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UK Domestic Air Conditioning: A study of occupant use and energy efficiency

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Abstract
This paper presents the results of a study of air-conditioning usage in homes in the southeast of England. First part of the study consisted surveying 13 dwellings with air-conditioning for a series of 4 week periods during the summer of 2004. The second part involved testing energy efficiency of "single-split" and "portable" air-conditioning units under "in-use" conditions. Data on usage patterns and typical temperature profiles during operation was collected and is presented here.

Temperatures at which users switched their units on were, on average, 24-25^{o}C, while typical running times for a single operation were found to be around 5 hours during daytime and 7 hours at night in bedrooms. The study also indicated high occupant satisfaction rates with split-units. An unexpectedly high overall energy efficiency ratio (EER), of 5-10, was found for the single-split unit tested during the relatively mild autumn weather. However, a very poor EER, of less than 1, was found for the portable unit tested. Further work is needed to increase the reliability and statistical significance of the results.

Keywords: domestic or residential air conditioning, energy efficiency ratio (EER), coefficient of performance, split system air conditioning

Introduction
The recent extremely hot summers in Europe have seen a growing interest in mechanical cooling in the home and a rapidly expanding residential market in Europe. The extreme, hot, conditions in August 2003 are reported to have caused 35000 additional deaths across Europe, 2045 of which were reported in the UK for the 10 days of the heat wave [1]. Climate change predictions, by the UK Climate Impacts Programme, suggest that not only will future summers be hotter on average (by between 1.5 and 3.5 K, by 2050, depending on the scenario assumed, compared to the 1961-1990 baseline), but that there will be more hot spells [2].

Building Services Research and Information Association reports [3,4] suggest that over the fifteen years from 2000 to 2015, sales of portable air conditioning units will increase by over 450%, while sales of split systems will increase by over 150%. Evaporative coolers are predicted to become an important part of the market from around 2010. Others believe BSRIA's estimate to be far too conservative. For example, an article in the trade press suggests that market penetration could be as high as 15 to 20% of households in the "foreseeable future" [5]. Some suggest that powerful air conditioning should be a statutory obligation in all new housing and commercial developments [6]. Cars are now air conditioned as standard, and with the noise and external pollution, in the high density living predicted for the near future, residential cooling may become so too. In this context, overheating in the home is currently being reviewed for the new edition of the UK Building Regulations and the European Union has issued a directive on energy labelling for domestic units [7].

Buildings account for just under half of UK CO_2 emissions, and so clearly must be considered in any strategy for reducing carbon emissions. The domestic sector accounts for 29% (in 1999) of these emissions [8], and so needs to be given just as much consideration as commercial and industrial buildings. This is recognised in the government's Performance and Innovation Unit's report, which suggests a target improvement in home energy efficiency of 20% by 2010, and 40% by 2020 [9]. A significant increase in domestic air conditioning could easily make this goal unattainable, and could compromise the UK’s Kyoto reduction target, set in 1998, to reduce UK greenhouse gas emissions by 12.5% below 1990 levels, over the period 2008-2012 [10].

In the light of these concerns, the study presented in this paper, funded by the EPSRC over two years, collected information to understand the motivation behind people’s purchase of home air conditioning, and sufficient data to estimate typical annual energy consumption. In respect of the latter, it was necessary to know

- the typical use patterns of cooling in the home (specifically, typical switch-on temperature, duration of operation, desired room temperature and the temperatures achieved)
- the energy efficiency performance, or energy efficiency ratio (EER), of typical units in use over the cooling season
- and the typical cooling demand of dwellings in the UK.

With this data it is possible to make a rough estimate of the energy requirement and environmental impact of residential air conditioning. Projections into the future, under a number of scenarios, can then be made to assist the air conditioning industry and policy makers in dealing with the impacts and opportunities. The present paper sets out the first part of this study, and presents the results of the field and lab work carried out in 2004.

Methodology

The units tested ranged in nominal capacity, as stated by the manufacturer, from 2.45 to 6.7 kW. The study concerns mainly “hard-plumbed” single-split vapour-compression units (or “single-splits”) installed within dwellings in southeast England, “in-use” during the summer of 2004. Two portable units (ducted with a flexible hose to outdoors) and one evaporative cooler were also studied. The study involved a questionnaire survey of occupants, as well as monitoring of the cooling units and temperatures within and around the dwellings. Due to difficulties of gaining access to the wiring of the units, the measurement of the in-use EER was carried out in the “lab”. This was actually a small workshop in the Bartlett School of Architecture, where the occupant was asked to use the system as if at home, and where a single-split, with inverter control, or variable speed control of the compressor was installed. This unit was donated by one of the project’s industrial partners. In addition a “lab” study of one evaporative cooler was carried out in the bedroom of one of the authors. This was purchased at random from a department store.

Details of the methodology can be split into two parts: i) for the field study and ii) for the measurement of the EER for the two units. The presentation of the results and their discussion, which follows, is split into three parts: i) the monitoring study, ii) the questionnaire survey and iii) the EER tests.

Methodology of the field study

The field study itself was carried out in two parts, a user questionnaire survey and the monitoring of the temperature and humidity conditions over a period of around four weeks from late July to mid September 2004, with one additional dwelling monitored from late September to mid October. End users were contacted through the installers of the larger manufacturers, who wrote to their clients asking if they would be prepared to take part, and so respondents were self-selected rather than randomly selected. No incentive was offered and no payment was made following the questionnaire and monitoring.

