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Thermal experience in an era of low exergy domestic heating systems

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Abstract

Existing theories of thermal comfort are largely blind to the way heat is delivered to spaces. Field studies, however, show that people create and enjoy thermal conditions that lie outside conventional definitions of comfort—the thermal experience itself is valued—some of which are tied to particular ways of delivering heat. The concept “exergy” can be used to describe the quality of heat energy and its ability to provide warmth. A shift from fossil fuels towards renewable sources heralds a new era of space heating consisting mainly of low exergy sources, such as heat pumps. This marks a major turning point in the history of domestic heating. This paper begins by discussing variations in domestic thermal environments before considering new forms of low carbon heating. Later sections analyse the way in which these systems deliver heat within people’s homes and consider the implications for thermal experience, comfort and energy consumption.

Keywords: thermal experience, heating systems, alliesthesia, low energy design

Introduction

Existing theories of thermal comfort are largely agnostic about the way in which heat is delivered to occupied spaces in buildings. Although there has been some discussion about problems caused by draughts and asymmetric heating or cooling, thermal comfort is usually discussed in relation to the standard variables of air temperature, mean radiant temperature, relative humidity and air velocity (de Dear 2011). We know, however, that occupants’ experience of thermal environments is complex and that people respond to a range of different conditions both physiologically and through adaptive behaviour. Ongoing field studies conducted by the Welsh School of Architecture confirm that the range of thermal conditions found in people’s homes appears to be underdetermined by thermal comfort criteria. People often deliberately create or seek conditions that lie outside conventional definitions (Stoops 2004; de Dear 2011), some of which are dependent on particular forms of heat delivery. This paper considers the implications for thermal experience resulting from changes to the way in which heat is delivered to spaces in low energy dwellings.

The concept “exergy” can be used to describe the quality of heat energy. The exergy of a heat source might be described as its warming ability for occupants. Thus the move away from fossil fuels towards renewable energy heralds a new era of heating systems, characterised mainly by low rather than high temperatures, or low exergy systems. Heat pumps, for example, typically operate with flow temperatures of 30°C as opposed to the conventional hot water radiator system flow temperatures greater than 60°C. Surface temperatures typically lie somewhere between room air temperature and surface skin temperatures of occupants. A common complaint, therefore, is that the "heating is not working" because radiators feel cooler than the skin to the touch. Similarly, mechanical ventilation with heat recovery (MVHR), the principal heat delivery mechanism component in Passivhaus buildings, provides a low temperature air stream that warms rather than heats the interior spaces. The system used to top-up the heat does not have to be a low exergy system, but the fact that the heat is delivered via warm air effectively sets an upper boundary to the incoming air temperature. These new forms of heating are major departures from the high temperature sources people have gathered around since the discovery of fire, and the time varying profiles of heat delivery provided by these systems creates a very different dynamic in the home.

The paper begins by discussing the variety of thermal environments created in dwellings before considering the new forms of heating that are being introduced in low energy dwellings through refurbishment and new build. The final section of the paper discusses the way in which these systems deliver heat within people's homes and consider the possible implications for thermal experience and comfort.

Variations in thermal conditions in people's homes

Most studies of thermal comfort have taken place in on-domestic settings, and have largely been driven by the need to inform the Heating, Ventilation and Air Conditioning (HVAC) industry about how to design to meet the requirements of occupants. Studies of thermal comfort in the home are as important as they are rare. According to the GB Housing Energy Fact File 2011 (Palmer and Cooper 2011) housing accounts for more than a quarter of the energy consumed in the UK, of which nearly 70% is currently used to provide space heating. Thus the potential for energy savings in the space heating of dwellings is high and key government initiatives are aiming to make improvements. Among these, there is a growing recognition of the limitations of technical changes. As a result, interest is switching to how to achieve behaviour changes that will reduce the demand for energy in the home. Much of this is directed towards reducing heating demand, and yet it is difficult to see how this can be achieved without understanding why and how people create their preferred thermal conditions at home. Detailed studies of thermal comfort and behaviour in the home are rare with most existing research using large scale modelling techniques to develop a picture of housing energy demand. Perhaps the lack of detailed comfort studies is because of the difficulties in recruiting and observing people in their own homes and other challenges presented by working outside relatively controlled non-domestic environments.

The main difference between domestic and non-domestic settings is that when people are at home, they can usually decide and achieve the thermal conditions they want, provided they are within the capabilities of the space conditioning equipment and the fabric of the building. People can, and frequently do, adjust the timer and thermostatic controls for their central heating systems. This level of control is rarely available to occupants in offices and other non-domestic environments, where the operation of the space conditioning systems and sometimes the building fabric is in the hands of a few individuals, such as an energy or facilities manager for the building or estate. It can be argued, therefore, that occupants at home have much greater agency and freedom to decide the conditions within the home. It is rarely so straightforward, however, since the thermal conditions at any given time will be the result of the occupants' actions, the thermal properties of the dwelling—rate of heat loss through the fabric, heating and cooling time constants for the fabric and contents, the heat delivery profiles of heaters, the ability and willingness of the occupants to pay for the fuel, etc. It is difficult, therefore, to establish causal links in such a complicated setting, and we should be cautious about the interpretation of measured data from the home environment, particularly in assuming physiological and other conventional explanations for observed behaviours. Multiple occupancy of a dwelling adds a further layer of complexity, leading to 'contested environments' in which social and power relations decide which conditions prevail.

