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Large Scale Energy Surveys in the UK Retail Sector

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The UK retail sector accounts for around 18% of total non-domestic UK building floor space and a significant proportion of UK energy use. Much of the information available about energy use was collected several years ago, much of it from the major 'Four Towns' study carried out in the early 1990s. Since then there have been many changes in the sector, with a shift to out-of-town shopping, a changing mix of high street shops and increasing use of air conditioning. To improve the information in this area, large-scale, low-level surveys of about 600 retail premises in Stamford, Leicester, Chesterfield and London were carried out, spanning a range of town sizes and types of shopping area. Summer surveys in warm weather to establish air conditioning were followed by winter surveys to establish heating practices. The purpose was to establish the extent of air conditioning, door opening practices, use of air curtains and types of lighting, and relate these to location and type of premise. Data, including digital photographs of every premise, were stored in a relational database. About 50% of premises were found to be air conditioned, with higher proportions for city centres, larger premises and chain stores. In summer, many air conditioned premises had open doors with no air curtains, causing additional cooling demand. Estimates of heating and cooling wastage have been made using computer simulation and empirical equations to model air flow through open doors with an inside to outside temperature difference. Another technique that has been explored is the use of Infrared Imaging, principally to research covering large urban areas in a more expedite way. State-of-the-art cameras were used for technology appraisal.

Keywords: building, air-conditioning, retail, energy, efficiency, air, curtain.

INTRODUCTION

Since the early 1970s the rate of growth in UK energy consumption in the service sector (i.e. commercial and public buildings) has increased by approximately 30% compared with a 25% increase in the domestic sector (DTI, 2005). Of the total UK energy consumption of 6,695PJ in 2000, 880PJ was used by the service sector, of which 160PJ or 15% was consumed by the retail sector (Pout *et al.*, 2002). Rising energy intensity accompanies service sector floor space increases. In office buildings, demand for AChas grown rapidly alongside a dramatic increase in CO_2 emissions (Scrase, 2001). In the EU as a whole, the growth in air conditioner (AC) use by treated floor area increased by almost 400% since 1980 (Marchio, 2005). For the UK in 2000, total area air conditioned in all buildings, under both cooling and reverse systems, was estimated to almost double (188%) from the previous decade to 204 Mm², and is projected to nearly double again (196%) by 2020 to more than 400 Mm² (EECCAC, 2002). This corresponds to an increase in energy consumption from 8.5PJ in 2000, to almost 16PJ in 2020 and a rise from 826kt to 1540kt in CO_2 emissions. Detailed figures for UK energy consumption by sub-sector or by AC system are sparse. However by the end of 1994, about 11%, or approximately 10 Mm^2, of retail area was estimated as being air conditioned (Hitchin *et al.*, 2000). By 2000, ventilation and cooling was calculated as accounting for about 8PJ or 5% of annual energy consumption in the retail sector, with rapid growth expected particularly for packaged rather than central AC systems (EECCAC, 2002; Hitchin *et al.*, 2000). The UK has a temperate climate; however eight out of the ten warmest years recorded in England happened in the last 16 years. AC usage in the UK's retail sector is a relatively recent phenomenon but as the global climate warms, the sudden growth of AC usage causes concern.

These low depth surveys were conceived by Harry Bruhns in 2005 (Brown *et al.*, 2005), whereby examining a statistically large number of premises can provide an indicator to the growth of AC use in the UK within the retail sector. AC use year on year is also interesting, so in addition to examining this growth, energy efficiency measures were assessed. These include air curtains, traditionally used in the UK to isolate a heated area from the outside in winter, also used in commercial refrigeration (Cui and Wang, 2004). Self-closing, or automatically closing doors may also be useful in containing cooled air. While retail related papers are sparse, a survey of 4 shopping centres in Hong Kong, (Lam and Li, 2003), found that air conditioning and electric lighting accounted for around 85% of the total building energy use. Work in Turkey (Cambay *et al.*, 2004) aimed to reduce energy consumption by defining new shopping centre HVAC control strategies and tuning control loops. New strategies were implemented with the help of the existing building management system (BMS), achieving around a 22% energy saving.