The questionnaire was administered by one of the authors as a face-to-face interview, where the respondent had opportunities to make additional comments, all recorded manually. The questionnaire collected information mainly in the following areas: the user's motivation for purchase, health status, satisfaction rating, pattern of use and socio-economic background and their estimate of capital, running and maintenance costs.

Temperature and relative humidity were recorded every 5 minutes using TinyTag dataloggers. Conditions were measured in the room, and onto and off the air conditioning unit to establish when the units were running and to determine the switch-on and maintained environmental conditions. It was not possible to test all properties simultaneously, although there was considerable overlap in the monitoring period, which lasted overall from 23rd July 2004 to 14th September 2004, with an additional single split being monitored between 20th September 2004 and 14th October 2004, during unseasonably warm weather. Permission was not always given to attach a datalogger to a unit, in which case a datalogger was placed as close as possible to the air stream from the unit. Outdoor conditions were logged in a sheltered position in the garden or under cover in an external part of the dwelling, such as under the eaves on the north side, or in an open shaded porch. Not all the conditioned spaces/rooms in the dwellings surveyed were monitored. For dwellings with more than one conditioned room, only the two most frequently used were monitored. Occupants were asked to specify any periods when they were away from home for more than 3 days during the monitoring period. With the collected field data, the switch-on temperature and duration of operation were determined by simply comparing the difference between the room temperature and unit outlet temperature. The temperatures maintained by the systems were also obtained. Simple arithmetic averaging was used to determine typical values for all the variables. A total of 13 houses located in and around London were visited during the study.

Methodology of the EER tests

Both units were tested using the same methodology, although slightly different equipment was used in each case. The cooling capacity was obtained by first measuring the temperature and relative humidity (by TinyTag dataloggers) of the room air entering the units together with the air leaving it. From these values the psychrometric conditions of the room and cooled air were derived. The speed of the air leaving the unit was measured by a vane anemometer (by Schiltknecht) attached to a datalogger (by Onset Computing), in the case of the single-split and a datalogging hot wire anemometer (by Testo) for the portable. By multiplying by the cross sectional area of the outlets, the volumetric flow rates for the two units, could be estimated. From this information the rate of cooling was calculated. To obtain the input power, current clamps around the mains cable, connected to dataloggers (both by Onset Computing), were used to measure the currents drawn by the two unit. Assumptions were made concerning the mains voltage and power factor. Values of 230 V and 0.9 respectively were taken, and the results were tested for sensitivity to these assumptions. Data was collected at 2 minute intervals. It is appreciated that the method can only give approximate results. Nevertheless, given the importance of the results in terms of sustainability issues and the resources available to the project, the method was felt to be appropriate.

Results of the monitoring study

Table 1 gives details of the dwellings studied, while Table 2 gives details of the air conditioning units in the dwellings. The units surveyed included 7 single-split systems, 2 small-sized central systems or multiple ducted single-split systems, 2 multiple-split systems, 2 portable units, 1 evaporative cooler and 1 large variable refrigerant flow (VRF) central system. Of the 13 dwellings, 5 had units installed in one space only, while the rest had units installed in more than one room. Except for one dwelling, which had a VRF central system, where all rooms were cooled, 7 of the 13 dwellings had units in bedrooms; 6 in sitting rooms; 3 in kitchen/dinning rooms and 2 in conservatories. Some dwellings had more than one unit. For example, Site 7 had a portable unit in the bedroom and a single-split in the kitchen. Site 10 had two multiple-split systems installed in a number of different rooms.

Table 1: Details of the Dwellings Studied

Site	**Location**	**Description**	**No. of Bedrooms**	**Date of Construction**	**Date Air Conditioning Unit(s) Installed**
1	Suburban London	Semi-detached house	3	1911	February 2001
2	Central London	Mid-terrace house	3	1898	January 2002
3	East Sussex	Detached timber-framed house	4	1987	January 2004
4	Central London	End-terrace house	4	1913	March 2004
5	Surrey	Detached house	4	1960	February 2004
6	Central London	Top floor purpose-built flat	2	1960	June 1995
7	Suffolk	Detached house	4	1405	Split unit: July 2002 Portable: July 2003
8	Surrey	Detached house	4	1926	June 1999
9	Surrey	Detached house	4	1980	March 2004
10	Bedfordshire	Bungalow with loft conversion	4	1985	February 2004
11	Central London	Luxury flat	3	2001	2001
12	Central London	Top floor purpose-built flat	2	1973	Portable: September 1995 Evaporative cooler : May 1999
13	Surrey	Detached	4	1995	2000