The variation in energy consumption across otherwise similar dwellings is well known and is usually attributed to different modes of operation arising from the behaviour of the occupants (Anon 2011). The precise reason for large variations is less well known. The authors are currently engaged in field studies of nine occupied dwellings in the South Wales area. The research is part of the collaborative EPSRC funded *Carbon, Control and Comfort: User-centred control systems for comfort, carbon saving and energy management (CCC)* project involving seven universities across the UK. The detailed monitoring of energy consumptions, environmental conditions and thermal comfort surveys reveal interesting differences between the dwellings.

Figure 1 shows recorded living room temperatures for two of the dwellings; they are both mid-terrace, pre-1920's (solid wall) construction. One can see very different operating strategies for the heating system at play here (A01 and A06 both report using direct on/off control of the boiler, but the latter achieves temperatures 5°C higher on a regular basis).

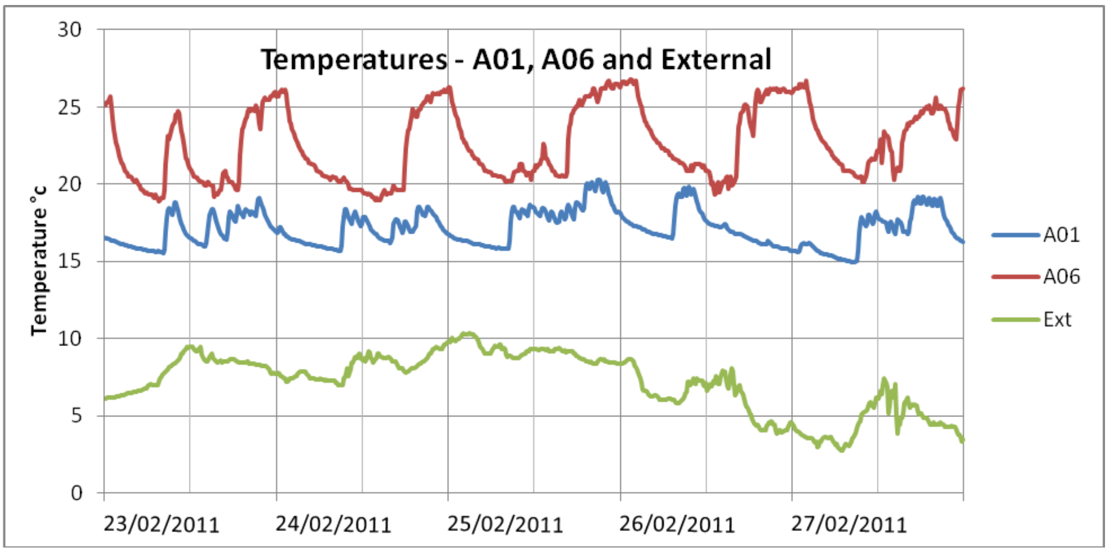


Figure 1: measured living room and external air temperatures for two dwellings.

In Dwelling A01 the indoor temperature varies between 15 and 20°C, tending toward the higher end in the evenings. There is some correlation between indoor temperature and external temperature, suggesting that the occupants' heating strategy is influenced by external conditions. As a result, the heating profile does not appear to form part of a routine.

In A06, however, the occupants' operating strategy results in a distinctive saw-tooth profile for the living room temperature, with a regular, substantial rise in the early evening, reaching a peak and tailing off after midnight. The temperature range is between 18°C and 25°C. The heating pattern and temperature range indicate a habitual approach to heating control, which aims to achieve thermal comfort via the heating system and is not evidently driven by external conditions.

