renewable energy and the use of heat pumps and other energy efficiency measures. Domestic Hot Water energy savings have also proceeded through improved water usage of "white goods", aerated taps, improved storage tank designs and once again lifestyle changes. However, combination boilers (gas and oil) have made significant inroads into hot water storage tank deployment which has in turn affected variable renewable energy demand side management potential at a domestic level. Therefore, in terms of hot water decarbonisation, can the vapour compression heat pump respond with similar personal expectations in terms of heat-up time and flow rates to that of the combination boiler for domestic hot water usage? A new UK Engineering & Physical Sciences Research Council project entitled 4S-DHW (EP/N021304/1 Small Smart Sustainable Systems for future Domestic Hot Water) aims to evaluate the latest wide speed range variable speed scroll compressors as a direct competitor to the combination boiler. Initial concepts will devise domestic hot water use patterns for individual homes including temperature, flow rates durations and drive a compressor to meet these needs. Based on the response of the compressor, minimal indirect water heating provided through novel thermal energy storage utilising will be integrated into the heat pump to meet end-user demands. This paper describes likely concepts that can meet this need, experimental development and initial modelling indications.

Keywords: Domestic; Hot water; Heat pump;

1 Introduction

Domestic Hot Water (DHW) accounts for 14% of heat used in the UK home. This compares with 63% in space heating but is much more challenging to a major reduction than is space heating due to its relationships to hygiene and health. In the UK, domestic hot water accounts for 80 TWh delivered energy per year [1][2]. With the move towards a low-carbon future, it can be expected that a combination of improved building insulation and the application of heat pumps or other technologies to space heating will drastically reduce carbon emissions. However, present heat pump systems are unable to supply instantaneous hot water; a combination boiler ('combi') can deliver 20-30 kW or more for this purpose and heat pumps sized to meet typical house space heating demand are rated around the 10 kW level. A larger heat pump would be uneconomic and would have an unacceptable capacity to meet normal requirements. Thus, the only way that present conventional heat pump systems can provide hot water is to charge a conventional DHW tank. This would not be an issue except that new build houses tend to be designed without space for domestic hot water tanks and opt for instantaneous hot water via a combi gas boiler. Also, there is a strong trend when replacing gas boilers to choose combi boilers and discard the storage tank to provide more space within the home. At present, almost two-thirds of the 23 million gas boilers in UK homes are 'combi' boilers with no large hot water tank [3]. It should be noted that combi condensing boilers do not deliver DHW with laboratory test efficiency due to start up transients, hot water left in pipe runs etc. The mean efficiency of a trial set of combination boilers tested for the EST was 82.5% [4]. The dynamics of state-of-the-art combi condensing boilers were noted by Atmac et al [5] who observed for example that hot water production at 55°C from a 10°C inlet was achieved in 100 seconds. Much is made of 'hybrid' heat pumps to provide both space and water heating but essentially, they are an electric heat pump plus gas boiler with integrated control system. When supplying DHW the load is met by the gas boiler and is no more efficient than a combi. Off-gas grid consumers using direct electricity are also disadvantaged by higher fuel costs [6].

A 'hidden' DHW load is the demand by appliances such as dishwashers and washing machines which use 14% of domestic electricity [3]. In recent years, the trend has been towards cold-fill appliances with electric heating. The argument in favour of this is that efficiency is higher than if an electric water heater is used and losses occur from the DHW cylinder and pipework between appliance and cylinder. This should be revisited if DHW is supplied by a high efficiency heat pump and also if future appliances can request water at the required temperature from a smart supply. More efficient alternatives must be made available to respond to these market drivers.

Assuming that government regulation will not decree storage tanks in all houses, a technical option is required that are compact, appealing to consumers, economically viable and deliver DHW with much reduced energy consumption/carbon emissions. DECC and other projections [2][7][8] imply that the UK will still have to use a significant quantity of gas well into the 2030s and even the 2040s. This is partly due to the intermittent nature of the renewables used to decarbonise electricity and also due to the cost. DECC [9] suggest that in an all-electric future the peak load of 55 GWe could rise to 90-120 GWe, possibly higher, and that reinforcing the transmission and distributions networks in line could cost £46bn NPV (2012-2050). Whatever the future does hold regarding gas supply, whether conventional, fracked, hydrogen or biogas, it is important to have a suite of technologies that will between them constitute a future-proofed and flexible response to the evolving energy infrastructure.

Thus, there is a need to develop energy efficient electric heat pump systems that do not need conventional large DHW tanks and can meet consumer needs. Such systems must initially utilise the existing infrastructure but be adaptable to uncertain future infrastructure and change.

2 Domestic Hot Water

The challenge is that of delivery of hot water at a maximum of 44°C. This temperature is deemed the maximum temperature by the UK's Health and Safety Executive in terms of "Managing the risks from hot water and surfaces in health and social care" [10]. Temperatures and flow rates are established from the UK's Energy Saving Trust and other sources and can be summarised as follows.

For low pressure (gravity-fed) installations i.e. that typically for a two-storey house with cold water tank in loft serving hot water cylinder on the first floor, the bathroom taps would have approximately 0.2 bar pressure, a shower head would have approximately 0.1 bar pressure and the gravity fed taps on the ground floor would have approximately 0.4-0.5 bar pressure. Normally the kitchen sink cold tap would be supplied from the incoming mains water supply and would be high pressure at anything above 1bar pressure. A gravity shower on the ground floor with 0.5 bar pressure would have approximately 0.2 l/s depending on the actual shower valve. For high pressure systems, i.e. those fed by the mains, are normally restricted to 2.5 to 3 bar pressure and would give flow rates of up to 0.416 l/s. However, for gas-combi boilers, which are rated based on their heating capacity, the hot water supply rates would be 0.150 l/s, 0.2 l/s and 0.233 l/s for 24 kW, 28 kW and 35 kW system respectively. The approximate flow rates for tap systems in Litres per Second (l/s) have been summarised in Table 1.

