

Thermally Active Clothing for Building Carbon Footprint Reduction

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Abstract - Clothing with built in heat sources and thermal controls is becoming more popular. This study investigates possibilities for reducing the energy consumption of buildings through smart use of this novel clothing. Crossover benefits in health and recreation are explored. Various technologies are reviewed and further actions suggested. Analysis has shown that energy consumption of buildings can be significantly reduced with associated reductions in carbon footprint. Further work is required into the effect on acceptable ambient temperatures of wearing actively heated clothing, along with opportunities for closer integration with building control systems.

INTRODUCTION

Clothing with integral active thermal controls is becoming more widespread.

New technologies are being applied in fields from extreme environment workwear to healthcare to recreation.

More recently, a global search is being made for ways to reduce energy consumption. This paper seeks to address the question: “*Can thermally active clothing help to reduce household energy consumption ?*”.

The thermodynamics of home and body heat transfer are investigated and modelled, as shown in Figure 1. This provides a model for calculating potential energy savings [4].

Cost savings are investigated, along with carbon footprint analysis to ensure that the embodied CO₂ equivalent [7] emissions do not cancel out operational savings.

Conclusions and suggestions for further investigation are given.

BODY, CLOTHING AND BUILDING MODELS

Thermodynamic modelling of energy consumption

Figure 1 shows a simplified heat flow model for the scenario whereby one person occupies a heated home or dwelling.

Several heat sources are present, namely the metabolic heat from the human body, heat from a thermally active clothing element, heat from the home central heating and heat from the external environment. Heat flow follows the temperature gradient from the body surface to the external environment, penetrating various barriers on the way such as clothing and walls.

Typical surface areas for these barriers, along with thermal resistance (or R value) of each are estimated for an average person living in a medium sized UK house. Values are given in Table 1. The clothing R values equate to 1 clo [9].

Item	R Value (m ² K/W)	Surface area (m ²)
Inner clothing	0.075	2.1
Outer clothing	0.075	2.1
House walls	0.5 to 3.33	350

Table 1: Heat flow coefficients

External temperatures are taken from 1st December 2009 to 28th February 2010 for Southampton in the UK [1].

The internal temperature of the home is set to 16°C which is a compromise between comfort from exposed areas of flesh and heat loss from the home [3]. Many studies on comfort measurement have been undertaken [2]. The PMV or “persistent mean vote” is the most commonly used methodology as defined by ISO 7730.

A spreadsheet model [4] is utilised to calculate the cost per hour of maintaining a skin surface temperature of 34°C [10] utilizing both metabolic energy, energy from a clothing based heating element powered from a rechargeable battery, and energy from a gas fired central heating boiler.

Adding extra layers of clothing is not sufficient to provide the desired comfort level. This is because a certain degree of heat loss is required to maintain comfort through a range of metabolic energy output levels, such as moderate activity or consumption of hot food or drinks. Excessive clothing R values cause thermal discomfort during these activates if they are not removed. This is why most homes prefer to maintain a 21°C rather than a 16°C ambient temperature plus extra clothing.

Note that some time was spent attempting to trace the provenance of the UK government's often quoted 10% reduction in energy bills per degree Celsius thermostat set point [15]. A validated scientific source for this statement could not be identified. It is not needed however, as known surface area and R values allow the calculation to be made from first principles of thermodynamics.

