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'Intelligent furniture': the potential for heated armchairs to deliver thermal comfort with energy savings in the UK residential context

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Abstract Personal heating (or cooling) has long been considered a means for reducing energy demand and providing thermal comfort, most commonly in the form of heated seats. In this paper, findings are reported of what may be the first investigation of the potential for heated furniture to maintain occupant thermal comfort in the UK residential context. In a thermally-controlled environmental room, a thermal manikin was seated in a living-room armchair equipped with an electrically-heated blanket. Results suggested that the manikin total heat flux recorded for the PMV range -0.5 to +0.5 without heated blanket could be achieved in a room 0.7°C cooler but with the blanket operating as compensation. Chest/back radiant asymmetry across the body, and surface contact temperatures of the blanket, were both found to be well-within acceptable limits. The implication for residential energy usage was analytically simulated using an apartment ('flat') as a case study. This showed that energy-saving potential was dependant on the building's thermal performance, the building's dimensions and occupant behaviours. When extrapolated to the UK housing stock it was found that around 5.6 TWh of energy might be saved by using heated armchairs in the UK instead of whole house heating systems. 'Intelligent furniture', in the form of heated armchairs, can potentially contribute to energy saving in the UK residential context, and further investigation is warranted.

Keywords: Thermal comfort; Personal heating; Dwelling; Thermal manikin; Building energy modelling

1. Introduction

To help mitigate climate change, the UK has committed to an 80% reduction in national greenhouse gas emissions by the year 2050, compared to the 1990 baseline (HM Government, 2008). Energy use by buildings represents 40% of the total UK energy consumption (DECC, 2014). According to the Digest of UK Energy Statistics (DUKES, 2011), energy consumption by the residential sector accounted for 30.5% of final energy consumption in 2010, second only to the transport sector (35%). Meanwhile, DBEIS (2016) reports that in 2015 the residential sector consumed 29% of UK final energy consumption, with 80% of household energy being used for space and water heating.

Personal heating (or cooling) has long been considered a means for reducing the energy demand required for providing thermal comfort in the context of buildings and automotive environments. Arens et al (1998) reported that floor fans generating airspeeds of 1.4 m/s were able to extend the upper limit of acceptable temperature to 31°C at a typical office activity level (1.0 met). This finding has been supported by Zhai et al (2013) who observed that at the thermal condition of 30°C, 60% RH was acceptable with the use of floor fans in a study employing a climate chamber representing an office setting. Zhang et al (2010) set up office workstations with task-ambient conditioning systems in a chamber-based investigation, and found that the comfortable condition was maintained at temperatures ranging from 18°C to 30°C, with corresponding energy saving potential of up to 40%. Better perceived air quality will also be provided by personal cooling devices (Kaczmarczyk et al, 2004). Personal conditioning chairs that provide direct heating or cooling to local body parts, normally the back, pelvis and thighs, are widely investigated in both research and practice, especially in automotive environments. Brooks et al (1999) investigated the possibility of using heated automobile seats to improve thermal comfort in vehicle environments, which indicated that heated seats could effectively eliminate cold thermal sensation and improve thermal comfort in cool conditions. Similarly, Oi et al (2011) reported that heated seats in the vehicle cabin with operative temperatures of 10 or 20°C were able to offset the "neutral" temperature by 3°C and potentially reduce energy consumption in automobiles.

For building applications, Veselý et al (2017) compared the effects of three types of heaters (heated chair, heated desk mat and heated floor mat) on thermal comfort in a test chamber representing an office setting, and found that a heated chair was the most effective in improving thermal comfort and saving energy. Pasut et al (2015) converted a typical office chair into a heated/cooled chair by embedding fans and heating elements, to provide local heating/cooling. His chamber-based investigation demonstrated an extended acceptable temperature range from 18°C to 29°C. To evaluate the applicability of thermal chairs in the field, Shahzad et al (2017) conducted a study testing the performance of thermal chairs in an open-plan office. The results indicated that such a thermal chair was able to improve thermal comfort and satisfaction of office workers by 20% and 35%, respectively, compared to standard office chairs. Apart from applications in office buildings, Limpens-Neilen (2006) investigated the applicability of heated benches in churches, and found that the air temperature near to seated occupants was increased by 4°C to 10°C and thermal comfort was improved, though this has limited capability to heat the entire space of churches.

There have been few, if any, studies of the use of personal heating/cooling in UK dwellings, and this study may be the first investigation of the potential for 'intelligent' furniture, in the form of heated armchairs, to maintain thermal comfort for sedentary occupants in the UK residential context. The investigation reported in this paper comprises three parts. Firstly, an experimental study was conducted aimed at examining the extent to which localised armchair heating can maintain sedentary whole-body thermal comfort whilst room operative temperatures are lowered, tested using a thermal manikin in a well-controlled environmental chamber. Secondly, the wider aspects of implementing heated armchairs will be considered, in terms of comfort criteria, general health issues and practical application in the UK's residential context. Finally, the estimated potential energy benefits and limitations will be discussed.