Table 1 Tap flow rates

Flow Rates UK	Litres/sec	Winter kW 10˚C
Old style 3/4" bath tap	0.25	33.44
Old style 1/2" basin tap	0.166	22.20
Old style 1/2" kitchen tap	0.2	26.75
Old style 3/4" mixer bath	0.2	26.75
Modern Monobloc	0.133	17.79
Modern basin mixer 10-12mm	0.083	11.10
9.5 kW electric shower	0.085	11.37
8.5 kW electric shower	0.075	10.03
10.5 kW power shower	0.233	31.17

For showers with an average shower time of 8 to 12 minutes has a flow rate of 0.25 l/s. The above figures account for legionella, storage over 60°C and 60%/40% mixing with incoming cold mains water. A heat pump will take incoming mains cold water and heat this to 44°C maximum temperature. The seasonal temperature variation of incoming cold mains water remains between 10°C to 20°C. Figure 1 shows cold water seasonal temperature variation whereas Figure 2 shows typical draws off volume of hot water at different source for a typical day.

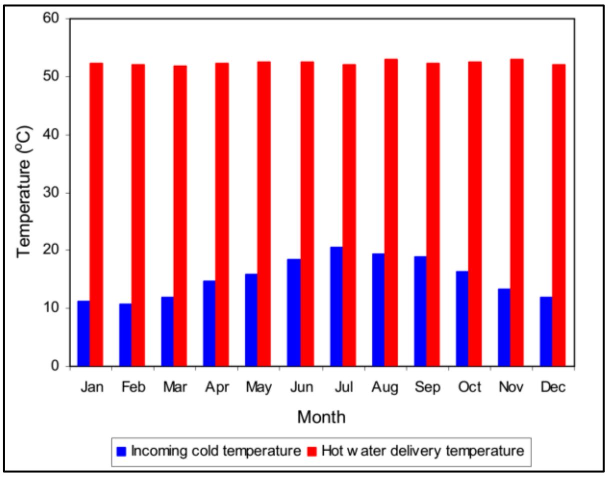

Figure 1 Cold water seasonal temperature variation (Source: EST, 2008)

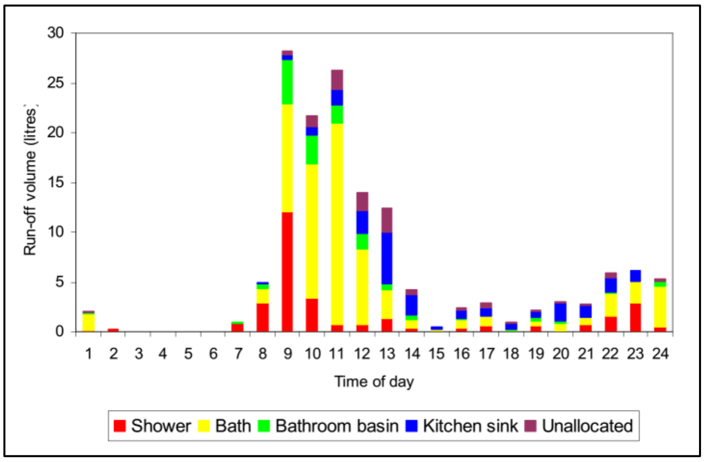

Figure 2 Hot water draw off times by hot water source (source: EST, 2008)

However, in reality i.e. a worse case is that "all" hot water demands could occur and therefore a heat pump could be asked to deliver a vast quantity of hot water over and above space heating demands. Hence, proper heat pump design and selection plays vital role for efficient operation.

3 Variable Speed Compressors/Economised vapour injection concept for Air-source Heat Pump Applications

In order to improve performance at low ambient temperature or to meet sudden hot water demand alternative approaches are required for vapour compression heat pump technology. An alternative approach developed with industry saw a compressor that was suitable for high temperature lift applications by operating in part as a two-stage unit utilising a portion of the condenser refrigerant flow to subcool the refrigerant after the condenser. The disadvantage of traditional air-source vapour compression heat pump is that it will lose capacity as the air temperature drops because of the excessive flashing of refrigerant liquid which is then not available for heat transfer. This impact can be reduced by economised vapour injection and expansion energy recovery. The high stage compression is accomplished by extracting a portion of the condenser liquid and expanding it through a thermostatic expansion valve. The expanded refrigerant acts as a subcooler evaporating in a counter-flow heat exchanger (Figure 13). The superheated vapour is then injected into an intermediate compressor port and the subcooled liquid shows the decreased evaporator inlet enthalpy. The condensing capacity results increased since the mass flow through the condenser increases. The increased evaporator capacity by reducing its enthalpy inlet, causes increasing of refrigeration effect. The two-stage cycle achieves higher efficiency compared to a conventional single-stage cycle delivering the same capacity, because the added capacity requires less power.