METHODOLOGY

Summer surveys were carried out in many cases by examination of installed air conditioning and energy efficiency measures from outside. When air conditioning use was unclear, the survey was extended by entering the retail premises, frequently interviewing shop staff. A reasonable range of town sizes was selected for surveys during 2005/2006. Temperatures varied in the range of 18 - 23°C. The cities chosen are located in two distinct climatic regions, Leicester, Chesterfield and Stamford, having cooler summers when compared with London. The regional cooling degree-days for England's Midlands are below 50 whilst for the Thames Valley region they are between 50 and 100.

Winter surveys were conducted to examine differences in energy use behaviour between winter and summer. In addition, lighting types are easier to identify during winter, and the spread of lighting types which will increase cooling loads in summer may be assessed as part of a longitudinal study.

SHOP SURVEYS

The ratio of shops with and without air conditioning is shown below in Fig. 1. It is interesting to note the greatest proportion of AC use in London, whereas Leicester and Chesterfield were approximately equal.

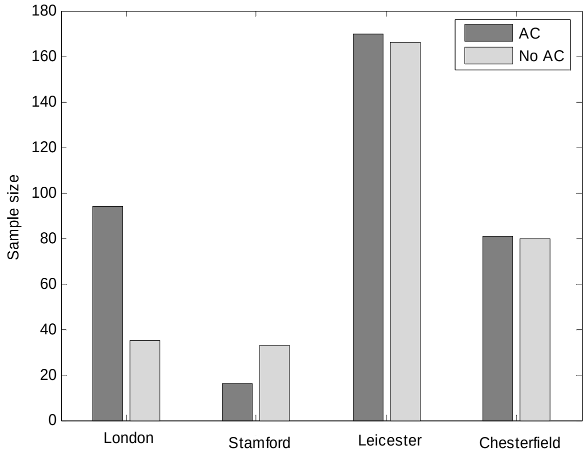

Fig. 1: AC vs. no AC by town.

SUMMER SURVEYS

Fig. 2 shows the proportions of AC configuration and installation from the dataset for shops which are not in shopping malls. A summary of these results is given in Table 1. Fig. 3 shows the door configurations within AC treated shops only. It can be seen that only around 40% of shops with air conditioning employ any energy saving measures during the cooling season.

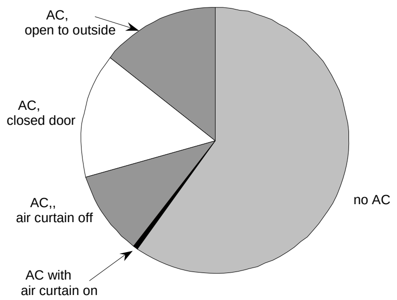

Fig. 2: AC and door configurations.

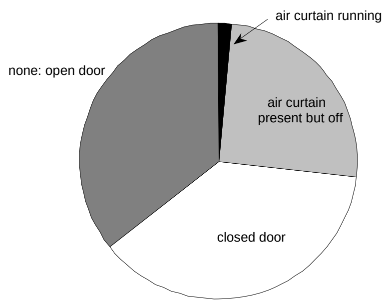

Fig. 3: Door configurations for AC treated shops.

AC configuration	Number of samples	%age of total	%age of AC treated only (Fig. 3)
No AC	388	59.8	
AC, Air Curtain Off	66	10.2	25.3
AC, Air Curtain, On	4	0.6	1.5
AC, Closed Door	98	15.1	37.5
AC, Open to Outside	93	14.3	35.6

Table 1: Summary of AC and door configurations for the cooling season.

WINTER SURVEYS

Results from winter surveys are shown below in Fig. 4. It is interesting to note that the overall pattern of door usage suggests that winter energy conservation is seen as more important than during summer. Also of interest is that 5 shops from the dataset (i.e. 0.77%) had air conditioning units providing cooling during winter.

