Title
Development of a Personal Heater Efficiency Index

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Development of a Personal Heater Efficiency Index

By

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Abstract
There is currently no quantitative method for evaluating the effectiveness and efficiency of personal heaters, which are commonly used in workplace situations to achieve thermal comfort. Instead, personal heaters are currently evaluated by their total energy use and heating method. We propose a new index and method of test by which efficiency of personal heaters may be calculated and assessed, taking into account both heating effectiveness and power use. This method was tested on a sample of 12 personal heaters, of various types: conductive, radiant, and convective. Each heater was tested in an environmental chamber, using a thermal manikin to quantitatively determine the amount of heat delivered to a subject. Heater location was standardized across the heaters prior to testing, so that all results are comparable. Results indicated that convective heaters were the least efficient, radiant heaters approximately twice as efficient, and conductive heaters 20 times more efficient than convective heaters. These results could indicate substantial possibilities for plug load savings or lower heating set points in new and existing office buildings.

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Symbols/Terminology

$h_{cal,i}$ = Heating coefficient for the calculation of the equivalent temperature (W/m^2K)
P_i = Heater power (kW)
$P_{s,i}$ = Power recorded by segment i of the manikin (W)
$t_{cal,i}$ = Equivalent temperature of the room (the calibration temperature) (°C)
t_{eq} = Equivalent temperature of the manikin (°C)
Δt_{eq} = Change in equivalent temperature with and without the personal heater (°C)
$t_{eq, ph\text{-}off}$ = Equivalent temperature measured when the personal heater is off (°C)
$t_{eq,ph\text{-}on}$ = Equivalent temperature measured when the personal heater is on (°C)
t_{sk} = Skin temperature of the manikin (°C)
$t_{sk,i}$ = Local skin temperature for segment (i) (°C)

CBE – Center for the Built Environment
HE – Heating Effect
HVAC – Heating Ventilation and Air Conditioning
PHE – Personal Heater Efficiency

1.0 - Introduction

Thermal comfort is an important factor to human health, well-being and productivity. Although there has been substantial research carried out on how different types of HVAC systems affect thermal control, there has been no peer-reviewed work carried out on personal heaters designed for individual use. ASHRAE Standard 55-2013 mandates thermal conditions in order to attain thermal comfort for at least 80% of occupants, leaving at worst 20% thermally dissatisfied [1]. In order to attain control over their personal thermal environments, many building occupants who feel cold use personal heaters [2]. As they are primarily based off of electric resistance heating, personal heaters contribute significantly to buildings' electric plug loads [3], which are becoming more crucial for the goal of attaining net zero energy as other systems become more efficient. The development of a personal heating efficiency index will allow customers, manufacturers, designers and policy makers to make informed, quantitatively based decisions regarding which personal heaters to buy and how they should be used while the goal of energy efficient buildings is pursued.

Real and perceived control over one's thermal environment has a substantial positive effect on the feeling of thermal comfort [4, 10], but most of the occupants of commercial buildings tend to have little control over their thermal environments [5]. Personal heaters address both of these issues, by allowing users to control their environment, and adjust it as they become accommodated to the current thermal sensation.

The primary purpose of this research is to: (1) develop a definition and method of classification of personal heaters; (2) Define a personal heater efficiency index and critically describe how it could be measured; (3) Experimentally test a selection of personal heaters and determine which type(s) of heaters are most efficient.

For the purpose of this study, personal heaters shall be defined as:

"Portable devices built to convert electrical energy to heat in order to provide thermal comfort to people while indoors."

Only electric personal heaters will be tested in this study. The heaters tested are low powered (less than or equal to 1500 W, as per UL 1278 [6]) heaters that are designed for indoor use. We classified heaters as falling into three categories, based on their main methods of heat transfer to the user: conductive, radiant, and convective (natural or forced-air), as shown in Table 1.

Table 1: Categories of heater technologies, along with the materials and methods most commonly used in making the heaters

Heater Type	Material
Conductive heater	**Any material safe to touch**
Relies on physical contact to transmit heat	Heat is delivered in low intensity to a material designed to distribute it across the user, usually by sitting or standing on the heater.
Radiant heater	**Aluminium**
Outputs 50% or more of its heat as radiant heat	Heat is distributed across a metallic panel (primarily aluminium) via conductive wiring
	Halogen lamp
	Halogen bulb is heated and emits short-wave radiation and light
	Quartz lamp
	Quartz infrared lamp is heated and emits short-wave radiation and light
Convective heater	**Micathermic**
Outputs less than 50% of its heat as radiant heat. Remaining heat is transferred by air currents using forced or natural convection.	Natural convection or fan-driven air (forced) over heated slab of mica. Also outputs considerable radiant heat.
	Heated oil
	Air movement driven by natural convection over heated oil contained in a metallic shell.
	Metallic coil
	Fan driven air over a heated metallic coil
	Ceramic
	Fan driven air over a heated ceramic plate

We defined the efficiency of a personal heater based on two factors: its heating effect (Δt_{eq}), and the amount of power from the heater necessary to produce that effect (P_i), as shown in Equation (1). Heating Effect (HE) in this scenario is related to the amount of heat that is produced by the heater and absorbed by the subject. The Heating Effect relates to the amount of temperature reduction that can be imposed on a space, in which a subject is using a personal heater, without changing his/her thermal sensation. Distance is not included as a factor in the efficiency due to the calibration for distance testing as described in Section 2.2. The personal heater efficiency index is closely related and resultant from the development and testing of the Cooling-Fan Efficiency Index by Schiavon and Melikov [11, 12]

$$Personal\,Heater\,Efficiency = \frac{Heating\,Effect}{Heater\,Power} = \frac{\Delta t_{eq}}{P_i} \quad (1)$$

In order to test personal heaters their thermal effects on users needed to be determined. The thermal conditions of an environment may be measured in one of four ways: a subjective human subjects test, a thermal manikin test, sensor testing, or a computer simulation. Each of these methods was analyzed to determine whether they would be accurate, give the results necessary to determine heater efficiency, and be feasible in price, both in the context of these tests and looking forward to the continuation of this work in industry. For the purposes of this study, it was determined that a thermal manikin would be the best tradeoff between accuracy and cost. Computer simulations are unlikely to model real world commercial heaters accurately, while human subjects are expensive and individual sensors give insufficient granular data for this analysis.