Figure 3 such EVI concept, laboratory concept and test chamber for performance analysis. Initial laboratory results were promising when tested to EN14511 test standard and a facility was field trialled with a seasonal coefficient of performance (COP) of 3.7 being achieved. However, a number of challenges arose regarding part-load operation in summer where such a monovalent heat pump (marginally oversized for winter conditions) suffered failures due to very short cycling in hot-water only mode. Variable speed drives have been investigated as a mechanism of managing changing demands. Figure 4 illustrates results from testing a variable speed drive on an EVI compressor. The ability to over-speed and under-speed was limited 40 and 65 Hz and of course best performance occurred at 50 Hz. Future works demonstrated the impact of this on future EVI heat pump design. However, the illustrated heat demand associated with the field trial house of the initial fixed speed EVI heat pump illustrates that a range of 70Hz to 37.5Hz would be very beneficial in terms of power but with a drop-in COP.

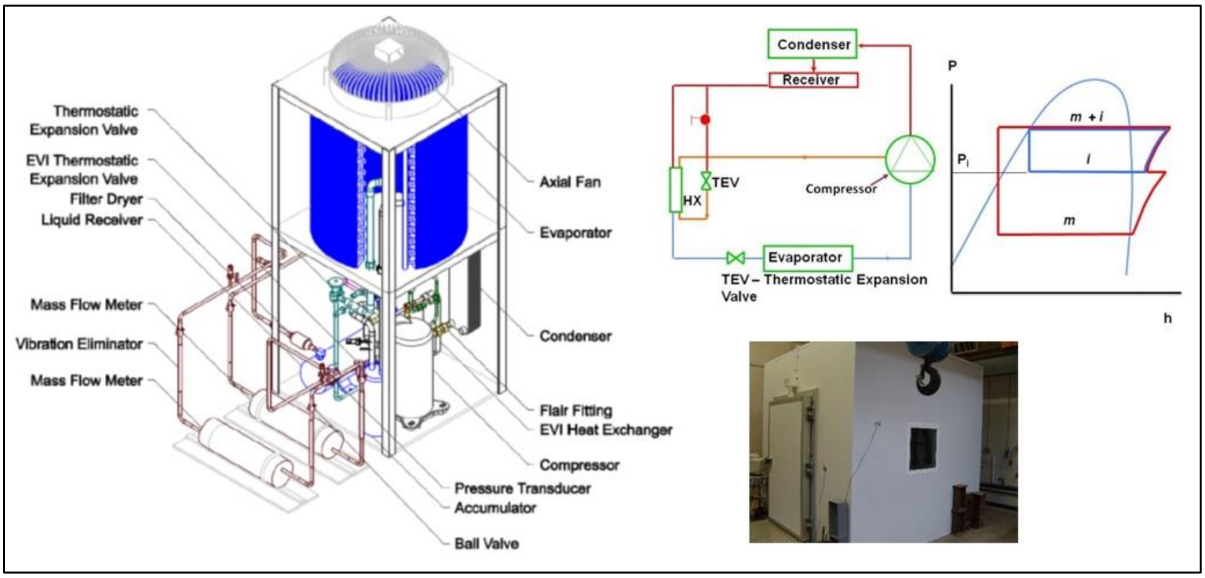

Figure 3 The EVI concept, laboratory test rig and test chamber

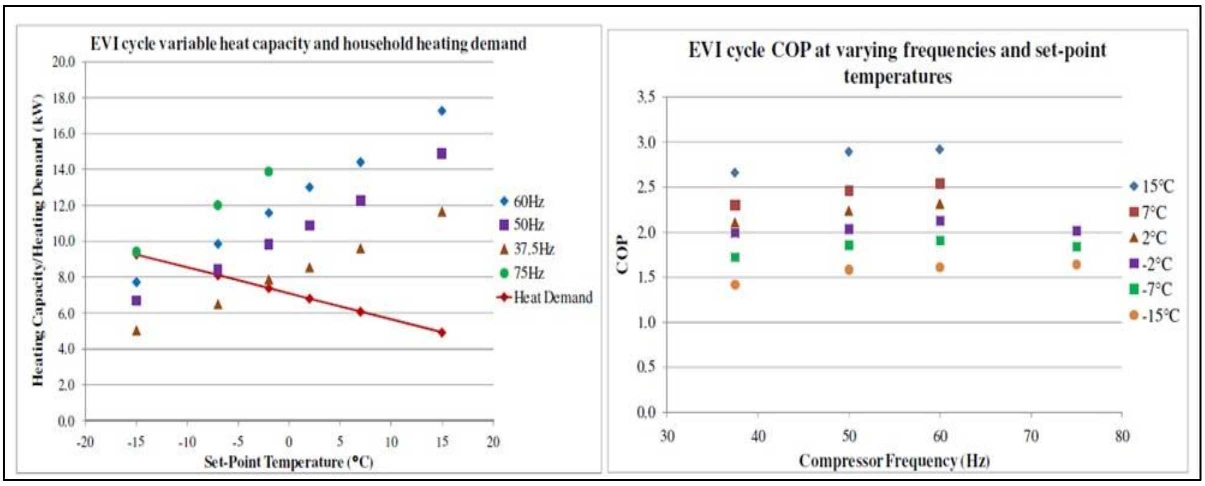

Figure 4 EVI variable speed drive tests

4 Design Considerations for a Dynamic Hot Water Air-Source Retrofit Heat Pump

In developing an air source heat pump (ASHP) that will provide both space heating and domestic hot water without DHW storage, a range of scenarios where created for the UK housing stock. While this is not totally inclusive, it gives an indication of the challenges faced by the utilisation of ASHPs in providing both space heating and hot water for without DHW storage.