2. Methodology

The use of thermal manikins to evaluate thermal environments has been adopted in many studies. Generally, thermal manikins indicate the total heat loss from the manikin's surfaces in particular environmental conditions, and this is typically transformed into an equivalent temperature (ET*). For example, a dry thermal manikin "VOLTMAN" was used in defining the human requirements envelope in vehicle environments by measuring the manikin's total heat loss (Wyon et al, 1989). Nilsson et al (1997) compared the experimental results from a manikin with subjective votes, and found high correlations for each body segment between the heat flux of manikin and mean thermal sensation of subjects and between equivalent temperature and mean thermal sensation of subjects. Watanabe et al (2010) investigated the heating/cooling effects of individually-controlled systems and successfully revealed its heating/cooling capacity using a 23-segment thermal manikin to measure heat loss under various thermal conditions. This, together with the preceding literature reported, underpinned the approach adopted for the design of the experimental work reported here. It is recognised that the PMV model is applicable to whole body thermal sensations under steady-state conditions, and may not be best-suited to the complexities of non-uniform conditions (Schellen et al, 2013) and the resulting human thermal sensations (Oi et al, 2012) as generated by localised heating. Furthermore, Tanabe (1994) suggested that using equivalent temperature (teq) based on the heat loss of a thermal manikin could be an accurate method to calculate PMV in non-uniform environments. However, since our study is a first approximation at establishing the magnitude of room operative temperature reduction, the original PMV calculation method was adopted.

This experiment was conducted in a well-controlled environmental room representing a residential living room, in which the heating effect of a 'thermal armchair' (equipped with a heated blanket) was investigated using a thermal manikin, followed by a simulation-based analysis. Specifically, with the heated blanket turned 'off' or 'on', total heat flux from the manikin was recorded for a series of room temperatures (air and mean radiant temperatures maintained equal) giving room thermal conditions that generated a range of Predicted Mean Vote (PMV) values (for known values of metabolic rate and clothing thermal insulation). The extent to which room operative temperature could be lowered whilst compensating for sedentary whole-body thermal comfort through use of the thermal armchair was then determined. For the reduced value of room operative temperature combined with operation of the heated armchair, an energy-saving analysis was carried out in the UK's housing context, using the simulation software 'Design Builder'.

2.1. Description of Environmental Room

The environmental room is located in the Sir Frank Gibb Laboratory at Loughborough University. The room is 5.4 m long, 3.05 m wide and 2.35 m high. The indoor climate condition is controlled by convective conditioning supplied by a tempered ventilation system, and radiative conditioning is provided by tempered water flowing in pipes within the four bounding walls, as shown in Figure 1. The temperatures of air supply and of each wall surface can be individually controlled.

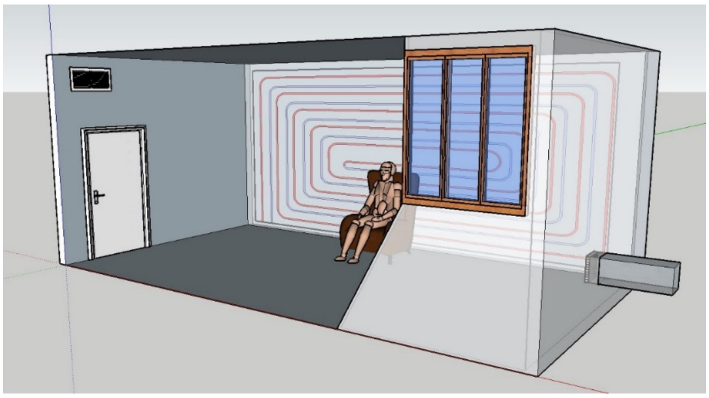


Figure 1 Schematic illustration of the environmental room, showing locations of door, window, and manikin in thermal armchair

The velocity of supply air can be controlled via a central control system which is able to effectively supply air flow in a range from 34 l/s to 75 l/s. The room has a door to the general laboratory space, as well as a multi-layer window facing the outdoor environment, and can achieve indoor temperatures within the range approximately 14-30^{o}C.

2.2. Thermal Manikin

"Victoria" is a female-form thermal manikin used in this experiment, with 20 independently-controlled segments, as shown in Figure 2. The manikin was placed in the centre of the room close to the northern wall, seated in a standard living room armchair upon a heated blanket that covered the back and seat areas of the chair. Heat flux from the manikin (total and segmental) were recorded with an estimated uncertainty of ± 1 Watt, and these values were used comparatively to assess the effect of the presence or absence of heat from the armchair on likely whole-body thermal sensations under a range of room thermal conditions.

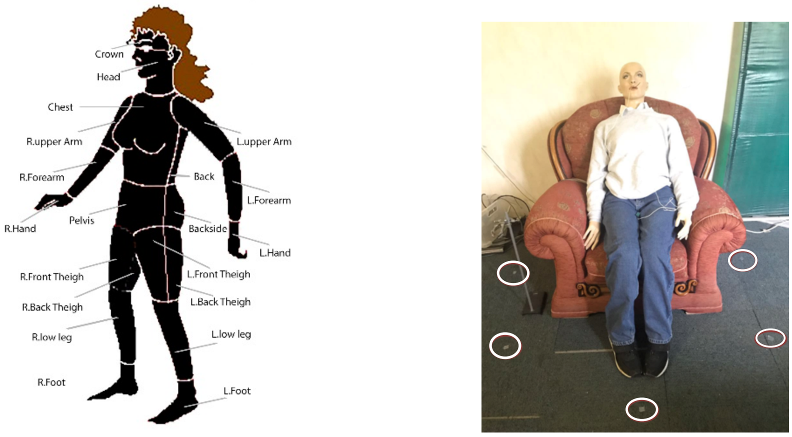


Figure 2 The thermal manikin, illustrating controllable segments (left) and seated in the armchair, wearing typical residential clothing (right)