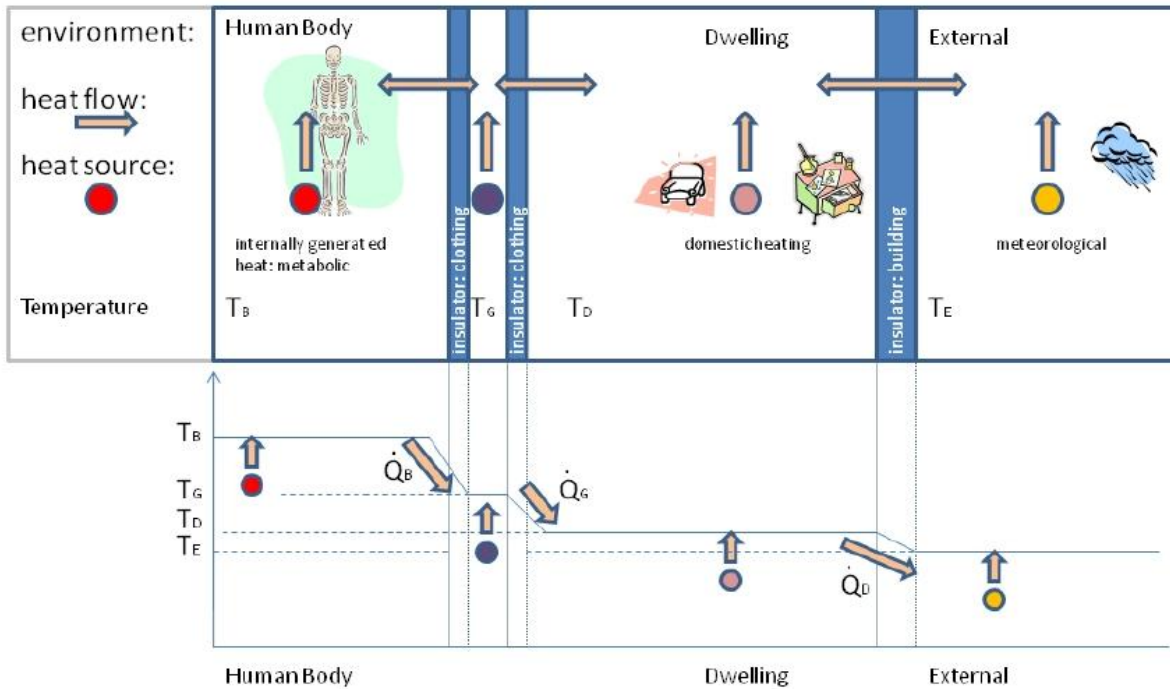


Figure 1 : Heat flow model with localised heat source

Economics modelling method

The cost per joule of energy from natural gas is calculated from the Southern Electricity Standard Energy Tariff [16]. Installation, operation and maintenance costs for the gas central heating system are ignored, though they typically equate to £200 per annum.

It is assumed that the heated clothing uses a heating element plus a Li-ion battery. The battery chosen for reference is that used by the Dell Inspiron 1525 [5], with a retail cost of US\$30 and a capacity of 7.2Ah. A cycle life of 1200 is used [6]. At one charge per day, this equates to 40 months of use.

Carbon accounting method

Carbon accounting calculations use research from [7] and [11], which states that natural gas generates 0.19Kg of CO₂ per kWh.

Electricity to charge the battery comes from the UK National Grid which emits 0.43kg CO₂ per kWh [7].

An approximate figure for the carbon footprint of battery manufacture and disposal is based on the calculation in [7] of 200 Kg for the carbon footprint of a laptop PC. The battery is approximately 15% of the laptop by weight. Thus a good estimate would be 30Kg per battery, giving 60Kg for the two. Reference [7] also quotes 80% reductions in the manufacturing carbon footprint achieved by recycling, so applying this factor reduces the two battery footprint to 12 kg. This method is very approximate. It could be incorrect by a factor of 2, but serves as a useful first level approximation.

ENERGY CONSUMPTION, ECONOMIC AND CARBON RESULTS

Building savings results

Given the data set for external temperatures for Southampton, UK from 1st Dec 2009 to 28th Feb 2010 [1], a house of R value 1.0m²K/W [8] and wall area 350m² (a

medium sized UK house). Table 2 shows the energy use over the 3 month period.