In developing models that take into account the likely range of operation that such heat pumps should cover and the initial assumption that only a limited number of ASHP variants should be available to minimise manufacturing costs through mass production techniques. Therefore, the following data was used to address household energy needs [ ].

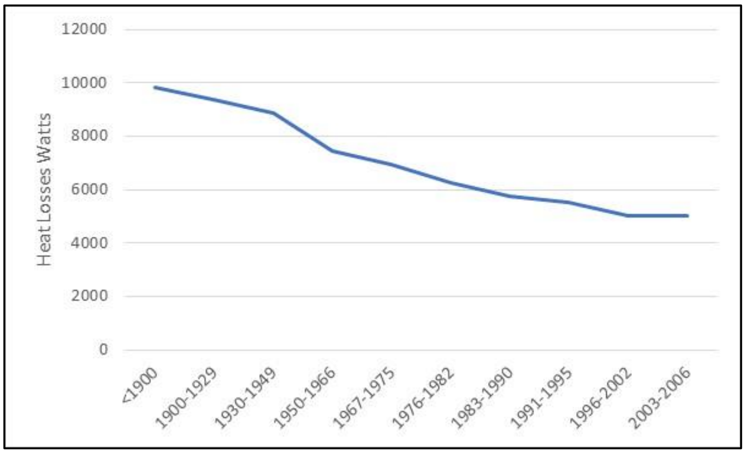

Figure 5 Heat loss reduction due to retrofit measures over the time

UK homes typically require 5kW and 10kW space heating when accounting for all losses which accounts for the impacts of various retrofitting processes depending on age (Figure 5). However, hot water has received less attention with very little understanding of the relationship between the age of the home, the levels of occupancy and the amounts of hot water used. Therefore, the values noted in Table 1have huge consequences for heat pump selection.

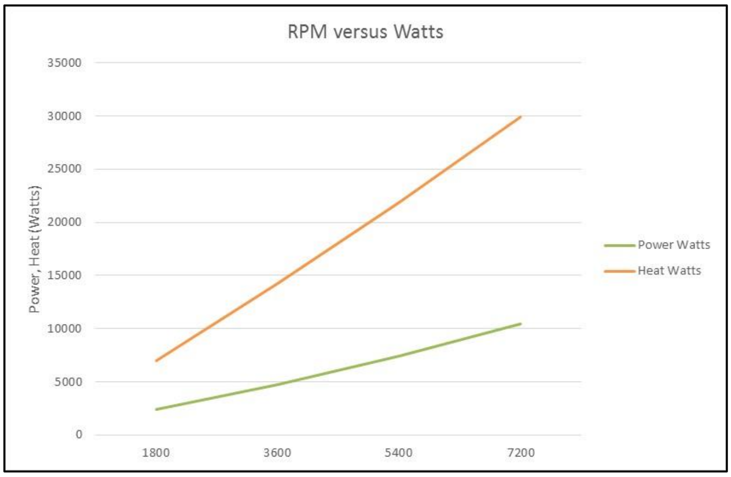

Figure 6 Typical performance of domestic compressor : RPM vs Power and RPM vs Heat

An examination of the characteristics of scroll compressors (typical of those in domestic applications) has been made. A speed range of 1800 rpm to 7200 rpm was found to be typical and the following performance was extrapolated from manufacturer's data to meet the "worst case" scenario of over 30kW of hot water. Figure 6 shows variation in heat and power with respect to compressor speed for worst case scenario.

A number of challenges now exist for the retrofit air-source heat pump in UK homes. These include efficient heat demand at potentially lower space heating needs, compressor performance at low speed operation and space heating/shower temperature incompatibilities.

4.1 Efficient Heating Demands at Lower Space Heating Needs

The challenge of sizing a heat pump to overcome such a range of capacity is dependent on the properties of the compressor in terms of speed management. In theory, the speed range noted in the above figure can accommodate the building demands. However, a number of challenges arise and these include compressor performance and heat pump control and cycling. Compressor performance will be addressed in the following section but heat pump control and cycling will be addressed here.

The hypothetical variable speed compressor proposed here has a lower speed limit of 1800 rpm. In order to achieve 30kW, it will operate at 7200rpm (Figure 7). However, the heating demands are less often at the design point for the home as longer extreme cold events are increasingly rare. Nonetheless, the ability to achieve such a capacity must be retained.

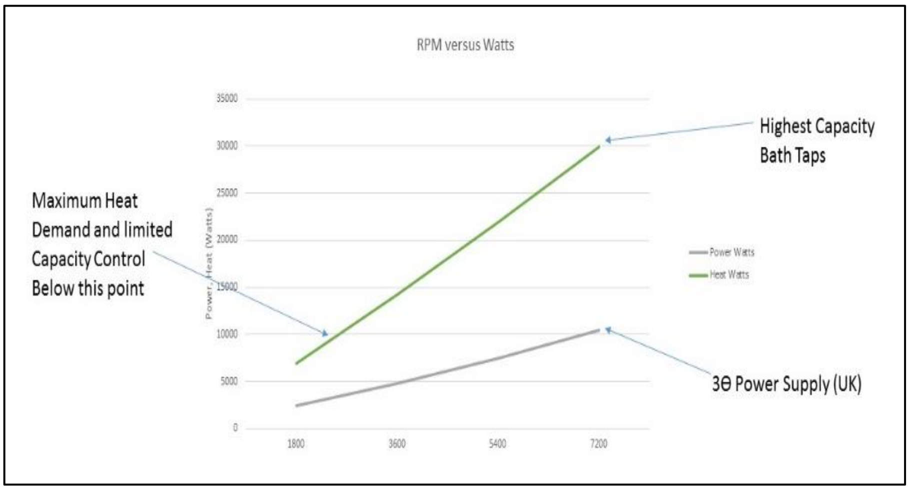

Figure 7 Potential compressor speed variation for DHW

UK challenges include 3Θ power supply needs which are virtually absent at a domestic level. In addition, there is a loss of capacity control for space heating only, even within the oldest houses with the highest heating loads. Compressor cycling reduces performance and shortens compressor life.