Heating effect of each heater was determined by calculating the change in equivalent temperature of the manikin between ambient conditions and while the heater was running. The equivalent temperature accounts for the effects of mean radiant temperature, air temperature, and air movement, and was attained by calibrating the manikin at a range of ambient temperatures (15-30 °C) and using equations (2) and (3).

$$h_{cal,i} = \frac{P_{s,i}}{t_{sk,i} - t_{cal,i}} \quad (2)$$

$h_{cal,i}$ = Heating coefficient for the calculation of the equivalent temperature (W/m^{2}K)

$P_{s,i}$ = Power recorded by segment i of the manikin (W)

$t_{sk,i}$ = Skin temperature of segment i of the manikin (°C)

$t_{cal,i}$ = Equivalent temperature of the room (the calibration temperature) (°C)

This factor may then be used to calculate equivalent temperature during further experiments in which radiant temperature and air velocity are not controlled using (3).

$$t_{eq}=t_{sk}-\left(\frac{P_{s,i}}{h_{cal,i}}\right) \quad (3)$$

t_{eq} = Equivalent temperature of the manikin (°C)

We defined and calculated the Heating Effect of each heater using (4).

$$Heating\ Effect\,(HE)=t_{eq,ph-on}-t_{eq,ph-off}=\Delta t_{eq} \quad (4)$$

2.0 – Method of test

Twelve personal heaters were evaluated in this study. Heaters were selected based on their popularity in online retailers and from a variety of manufacturers. Most importantly, they were chosen such that they covered all previously discussed categories (conductive, radiant, convective). The experiments were carried out at the environmental chamber at the Center for the Built Environment (CBE), University of California, Berkeley. Experiments were conducted in controlled environmental conditions, measuring temperature, humidity, and air velocity within the space. Each personal heater was set up to heat the thermal manikin and left undisturbed until a steady state condition (see definition in 2.3) had been achieved in the manikin.

In practice, the amount of heat delivered to a subject is dependent not only on the power of the heater, but also on the method by which the heat is delivered (convective, radiant, or conductive), air speed field, view factor of the subject to the heater, positioning of the heater (angle and distance to the subject), body posture, clothing insulation and distribution, air temperature and humidity. The use of a thermal manikin maintains subject consistency in all tests, while environmental consistency was obtained by performing tests within an environmental chamber. By maintaining a constant room temperature in the environmental chamber the heater's ability to improve comfort by increasing the overall temperature of the space surrounding the subject was not tested. This is so that the size and dimensions of the room are negligible to the final result, making the test repeatable elsewhere and applicable to any space.

In these tests a segmented, 16-zone thermal manikin developed by PT Teknik (Denmark) was used to monitor heat output by the heaters. The manikin was fully calibrated as per the manufacturer guidelines prior to the study and the clothing insulation value was determined using the method discussed in detail in Lee, Zhang, & Arens, 2013 [7]. For this study the manikin was clothed in standard office worker attire and seated at a high backed rolling desk chair. The thermal manikin was heated by maintaining a constant 55 W/m^2 of power delivered to each body segment throughout each test of the study).

Table 2: Manikin sections and the size of each section relative to the entire manikin. Additionally, the manikin has been split into four multi-bodypart segments: Lower body, Upper body, Extremeties, and Core

Body Part	**Lower Body**	**Upper Body**	**Extremities**	**Core**	**Area (m^2)**	**Fraction of whole**
Left Foot					0.043	0.029
Right Foot					0.041	0.028
Left Leg					0.089	0.061
Right Leg					0.089	0.061
Left Thigh					0.16	0.109
Right Thigh					0.165	0.112
Pelvis					0.182	0.124
Head					0.1	0.068
Left Hand					0.038	0.026
Right Hand					0.037	0.025
Left Arm					0.052	0.035
Right Arm					0.052	0.035
Left Shoulder					0.073	0.050
Right Shoulder					0.073	0.050
Chest					0.144	0.098
Back					0.133	0.090
Total					**1.471**	**1.000**

The CBE environmental chamber (Figure 1A) measures 5.5 m × 5.5 m × 2.5 m, controlling temperature to an accuracy of ±0.2 °C, and RH ±3 % [8]. The chamber has windows on two sides, South and West. The windows are well shaded by fixed external shades and by internal venetian blinds. The windows temperature is controlled by a dedicated air system. The temperature of the inner glass pane is controllable and was kept isothermal with the interior. Before testing, the thermal manikin was seated at a desk in the center of the chamber. On two sides of the chamber curtain/cloth walls were hung in a double layer, with approximately 0.5 m of space between layers, behind which the researchers sat. The double-layer curtain walls prevented any unwanted radiant heat from reaching the manikin. Additional space heaters were also set up behind the curtain walls, and were switched on as necessary in order to maintain a constant load within the chamber of approximately 2000 W. An array of fans was set up behind the curtain walls to distribute air through the room and prevent temperature stratification, while minimizing air movement at the manikin. Approximately 2/3 of the under floor air distribution (UFAD) air vents were shut so that air coming from the remaining ones would move faster and rise higher, enhancing mixing.

Air speed and temperature near the manikin were measured by an AirDistSys 5000 global anemometer (SENSOR Electronic, Poland) set arranged at heights of 0.1, 0.6, 1.1, and 1.8 m near the manikin but not within the direct influence of the heater. Room temperature was also measured by temperature thermocouples attached to a Hobo U12-006 4-channel data logger (Onset, USA). These thermocouples were also arranged at heights of 0.1, 0.6, 1.1, and 1.8 m, but further from the manikin, and confirmed at the conclusion of each test using a mercury bulb thermometer. Heater power was recorded by a WattsUp Pro plug load meter (Vernier, USA) every minute.