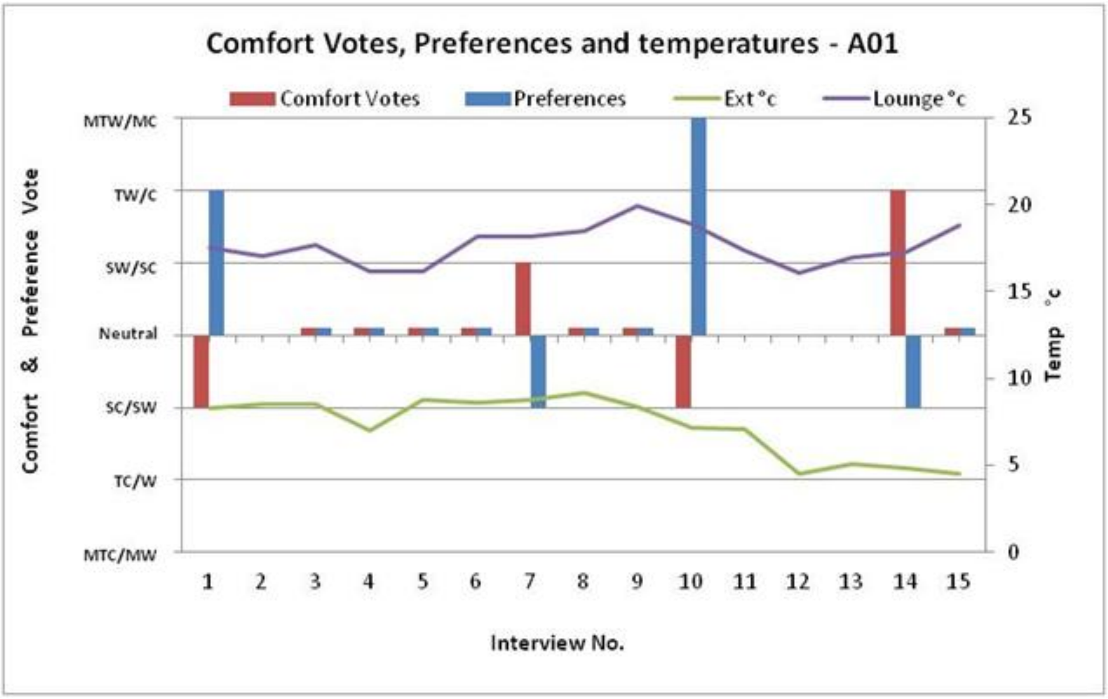
In parallel with these physical measurements, the research team carried out three telephone comfort surveys per day at specific times over five days that enabled accurate comparison between the physical and comfort data. The results of the comfort surveys are presented in Figure 2.

The survey and interview data show that A01 reports comfort in most cases, but will use a range of adaptive strategies to achieve thermal comfort e.g. using a hot water bottle, extra clothing or blanket rather than raising room temperature (A01 stresses that the cost of gas does influence her heating strategy).

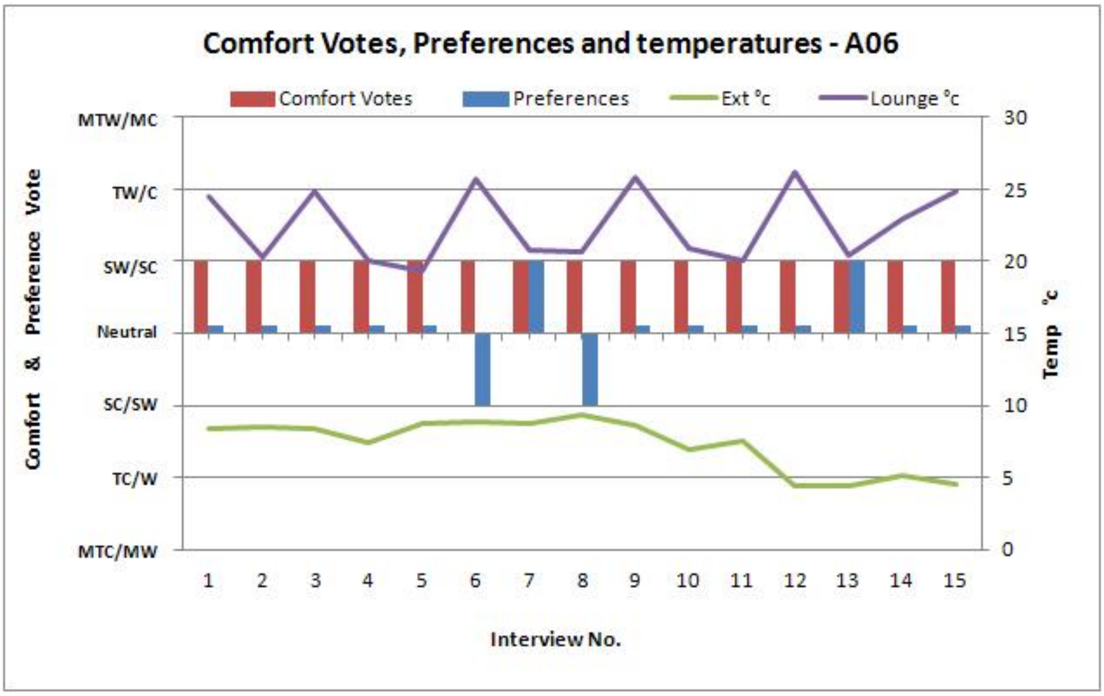
A06 regularly reports being "Slightly Too Warm", but rarely indicates a preference for being "cooler":

[CA06: "Like I say, I've got a boiler over there, so I've only got to knock it on. I keeps it on for about an hour, hour and a half; the place is all heated up so I just knock it off then."]