4.2 Long Term Low Speed Operation

Typical scroll compressors (of the type typically found in domestic applications due to their size, efficiency and quiet operation) require compressor lubricant to be transferred to ensure moving parts are suitably lubricated. For example, an Archimedes screw principle is utilised to transfer lubricant from the compressor sump to the upper bearings. Such a principle requires a minimum speed of rotation to ensure lubrication. However, when lubricant has been provided, it will operate successfully for a period of time and this dictates the length of time of operation at low speed.

A general rule is that low speed applications are associated with low temperature lift demands. Increasing temperature demands often require increased speeds. In addition, prolonged operation at low speed (i.e. no/limited lubricant transfer) requires a period of higher speed operation to ensure adequate lubrication. Thus, at periods of lower demand, there is a question over the need for the extra heat energy generated. There is also a question over heat capacity i.e. at low speed can the heat pump deliver satisfactory flow temperatures in houses with high temperature radiators at low compressor capacities i.e. low speeds. Figure 8 shows relationship between compressor speed and possible temperature lift and limitation for domestic application.

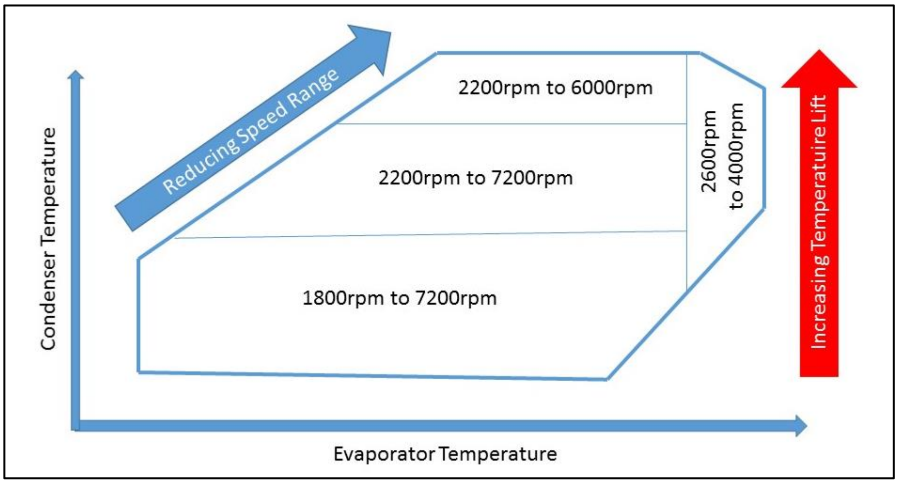

Figure 8 Compressor speed range and temperature lift limitation

Therefore, the question arises that a heat pump designed with current technology cannot address very high water flows and significantly lower space heating needs

4.3 Space Heating/Shower Temperature Incompatibilities

The ultimate challenge is associated with the operation of an ASHP as both a hot water supplier and a space heating supplier. The ASHP could be located outside (as opposed to being ducted into a cellar/basement) and thus will after a cold night and limited/no operation, will be at ambient temperature. Therefore, the thermal mass of the heat pump comes into play.

Assuming a 30kW air source heat pump, a brief review of various manufacturers revealed the relevant thermal mass of heat pump i.e. condenser and compressor revealed approximately 40 kg of assorted metals needs to be brought up to shower temperature i.e. 42°C. Therefore, the minimum time to overcome the thermal mass of the heat pump is 29 seconds. This is achieved by utilising a heating bypass to ensure a rapid heat up time. Figure 9 shows simulation time required to overcome thermal mass for shower at 42˚C. This case assumes underfloor heating and shower temperature requirement at same flow temperatures. However, ASHP is installed in other settings such as radiators or storage tanks then time required to overcome thermal mass will changes respectively.

Figure 10 shows scenario with high temperature radiator operation which represent existing radiators system in retrofit settings. In such scenario ASHP response time response time to 65°C is 52 seconds. Of course, a mixer valve would be required for the shower for safe operation.