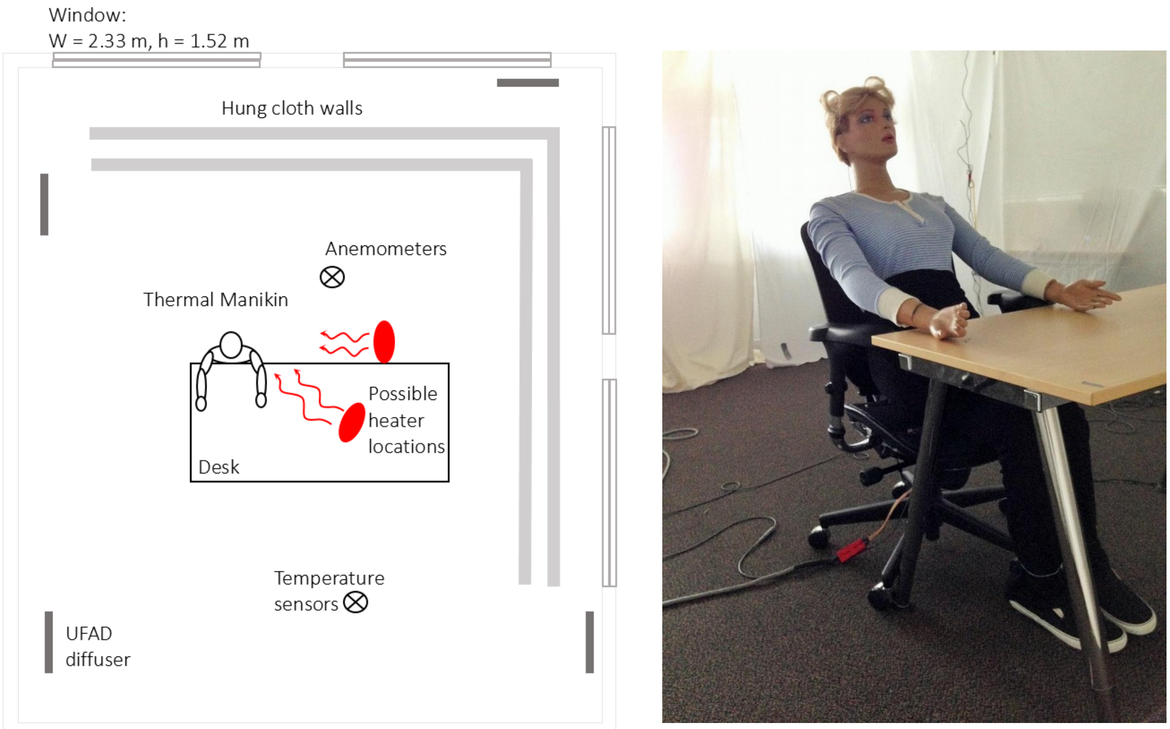


Figure 1: (A) CBE Environmental chamber and experimental setup. (B) Thermal manikin set up as used in experiments.

2.1 - Chamber Conditions

All heater experiments were carried out with the environmental chamber set to an operative temperature of 18 °C and 50% RH. The manikin was clothed such that the insulation provided by the clothing and chair was calculated to be 0.71 clo. Operative temperatures of 22, 20, and 18 °C were tested and it was determined that 18 °C provided the clearest signal and was a realistic scenario for heaters to be used in.

2.2 – Heater Distance/Angle Determination

The effectiveness of heaters upon an individual is heavily influenced by the distance across which they must transmit heat and the viewable area of the individual by the heater. To make the PHE index comparable across all heaters tested the distances and angles must be standardized. We decided to orient heaters in the manner that they were most likely to be used, so that results are relatable with actual use conditions. However, in order to make results comparable the heaters were oriented identically depending upon their vertical location. Heaters designed to be placed on top of desks were oriented at a 45° angle relative to the thermal manikin. Heaters designed for floor use were placed 90° to the left of the thermal manikin, pointed directly at its side/legs. Heaters designed to use conductive heat or with a specific placement necessary (such as the seat warmer) were placed at the locations they were designed to be used in.

The determination of the heater distance from the manikin is crucial for comparability between heaters and repeatability of tests. Two options are possible in order to make results comparable between heaters: either maintaining a set distance for all tests between the manikin and heater, or determining the distance at which a predetermined temperature may be achieved. Temperature limitations of the thermal manikin restricted the maximum temperature to 50 °C before risking malfunctions, inaccurate temperature readings, or damage to the hardware. Maintaining a constant distance could cause the most effective heaters to heat sections of the manikin beyond this level, or the less effective heaters to not heat the manikin at all. All personal heaters decrease in effectiveness as distance is increased. If the “set distance” to the manikin were beyond the limit of the space heater it would appear to have a personal effectiveness of zero even though it is creating heat. In order to attain an effectiveness rating there must be a measurable heat gain in the manikin when the heater is powered on.

Rather than set a standard distance for all heaters to be tested at, a minimum acceptable use distance was determined for each non-conductive heater individually (Table 3) such that a grey globe thermometer split in half (Figure 2A) achieved “comfortable heating temperature”. This temperature, 38 °C (100 °F), was determined by us to be the point prior to the pain threshold at which significant heat was felt from the heater. This measurement technique took into account both radiant and convective heat being produced by the heater, without allowing radiant heat or airflow around the back of the globe to be a factor, thus making only the heat coming directly from the heater to the thermometer a factor.

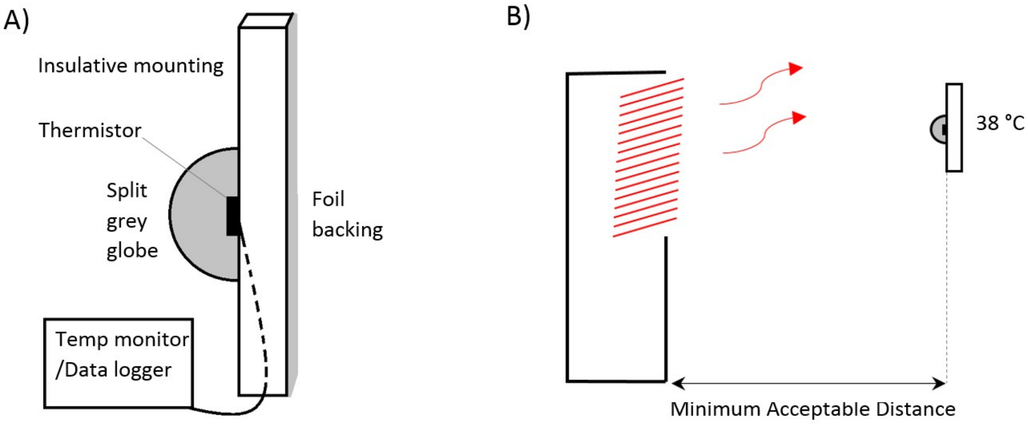


Figure SEQ Figure * ARABIC 2: (A) Split globe thermometer, made of half a grey globe mounted on a wood backing with foil on the rear, within which a thermistor connected to a data logger records temperature. (B) The minimum acceptable distance a given heater may be used, calculated as the horizontal distance from the heater at which the split globe thermometer

2.3 - Testing

Tests were carried out only after the thermal mass in the chamber had equilibrated to 18±0.2 °C, due to the 0.2 °C level of accuracy in the chamber setpoint. The thermal manikin and heater were run together and the temperature of the thermal manikin monitored until steady state was achieved, defined in this study as less than 0.2 °C variation in the body temperature over a 10 min period, with a minimum of 40 min testing time, to ensure that the thermal mass of the manikin reached steady state. Air speeds never exceeded 0.2 m/s. The sequence of tests, including identifiers, is given in Table 3. Identifiers were arranged by: [heating technology]-[heater number, of the given technology]-[power level]. The heating technology was shortened to "Cd" for conductive, "Ra" for radiant, and "Cv" for convective. Power levels were limited to low (L) or high (H). Products that only had one power setpoint were given the power identifier of "high". One product (conductive heater #3) was unable to be tested at its high setting due to overheating of the manikin, and so testing results are only available for the low setting. In analyzing the results of the tests, the final 10 min of results from each sensor were analyzed.