Table 2: Details of Installed Air Conditioning Units

Site	AC Unit Type	System Description	Cooling Cap. (kW)*	EER*	Location	Site
1	***Ducted Single split***	*Indoor*: Unico Model 1218 multiple ducted system; *Outdoor*: Carrier	5.3	2.6	Sitting room, main bedroom, study (loft conversion)	1
2		*Indoor*: Airwell DXD20 multiple ducted system; *Outdoor*: Airwell MCU15	3(e)	2.7(e)	Sitting room, main bedroom, study	2
3	***Single Split***	3 Toshiba units, *Indoor*: RAS-13JKVP; *Outdoor*: RAS-13JAVP	3.5	3.68	Sitting/dining room, kitchen, bedroom	3
4		*Indoor*: Daikin FTXS20CVMB; *Outdoor*: Daikin RXH20CVMB	2	4	Bedroom (loft conversion)	4
5		*Indoor*: Daikin FTXS50BVMB; *Outdoor*: Daikin RXS50BVMB	5	3.01	Conservatory	5
6		*Indoor*: Toshiba RAS-09UKR; *Outdoor*: Toshiba RAS-09UA	n/a	n/a	Bedroom	6
7		*Indoor/outdoor combined*: Olimpia Splendid Unico	2.45	2.23	Dining room/kitchen	7
8		*Indoor*: Mitsubishi MSH-24NV *Outdoor*: n/a	6	2.37	Conservatory	8
9		*Indoor*: Toshiba RAS-10JKVP-E *Outdoor*: Toshiba RAS-10JAVP-E	2.5	2.5	Sitting room	9
10	***Multiple Split***	*Indoor*: Toshiba RAS M10 UKCVE X 2 *Outdoor*: Toshiba RAS M18 YACV-E	5.2	n/a	Various rooms	10
10		*Indoor*: Toshiba RAS M16 UKCVE X 1 + RASM10UKCVE X 2 *Outdoor*: Toshiba RAS3 M23 YACV-E	6.7	n/a	Various rooms	10
11	***VRF *****	*Central system*: Daikin	n/a	n/a	All rooms	11
12	***Portable***	Electro Aire	n/a	n/a	Sitting room	12
7	***Portable***	Gree RCS-M2000	n/a	n/a	Bedroom	7
12	***Evaporative***	ConAir	n/a	n/a	Sitting room	12
13	***Single split***	n/a	n/a	n/a	Dining room/kitchen	13

n/a Not available
* These values are the manufacturer's rated Cooling Capacity (kW) and Energy Efficiency Ratio.
** VRF stands for a central "Variable Refrigerant Flow" system.

Figure 1 shows the external, room and air conditioning unit outlet temperature, together with the difference temperature for a conservatory at site 5, for an operational period of around 14 hours. The plot clearly shows when the unit was in operation, however, not all the monitoring results were as clear as this, and visual inspection of the data was used to determine when the units were on and off.

From plots such as figure 1 and the outputs of the temperature and humidity dataloggers, table 3 was produced which gives the averaged switch-on and maintained temperatures and duration of operation, for nine of the dwellings. Four returned unusable data. In one case the datalogger was too far away from the unit to detect when it was on. In another, the unit was automatically heating and cooling alternatively to maintain a fixed condition. Another, in a conservatory was rarely used, and the central VRF system, as might be expected, ran continuously with little variation in temperature. The last column of Table 3 indicates the differences in patterns of use, with the final value giving the percentage of the total monitoring period the units were used. Site 13 is included because, although late in the year, the weather was still warm.

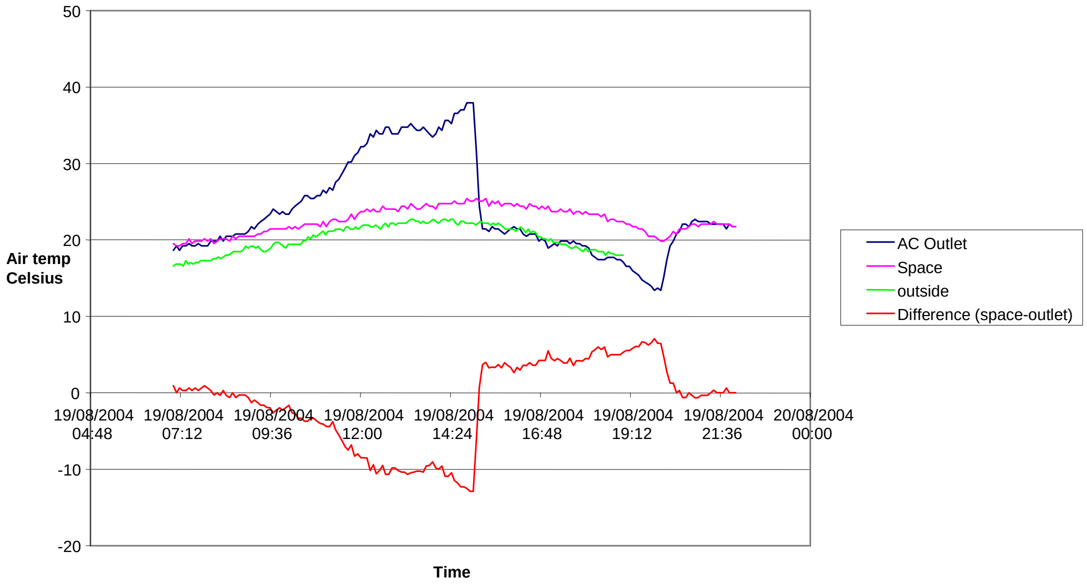

Figure 1: Plot of Room, Unit Outlet, Difference and External Temperature for the Conservatory at Site 5

Table 3: Average Switch-On and Maintained Temperatures and Relative Humidity and Duration of Operation