Since the mean human skin temperature remains at approximately 34°C at thermally neutral conditions (Huizenga et al, 2004), the surface temperature of the thermal manikin was set to 34 °C to simulate the heat flux scenarios of an actual near-neutral thermal environment. The dynamic heat flux and surface temperature of each body segment were recorded at one-minute intervals via a data logger. To assess the effect of the thermal armchair in a residential setting, the thermal manikin was dressed in an ensemble typical of UK residences during winter periods. The ensemble is described in Table 1, and had a total insulation value of 0.93 clo. To this was added an additional 0.15 clo to account for the thermal insulation provided by the armchair

Table 1 Description of clothing ensemble and insulation

Garment description	Insulation value (clo)
Long-sleeved shirt	0.25
Long-sleeved sweatshirt	0.34
Straight trousers (thin)	0.15
Ankle-length athletic socks	0.02
Thin-soled shoes	0.02
Executive chair = 'armchair'	0.15

2.3. Experimental Equipment

(1) Heating Blanket

The electrically-operated heating blanket (Figure 3) was 1.25 m long and 0.6 m wide, and was placed flat upon the sitting and backrest areas of the armchair. This provided heating directly to the back, rear pelvic and back-of-thigh regions of the thermal manikin. The blanket had three heating settings, but to ensure that the heat flow throughout all experiments remained in the direction from manikin to blanket (necessary for correct manikin operation), only the first heating level was employed, which provided a blanket surface temperature of approximately 31.5°C and a blanket measured heat emission of 10.5 Watts.

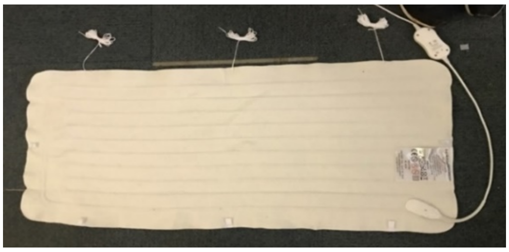


Figure 3 The experimental heating blanket

(2) Measurement Devices

The four environmental parameters: air temperature, mean radiant temperature, relative humidity and air velocity (Fanger, 1970) were continuously recorded. Specifically, during the experiment, relative humidity and air temperature were measured in front of the manikin using a HOBO MX1101 every 15 seconds. The mean radiant temperature was logged every 15 seconds in the centre of the room. Air velocity was measured with an anemometer placed near the manikin at the knee height. The type and levels of uncertainty of each equipment are listed in Table 2.

Table 2 The type and levels of uncertainty of the measuring equipment

Environmental factor	Equipment type	Accuracy
Air temperature	HOBO MX1101	± 0.2 °C
Mean radiant temperature	HOBO UX100-014M	± 0.6 °C
Relative humidity	HOBO MX1101	± 2%
Air speed	Testo 425	±0.03 m/s

2.4. Experimental Procedure

Before beginning the experiment, air velocity and air temperature were measured in the space around manikin at five points illustrated in Figure 2 (white circles) and at heights of 0.1m, 0.6m and 1.1m above the floor. This ensured that the operating manikin was in a thermally stable environment (air speed less than 0.1m/s and air temperature stable) in the experiment. A total of 14 test cases were generated, each corresponding to a different environmental condition (Table 3) across the (air and mean radiant) temperature range 16.3 – 27.4 ^{o}C. Each environmental condition was tested twice - with or without - the heating blanket operating. The environmental conditions were designed to achieve a certain PMV (predicted mean vote) value for situations without the operation of the heating blanket. To do this, it was assumed that activity level remained at 1 met to simulate the metabolic rate of a sedentary occupant in their living room, with insulation of 0.93 clo (see section 2.2). As a result, the corresponding PMV ranged from +1.0 to -2.0, indicating whole-body thermal sensations ranging from ‘slightly warm’ to ‘cool’.

Table 3 the experiment conditions

Environmental condition	Air temp (equal to) mean radiant temp (°C)	Relative humidity (%)	Air speed (m/s)	Activity level (met)	Clo value (Clo)	PMV
Condition 1	16.3	64	0.04	1.0	0.93	-2
Condition 2	18.2	55	0.04	1.0	0.93	-1.5
Condition 3	20.0	52	0.04	1.0	0.93	- 1
Condition 4	21.8	47	0.04	1.0	0.93	-0.5
Condition 5	23.7	44	0.04	1.0	0.93	0
Condition 6	25.5	39	0.04	1.0	0.93	+ 0.5
Condition 7	27.4	36	0.04	1.0	0.93	+ 1.0

For each case, whole-body heat flux from the manikin was recorded at steady state conditions, with and without the operation of the heating blanket. Figure 4 illustrates the procedure. To avoid additional heat gains, experimenters remained outside the environmental room during tests.

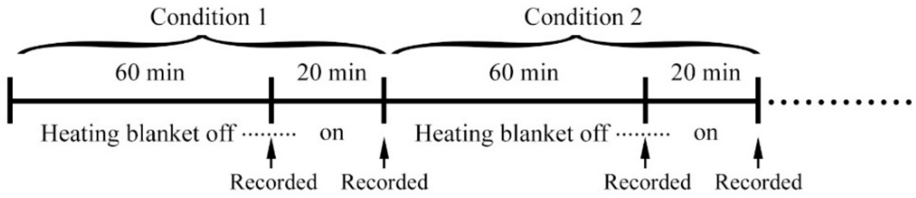


Figure 4 The schematic procedure of experiment

3. Experiment Results

The heat losses through the surfaces of the thermal manikin were compared in the aspects of environmental conditions and heating blanket operations. For the situations without heating blanket operation, and for all the environmental conditions tested, Figure 6 summarises the averaged whole-body heat loss of the thermal manikin as a function of PMV values ranging from -2 to +1.