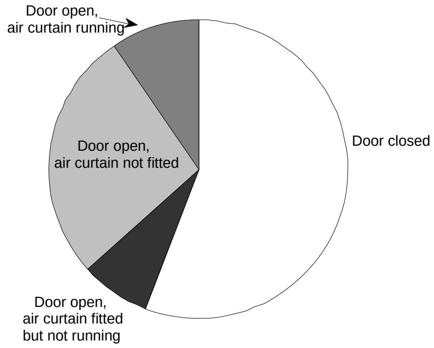

Fig. 4: Winter door and air curtain usage

Door / air curtain configuration	Number of samples	Percentage of total
Door open, air curtain running	67	10.3
Door open, air curtain not fitted	190	29.3
Door open, air curtain fitted but not running	53	8.2
Door closed	391	60.2

Table 2: Door usage during the heating season

COMPARISON BEWTEEN WINTER AND SUMMER DOOR AND AIR CURTAIN USAGE

It is interesting to compare individual shops' summer and winter practices to see if air conditioning and heating are treated differently. The results for the 261 air conditioned shops are shown in Fig. 5. It was thought that shops would practise energy efficiency in the winter, due to the mild summer and cooler UK winter. It is surprising to note the proportion of shops which may use closed doors or an air curtain in summer only. Approximately 52% of air conditioned retail stock only, appears to employ energy efficiency measures in both summer and winter.

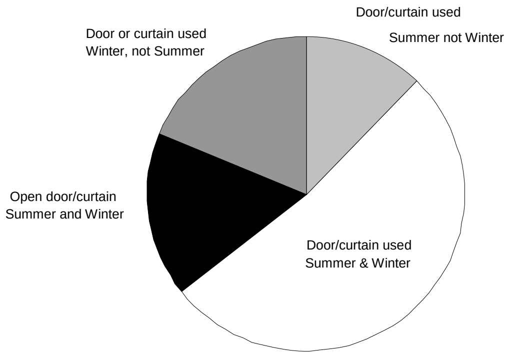

Fig. 5: Summer and winter door and air curtain usage for AC treated shops.

Summer/Winter Configuration for AC treated shops	Number of Samples	Percentage of total
Door or curtain used Winter, not Summer	49	18.8
Door/Curtain not used at all	44	16.9
Door/curtain used Summer & Winter	136	52.1
Door/curtain used Summer, not Winter	32	12.2

Table 3: Summer vs. winter door configurations.

Some retailers cite a potential drop in custom as the main reason to keep doors open, but a significant proportion of shops are able to carry out energy efficiency measures including closing of doors or use of air curtains. It is interesting that some air conditioned shops practise energy efficiency in summer but not in winter, since it was expected that energy efficiency would be taken more seriously in the heating season. This is more strongly suggested when viewing the charts for the complete dataset (air conditioned and non air conditioned) Fig. 2 and Fig. 4. It is very apparent however from all of the data that a significant proportion of shops are doing nothing to conserve heat or cooling. The data show that the potential for energy saving through the use of closed doors or air curtains is clear.

INFRA RED SURVEYS

IR imaging is considered an important tool in determining the thermal performance of buildings either being heated or cooled. Most heat loss is by conduction, air leakage or excessive ventilation. Thermal scanning facilitates identification of such types of heat loss, but cannot directly indicate the rate of heat loss due to each. The use of IR for field surveys has thus to be viewed more appropriately as an aid tool capable of providing qualitative information rather than precise figures on heat losses. Some of the applications currently being investigated are the use of IR imaging to tell apart which shops are being air conditioned and the use of aerial IR thermography to assess AC use density in hot weather. IR imaging avoids the need for building entry, but provides instant data, storable for post processing. IR thermography allows rapid surveying of commercial buildings that have no direct access from the street; for example, offices and shops in multi-storey buildings.

Operation involves facing the camera towards windows from an appropriate angle. There is also the need for skill and experience to translate a surface temperature survey into reasonably accurate results. Some common sources of interference during thermography must be considered, potentially distorting results, including reflected sunlight and windy conditions. Additionally, indoor/outdoor temperature differences should exceed 10^0C. Basic heat sink detection is insufficient for accurate indoor air temperature measurement. As air emits infinitesimal thermal radiation, the camera has to point towards merchandise on display, internal walls or adjacent parts near air vents. However, as different materials have different emissivities, inaccuracies in readings are probable. Preliminary results from several IR tests are encouraging, showing marked differences between IR pictures of air conditioned and non air conditioned shops.