Thermal comfort data indicates that the average 'clo' value for A01 and A06 is 0.65 and 0.5 respectively.



(a)



(b)

Figure 2: comfort and preference votes for dwellings A01 (a) and A06 (b).

Heat delivery and temperature profiles

These profiles are produced by different occupants in similar dwellings with the same type of heating system. By way of contrast, the following example shows profiles for another dwelling, with a different occupant and a very different heating system: an electric storage heater. While A03 is a different type of dwelling, it is still worth considering the data and temperature profiles as they reveal another set of distinct heating strategies and practices.

The dwelling is a self-contained apartment within a block, built within the last 20 years. The apartment itself has only two external facades and uses *Economy 7* heating. The temperature range in the main living space is particularly interesting as there is little variation over time; the occupant manages to maintain an average temperature of almost 20°C, with a standard variation of 1°C, even with average external temperatures of less than 0°C. Economy 7 provides very little flexibility in the way it delivers heat, unless the user is prepared to pay the price of peak electricity. Both the monitoring data and the occupant confirm that 'peak' *Economy 7* tariff is not used. The occupant described his use of internal doors to help maintain the temperature in the living room. The telephone comfort survey data show that the occupant ordinarily wears a higher *clo* value than the examples above (0.7 clo) and is very consistent in his dress.

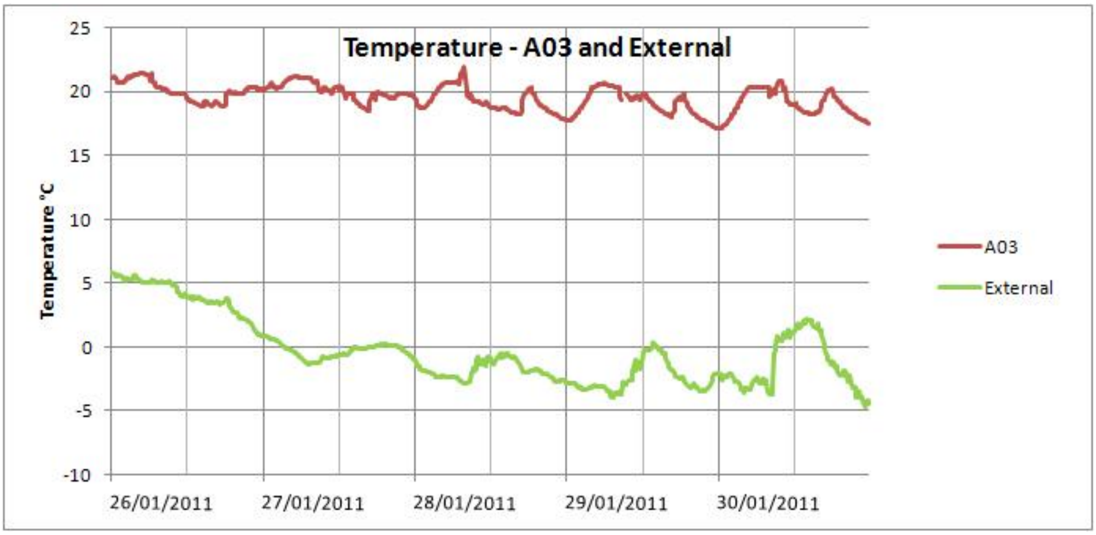


Figure 3: Lounge and external air temperatures for A03.