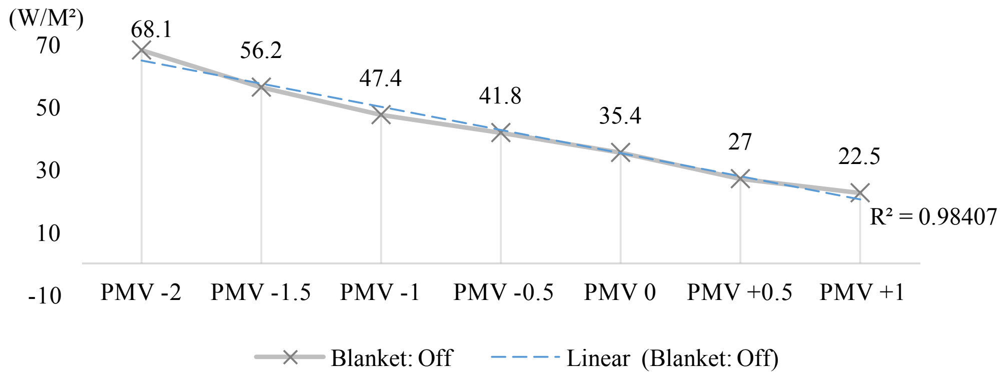


Figure 6 Whole-body heat loss of the manikin versus PMV (heating blanket off). (Manikin heat flux uncertainty estimated as ± 1 Watt).

A highly linear relationship (R^2 = 0.98) was found between manikin whole-body heat loss and PMV, with heat loss consistently decreasing as the PMV changed from 'cool' to 'slightly warm', which confirms alignment with the approach described by Gao et al (2017) and supports the statement of Nilsson et al (1997) who found that the thermal mean votes correlated to the change of the heat loss of manikins.

The above approach was used to compare the likely effect of armchair-based heating blanket usage on thermal comfort. Whole-body heat loss from the thermal manikin was compared for the two heating blanket operation modes (on/off) at the different PMV conditions, as shown in Figure 7.

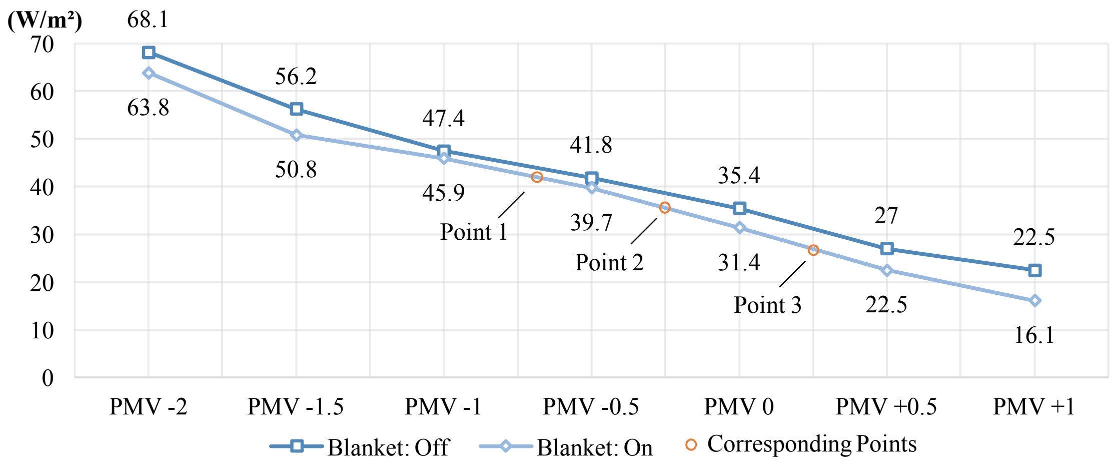


Figure 7 Manikin whole-body heat loss for blanket on or off versus PMV conditions (manikin heat flux uncertainty estimated as ± 1 Watt).

Figure 7 illustrates that operation of the heating blanket (acting as a heated armchair) reduced the whole-body heat losses from the manikin at all thermal conditions tested.

Focussing specifically on the PMV range considered acceptable for thermal comfort (PMV -0.5 to PMV +0.5), use of the heating blanket compensates for, and enables acceptability of, room thermal conditions ranging from PMVs of -0.67 to +0.26 (refer to points 1, 2 and 3 in Figure 7). These points indicate that using the heating blanket could result in preserving the same value of whole-body heat loss, but for the cooler room thermal conditions. To be specific, the previously acceptable room thermal conditions with PMV values at -0.5, 0 and +0.5 could be shifted to the new room thermal conditions with PMV values at -0.67, -0.24 and +0.26 (point 1, 2 and 3), respectively. For the situations tested, these correspond to a reduction in room temperature of 0.7°C, as demonstrated in Table 4.