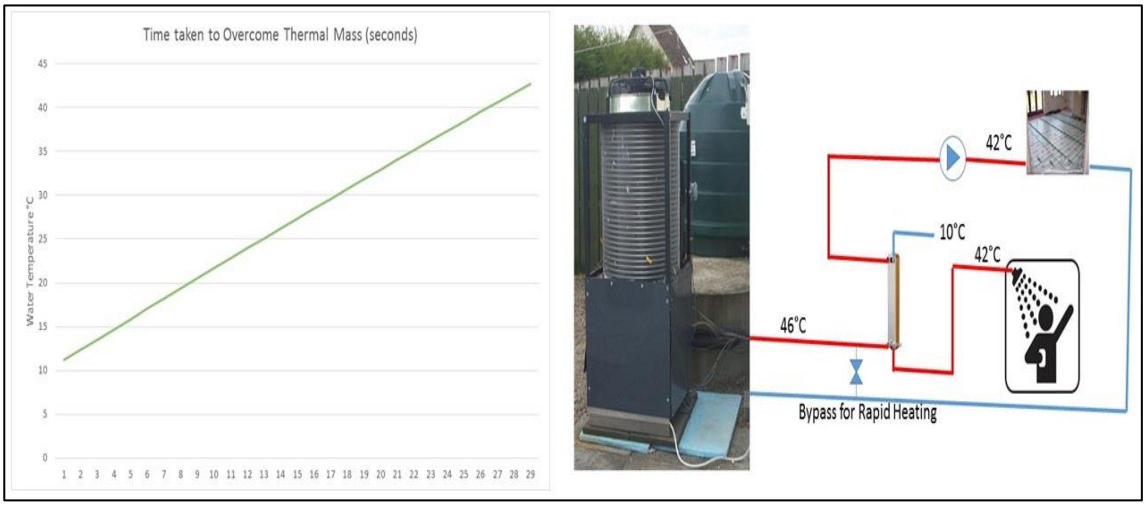

Figure 9 Time required to overcome thermal mass: Shower at 42˚C

Figure 10 Time required to overcome thermal mass: Retrofit conditions

Therefore, what are the likely solutions? Additional thermal storage could overcome thermal mass issues associated with cold start operation and the undesired thermal lag. Ideally this would be sited inside the home to minimise losses but also could be integrated into the condenser insulation as part of the heat pump "system" via the use of phase change materials. However, the major conclusion of this section is that for the likely retrofit heat pump (air source), the domestic hot water demands must be compatible with the space heating demands. Therefore, for the classic scale of UK home illustrated here, the displacement of the electrical shower with a heat pump shower is more likely.

5 Air-Source Heat Pump for Space Heating and Instantaneous Domestic Hot Water

Having arrived at the conclusion that an air-source heat pumps should have a similar demand in both space heating and domestic hot water, the discussion as to their sizing should be enlarged. As an initial start point, the units are designed for 10kW of space heating. Thus, the characteristics of the potential compressor can be seen in Figure 11.

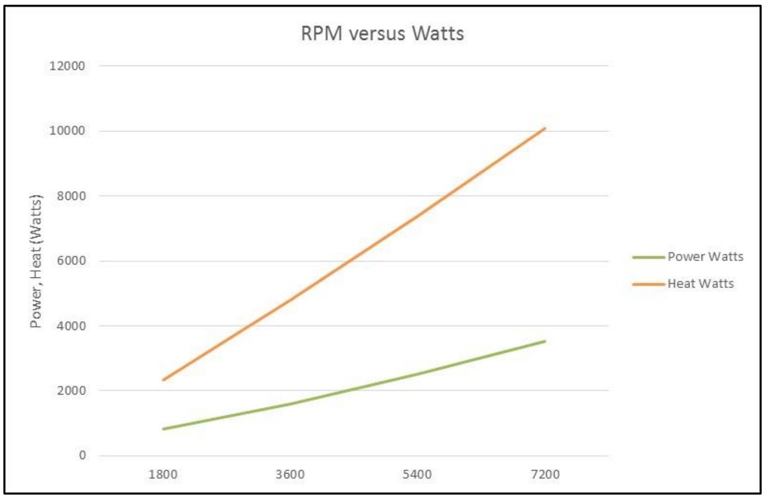

Figure 11 Potential compressor characteristics for 10 kW of space heating

The main concern when addressing instantaneous hot water demand is the thermal mass of the unit during a cold start. Firstly, the weight i.e. relevant thermal mass of components reduces to an estimated 20kg. Likely solutions to this can range from smart control of bathroom sensors in that entering the bathroom with the heat pump unit or condenser water exit temperature below a certain temperature i.e. 30°C for example. Alternative approaches might involve additional storage to overcome the thermal mass of the heat pump unit, internal installation (i.e. in a basement – which are not common in the UK), a pair of compressors and the variable speed drive for the heat pump.

5.1 Exploring the Variable Speed Compressor Performance

An example of a variable speed drive performance is noted in Figure 12. While the speed capacity is 1800-7200 is possible under certain conditions, the likely speed for our chosen application is 6500rpm and therefore there is added complexity for sizing of such future heat pumps that can respond to both space heat and instantaneous domestic hot water supply.

Therefore, for our simplified sizing approach, the actual heat pump capacity could be 12kW at a maximum speed of 6500 rpm to address the space heating load or the instantaneous domestic hot water load. The ability to perform both has been discounted at this stage due to the overcapacity and inflexibility regarding space heating demands at higher ambient temperatures (and lower speeds) discussed earlier. In particular, the low speed operation i.e. 1800 rpm appears to be limited to condenser temperatures below 55°C. This corresponds to the lead authors home for example where the weather compensated control curve illustrates that space heating with existing emitters would meet thermal comfort needs at these temperatures (Figure 13).

However, this is not the only issue. At higher ambient temperatures, the speed is further reduced to 4500rpm and once again, delivering a shower capacity of 10kW would imply a maximum capacity at 7200rpm of almost 17kW.