Site and location	**Main usage time**	**Average switch-on temp & rh**		**Average maintained temp & rh**		**Average outdoor temp (day & night)**		**Start and finish dates of monitoring**	**Average duration of single operation**	**Total duration of operation**	
		°C	**%**	**°C**	**%**	**°C $_{day}$**	**°C $_{night}$**		**h:m**	**h**	**%**
1: Study (loft)	Day/ Night	22.3	51	21.3	53	23	17	23 Jul - 17 Aug	08:45	245	41
2: Bedroom	Night	23.8	50	22.1	46	21	14 *	2 Aug - 30 Aug	08:30	177	26
3: Bedroom	Night	24.2	48	18.8	46	21	14	4 Aug - 1 Sep	10:00	210	31
5: Conservatory	Day	23.5	55	22.9	52	20	21	17 Aug - 14 Sep	06:10	68	10
6: Bedroom	Night	25.0	48	21.2	52	20	18 *	12 Aug - 9 Sep	08:15	54	8
7: Kitchen/dining	Day	22.8	61	22.1	55	20	15	13 Aug - 10 Sep	04:20	48	7
10: Bedroom	Night	22.7	58	19.1	64	19	15	11 Aug - 8 Sep	09:45	205	31
12: Sitting room	Day	27.9	50	27.8	54	23	17 *	26 Jul - 23 Aug	04:30	124	18
13: kitchen/dining	Day	25.9	43	25.5	40	22	15	20 Sep - 14 Oct	00:45	9	2
Overall Average		**24.2**	**51**	**22.3**	**51**	**20**	**17**		**07:00**	**127**	**19**

* UK Meteorological Office data for London

With only nine values, no statistical significance can be claimed; however, there does seem to be a difference between day and night use. Ignoring site 1, four of the units were used only at night and four during the day. The average duration of night use is just over 9 hours, whereas day use is just under 4 hours. Without the anomalous site 13, the average for day use is 5 hours. Clearly units used in bedrooms are left on all night, whereas units are used only when necessary during the day. The data indicates a wide range of usage patterns, with the average temperature at which units are switched on being 24.2°C with a standard deviation of 1.8°C. The maintained temperature shows even greater variation, with an average value of 22.3°C (sd: 2.9°C).

There is little difference between day and night switch-on temperatures (day: 25.0°C; night: 23.9°C), however, the average maintained temperatures differ, with a day average of 24.6°C (sd: 2.6°C) and a night average of 20.3°C (sd: 1.6°C), which, interestingly is lower than the usually maintained winter temperature in living rooms. The units appear to be on most of the night, which means that with the lower heat gains, they can maintain lower temperatures.

Results of the questionnaire survey

The results of the face-to-face questionnaire/interviews have been arranged into seven categories, i) reasons for purchase, ii) usage patterns, iii) running costs iv) maintenance, v) noise, vi) health issues and vii) satisfaction level. Respondents were self-selected, with the following profile. Ages ranged from mid-30s to 83, with most in the 50 to 70 range, while the average number of occupants per dwelling was 2. The occupants in 5 of the dwellings were retired, with the average income range, for the remainder, being between £40,000 and £150,000 per year per dwelling. Eleven respondents reported awareness of the fact that some refrigerants can deplete the ozone layer, while two knew the name of the refrigerant contained in their unit.

Reasons for purchasing air conditioning

Of the 13 dwellings surveyed, 8 respondents stated the primary reason for purchasing an air conditioner was its ability to cool, while 2 referred to its ability to cool and provide fresh air. Only 2 mentioned the fact that it could heat as well as cool as a reason for purchase, although one mentioned the ability of their unit to provide background heating in a conservatory as an added and unexpected bonus. The resident with the central VRF system stated that the air conditioning came as standard with the flat. With respect to the deciding factors in buying a particular brand, 3 respondents mentioned recommendation from installers, 2 concern over energy consumption, 2 the look of the system, and 1 the recommendation from friends.

Use patterns

Most of the occupants were unsure about the temperature at which they switched their units on, stating merely that they switch them on when they feel hot. Only 4 were prepared to offer a value, which ranged from 22 to 24°C. This compares to a measured average value of 24.2°C. The temperature the occupants set on the remote controllers ranged from 18 to 25.5 °C, with the lower value representing an attempt to pull the temperature down quickly. This compares to an average measured maintained temperature of 22.3°C. The duration of the switch on period varied widely from a couple of hours to more than 12, compared to an average measured period of 7 hours.

Running cost

Of the 13 respondents, 8 were unprepared to make a guess at the running cost of their unit(s) during a typical summer. One respondent suggested that the running cost might be around 5% of their electricity bill, while the remaining 4 suggested figures of £20, £30, £60 and £150[1]. No attempt was made to measure the actual electricity consumption (and therefore running costs) during the monitoring as interfering with the electrics would have been problematic. Meter reading was a possibility, but would have yielded little sensible data,

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[1] A 3 kW unit with an EER of 3, running for 4 hours per day, say, for 30 days per year, will use 120kWh of electricity per annum. At 7 p/kWh, this would cost £8.40.

given all the other power consuming devices running at the same time. Further work was carried out, and reported, on the results of computer simulation of energy consumption.[2]

Maintenance
Of the 13 dwellings surveyed, with units ranging in age from 5 months to 9 years, only 3 reported breakdowns. These were due to i) a filter which had disintegrated in a single-split, ii) a refrigerant leak in a ducted single-split and iii) a broken flow valve in the central VRF system. Only 4 of the 13 respondents had a maintenance contract, with the reported annual cost ranging from £32 to £90. Apart from 1 respondent, who had paid £30 for a new filter, maintenance costs (other than contracts) were zero.