Thermostat set point	3 Month energy use
16°C	8875kWh
21°C	12655kWh
23°C	14167kWh

Table 2 : Three month house energy use vs. thermostat set points for 1.0 R-value walls

Note that house energy use varies significantly with house wall construction method. Table 3 shows energy, cost and CO₂ savings for a drop in thermostat set point from 21°C to 16°C for each construction type over the three month period.

R-value[8]	Wall type	kWh	£	kg CO ₂
0.5	Solid brick	7560	226	1436
1	Insulated cavity	3780	113	718
3.33	Brick+ 70mm foam	1135	34	216

Table 3 : Savings over 3 months vs. house R-value in m²K/W from a 21°C to 16°C room stat set point reduction

Heated clothing cost results

The scenario used involves one person in an ambient temperature of 16°C with a skin temperature of 34°C [10], surface area of 2.1 m² [23] wearing 1clo of clothing [9] equivalent to 0.155m²K/W.

The heat flow from the body in this scenario is 244W.

The same calculation for a 21°C ambient temperature yields a heat flow of 176W. Which is a level of heat loss that maintains comfort levels [9]. Hence 68W is required to make up the shortfall. Some heat will be lost directly into the home without improving comfort, plus the charging process is not 100% efficient. So we add 20% to give a total clothing power draw of 82W.

Over 3 months, with 12 hours per day of use (requiring two battery packs), total energy expended by the heated clothing is 86kWh. [7] allows us to calculate the kg of CO₂ emitted as 37kg CO₂. The cost of the electricity is £15 [16].

Daily use for 3 months (out of the 40 month battery life) equates to £3 purchase cost and 0.9kg CO₂ lifecycle cost for the two batteries.

The results for power used, cost and CO₂ footprint for the three months are summarised in Table 4.

	kWh	£	kg CO ₂
Operating costs	86	15	37
Lifecycle costs	-	3	0.9
Total	86	18	38

Table 4 : Three month operating and lifecycle costs for heated clothing

Total savings from heated clothing use

subtracting the costs incurred by using the thermally active clothing from the savings made by reducing the building temperature gives figures for total savings made. These are summarised for the three month period in Table 5.

	kWh	£	Kg CO ₂
Building heating savings ¹	3780	113	718
Heated clothing expenditure	86	18	38
Total Savings	3694	95	680

Table 5 : Three month savings from use of thermally active clothing

DISCUSSION OF RESULTS

The scenario used in this study involves a medium sized house with an average sized occupant with the external temperatures for Southampton UK from 1st December 2009 to 28th February 2010. The house is of insulated brick cavity wall construction.

Purchase and maintenance costs have not been considered for the clothing or the central heating system. The replacement cost of the batteries has been included.

There is a theoretical energy saving for this scenario of 3694 kWh resulting in a considerable 680kg CO₂ saved. This is equivalent to travelling 3,200 miles in an average car [7]. There is a cost saving of £95.

The savings increase with larger and more poorly insulated houses. They decrease with smaller, more efficient houses or flats.

¹ Insulated cavity brick wall

Assumptions include a 16°C ambient temperature for the home. This is thought to still be comfortable, though field trials would be required to verify this. It is also enough to mitigate against dampness and condensation issues in the home. Another assumption made is the duration for which the heated clothing is used per day, set at 12 hours. This could prove to be an over or underestimate. Again field trials would provide more accurate data.

The battery cycle life of 1200 would need to be evaluated by field trial, as cycle life data for this particular application has not been identified.

Clothing of 1 clo or 0.155m²K/W was chosen. In practise it may be more comfortable to use higher or lower levels of insulation. Heat transfer between the heating element and the body would also need field trials to find the optimum mix of element temperature and clothing layer properties.

APPLICATIONS OF THERMALLY ACTIVE CLOTHING

Healthcare

Heat sources have long been used to treat various medical conditions. Examples include heat lamps, liniments, wax baths, short wave diathermy, vigorous massage and thermally active materials.