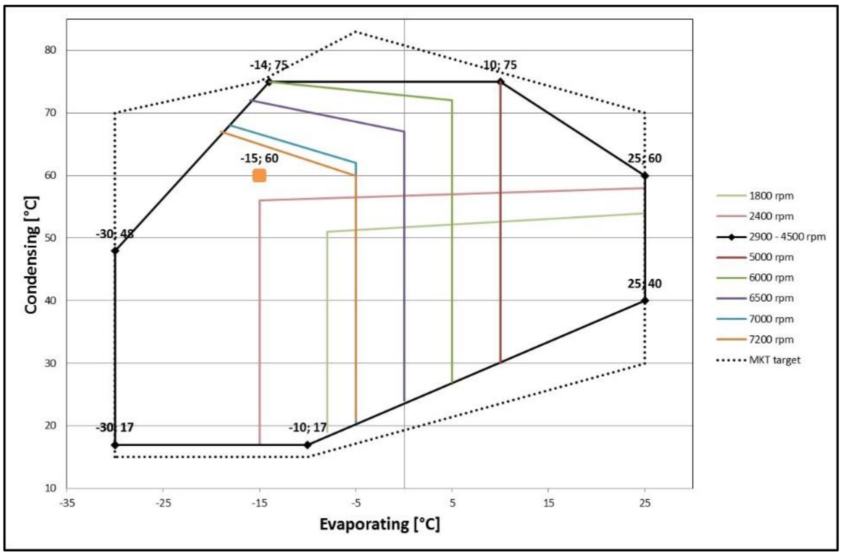

Figure 12 Variable speed compressor working envelop and limitation

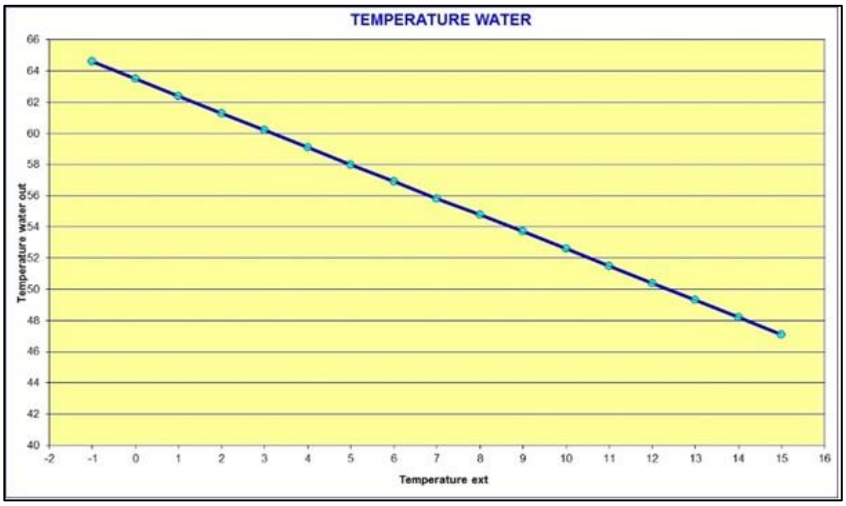

Figure 13 Example of weather compensated control curve

5.2 The 17 kW Heat Pump Operation

Variation in ambient temperature plays big role when considering variable speed compressor design to meet shower and space heating demand together. Figure 14 illustrates the likely temperatures encountered in a typical year using the example of the author's home.

Thus, a series of points where selected to examine the likely performance of a heat pump across this range of temperatures. This results in the compressor speed curve throughout the year (Figure 15).