Table 4 The changes of acceptable ambient temperature in conjunction with the heating blanket

Acceptable thermal conditions (Blanket Off)	Acceptable thermal conditions (Blanket On)	Ambient Temp (Blanket Off)	Ambient Temp (Blanket On)	Temperature difference
PMV +0.5	PMV +0.26	25.4 °C	24.7 °C	0.7 °C
PMV 0	PMV -0.24	23.7 °C	23.0 °C	0.7 °C
PMV -0.5	PMV -0.67	21.7 °C	21.0 °C	0.7 °C

Were this to remain fully applicable in the living areas of dwellings, then the usage of heated ('intelligent') armchairs might allow a reduction of 0.7 °C in indoor room ambient temperatures without adversely influencing the overall thermal sensation of seated occupants under steady state conditions and wearing similar clothing to that tested. The potential effects of this in terms of energy savings are discussed in the next section.

4. Analysis and Discussion in the UK residential context

According to English Housing Survey (DCLG, 2017), in England, there were approximately 23.5 million residential buildings in 2015. Based on English Housing Survey, typical dwelling types in the UK can be grouped into 10 categories while the usable floor area of UK dwellings can be grouped into 5 categories, as demonstrated in Table 5. Among these building types, the proportion of apartments (commonly termed 'flats' in the UK) was approximately 42% of total dwellings in England in 2015 (DCLG, 2017). Therefore, a flat was used as a simulation model in this study due to its universality.

Table 5 Typical dwelling types, insulation performance and usable floor area of dwellings in the UK

Dwelling types		Limiting U-value of previous regulation (W/m2 K)						Usable floor area
		Year	Wall	Windows	Roof	Floor		
Terraced house; Semi-detached house; Detached house; Bungalow; Flat		1976	1.0	n/a	0.6	n/a		Less than 50m^2
		1982	0.6	n/a	0.35	n/a		50 to 69 m^2
		1990	0.54	3.3	0.25	0.45		70 to 89 m^2
		1995	0.45	3.3	0.25	0.35		90 to 109 m^2
		2000	0.35	2.2	0.25	0.25		110 m^2 or more
		2006	0.35	2.1	0.2	0.25		
		2010	0.3	2	0.2	0.25		

The first building regulation for U-value of building envelopes in England was established in 1976 (Killip, 2005), while Dowson et al (2012) summarised the historic U-value of thermal envelope in each building regulation since 1976, as shown in Table 5. However, according to English Housing Survey (DCLG, 2017), until 2015, nearly half of the existing domestic stocks were built before 1964, and only 49.1% and 81.4% of dwellings were installed with wall insulation and full double glazing, respectively.

Meanwhile, Steemers et al (2009) and Firth et al (2010) reported the average number of occupants in households was 2.52 people and 2.65 people, respectively.

Considering the energy-saving performance of the heated armchair would be affected by heating loads in homes, this simulation would focus on the influencing variables on heating loads, such as thermal performance of building envelopes, the dimension of buildings, the glazing ratio and the number of occupants. Meanwhile, the operation time of heated armchairs would be simulated as another variable.

According to DECC (2014), the heating season in the UK generally lasts for 5.6 months, which starts from October and extends to April the following year. SAP (2012) suggests the demand temperature in the living areas of dwellings is 21°C, while the whole house needs to be heated for 9 hours a day on weekdays and 16 hours a day on weekends. Martínez-González et al (1999) investigated the average seating time, including all seated leisure activities, of male and female adults at home per week in the European countries, and found on average that males spent 24.6 hours per week sitting at home whilst females spent 23.2 hours seated.

Additionally, although a dynamic ventilation rate depending on the number of occupants is required in new-built dwellings by Part F of the Building Regulations (Regulations, 2010), the main approach of obtaining fresh air in the majority of dwellings in the UK relies on air infiltration through the building fabric. Pan (2010) summarised the typical air permeability of dwellings in UK's building regulations ranges from 10 m^3/(h m^2) to 1 m^3/(h m^2) at 50 Pa, while Grigg et al (2004) revealed the average air permeability of new-built dwellings in 2002 was about 9 m^3/(h m^2) at 50 Pa. Hence, in this simulation, the ventilation rate is determined by 5 m^3/(h m^2) at 50 Pa of air permeability which is also recommended by SAP (2012).

Based on the information summarised above, several energy simulations have been conducted using DesignBuilder to determine the energy-saving potentials of thermal furniture in the UK dwellings. In the simulation, weather data at the location of London Gatwick Airport was selected in this simulation. The heating is assumed to heat the whole building in the heating seasons (October – April), while the heating operation periods required is presumed to be 9 hours and 16 hours for weekdays and weekends, respectively. The operation period of heated armchairs depends on the assumption in the simulation, but is considered to be up to 77 hours per week, as specified in Table 6.

Based on the experiment result, the use of heated armchairs is able to compensate 0.7°C of indoor ambient temperature. Therefore, it is assumed the ambient temperature in homes will be reduced from 23.7°C to 23.0°C in heating seasons when hated armchairs are in operation.

The simulation scenarios are shown in Table 6. There are 5 variables factors and totally 20 scenarios. For each scenario, except for the values specified in the table, the rest of values are the same as those in the baseline. Each scenario would be simulated twice in cases with and without heated armchairs.

4.1. Energy-saving Potential

The energy saving potential, here, is defined as the difference between the energy consumption in the condition of operative temperature of 23.7°C (PMV = 0, suggested in Table 4) without heated armchairs and the energy consumption in the condition of operative temperature of 23.0 °C plus the energy consumption from the heated armchair.