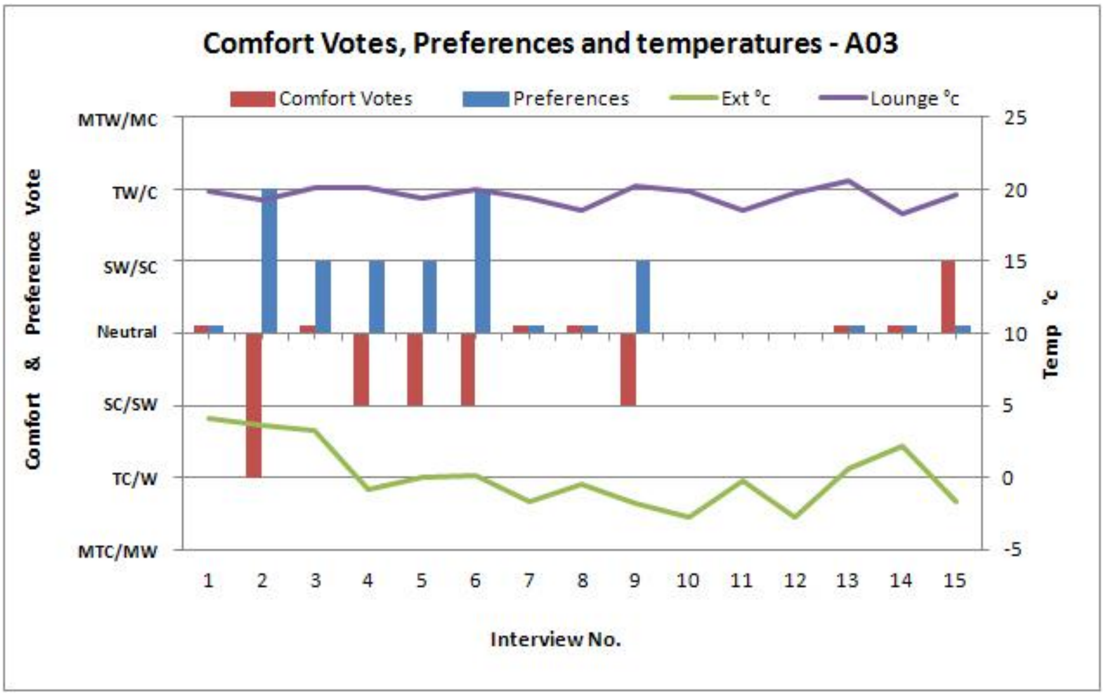


Figure 4: comfort and preference votes for Dwelling A03.

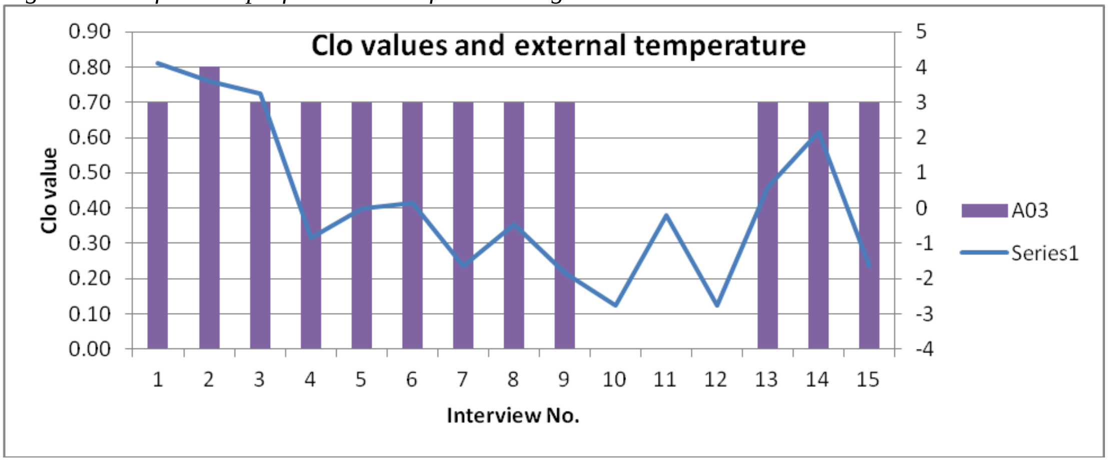


Figure 5: clo *values (clothing level) reported by the (sole) occupant of Dwelling A03 and external air temperature.*

The above graphs show diversity even within this small sample, though they are unable to show preferences for a particular form of heating. What is revealing, however, is that in conversations with the occupant of A03 it emerged that he had bought a halogen heater at the local DIY store and had subsequently bought others for residents in the same apartment block to provide a boost of heat on cold days.

Thermal comfort and experience

So, while thermal comfort defines the baseline for comparing the quality of building performance, it seems it is not enough to assess the quality of occupant satisfaction with the thermal environment. As Baker notes: "it is not just a matter of regulating the four environmental parameters which control the instantaneous heat balance. Rather, comfort is a holistic experience in which the interaction between people and their environments is crucial."

Much existing research assumes that because people desire comfort (or lack of discomfort) buildings should aim to minimise the risk of discomfort. However, as sociological studies advance into the domain it has become clear that thermal comfort is more complex than we have previously assumed. Stoops, for example, questions the assumption that we should always seek to create conditions that avoid any stress on the body:

“So people often intentionally make themselves thermally uncomfortable yet the entire foundation of providing the thermal environment in our buildings is done to minimize the percentage of people thermally dissatisfied.” (Stoops 2004)

Furthermore,

“There does not appear to be direct relationship between improved thermal control and improved thermal satisfaction.” (Stoops 2004)

These statements are supported by the findings in the various dwellings reported above. But we find this has been known for some time. In a paper based on analysis of how people actively pursue thermal comfort, McGeevor contrasts results from laboratory based, climate-controlled studies with *in situ* observations of how people create and judge the quality of their thermal environments. The paper notes that the three components of an implicit theory of human action embedded in energy policy of the time were that the goal of human action in this context was to achieve thermal comfort as determined by laboratory studies, that comfort had an economic cost which obeyed the normal 'laws' of economics and that to achieve comfort economically the individual needs information and knowledge. The paper subsequently questions all three of these assumptions about human action and suggests how they might be revised.