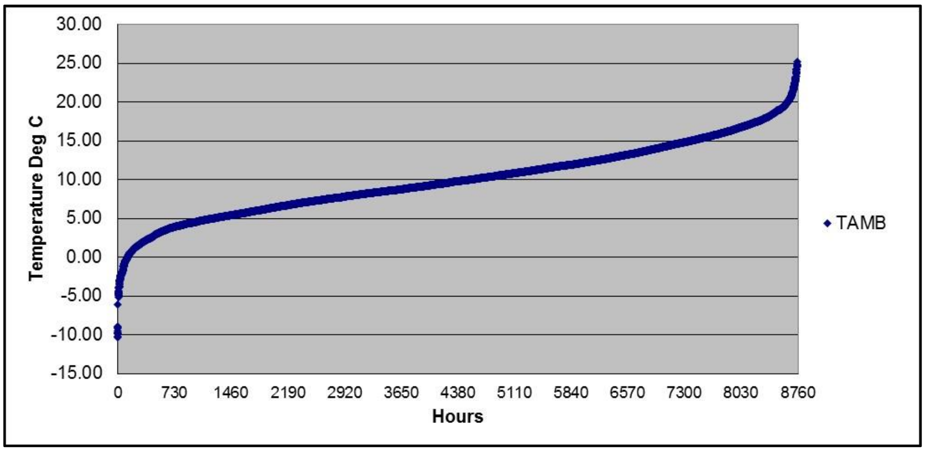

Figure 14 Likely occurrence of ambient temperatures

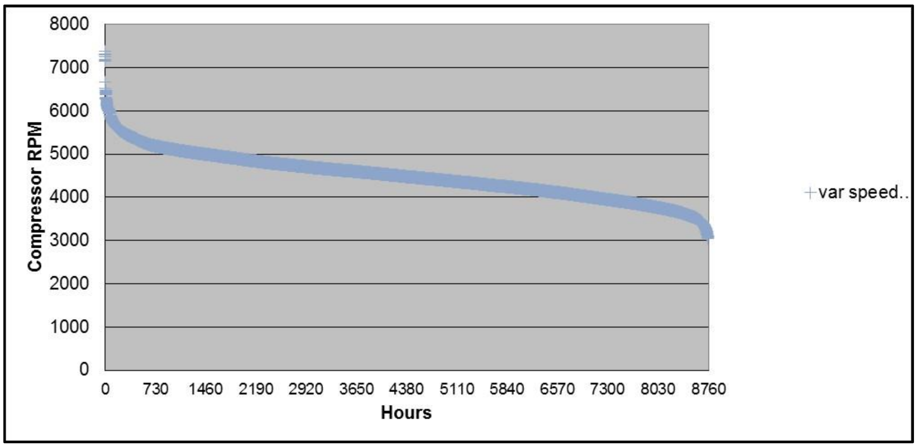

Figure 15 Variable compressor speed at ambient temperature for hot water heating

Therefore it can be seen that for shower operation, the majority of compressor operation is above the typical motor speed of 3600 rpm. Referring to the compressor performance map, it can be seen that this coincides with the likely performance of the compressor and that low speed operation is minimised and therefore lubrication issues are also reduced.

6 The Role of Small Scale Thermal Storage

The consideration of delivering a shower within 100 seconds of its request has therefore two significant challenges: 1) the relevant thermal mass of the outdoor unit and b) the internal domestic hot water pipe runs associated with the building. There is very little possibility of matching the rapid electric shower response as this would be beyond both system performance and capital cost possibilities.

Utilising buffer storage as an indirect heating support in a retrofit application would address the thermal lag caused by the thermal mass of the heat pump, thus leaving the home owner with a shower heat pump time similar to that prior to heat pump installation.

Assuming a heat transfer temperature difference of 5K for an indirect water system, a 50 second lag would require approximately 7 litres of indirect hot water. However, such a tank will lose heat and it has been calculated that such a copper tank with 100mm of Styrofoam insulation would drop significantly.

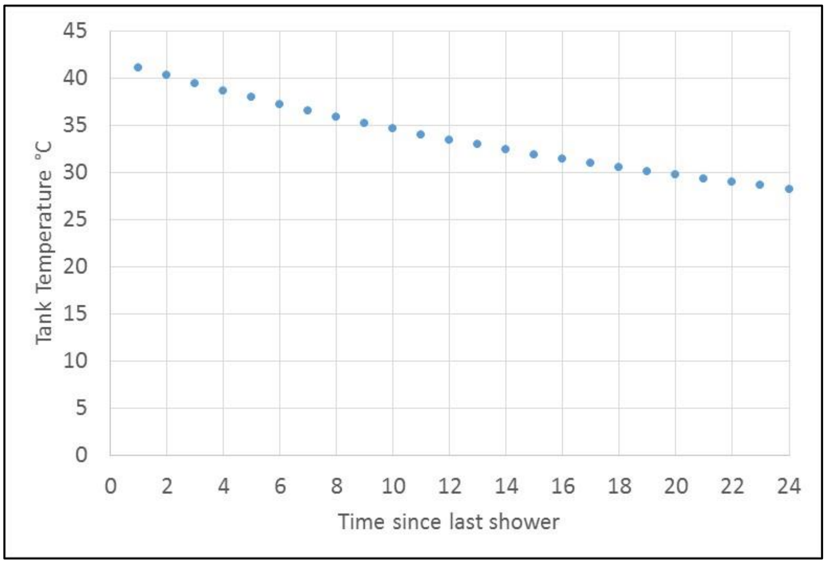

Figure 16 Storage tank temperature and time for shower

Given the heat loss from the tank daily (as a worst-case scenario), heat up time will be reduced by 10 seconds (Figure 16). However as the heat pump will operate in space heating mode for much of the year, especially in the more northerly parts of the UK, it can be expected that such a tank would make a positive contribution for much of the year.

7 Discussion and Conclusions

Vapour compression heat pump compressor progress has seen the development of scroll compressors with significantly enhanced speed ranges that facilitate a wide range of capacities. Such compressor overcame lubrication issues and motor limitations and thus have demonstrable advantages for air-source heat pumps.

However, such equipment would require hot water storage (which could be heated by the heat pump or additional electrical heating) to provide sufficient amounts of legionella free hot water. Alternatively, the emerging hybrid heat pump (a heat pump with integrated gas boiler) could also provide such a service in a situation where hot water storage was not required.

However, the aim of this work is to address whether a single heat pump can address space heating and instantaneous hot water, and the example of a shower was used as a high capacity operation to evaluate this concept. It was very clearly illustrated that the examples of older houses with original (and often desirable) features would require a heat pump that was significantly oversized. The wide ranging variable speed drives imagined for this process would therefore have to operate for much of their time at their lower speed settings thus enforcing a regular speeding up to lubricate upper compressor bearings via the Archimedes screw principle associated with their drive shafts for example. Thus an early conclusion was that the space heating and hot water demands would have to be comparable.

A rapid heating time for the shower would have to overcome the thermal mass of the heating components of an outdoor air source heat pump unit. In colder weather with colder mains water being directly heated for shower applications, an additional thermal lag of 30 to 60 seconds would be added thus raising a question over end-user satisfaction. A reheating bypass, a small buffer tank and perhaps a little end-user acceptance overcomes this challenge.

Finally, these are only some examples of the challenges this research will overcome. The major challenge to be tested experimentally is the continual high speed starting for small amounts of hot water. This may require additional compact thermal storage which could employ phase change materials to provide indirect heating, if the rate of heat release is sufficient for short applications of hot water e.g. hand washing.

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