Fig. 6 and 7 show external IR photos of a bookshop with an open door and no air conditioning. It can be seen that the shop has many internal heat sources including incandescent and halogen lighting. Figures 8 and 9 show a heavily air conditioned food store with an automatic door. These shops were located a few meters from each other and shaded from direct sunlight. The darker colour of the IR photography of shop 2 clearly indicates the lower indoors temperature comparatively to shop 1. It is also worth noting the lighter colours of passers by, providing a temperature reference. IR thermography results show that rapid surveys are possible for retail premises, with a clear indication of heat loss or ingress to the premises. Aerial IR thermography is perhaps the most interesting application of this technology, as IR cameras can read temperatures from virtually any distance and therefore vast urban areas could be covered. It is believed that rooftop AC outdoor units could be spotted from a long distance as their temperatures can easily reach 70^{0}C-80^{0}C when operating. This range of temperatures is likely to be far higher than any of the surrounding surfaces not directly exposed to sunlight, showing clearly on an IR image or detectable using appropriate software.

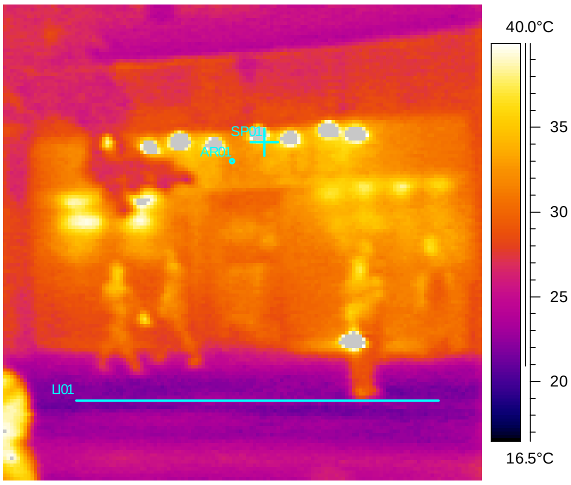

Fig. 6: IR thermograph of sample shop 1.

Fig. 7: Digital photography of sample shop 1.

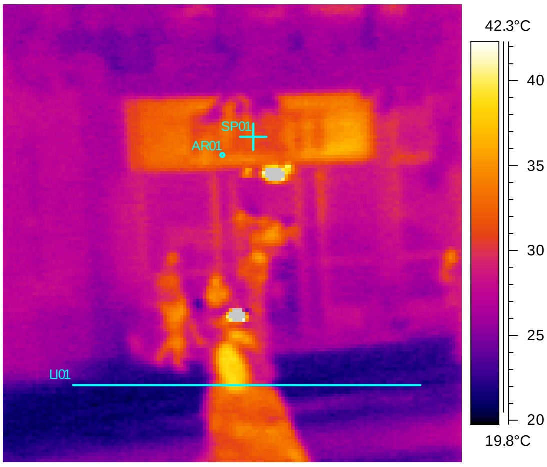

Fig. 8: IR thermograph of sample shop 2.

Fig. 9: Digital photography of sample shop 2.

ENERGY LOSS THROUGH DOORWAYS

The surprisingly high proportion of air conditioned shops with doors open or no air curtain in summer raises the question of how much cooled air is lost through doorways, and consequent energy. An appropriate 'wastage' definition is the difference between the energy consumption for mechanical cooling with doors fixed open and with doors normally closed, over a defined period and set of temperature and weather conditions. This ignores the effects of door opening by customers because their short duration has minimal effect.

Estimation tools include: detailed field measurements; empirical equations derived mathematically and experimentally; computational fluid dynamics (CFD); and bulk airflow analysis. Two methods are compared here: empirical equations and bulk airflow analysis embedded in a thermal simulation program.