Table 3: Heaters tested and the label assigned to each test

Heater	Heater Type	Power Use (W)	Location	Distance (m)	Identifier
CBE Chair (low)	Conductive	11.0	Seat	0	Cd-1-L

CBE Chair (high)	Conductive	15.0	Seat	0	Cd-1-H
Cozy Products Heated Mat	Conductive	42.9	Floor	0	Cd-2-H
Amazon Basics Heated Seat Cushion	Conductive	40.9	Seat	0	Cd-3-L
CBE Foot warmer (low)	Radiant	84.7	Ground	0.05	Ra-1-L
CBE Foot warmer (high)	Radiant	154.1	Ground	0.05	Ra-1-H
Optimus 9-inch dish heater	Radiant	304.4	Desk	0.51	Ra-2-H
CBE Radiant Panel	Radiant	203.0	Ground	0.10	Ra-3-H
Sengoku Radiant Panel	Radiant	152.0	Ground	0.08	Ra-4-H
Soleus Air MS-09 (low)	Radiant	449.2	Desk	0.53	Ra-5-L
Soleus Air MS-09 (high)	Radiant	764.3	Desk	0.63	Ra-5-H
Crane EE-6490 (low)	Convective	822.2	Ground	0.61	Cv-1-L
Crane EE-6490 (high)	Convective	1216.7	Ground	0.71	Cv-1-H
MyHeat	Convective	206.6	Desk	0.23	Cv-2-H
Soleus Air HC7-15-01 (low)	Convective	775.2	Ground	0.45	Cv-3-L
Soleus Air HC7-15-01 (high)	Convective	1424.0	Ground	0.51	Cv-3-H
Bionaire Micathermic (high)	Convective	1482.5	Ground	0.33	Cv-4-H
Bionaire Micathermic (low)	Convective	11.0	Ground	0.25	Cv-4-L

3.0 – Results

12 heaters were tested for heating effect and efficiency using the thermal manikin method, at varying power level settings when possible, and given the identifier shown in Table 3. Additionally, tests Ra-5-H and Cv-1-H were repeated at varying distances and angles relative to the manikin in order to determine the effect of positioning upon heating effect and efficiency values. Finally, test Ra-5-L was repeated four times in order to determine whether this testing method produced consistent results.

3.1 – Heating Effect

Figure *3*A and 3B show the heater power and Heating Effect across the entire manikin and the power use of each heater (A) and of the heaters as grouped by heating type (B). While the average HE is mostly unrelated to power use within each heater type, and very similar for all three categories of heaters, the power use of conductive heaters is much lower than other types. The HE is almost the same because the heaters were designed with a target heating effect (not too weak, not too strong).

3.2 – Personal Heater Efficiency (PHE)

Figure 3C shows the overall heater efficiencies across the entire manikin body for each heater tested. The least efficient heaters were the convective, while the most efficient were the conductive heaters. Radiant heaters were approximately twice as efficient as convective and conductive heaters were 10-20 times more efficient than radiant and convective heater respectively. This is due to the power use of each type of heater; while convective heaters often required over 1000 W, radiant heaters used approximately 200-750 W, and the conductive heaters used only 11-15 W (~1% of many convective heaters). For all heaters that had a high and low setting, the high setting was slightly less efficient than the low setting.

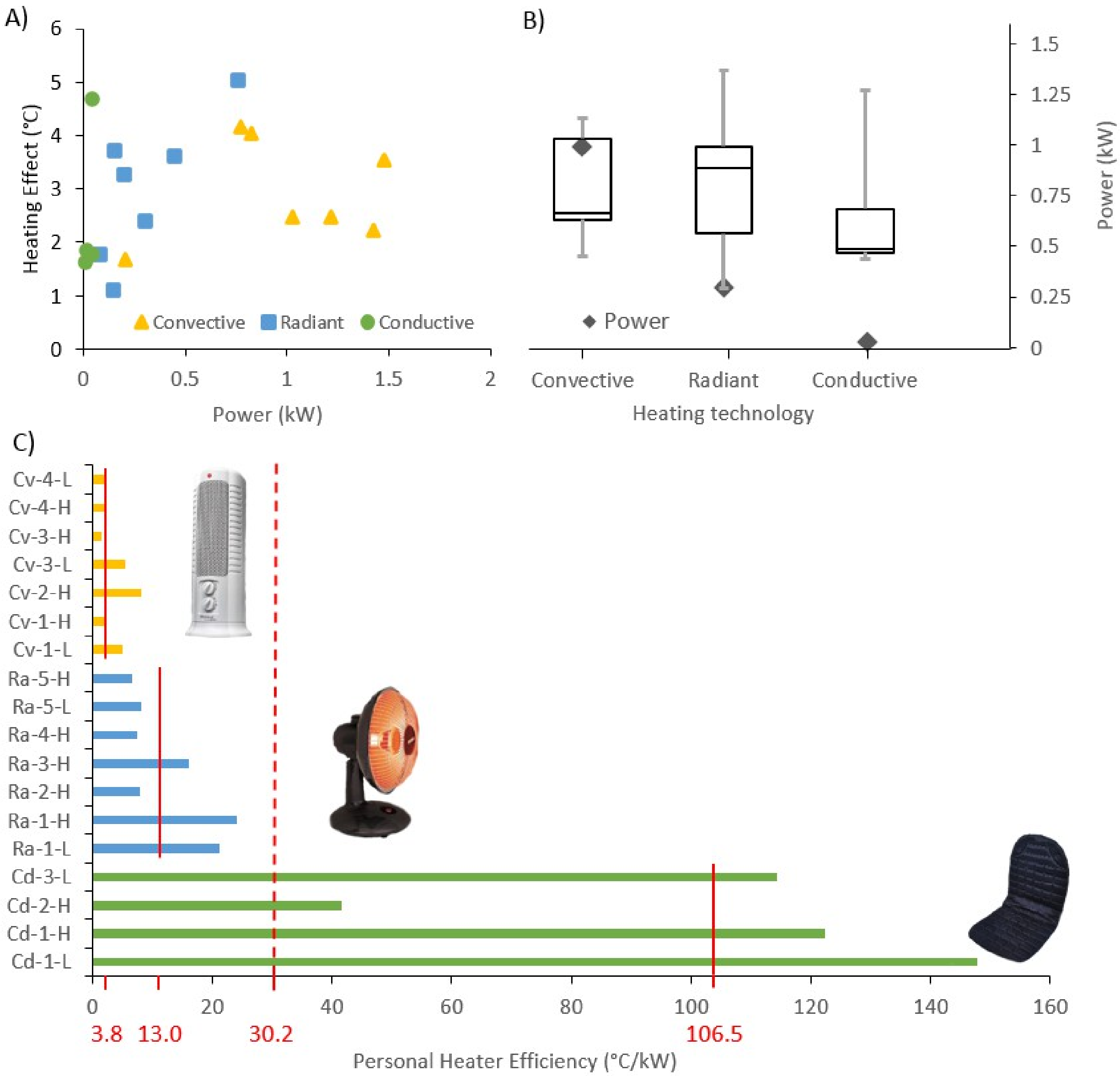


Figure 3: (A) Power against heating effect for all heaters tested, grouped by heater type. The range of heating effects is similar for all heater types, while power use tends to be higher for convective heaters and lowest for conductive. (B) Box plots of heating effect for each heater type, with the average power use of heaters in each category. (C) Calculated Personal Heater Efficiency value for all heaters tested, grouped by heater type. The solid vertical line within that category shows average efficiency for each category of heater type, while the dashed vertical line shows the overall average for all heaters tested.