Developed countries are now combating increased elderly care costs through deployment of technological solutions. One such area is tele-medicine. This reduces health care costs through treatment of the patient in their own home. Thermally active clothing can be utilised to better control patient core temperature. On-body sensors can be integrated into the data capture and reporting infrastructure. These points are discussed in more detail in [24].

Arizant Temperature management systems [14] supply a range of thermally active garments and bed clothes for use in situations requiring active patient temperature control.

Symptoms of Reynaud's disease whereby blood flow to the extremities can vary abnormally causing large shifts in skin temperature can be eased using thermally active clothing.

Sport

North Face created the MET5 jacket [17] that utilises heating technology from Polartec. The added value being that far less clothing needs to be carried because one jacket can maintain comfort over a wide range of conditions.

There are many examples of ski boot and ski glove warming technology. Most utilise Li-ion batteries and heating elements [18].

Surfing wetsuits such as the RipCurl H-Bomb™ are available with built in heat sources [22].

General Purpose

General purpose clothing is available with heating sources. For instance the heated gilet from the high street Maplin store [19].

Heated motorcycle gloves and boots are another common application [20].

The Outlast™ phase change technology is widely available as under-blankets.

Industry

Diving in particular uses electrically heated clothing to maintain temperature in cold waters. [21].

OVERVIEW OF TECHNOLOGIES

The principal technologies utilised in thermally active clothing are described in this section.

Improved insulation

Substances with a high thermal resistance (R) can be used to give clothing increased insulating properties. This is just an extension of the traditional means of keeping a body warm, i.e. by wearing enough clothing. However, advanced substances may allow clothing with extremely good thermal insulation properties to be also lightweight and easy to wear. Advancements in this area may include developments of the "Aerogel" concept, but are not yet advanced enough for use in clothing.

Phase change materials.

When a substance changes phase from solid to liquid by applying heat energy, energy is absorbed in breaking the molecules free rather than in simply increasing the temperature (vibrational energy) of the molecules. Conversely, when cooling, energy is released as the molecules return to their solid configuration and bonds are formed. The effect can be utilized as an energy store. (analogous to pump-storage hydro-electricity or hybrid cars.) All substances will exhibit this effect at their melting point. A similar effect occurs at their boiling point.

If a substance with a melting point near to skin temperature is incorporated into clothing, then the body's excess heat can be absorbed by the substance as it changes phase. This absorption of heat is felt by the body as a cooling effect. (A similar effect is in play when the body sweats as the evaporating moisture causes a cooling effect). Conversely, if the body cools down below the melting point, then heat is returned by the substance as the substance cools.

This form of heating and cooling is accomplished entirely through direct thermodynamics and requires no electrical or other energy source, so its economics and convenience are likely to be attractive.

A notable phase change product is Outlast™ [12] which uses capsules of a paraffin based compound woven into the material to absorb excess heat by changing to a liquid phase or radiate heat when required by reverting to solid phase.

Work by Havenith [25] and others suggests that the technology could still be developed further to enhance the effectiveness of this approach.

Resistive heating elements

This traditional heating technology requires an electrical energy source and uses wires with sufficient resistance to generate heat as an electric current is passed. The most familiar application is a mains-powered electric blanket. Using this technique in clothing is a more recent innovation made possible by advancements in battery technology. Fine carbon filaments, or resistive wire are woven into the fabric, or added as additional layers.

It is this technology that this paper mostly concerns.

Polymers

Materials such as EXO²™ [13] are in development. These are very flexible, but also emit low infra red when passing a current. They are finding applications in work wear and healthcare. For instance, the Arizant patient thermal management systems [14].

INTEGRATION INTO BUILDING SYSTEMS

It is important to consider how the heated clothing will interact with the building control systems.

It is proposed that the heated clothing include an on-body temperature sensor. This is used to regulate heat output from the clothing element. However, outside of a certain range or “guard band”, this on body thermometer can also send a wireless signal to enable or disable the building heat source. The “guard band” ensures that body centric heating takes precedence (as it is more efficient) and also avoids instability. Note that more complex body sensing could be used such as forearm to hand temperature differentials [10]. Figure 2 gives flow diagrams for this type of control system. Figure 3 illustrates how the on-body sensors can control the central heating systems.