EMPIRICAL CALCULATIONS

(Davies, 2004) gives a detailed review of experimental studies of the mathematics of heat flows through openings between spaces at different temperatures. (Santamouris, 1995) compares several models of airflow through large openings, notably airflow driven by pressure differences, from temperature difference ΔT between outside and inside air. For such flow, the basic equation is

$$Nu = \frac{hH}{\lambda} = CGr^{1/2}\,\Pr$$

where *h* is the convection coefficient ($Wm^{-2}K^{-1}$), *H* is height of opening (m), λ is conductivity of air, (0.0257 $W\ m^{-1}K^{-1}$), C is a coefficient, Nu is the Nusselt number, Pr is the Prandtl number, and Gr is the Grashoff number. For this problem, substituting appropriate values, we have

$$Gr = 1.47E10^{8}\ \Delta TH^{3}$$

Substituting appropriate values and rearranging, it follows that

$$h = 221.2C(\Delta TH)^{1/2}$$

Then for a rectangular opening of area A, width × H, the heat flux Q (W) is

$$Q = h\Delta TA$$

(Net volume flow can be calculated by dividing *Q* by the heat capacity of air; as equal volumes of air are flowing in and out, the flow in one direction is half of this.) Given dimensions and temperature differences, it is simple to set up the equation for Q, calculating values hourly over a long period, for times when doors are open. According to the review by (Santamouris, 1995), values for C ranged from 0.13 up to 0.45 in different experiments using air temperature differences, with 0.2 – 0.25 as typical. Measurements of door openings in the Leicester survey showed that for 28 air conditioned shops with doors open in summer, the average height was 2m and the average width was 1.5m. A single door is about 1m wide, so the width value resulted from about half the shops having a single door open and the other half having a double door open. Since the value of *h* depends only on height, heat flow increases linearly with door width. Hourly dry bulb temperatures for a Design Summer Year (DSY) for Heathrow was chosen, which represents a one-in-eight 'hot summer' – actually the year 1989 (CIBSE, 2001). Flows were calculated hourly, assuming opening hours 09:00-17:00 Monday to Saturday, from 1 May to 30 September.

Only cooling loads resulting from summer conditions were considered, for various internal set point temperatures; when the outside temperature was below the set point the flow was set to zero, so there were no negative loads. The calculated total energy (kWh) represents loss of cold air, which for air conditioned shops is supplied by a mechanical cooling system. The actual energy needed to produce an amount X of cooling is X/COP, where COP is the coefficient of performance; typically electric air-source AC systems have a COP of about 2.5. Assuming a value of C=0.2 gave the results shown in Table 4. About half of the load occurs in July.

Set point °C	21	22	23	24	25
Cooling kWh	641	447	301	192	117
Electricity kWh (COP=2.5)	257	179	120	77	47
Cost £ @ 6p/kWh	15	11	7	5	3

Table 4: Cooling demand resulting from an open shop doorway 1.5 x 2m for various set points and a typical hot summer, using empirical equation.

As would be expected, the amount of cooling falls rapidly as the set point is increased, because both the number of hours over the set point and the temperature difference are reduced. The amount of energy used is, perhaps surprisingly, very small compared to typical shop usage of several thousand kWh per year, for the relatively cool UK climate.

COMPUTER SIMULATION

A rectangular single-storey building representing a shop was set up in the building simulation software IES (IES, 2004), with a single doorway facing north, in a city 'sheltered' location. All external surfaces were highly insulated with 0.5m insulation windowless, therefore conductive and solar flows were negligible. The door was the same dimensions as for the empirical calculations. Simulations were executed with identical weather data and door opening schedule. Airflow was simulated using the bulk airflow 'Macroflow' utility in IES software. This is not CFD (normally only used for steady-state problems), but calculates air flows through openings between zones at each time step according to pressure differences generated by wind and temperature differences between zones. In this case the flow is mainly generated by the temperature differences, plus some wind effects. Macroflow divides the door into several horizontal 'slices' and solves equations for pressure etc. across each slice, so is significantly different from the empirical equations, though based on the same underlying physics. Table 5 gives the results; loads are similar to, but somewhat less than the loads derived empirically, but follow a similar trend with increasing set point. For comparison with a warmer climate, using a Madrid Example Weather Year gives 1,987 kWh cooling at 23°C.