3.3 – Heater distances

Figure 4 shows the distances at which convective and radiant heaters were tested as compared with their power output. Both data sets are too small for a statistically sound analysis of any regression, although a trend may be forming of increasing power in radiant heaters resulting in increasing distance.

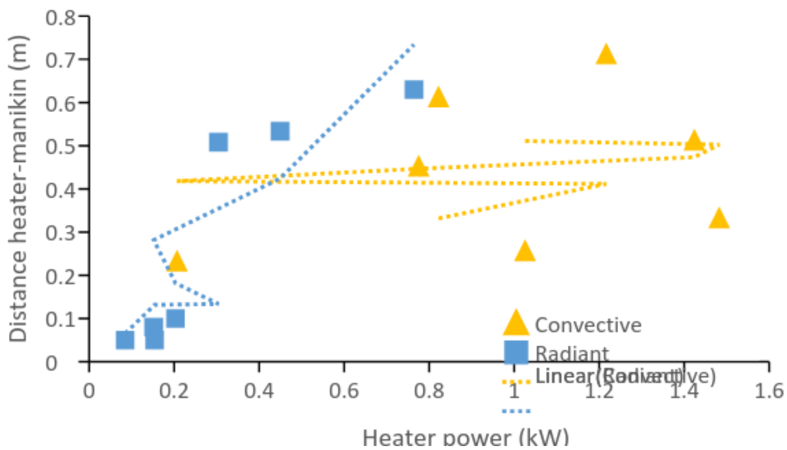


Figure 4: Distance between heater and manikin compared with the heater power. Heaters are grouped by heating technology used and only radiant and convective heaters are shown. Linear regressions for each category of heater are shown, in addition to their coefficient of determination.

3.4 – Chamber temperature and air movement

A typical set of results of temperature sensors and anemometers are shown in Figure 5. Temperature sensors indicated that temperatures were slightly higher (0.5 °C) at the location of the manikin compared to the room due to radiant heat from the manikin. Despite the use of fans, there was slight vertical temperature stratification in the chamber (approximately 1 °C), which was determined to be unavoidable given the underfloor air distribution system and the use of the heater. Average air movement over a period of 10 min in which the manikin had attained steady state while being heated remained at or below 0.1 m/s, while the maximum air velocity at these locations never reached 0.2 m/s.

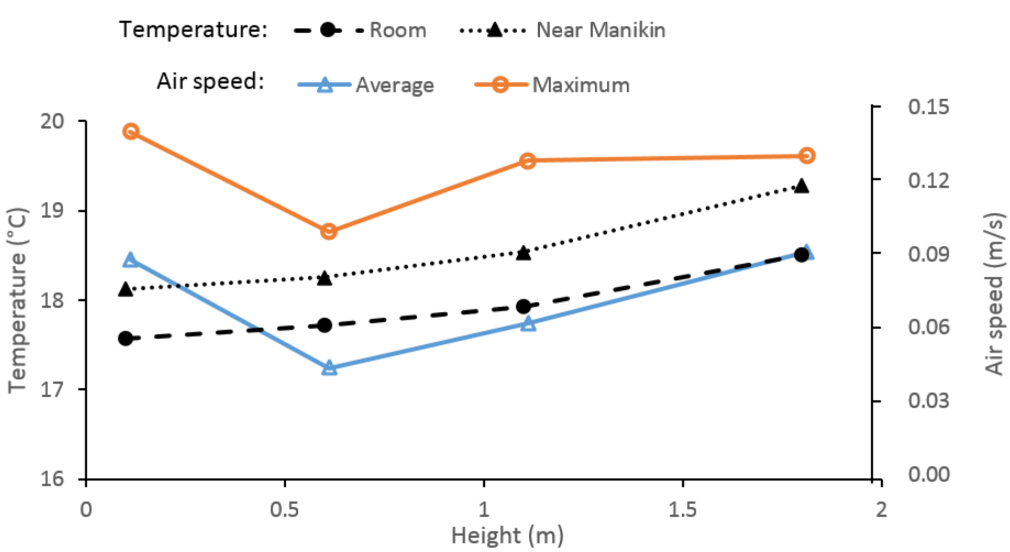


Figure SEQ Figure * ARABIC 5: Typical temperatures and air movement during heater testing at standard heights

3.5 – Temperature spread

The temperature spread across the manikin was evaluated for each personal heater, shown in **Figure 6**, to determine commonalities between heater types and locations. The highest disparities of temperature spread (difference between maximum and minimum temperatures recorded by the manikin) were among radiant heaters due to their directional heat output. For all heaters except the convective heaters the high setting resulted in a larger temperature spread. In convective heaters, however, the low setting resulted in a larger temperature spread, likely due to the low airflow only affecting the body section nearest the heater, whereas at a high setting there is sufficient airflow to more fully envelop the manikin.

These results were analyzed more thoroughly, evaluating the HE on specific body regions of the manikin and whether some regions were heated disproportionately based on the heater characteristics. For example, heater Cv-4 focuses much more heat upon the lower body than anywhere else. This is due to it being a floor-based, micathermic heater, and as such delivers a larger component of directed radiant heat than other floor-based convective heaters. Similarly, there is a more startling contrast across the left and right sides of the body for ground-based radiant heaters (Ra-1, Ra-3, and Ra-4) compared with ground-based convective heaters (Cv-1, Cv-3, and Cv-4). Among the conductive heaters, Cd-1 and Cd-3 indicated almost no HE in the extremities, while Cd-2 only heated the extremities. Since conductive heaters are designed to only heat body parts directly in contact with them, the heated seats (Cd-1 and Cd-3) were incapable of heating the hands and feet, while the heated floor mat (Cd-2) only heated the feet.