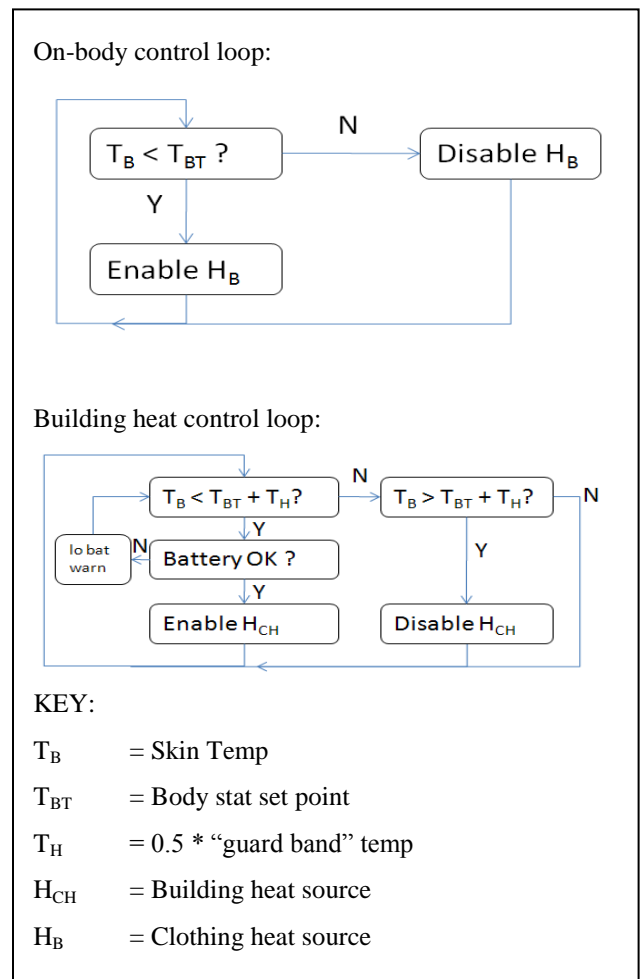


Figure 2 : Heating control loops

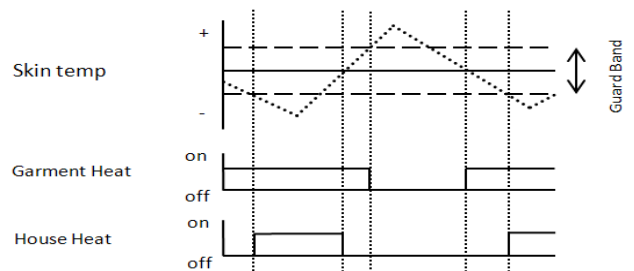


Figure 3 : Interaction of garment and building heat control

CONCLUSIONS AND FURTHER WORK

It has been shown that thermally active clothing can create significant CO₂ savings for single occupancy homes. Savings can equate to taking a car off the road for the average sized home.

Useful levels of cost savings are possible at today's Li-ion price points and cycle lives. Improvements in battery technology will only increase these in the future.

On top of the carbon benefits, there are considerable benefits for patient care, whereby closer control of the body temperature can be achieved.

The carbon and cost savings increase with the size of home occupied by a single person. Indeed for very large homes, savings will be achieved even with more than one occupant. Very large, inefficient house such as stately homes would be a big benefactor.

Field trials are required to verify this analysis. The effects of heated clothing versus ambient temperature levels versus comfort need to be measured in practise. Practical experimentation is required to optimize the ratio of R values of the clothing layers one and two. Optimum heating element location, shape and temperature needs further investigation.

Integration of on-body thermal controls and sensors with a wireless link to the home heating system is an area that warrants further exploration.

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