Firstly, thermal conditions measured in the field were often widely different from those suggested by laboratory studies and by existing theory. A key observation is that people judged thermal environments relative to their habitual experience of thermal conditions such that overheating was considered acceptable because it exceeded the crucial requirement of keeping warm during the cold British winter. One individual judged his heating system to be "marvellous" because it was capable of creating "sweltering" conditions . Second, the influence of the cost of energy on consumption in these homes was complex. Although residents were generally keen to reduce their fuel bills, in some cases, cost was ignored in favour of creating conditions that were in excess of what would normally be predicted as comfortable. This is explained by "short term hedonism and passive acceptance of fate" which suggests pricing of fuel to deter wastage and reduce consumption may not work. Finally, the study revealed an acute lack of understanding of how heating systems and controls worked but a well-developed body of folk wisdom about heating and fuel bills constructed and maintained by a local social network. It is worth noting that these studies were carried out in the 1980s.

A narrow focus on comfort criteria, therefore, limits possible explanations for people's behaviour in buildings, unless going to a local hardware store and purchasing a halogen or similar type of radiant heater is included in the definition of adaptive behaviour. As noted previously, this behaviour has been found in the field and it clearly subverts the intention behind low energy dwellings. This work, therefore, would suggest that in some cases, the desire for certain thermal experiences is a more important influence on occupant behaviour than thermal comfort. It is important, therefore, to widen our understanding of what people want (rather than merely need) in the design of low energy buildings.

Thermal experience and *alliesthesia*

There is support for this notion in recent explorations of thermal comfort focusing mainly on non-domestic environments. De Dear revives the concept of *alliesthesia*, originally coined by Cabanac (Cabanac 1992):

"any external or environmental stimulus that has the prospect of restoring the regulated variable within the *milieu interieur* to its set-point will be perceived as pleasant (positive alliesthesia), while any environ- mental stimulus that will further displace the error between the regulated variable and its set-point will be perceived as distinctly unpleasant, or even noxious in more extreme cases (negative alliesthesia)." (de Dear 2011)

Thermally, we can recognise this phenomenon in our own experience: the pleasure of a cool drink on a hot day, a 'roasting' fire on a cold winter's day, and so on. There is little in the comfort literature that acknowledges these aspects of our thermal experience. References to these phenomena are usually found in the humanities informed architectural treatments of thermal environments (Heschong 1980; Fernández-Galiano 2000). From these accounts, we may not know the physiological science behind why we feel pleasure, but they are important in documenting the phenomena.

De Dear differentiates the descriptive dimension of thermal experience from the affective or hedonic, i.e. like or dislike: "Sensation describes the magnitude and sign (warm versus cool) of the experience, whereas comfort qualitatively describes the hedonic tone or pleasantness of the stimulus (like versus dislike). It is possible to share with others the cause of one's pleasure (e.g. the air motion), but one is never sure that they share the same pleasure it arouses in oneself; 'One man's breeze is another man's draft.' For each individual, pleasure and displeasure merge into indifference in the centre, along a pleasure gradient that ranges from extremely negative (distress) to extremely positive (delight) (Cabanac 1992)."

What will be interesting to explore is under what conditions individuals take action to satisfy the requirements of *alliesthesia* and what repercussions this may have for energy consumption. This key question is flagged as an important topic for further research.

Changing methods of heating dwellings

Home technologies have flourished over the past 150 years (Rybczynski 1988). The development of enclosed flues to channel combustion gases out of the dwelling revolutionised the way people experienced heating in the home. The reduction and elimination of internal pollutants prompted greater use of fires in the home to allow people to stay warm. Of course the outside fire was and still is the primary source of warmth for many people. It has been argued that mankind's discovery of fire is what set the course for technological developments over the past millennia. Congregating around fires, to get warm, fostered social bonds as much as satisfying the immediate requirement to stave off the cold. Open fires and their tamer equivalents—wood burning stoves, radiant "coal effect" heaters—have provided a focus for warmth, social interaction and entertainment.

The second set of issues to question the continued use of fossil fuel based heating in the home concerns the availability of such fuel sources, both in the short and long terms. Security of supply, for gas for example, is no longer assured for much of northern Europe, and parts of the former Soviet Union. Europe relies on Russia for 70% of its gas supply, much of which is required for heating people's homes. This together with the need to reduce carbon dioxide emissions has driven the search for new fuels that are less polluting (with fewer carbon dioxide emissions), renewable, and readily available. The range of possible fuels has grown exponentially as we seek to extract energy in whatever form to provide heating for our buildings.

From fuel to heat: the influence of fuel types on thermal

experience

The path from primary fuel to delivered heat largely determines the options for creating a heating profile in a building. There are several key stages that influence was is possible:

- the choice of fuel;
- the way in which heat is delivered to a space—the medium and the network; and
- the design of the heat emitters in the space and their position.

Choice of fuel. The choice of fuel establishes the conversion process. Gas, for example, is instantaneous since it produces heat as soon as it is ignited. Electricity is also rapid response, though the heating device may take some time to achieve its maximum heating effect, depending on the mechanism used to emit heat in a space—for example, whether convective or radiant heating. Other fuels are less immediate. Biomass, for example, in the form of wood pellets fed to a boiler provides a delayed response to a call for heat, whereas a wood chip room heater can reach its operating temperature fairly quickly. All of these factors have an influence on the experience of the end user.