Noise
Apart from 1 respondent who disliked the noise produced by the outdoor unit while sitting in the garden, no one was disturbed by the noise either of the indoor or outdoor unit. No one had had any complaints from neighbours concerning the noise of the outdoor unit, although many were in the gardens of detached houses, well away from neighbours.

Health
None of the respondents quoted medical problems as a reason for purchase, although one stated that it helped a previous hay fever problem, as windows could be kept permanently shut. As regards the units being the cause of new health problems, no one reported any adverse health effects, apart from two respondents, one using a single-split and another using a ducted single split system, who stated that there was possibly an increase in sore throats.
Satisfaction

All respondents indicated that the expected benefits from their units had been achieved, except for the 2 portables. These users complained that the units were not large enough to achieve the desired cooling. Respondents with units in their bedrooms all reported much improved sleep, except for 1 portable user and 1 VRF user, both of whom reported only slight improvement in sleep. Overall, using a five point scale from highly satisfactory to highly unsatisfactory, 11 respondents rated their units as highly satisfactory, while 1 (the central VRF user) rated it between the top two ratings of highly and fairly satisfactory. The users of the 2 portables placed them in the second top category of fairly satisfactory.

Results of the EER tests
Table 4 gives the specifications of the two units tested. The single-split was the latest version with inverter speed control of the compressor. Both units were monitored at 2 minute intervals.

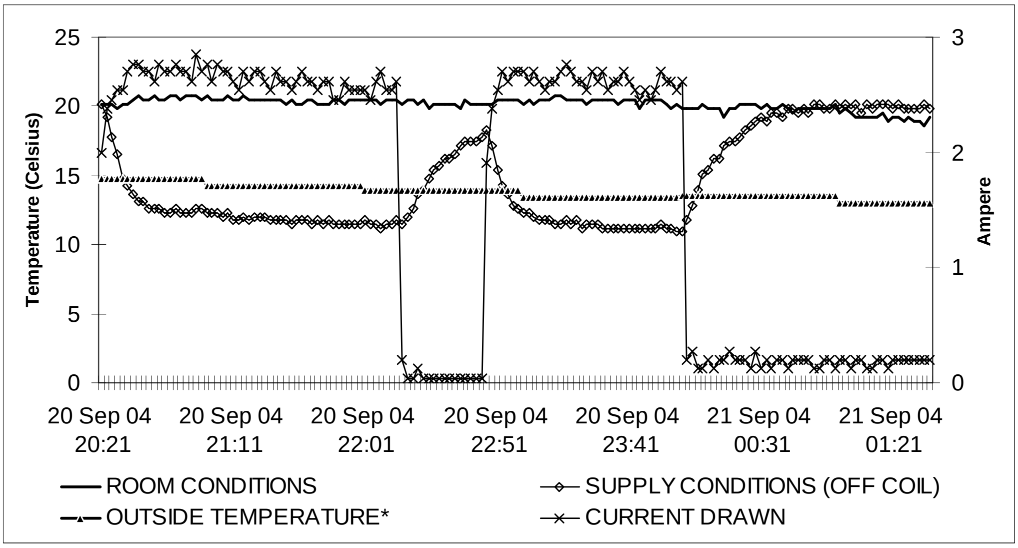
Table 4: Details of the Two Test Units

	Nominal Cooling Capacity (kW)	**EER (cooling)**	**Nominal Heating Capacity** (kW)	**COP ** (heating)**
Portable	8000 Btu/hr * (2.345)	-	-	-
Single-split with inverter control	2.5 *	4.39 * (max 5.45) *	3.2 *	4.27 * (max 5.00) *

*   Manufacturer's values
** Coefficient of Performance for heating

[2] He, J., Pathan, A., Young, A. N. and Oreszczyn, T. "Air Conditioning energy use in houses in southern England." (Research paper presented to DYNASTEE 2005 conference, Athens)

EER of the Portable Unit
Figure 2 presents the portable unit results for 5 hours and shows the variation in room (or on-coil), supply (or off-coil) and external temperatures, with the mains current drawn.



* Outside temperature is hourly data from the UK Meteorological Office

Figure 2: Monitored EER Test Data for the Portable Unit: Supply, room and outdoor temperatures and current drawn

Figure 2 shows two on-periods, followed by two off-periods. In the first of the off-periods, the unit was switched off completely, while in the second, the fan was left running with the compressor off. It can be seen that the supply temperature gradually rises towards the overall room temperature, while the "coolth" stored in the coil is slowly being dissipated into the room [11,12]. The unit appears to have little effect on the room conditions, probably because it was under-sized and unable to meet the heat gains, including heat stored in the heavy-weight structure and from other parts of the dwelling, which was open-plan. In the first on-period, the unit ran on the higher of the two possible cooling settings on the unit, while in the second it was set to the lower setting. Figure 3 shows a plot of the EER at the 2 minute intervals used, together with the power drawn, ignoring the two off-periods. The mains voltage and power factor were not measured. Assuming these respectively as 230 V and 0.9, the average EER during the first period, at the higher output, was 0.80, while for the second lower output period, it was 0.74, once the output of the unit had stabilised after about 20 minutes in each case. The standard deviations were 0.052 and 0.040, respectively. With the mains voltage held constant at 230 V, changing the power factor to 0.85, reduced the EER to 0.76 and 0.70 respectively, whereas holding the power factor at 0.9, and varying the voltage to 220 and 240 V, changed the EER to 0.84 and 0.77 at the higher output, and 0.77 and 0.71 at the lower. The overall sensitivity of the EER to voltage and power factor (220 to 240 volts and 0.85 to 0.95 power factor), was 0.81 ± 0.08, or about 10%.