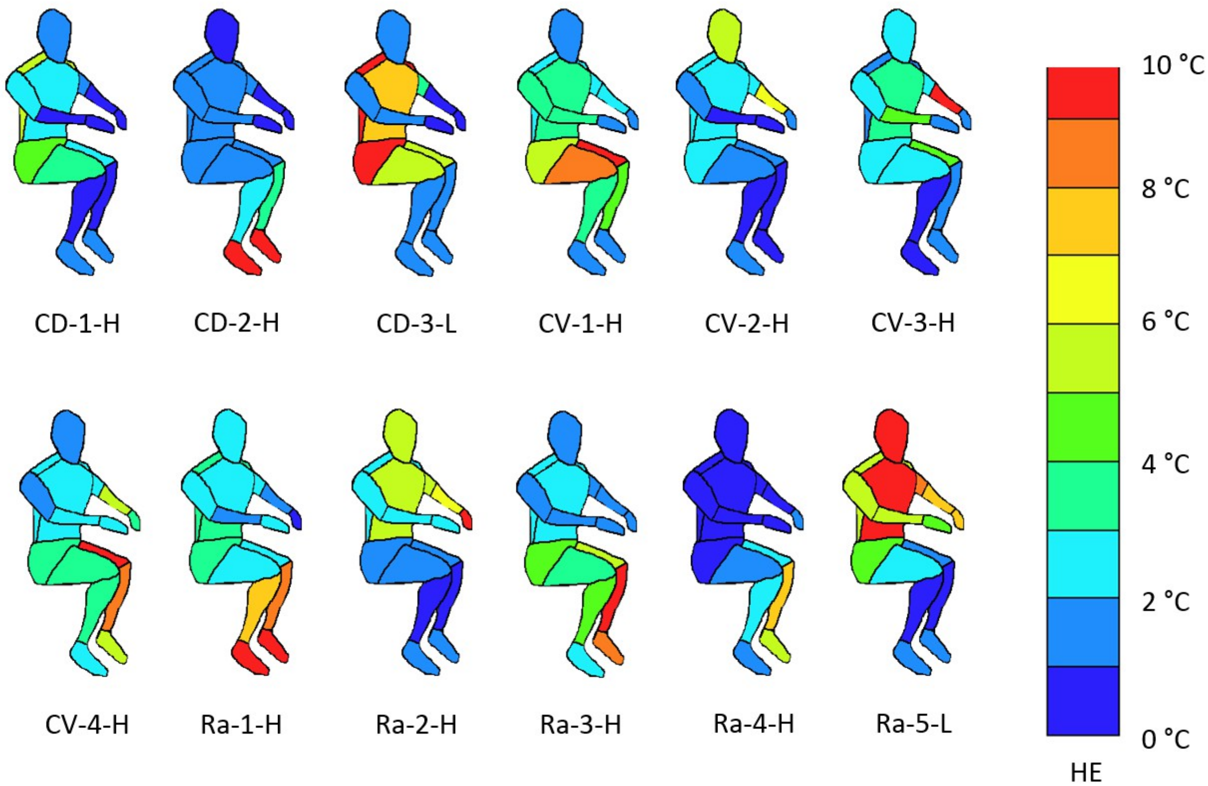


Figure 6: Temperature spread across the manikin for all heaters. Color scale is based Heating Effect (HE). Higher temperature manikin sections are being heated by the PH, either directly or indirectly.

3.6 – Distance and angle testing

In order to determine the effects of varying heater positions, distance and angle were individually examined as shown in Figure 8. Each series of distance and angle tests was carried out with one representative convective heater (Cv-1-H) and one radiant heater (Ra-5-H). The results are given in Figure 7 A-D.

Results of angular variation testing are given in Figure 7 A-B. The radiant heater was shown to be most effective at 45°, partially due to the heater having more sight of the manikin's arms than when directly facing the manikin, and partially to some of the heat reach the back of the manikin. The convective heater was most effective at 90°, perpendicular to the direction in which the manikin faced. This is likely due to this being the angle at which the entire left leg was being blown on by the heater, while the heater also warmed the desk bottom, which in turn radiated heat down onto the thighs of the manikin.

Results of distance variation testing are given in Figure 7 C-D. Heaters tended to decrease in efficiency as they were moved away from the manikin, although there was a slight increase at the maximum distance of the radiant heater. At this distance very little heat was reaching the manikin, and so this increase in efficiency may have been due to sensor drift or because at this distance the radiant heat began to heat the desk, which in turn radiated heat to the legs of the manikin.

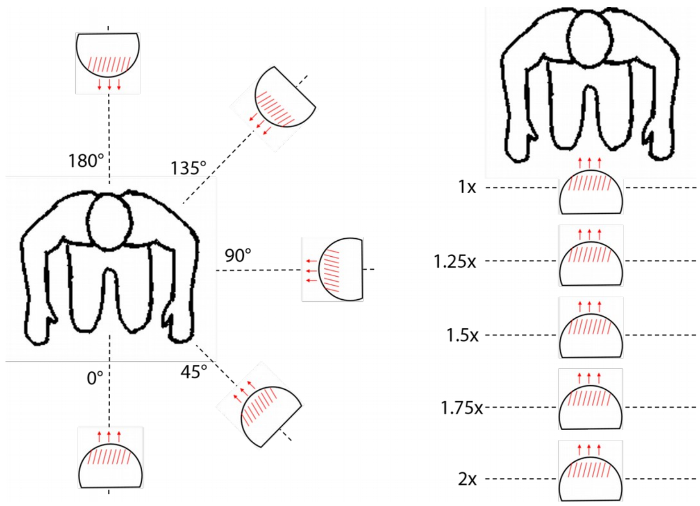
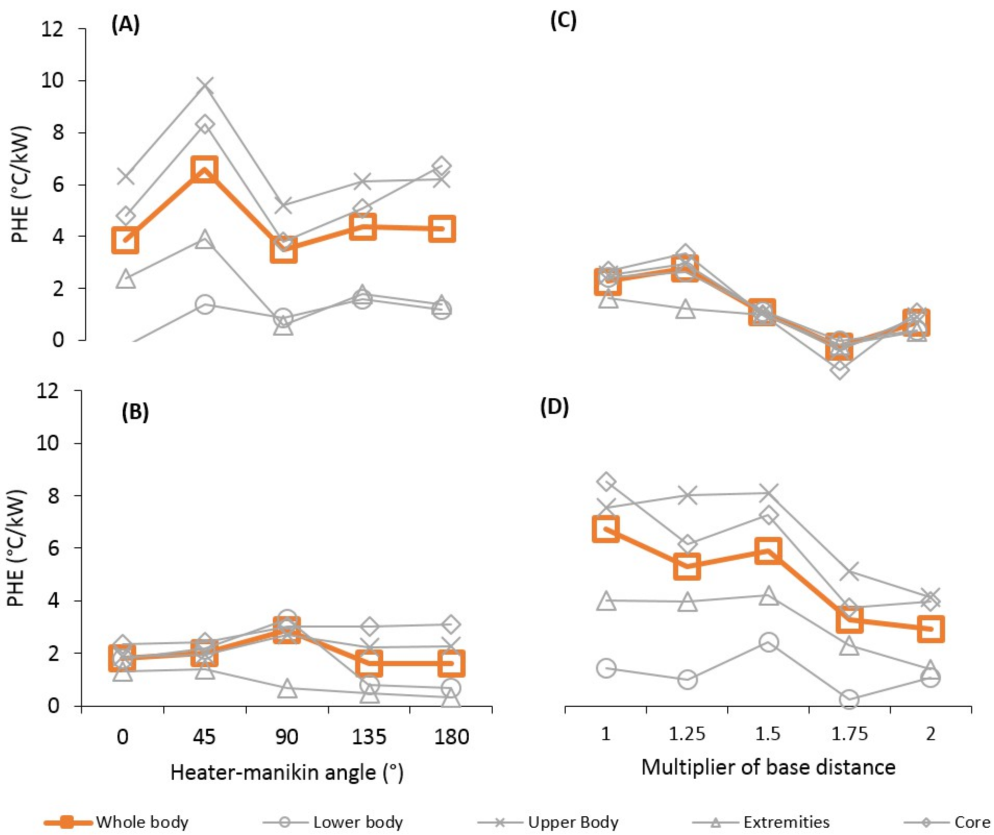