The medium and the network. There are two choices: either a central heating system in which heat is produced and then distributed via a medium in from a central location; or, individual, unconnected room heaters in which the fuel is converted directly to heat. Each has implications for heat delivery. A networked central system requires a medium with a specific heat capacity and a means of circulating the medium throughout the building. A room heater, on the other hand, introduces heat directly to the space, though the fuel must be delivered to the space.

The design of heat emitters. Regardless of where the heat is produced, the location of its entry to individual spaces and the mode of emission will have significant impact on thermal experience in those spaces. Much of the information about the thermal comfort ramifications for different emitter designs can be found in subject textbooks. What is interesting here is how the different designs and locations can produce different experiences, rather than simply provide a quantifiable set of environmental conditions.

Figure 6 illustrates the relations between fuels and the thermal experience of occupants in a dwelling. While this is not definitive, it covers most of the existing heating systems in common use in UK dwellings. It attempts to trace the path from the fuel sources on the left to the resulting thermal conditions and the experiences they produce for occupants on the right.

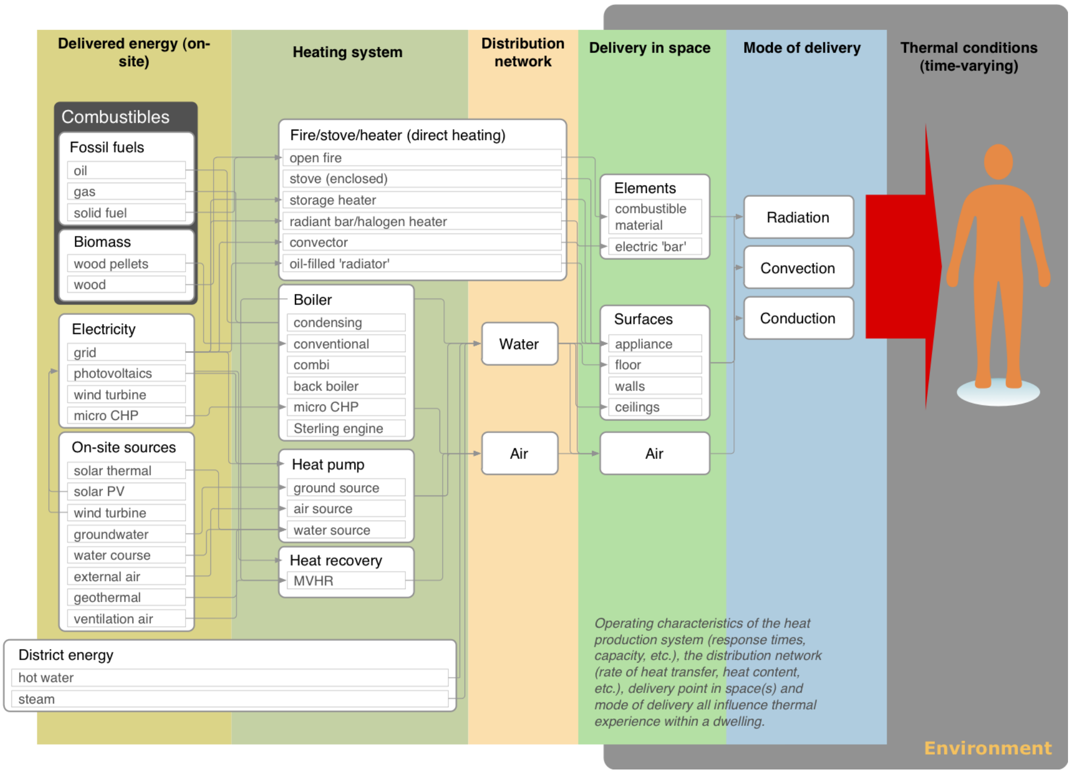


Figure 6: the path from fuel sources to thermal experience.

If nothing else, the figure seeks to establish a connection between fuel type, heat delivery mechanism and thermal experience provided to the occupants in dwellings.

The exergy of heating systems

The term "exergy" is used to assess the quality of a given energy source. It is defined as the ability of an energy source to "do work." For heating, this may be interpreted as the ability of a heat source to provide heat in sufficient quantity and with the desired quality to meet occupants' needs and wants when and where it is required. One way to think of exergy in this context, is as a shorthand for warming ability.

Unlike energy, which can never be destroyed, exergy is said to be zero when the difference in temperature between a heat source and its surroundings is eliminated. A heat source that has a small temperature difference with its surroundings is by definition, low exergy. The quantity of exergy is time variant. The diminishing quantity of exergy in an energy source is due to the increase in entropy. Following the "heat death" view of the earth, it might be argued that exergy is always falling because of the irreversibility of energy conversions.