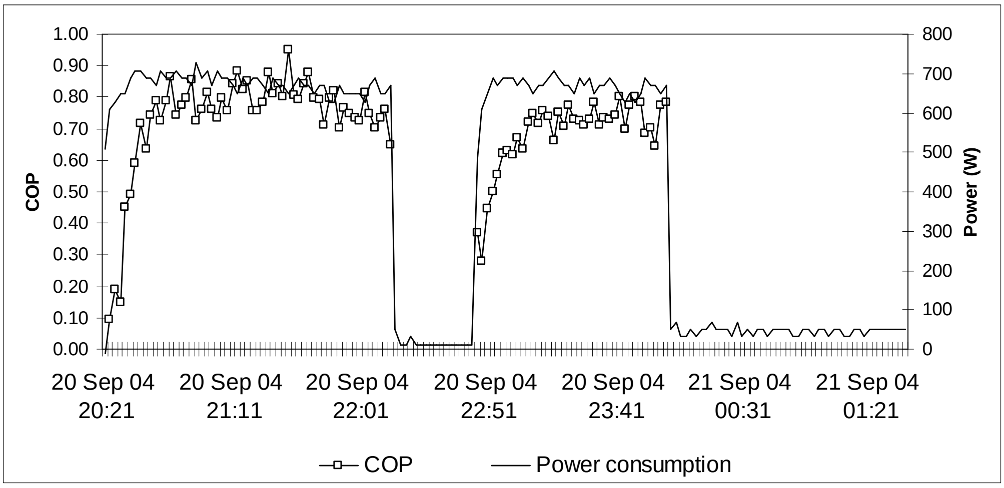
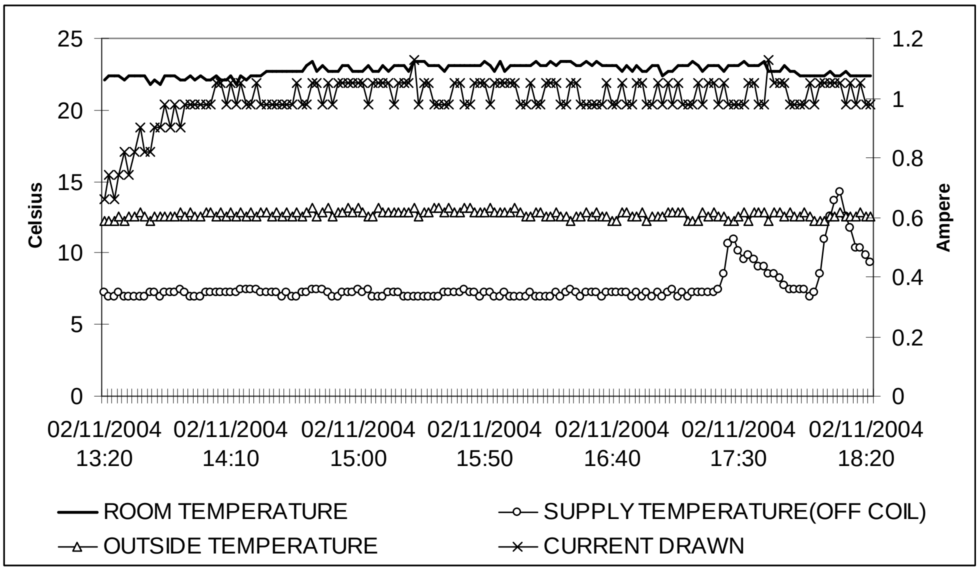


Figure 3: Monitored EER and Power Drawn for the Portable Unit

Even assuming the unit's EER in stable operation is somewhere around 0.8, this is much lower than the lowest energy efficiency rating (EER) category - G - in the EU energy labelling system for domestic air conditioners [13]. The low EER found in this study reinforces worries that the energy labelling system is not suitable for portable spot air-conditioners and other types of cooler (eg, dehumidifiers, and evaporative or desiccant coolers, etc).

EER of Inverter Single-Split System

Figure 4 shows the off-coil air flow temperature from the split system, the temperature of the return air to the system from the conditioned space (or room temperature) and the current drawn during cooling operation, again for around 5 hours, when the unit was operating under relatively stable conditions. The outside temperature is also displayed. While the current drawn by the split system was around 1A, it was around 2.5 A for the portable unit, when the compressor was on. It should be noted that this data was collected in November 2004 when the average outdoor temperature during the test was 12.7^{o}C.