Figure 8: Distance and angle testing locations. Heaters were tested at angles (shown on the left) ranging from 0° (directly in front of the manikin) to 180° (directly behind manikin) in 45° increments. Distances (shown on the right) were tested as multipliers of the original distance tested, ranging from 1x to 2x (double) the distance, in 0.25x increments. Distances were tested using the angle from which the given heater was originally tested.

Figure SEQ Figure * ARABIC 7: PHE from various angles, ranging from directly in front of the manikin (0°) to directly behind the manikin (180°) in 45° increments due (A) to radiant heater Ra-5-H and (B) to convective heater Cv-1-H. PHE due (C) to radiant heater Ra-5-H and (D) to convective heater Cv-1-H from various distances, ranging from the base distance (0.63 m and 0.71 m, respectively) to double that distance (1.26 m and 1.42 m, respectively), in 25% increments. The overall PHE is shown



3.7 – Repeatability

In order to determine whether this testing method and efficiency calculation resulted in reliable, repeatable results, a randomized personal heater (Ra-5-L) was tested four consecutive times. Each test was run identically, with the manikin and the room being allowed to return to their non-heated temperature between tests. As seen in Figure 9, the standard deviation of calculated efficiency results across the four tests was less than 1.25 °C/kW for all manikin body segments and regions (as split according to Table 2), with two notable exceptions: the left hand and the head. This consistency in deviation persisted regardless of the absolute value of the calculated efficiency or the size of the body part or region.

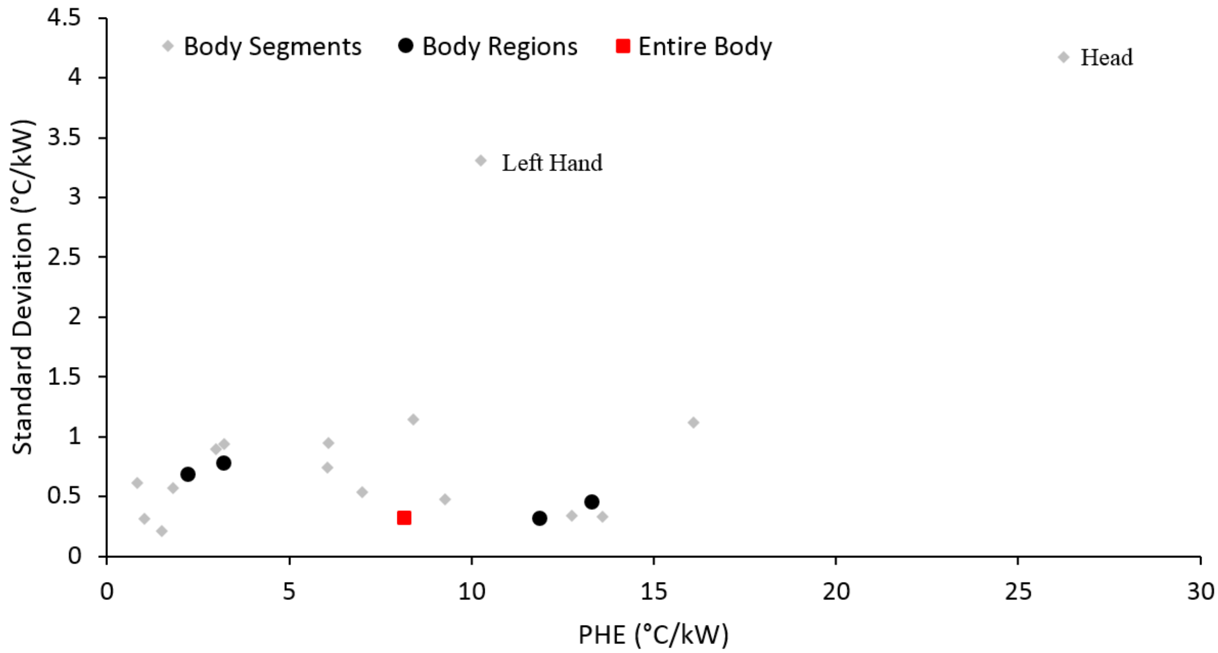


Figure 9: Standard deviation of PHE across 4 repeated tests versus the average PHE for all manikin sections, manikin regions (lower body, upper body, extremities, and core), and the entire manikin. In general, variability as a percentage decreases as the PHE increases, indicating a relatively consistent absolute variability in PHE. Two body segments, the left hand and the head, had unusually high absolute variabilities in PHE and are marked on the chart.

4.0 – Limitations and Uncertainty

Results analysis of this study is primarily limited by the sample size of heaters selected and tests conducted. The 12 heaters selected result in only 4-7 tests of each heater type. More heaters and additional testing would result in more accurate results and a better understanding of the statistical spread. Based on instrumental imprecisions the calculated uncertainty of the PHE of most heaters tested was less than 5%. However, due to the inaccuracy of the power meter used and low power use, conductive heaters had possible errors in calculated efficiency of 6.8%-26.6%.