Importantly, it is assumed that one heated armchair is only able to serve one person, and it would be used during heating seasons (28 weeks). The power of one heating blanket is 10.5W, and the energy consumption of one heated armchair in the heating season was manually calculated by the power times operation hours, as shown in equation 1.

$$W_{annual} = N_{armchair} \times P_{armchair} \times T_{per\ week} \times T_{weeks} \quad \text{...①}$$

Where, W_{annual} – Annual energy consumption of hated armchair (KWh);
$N_{armchair}$ – Number of heated armchairs in use;
$P_{armchair}$ – The power of each heated armchair (W);
$T_{per\ week}$ – Operation period of heated armchair per week (hours);
T_{weeks} – The period of heating season (weeks).

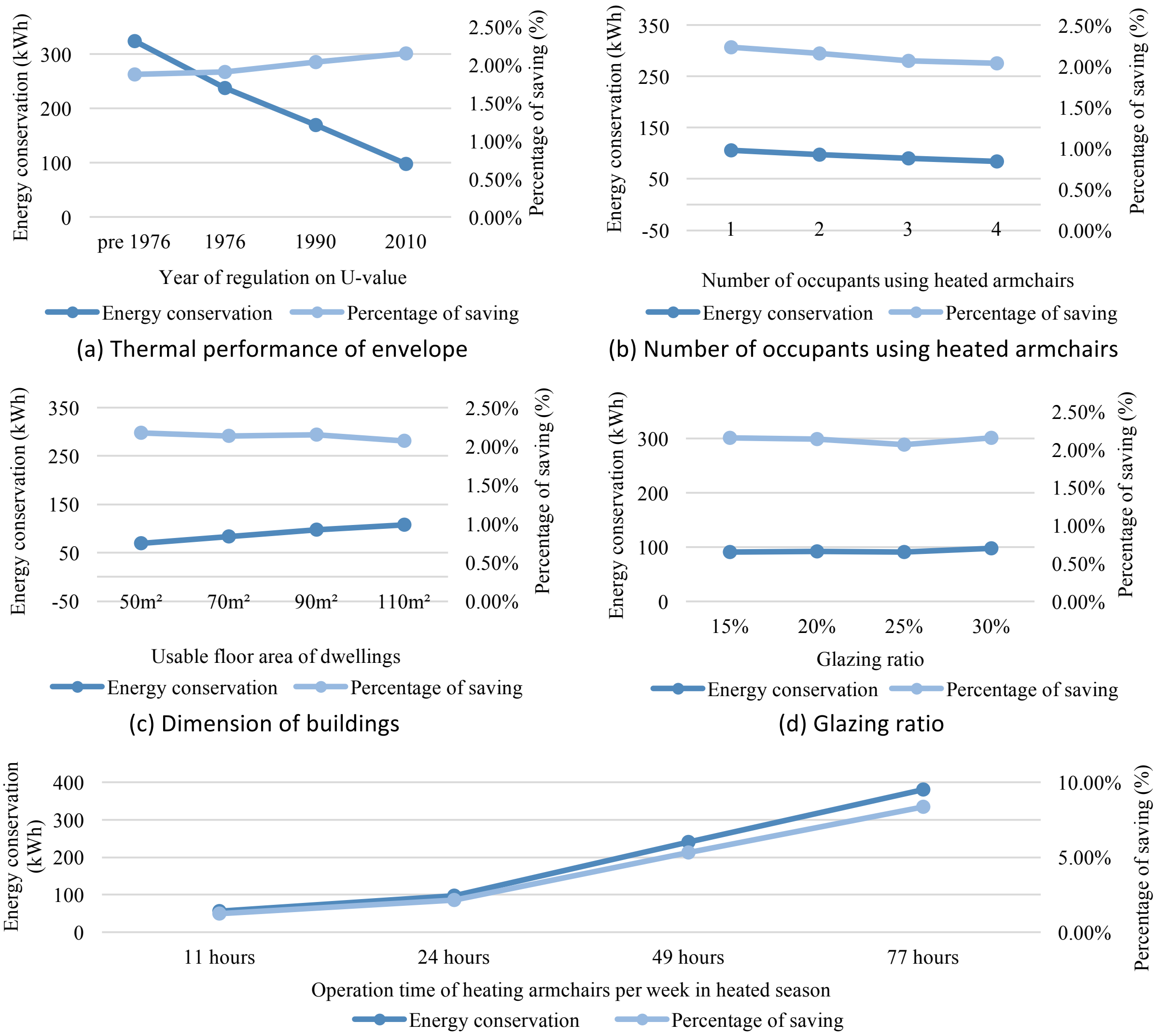
Table 6 The simulation scenarios

<table>
<tr><td colspan="9">Baseline</td></tr>
<tr><td rowspan="2"><u>Scenario No.</u></td><td colspan="4">U-value (W/m2 K)</td><td rowspan="2">No. of Occupants</td><td rowspan="2">Room Dimension (L*W*H) (m)</td><td rowspan="2">Glazing ratio</td><td rowspan="2">Operation time per week (h)[a]</td></tr>
<tr><td>Wall</td><td>Windows</td><td>Roof</td><td>Floor</td></tr>
<tr><td><u>Baseline</u></td><td>0.3</td><td>2.0</td><td>0.2</td><td>0.25</td><td>2</td><td>9*10*3.5</td><td>30%</td><td>24[e]</td></tr>
<tr><td colspan="9">Factor 1 – Thermal performance of building envelopes</td></tr>
<tr><td colspan="2"><u>Scenario No.</u></td><td colspan="2"><u>1</u></td><td colspan="2"><u>2</u></td><td colspan="2"><u>3</u></td><td><u>4</u></td></tr>
<tr><td rowspan="4">U-value (W/m2 K)</td><td>Wall</td><td colspan="2">2.0</td><td colspan="2">1.0</td><td colspan="2">0.54</td><td>0.3</td></tr>
<tr><td>Windows</td><td colspan="2">3.8</td><td colspan="2">3.8</td><td colspan="2">3.3</td><td>2.0</td></tr>
<tr><td>Roof</td><td colspan="2">1.0</td><td colspan="2">0.6</td><td colspan="2">0.25</td><td>0.2</td></tr>
<tr><td>Floor</td><td colspan="2">0.7</td><td colspan="2">0.5</td><td colspan="2">0.45</td><td>0.25</td></tr>
<tr><td colspan="9">Factor 2 – Number of occupants using heated armchairs</td></tr>
<tr><td colspan="2"><u>Scenario No.</u></td><td colspan="2"><u>5</u></td><td colspan="2"><u>6</u></td><td colspan="2"><u>7</u></td><td><u>8</u></td></tr>
<tr><td colspan="2">Number of occupants</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td><td>4</td></tr>
<tr><td colspan="9">Factor 3 – Dimension of buildings</td></tr>
<tr><td colspan="2"><u>Scenario No.</u></td><td colspan="2"><u>9</u></td><td colspan="2"><u>10</u></td><td colspan="2"><u>11</u></td><td><u>12</u></td></tr>
<tr><td colspan="2">Room Dimension (L*W*H) (m)</td><td colspan="2">5*10*3.5</td><td colspan="2">7*10*3.5</td><td colspan="2">9*10*3.5</td><td>11*10*3.5</td></tr>
<tr><td colspan="9">Factor 4 – Glazing ratio</td></tr>
<tr><td colspan="2"><u>Scenario No.</u></td><td colspan="2"><u>13</u></td><td colspan="2"><u>14</u></td><td colspan="2"><u>15</u></td><td><u>16</u></td></tr>
<tr><td colspan="2">Glazing ratio</td><td colspan="2">15%</td><td colspan="2">20%</td><td colspan="2">25%</td><td>30%</td></tr>
</table>

Factor 5 – Operation time of heated armchairs				
Scenario No.	17	18	19	20
Operation time per week (h)	11[b]	24[e]	49[c]	77[d]