* Outside temperature is hourly data from the UK Meteorological Office

Figure 4: Monitored EER Test Data for the Inverter Single-Split Unit: Supply, room and outdoor temperatures and current drawn

The EER of the system was calculated and plotted, together with power consumption, as shown in Figure 5. Assuming a mains supply of 230 V and a power factor of 0.9, the average of the EER over the whole period was 5.35, with a standard deviation of 1.12, with the instantaneous EER as high as 6 at times. It is clear that there is considerable instability in the system, with the EER dropping to almost zero at one point. In other monitoring periods, not presented in this paper, similar instability was observed, with EERs up to 10, with occasional extreme values up to 20. These spikes are most likely caused by the thermal lag in the system. When the control system calls for more cooling, the compressor speed increases with a resultant instantaneous increase in current drawn. Because of the time lag before the additional cooling appears at the evaporator as a reduction in supply temperature, the simple equations used predict a much reduced EER. Similarly when less cooling is required and the current drops, the "coolth" stored in the evaporator, produces an unrealistically high EER. It should also be noted that the external temperature, effectively the heat rejection temperature at the condenser was low, which will improve the performance above the manufacturer's rated value of 4.39 (maximum 5.45). Manufacturers' EER ratings are evaluated under EU standard test conditions* with an indoor temperature of 27^{o}C and outdoor temperature of 35^{o}C, with the system fully loaded. The present test was carried out with outside temperature around 13^{o}C. Moreover, for the whole of the test, the system was only partially loaded* as shown in Figure 6. As can be seen, from Figure 7, there is a strong correlation between the measured system load and EER, with the EER degrading as the load on the unit decreases. This suggests that the EER would have been even better if the unit had been working near full capacity. Extrapolating to full load, and assuming the linear relationship continues ($y = 10.273x - 0.1937$, with an R^2 of 0.77), produces an EER of around 10. For comparison, the theoretical Carnot efficiency, given by $T_e / (T_c - T_e)$, where T_e is the evaporating temperature and T_c is the condensing temperature, with both in kelvin is 55, if the average supply temperature (of 7.6^{o}C) is taken as T_e and 12.7^{o}C, the average outdoor temperature, is taken as T_c.

The average EER values varied with voltage (with power factor at 0.9) as follows: 5.59 at 220 V and 5.13 at 240 V. With power factor (voltage at 230 V), the variation was: 5.05 at a power factor of 0.85 and 5.65 at a power factor of 0.95. The uncertainty in the values was again found to be around 10%.

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* Eurovent Certification: ISO-DIS 5151

* System load is defined as the measured cooling output divided by the nominal cooling capacity.