For heating buildings and people, high exergy systems are frequently dependent on fossil fuels since these are capable of rapidly creating a large heating effect. Electricity is able to do this, if it can be generated with sufficient voltage, which may be achieved with a variety of primary fuels including fossil fuels, but also renewables (wind, biomass) and nuclear power. The substitution of primary energy sources, therefore, can have an impact on the creation of thermal conditions in people's homes.

The concept of exergy provides a useful concept with which to consider different fuels for heating and their suitability in providing the kind of thermal experiences we have grown accustomed to expecting within our environments. Every fuel, when used in a particular system, has a range of possible heat delivery profiles that define the space of possible thermal conditions in a given space. Thus, a ground source heat pump, for example, can only deliver heat to a space according to a specific shape of exergy-against-time profile. All heat delivery systems are imperfect. They are characterised by greater or lesser efficiencies in converting their fuel types to heat, which in turn may be further characterised by the properties and configuration of the distribution system in the dwelling. A gas fire located in an occupied space is capable of producing a very different heating profile to a hot water central heating system also using gas as fuel.

This is most noticeable when there is a mismatch between the heating system, the building fabric and the type of control. A warm air system installed in a lightweight building with a rapid response thermostatic control leads to rapid cycling of the heating system often with extreme fluctuations in the air temperature in the spaces. This produces an uncomfortable environment for most people.

Low carbon heating systems

The push towards renewable heating systems in the UK will receive a boost through the introduction of the Renewable Heat Incentive (RHI), which was introduced through the Energy Act 2008, provides a financial incentive to install low-carbon and/or renewable heating systems in place of fossil-fuel burning installations. The government estimates that the RHI will stimulate £4.5 billion of capital investment by 2020. (Rhodes 2011)

The European Renewable Energy Directive defines what are accepted as renewable technologies. These include;

- Biomass boilers and on-site biogas consumption
- Ground- and water-source heat pumps, as well as deep geothermal heating
- Energy from municipal solid waste
- Biomethane injection into the national grid.

Air-source heat pumps, as well as larger solar thermal and biogas installations, may be included in a later phase of the RHI.

Although the list contains systems which qualify as high exergy, the greatest interest in the UK domestic market has been in heat pumps, which are low exergy. There is a further development in the design of low energy dwellings that is encouraging the deployment of low exergy heating across Europe, including the UK: the interest in Passivhaus new build and retrofit. Passivhaus introduces another form of heating that is likely to have a significant impact on thermal experiences in the home.

Passivhaus is a German standard that specifies maximum energy requirements. The central principle of Passivhaus design is that the heat requirement for the building should be met through satisfying the ventilation requirements. Heat is primarily delivered through the incoming fresh air which has been heated by a combination of heat recovery topped up by some other form of heating, usually incorporated in a mechanical ventilation and heat recovery unit (MVHR). MVHR may also provide cooling during summer months. In some cases, MVHR is referred to as “comfort cooling” or “comfort conditioning”.

Key properties of low carbon heating systems

So, what are the key properties of heating systems that determine the thermal experience of occupants? All that really matters is the time-varying profile of heat input to a space. That profile is determined by:

- the maximum output of the heating system, as perceived in each space
- the response of the system to a request for heat
- the shape of the delivery curve in moving from one level of heating to another (heating up or cooling down)
- the mode of heat delivery.

Of course, the thermal conditions experienced in a given space are not entirely determined by the heating system and its emitters; the properties of the room influence the distribution and the character of the thermal environment in the space. Thus, the changes in thermal experience brought about largely through the introduction of new heating strategies, must also take account of the entire design. The heating system, however, is likely to play the major role.

Concluding remarks

This short paper introduces some points for further exploration about the impact of new types of heating system and low energy designs, such as the Passivhaus system, on people’s thermal experience and satisfaction with their home environments. It suggested some people may find difficulty in adjusting to new forms of heating, which have been characterised as low exergy, with low heating effect. Most renewable energy sources are incapable of generating heat at rates on a par with conventional fossil fuel sources.

The lack of high temperature heat sources in low carbon dwellings is unlikely to become a major issue, since at most it implies a loss of an aesthetic component of thermal experience. But perhaps we shouldn’t underestimate the importance of aesthetics as an influence on people’s behaviour. The pursuit of pleasure is recognised as a primary influence of behaviour. It would be entirely commensurate with arguments presented elsewhere that people will resort to extreme behaviour to bring modest pleasures. Anecdotally, at least, there is evidence to suggest that occupants will subvert the intended low carbon operating strategy by introducing auxiliary forms of heating. Many Passivhaus buildings in continental Europe come with wood-burning stoves to provide a top-up of high exergy heat in the cold winter months.

Perhaps the most important conclusion, therefore, is to signal this as an area for further research and encourage deeper study of thermal experience by enlisting the aid of phenomenological methods to probe the details of how the thermal environment is perceived rather than measured.

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