Note: a – it stands for the weekly operation time of heated armchairs; the maximum operation time for one week is 77 hours, which is calculated based on the required weekly heating period. b – weekday: 22:00-23:00; weekends: 20:00-23:00; c – weekday: 8:00-9:00, 19:00-23:00; weekends: 8:00-12:00, 13:00-17:00, 19:00-23:00; d – all heating period; e – weekdays: 21:00-23:00; weekends: 09:00-11:00; 20:00-23:00.				

Based on the simulation results, the energy saving potentials of using heated armchairs in different variable cases are shown in Figure 8, and discussed as follows.

Since heating loads can be reduced by increasing thermal performance of building envelopes, the amount of energy conservation by using heated armchairs decreased with improvement of U-values of envelope components. However, the highest percentage of energy saving is observed in the best-insulated case, which indicates the thermal furniture, such as heated armchairs, could lead to additional energy savings even though buildings have been well insulated.



(a) Thermal performance of envelope

(b) Number of occupants using heated armchairs

(c) Dimension of buildings

(d) Glazing ratio

(e) Operation time of heated armchairs

Figure 8 The energy conservation of heated armchairs in various scenarios

Based on Figure 8-b, less energy can be saved when there are more occupants using heated armchairs. The reason is total energy consumption is reduced in dwellings, as more occupants will result in more heat gains and less heating demand. Therefore, theoretically, the energy-saving potential of heated armchairs will be totally eliminated at a certain number of heated armchairs in operation, but such a large number of occupants in a single dwelling would be uncommon in the UK context.

This simulation adopted the fixed air permeability to supply sufficient fresh air. If the ventilation rate in dwellings is determined by the number of people, as suggested by Part F (Regulations 2010), more occupants may result in higher heating loads from ventilation, leading to increasing energy-saving potentials by using heated armchairs. Therefore, the usage of heated armchairs is suitable for multiple occupants in the UK, but the energy-saving effectiveness will depend on the number of occupants and the ventilation mode in dwellings.

Although there were some fluctuations, the smaller dimension of indoor space can, indeed, benefit from heated armchairs with better energy performance. For example, energy consumption could be reduced by 2% by two heated armchairs in dwellings with 50 m^2 floor area, as shown in Figure 8-c. However, dwellings with larger floor areas might potentially accommodate more occupants, so the energy saving potential may be greater in the large size dwellings in reality. Glazing ratio affecting solar heat gains shows relatively low impacts on the performance of heated armchairs. The range from 15% to 30% of glazing ratio has been found to show minor changes in either the amount or the percentage of energy saving.

Since different occupant behaviours in terms of sitting time at homes may influence the actual performance of heated armchairs, different operation scenarios have been simulated as the operational period of heated armchairs. Maximum 8% of the annual heating energy can be reduced by using heated armchairs 77 hours per week in the heating season. Even if only using heated armchairs 1 hour per weekday and 3 hours per weekend, it still can achieve about 1.24% of energy conservation.