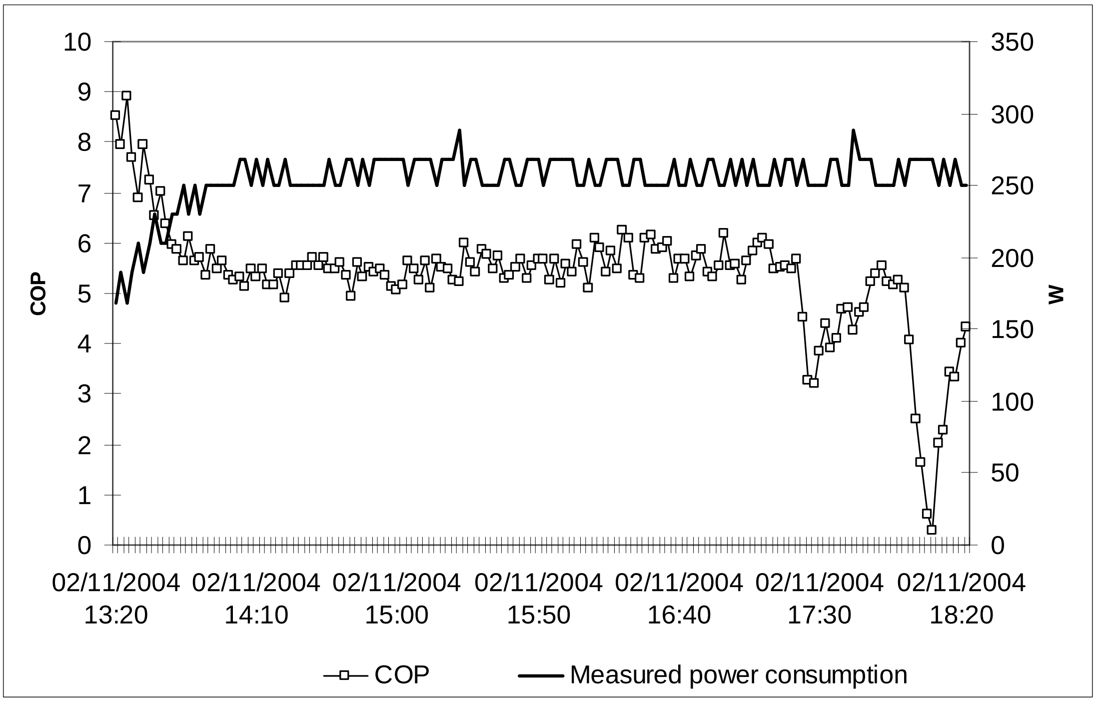

Figure 5: Monitored EER and Power Drawn for the Inverter Single-Split System

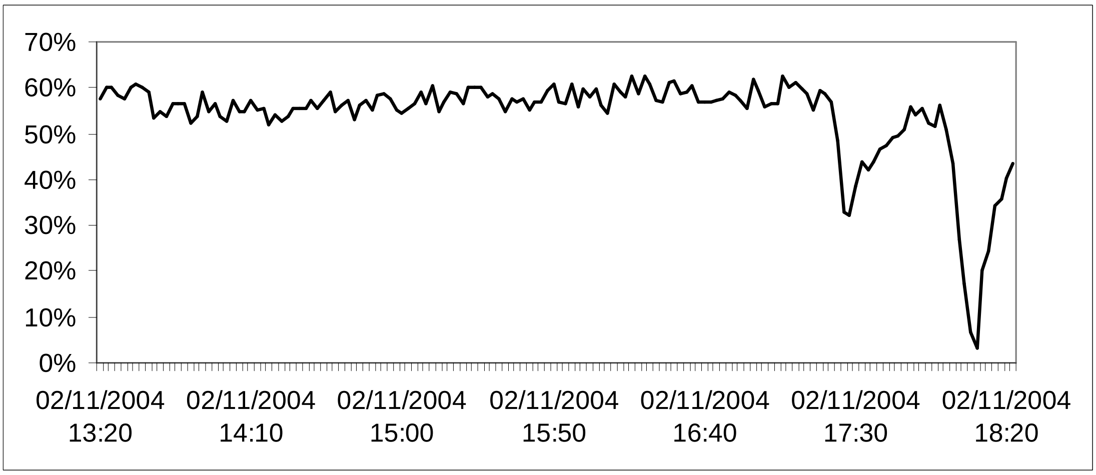

Figure 6: System Loading for the Inverter Single-Split System Test

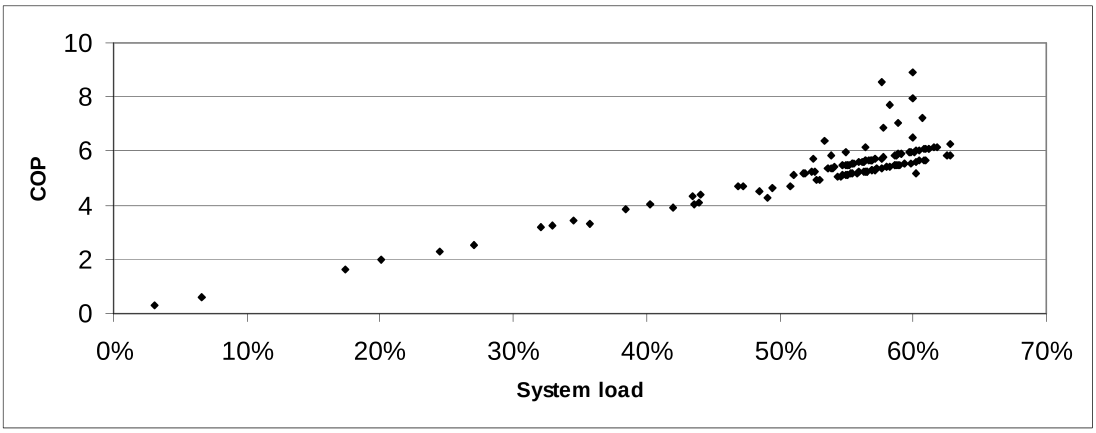

Figure 7: EER of Inverter Split System with System Load

There is still considerable work to be done to obtain reliable energy performance statistics for these units under real conditions - in actual dwellings, operated by real people, over the whole of the year.

Summary and conclusions

In this paper, a pilot field study of the use of air conditioning in 13 dwellings in the UK is presented. Although the results are preliminary and may not be statistically significant, it was considered important to publish these due to the considerable interest from other researchers in the filed. The main findings are given below. Further work will need to be carried out to improve the reliability of the results.

- There was a high level of satisfaction with residential cooling, particularly for the single-split vapour compression units.
- Units, which were bought manly for their ability to cool, were used in sitting rooms, bedrooms, kitchen/dining rooms and conservatories.
- There appeared to be no adverse health effects associated with using cooling in the home, neither was noise from the indoor or outdoor units problematic and where the units were used in bedrooms, the quality of sleep was reported to be better than without cooling.
- It was found that users switch on their units when indoor temperatures reach approximately 24.2^{o}C, while the temperature maintained was on average 24.6^{o}C in sitting rooms during the day, and 20.3^{o}C in bedrooms at night.
- The average duration of operation was 5 hours in rooms used during the day, and 9 hours in bedrooms.

The main findings from the energy efficiency tests are presented below, assuming a mains supply of 230 V and a power factor of 0.9.

- The one new portable air conditioner tested had an averaged EER of around 0.8 on its higher setting and around 0.74 on its lower setting.
- The one new single-split inverter system tested achieved a high average EER of 5.35 for cooling when tested with outdoor temperatures around 13^{o}C, and when loaded at 60% of its nominal cooling capacity.

This pilot study has shown that user satisfaction is high with single-split domestic air conditioners, indicating that there is considerable potential for growth in sales in the UK, particularly since running and maintenance costs are low, and if, as is predicted, the incidence of hot spells increases. The latest inverter controlled single-split units appear, on the basis of a single test, to perform at the upper end of their specified energy efficiency ratings, when outdoor temperatures are low. This study also indicates that to understand the potential impact of the growth of mechanical cooling in the domestic sector on the environment, it will be necessary to monitor real in-use performance, and then to simulate, under a number of climate and use pattern scenarios, the resultant carbon emissions.

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