Set point °C	21	22	23	24	25
Cooling kWh	552	352	210	117	65
Electricity kWh (COP=2.5)	221	141	84	47	26
Cost £ @ 6p/kWh	13	8	5	3	2

Table 5: Cooling demand resulting from an open shop doorway 1.5 x 2m for various set points and a typical hot summer, using computer simulation.

Another difference from the empirical method is that doubling the door width to 3m, for set point 23°C, increases the cooling from 210 to 494 kWh, or × 2.35. In the empirical solution the load would be increased in proportion to width, i.e. by × 2.
Visual comparison of the load profiles showed good agreement between the two approaches, although the simulation tended to give the higher values for large temperature differences and often the lower values for smaller differences. By varying the parameter C to minimise the sum-of-squares of the differences between the loads, a 'best fit' value can be obtained for C. For 23°C set point this was found to be 0.171, though the empirical total load was still higher at 257 kWh compared to 210 by simulation. Fig. 10 shows the load calculated using the two methods over 17 days of warm weather for this value of C. A value of C=0.14 gives the same total load but a larger sum-of-squares value.

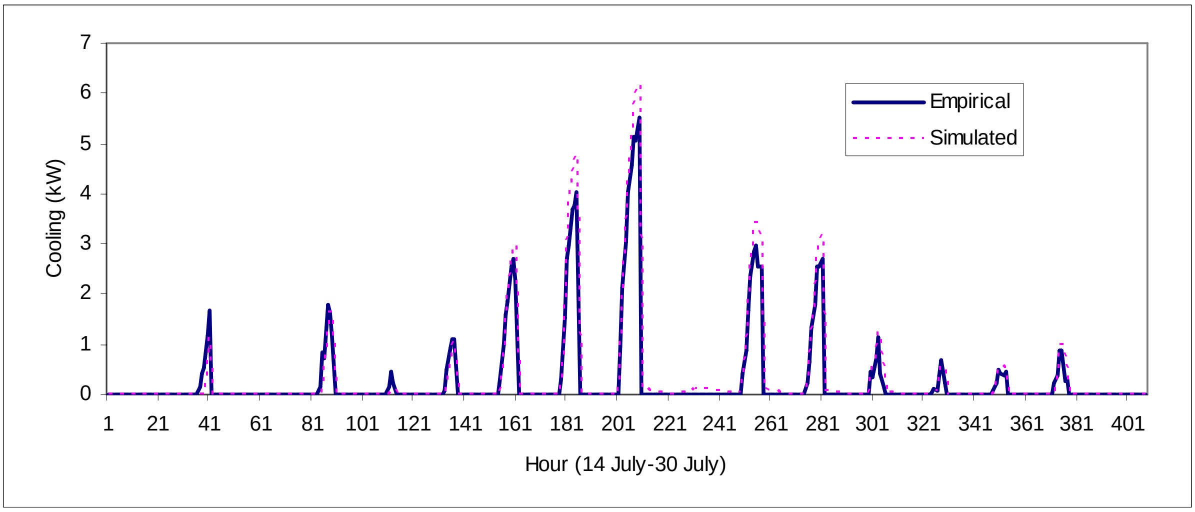

Fig. 10: Cooling loads derived from empirical equation and thermal simulation during hot period 14-30 July.

CONCLUSIONS

The results show that the use of energy saving measures during the cooling season, such as closing external doors or using air curtains, is minimal. Infra red imaging is emerging as a useful tool for deeper analysis of this. An empirical equation and bulk airflow thermal simulation have been compared for calculating losses of cooled air from shops in warm weather. These are in generally good agreement. There is some uncertainty about the most appropriate value of coefficient C to use in the empirical method. A value of 0.2 is suggested from the literature but lower values give better agreement with the more sophisticated thermal simulation approach. Actual energy consumption for cooling resulting from these flows is surprisingly small for the 'hot summer' used, but does increase rapidly with lower set points and for hotter weather. The results suggest that an empirical approach could be used in conjunction with field data on door areas and shop numbers to obtain a reasonably robust estimates of cooling losses from open doors, and similarly applied for the winter condition to calculate heat losses in a similar way. For this, one would expect much greater energy losses since outside air would be below the set point for most of the time.

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