4.2. Acceptability and Health issues

Alongside the discussions above of the potential of heated armchairs to save energy in the UK residential context, it is also important that wider aspects of thermal acceptability are considered. For the heated armchair to be considered thermally acceptable by its occupants, two conditions must be met: one is that the chair surface temperature must remain in the range considered safe and acceptable to humans (or household pets) in terms of skin contact temperature, and the other is that the temperature difference between the heated chair surface and the room ambient temperature must be within the limitation range of thermal asymmetry.

Havenith (2005) points out that the heat tolerance of people would depend on their age, gender, fitness, acclimatisation, morphology and fat, in which age and fitness are the most important factors. Wienert et al (1983) suggests that 43°C is the highest skin temperature which can be tolerated for about 8 hours with no restricted blood flow. The surface temperature of the heating blanket used in this study was 31.5°C, which is lower than the thresholds of causing physiological disorder. In terms of temperature asymmetry, assuming the condition for vertical surfaces applies (ASHRAE Standard 55, 2013), then this too remains acceptable for a chair surface temperature of 31.5°C and a room ambient temperature in the range 21-24.7°C as was the case in this study. In other studies, humidity has also been found to be a crucial factor in determining local thermal comfort of people sitting in chairs, as the water vapour released by the body's skin should be able to disperse.

As a solution, by improving the materials of seat covers, Glassford et al (1979) found that the inclusion of small holes in a seat's surface could change some unacceptable conditions into an acceptable range.

An extensive consideration of potential health issues (benefits or drawbacks) related to residential use of heated seats is beyond the scope of this paper. Such issues might relate to the long-term health effects of inhalation of air at slightly cooler temperatures than might currently prevail as a result of heated armchair use, whether there are any potential effects on male fertility (Jung et al, 2008), and whether heated chair use influences the length of time spent in sedentary mode by occupants in their homes with any consequences for health. It is recommended that all potential health-related aspects are fully investigated prior to adoption of heated 'intelligent' seating in homes.

4.3. Generalisation and Adaptation Opportunity

There were 23.5 million dwellings in the UK in 2015 (DCLG, 2017), and by 2011, approximately 280 TWh of energy was consumed by space heating in households (Palmer and Cooper, 2012). Based on the analysis above, 2% would be a reasonable percentage to be set as the energy saving potential of heated armchairs. Therefore, presumably, 5.6 TWh of energy could be saved by simply using heated armchairs in UK dwellings, though this number would depend on many factors, such as occupant behaviours, U-values of building envelope, occupant numbers and building dimensions.

The research described in this paper on heated armchairs has been conducted under steady state conditions and has employed the PMV approach for objective comparison of situations with and without the operation of the heated blanket. Adaptive opportunities have thus been assumed to be none. The findings might therefore be more applicable to domestic situations of extended sedentary periods with little or no adaptive actions. However, actual temperatures in UK homes are often lower than expected. For example, Kane et al (2011) investigated 292 dwellings in Leicester, UK and found average air temperature in living rooms was only 18.4°C during the day with a slightly higher temperature at evening (19.4°C) suggesting that adaptive opportunities play a significant role in achievement of residential thermal comfort. Thermal furniture, such as heated armchairs, may provide occupants with another thermal adaptation opportunity. In some cases, a single heated armchair in the living rooms could be able to offset the heating demand of occupants when they are not willing to increase energy bills by heating the entire home. In other cases, the heated armchair also offers a chance to satisfy the individual's thermal preference when the room temperature is neutral to others but cold to him/her. It is recommended that these aspects are investigated further.

Since the most uncomfortable local-body parts in cold conditions are the hands and feet, it may be valuable to add heating elements in the arm pads of armchairs in future designs, and/or foot-warming capability. Further, field studies involving human subjects should be conducted of actual energy performance, thermal comfort and usage acceptability of such heated armchairs in the context of dwellings.

5. Conclusions

Personal heating/cooling has long been considered a means for providing thermal comfort, leading to reducing the energy demand in the context of buildings and automotive environments. Heating/cooling chairs are one of the most common forms of personal conditioning devices. This paper reported the findings of what may be the first investigation of the potential for heated furniture to maintain occupant whole-body thermal comfort in the UK residential context. The investigation comprised laboratory work followed by thermal analysis and energy analysis. A thermal manikin was seated in an armchair, in a thermally-controlled environmental chamber operated as a standard living room, that had been equipped with an electrically-heated blanket for supplying heating to the back and rear pelvic/thigh regions.

The main findings are as follows.

- For living room thermal conditions, it was found that the manikin total heat flux recorded for the PMV range -0.5 to +0.5 without heated blanket operation could be achieved in a room 0.7°C cooler but with the blanket operating in compensation;
- Using heated armchairs in well-insulated dwellings can result in a higher proportion of energy saving than in poorly-insulated dwellings;
- The usage of heated armchairs is suitable for multiple occupants in the UK, but the energy-saving potential will depend on the number of occupants and the ventilation mode in dwellings;
- Ideally, 5.6 TWh of energy in dwellings in the UK might be saved by simply using heated armchairs, though this number would depend on many factors, such as occupancy, operation periods, U-values of building envelope, occupant numbers and building dimension; and whilst heated armchairs might offer individual dwellings a modest energy saving of only 2%, there may be other (non-energy) benefits that might lead householders to adopt this approach;
- Heated armchairs provide dwelling occupants with another thermal adaptation option, but the acceptability, health issues, energy performance and thermal comfort in real-world settings need to be fully investigated in the future, prior to adoption of this approach.

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