5.0 – Discussion & Conclusions

The control of the personal environment in the workplace through the use of personal heaters does not have to be at odds with the goal of reductions in plug loads and achieving extremely low energy performance in existing buildings. Based on the tests presented in this paper, heaters that rely on physical contact to transmit heat are approximately 20 times more energy-efficient than convective heaters, and over 10 times more compared to radiant heaters. A transition toward use of these heaters has the potential to save up to 95% of the energy currently used on personal heaters (assuming the standard personal heaters used are convective), and allow buildings to reduce their heating setpoint during winter months by approximately 2 °C. In the analysis performed by Hoyt et al. it was determined that in San Francisco reducing the heating setpoint by 2 °C could result in energy savings of approximately 25% [9]. This number would likely only increase in cooler climates.

Unfortunately, an immediate transition to widespread use of conductive heaters is not feasible. However, based on the results shown in Section 3.6 – Distance and angle testing, it is feasible to orient the convective and radiant heaters that are commonly in use in an ideal manner. By situating the heater at an appropriate distance and angle to provide the maximal efficiency in heat transfer to the user, based on the type of heater being used, users could use a lower power setting or keep the heater on for shorter periods during the day. Based on the results shown in these sections angular orientation can improve heater efficiency by approximately 50% in both radiant and convective heaters, while distance should be kept at the minimum possible while maintaining comfort (without reaching the discomfort threshold).

Further testing is recommended to refine this work. Radiant heat output of heaters should be measured so that they can be more precisely categorized [13]; the methodology and instrumentation for determining the distance at which heaters will be tested should be refined; and further testing should be carried out to determine whether a simplified array of sensors could be used in lieu of the thermal manikin.

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Appendices

Appendix A

Calculated Clothing Insulation Values

Table A44: Manikin clothing insulation values, separated from the insulation of the chair the manikin was seated upon

Body Section	Intrinsic Insulation of clothing (clo)
L. Foot	0.86
R. Foot	0.84
L. Low leg	0.56
R. Low leg	0.60
L. Thigh	0.47
R. Thigh	0.47
Pelvis	1.05
Head	0.37
L. Hand	-0.01
R. Hand	-0.02
L. Forearm	0.25
R. Forearm	0.23
L. Upper arm	0.35
R. Upper arm	0.36
Chest	1.34
Back	1.00
All	0.56

Appendix B

Chamber Conditions During Heater Testing

Table B1: Average air speed measured during tests of personal heaters near the manikin at heights of 0.1m, 0.6m 1.1m and 1.8m

Test ID	Height = 0.1m	Height = 0.6m	Height = 1.1m	Height = 1.8m

	Avg air speed (m/s)	Avg air speed (m/s)	Avg air speed (m/s)	Avg air speed (m/s)
Cd-1-L	0.14	0.14	0.13	0.15
Cd-1-H	0.13	0.11	0.11	0.13
Cd-2-H	0.20	0.13	0.10	0.12
Cd-3-L	0.33	0.15	0.12	0.12
Ra-1-L	0.02	0.04	0.07	0.09
Ra-1-H	0.12	0.13	0.12	0.19
Ra-2-H	0.10	0.06	0.07	0.10
Ra-3-H	0.03	0.04	0.03	0.05
Ra-4-H	0.09	0.04	0.06	0.09
Ra-5-L	0.10	0.14	0.12	0.10
Ra-5-H	0.06	0.03	0.06	0.12
Cv-1-L	0.14	0.09	0.10	0.10
Cv-1-H	0.04	0.08	0.13	0.11
Cv-2-H	0.04	0.03	0.03	0.09
Cv-3-L	0.07	0.06	0.09	0.10
Cv-3-H	0.10	0.08	0.08	0.08
Cv-4-H	0.10	0.10	0.07	0.07

Table B2: Average air temperature measured during tests of personal heaters near the manikin at heights of 0.1m, 0.6m 1.1m and 1.8m

Test ID	**Height = 0.1m** **Temp near manikin (°C)**	**Height = 0.6m** **Temp near manikin (°C)**	**Height = 1.1m** **Temp near manikin (°C)**	**Height = 1.8m** **Temp near manikin (°C)**
Cd-1-L	18.05	18.31	18.76	19.22
Cd-1-H	18.05	18.45	18.73	19.21
Cd-2-H	17.95	18.21	18.27	18.43
Cd-3-L	17.65	17.99	18.31	18.27
Ra-1-L	18.09	18.51	18.57	18.47
Ra-1-H	18.74	19.06	19.62	19.80
Ra-2-H	18.13	18.25	18.54	19.28
Ra-3-H	17.93	18.11	18.28	19.33
Ra-4-H	18.11	18.25	18.31	18.92
Ra-5-L	18.67	18.67	18.80	19.09
Ra-5-H	19.32	19.35	19.63	20.71
Cv-1-L	18.14	18.85	19.25	19.70
Cv-1-H	19.48	19.76	19.74	19.78
Cv-2-H	18.05	18.10	18.19	19.25
Cv-3-L	18.29	18.50	19.03	19.91
Cv-3-H	17.66	17.92	18.11	19.30
Cv-4-H	18.63	18.64	18.89	19.79

Table B3: Average air temperature of the environmental chamber (away from the manikin), as measured during tests of personal heaters at heights of 0.1m, 0.6m 1.1m and 1.8m

Test ID	**Height = 0.1m** **Reference Room Temp (°C)**	**Height = 0.6m** **Reference Room Temp (°C)**	**Height = 1.1m** **Reference Room Temp (°C)**	**Height = 1.8m** **Reference Room Temp (°C)**
Cd-1-L	18.27	18.66	18.95	18.97

Cd-1-H	18.37	18.71	19.08	19.05
Cd-2-H	17.97	18.02	18.09	18.15
Cd-3-L	17.92	17.90	18.06	18.16
Ra-1-L	17.68	17.89	18.01	18.00
Ra-1-H	18.79	19.45	19.83	19.79
Ra-2-H	17.57	17.72	17.92	18.51
Ra-3-H	17.56	17.88	17.91	18.18
Ra-4-H	17.67	17.82	18.13	18.63
Ra-5-L	18.15	18.78	19.45	19.62
Ra-5-H	18.65	18.93	19.35	19.84
Cv-1-L	17.76	18.01	18.44	19.08
Cv-1-H	18.74	19.04	19.22	19.27
Cv-2-H	17.60	17.93	18.02	18.15
Cv-3-L	17.78	18.06	18.10	18.86
Cv-3-H	17.66	17.92	18.11	19.30
Cv-4-H	17.81	18.22	18.78	19.07

Appendix C

Manikin Measured Temperatures

Table C1: Manikin skin temperature at steady state conditions during testing of conductive heaters

Manikin Body Section	$t_{sk,i}$ (°C)			
	Cd-1-L	Cd-1-H	Cd-2-H	Cd-3-L
L. Foot	28.33	28.20	41.30	28.90
R. Foot	28.04	27.90	40.00	28.50
L. Low leg	26.97	26.70	29.60	27.90
R. Low leg	27.25	26.93	29.42	27.80
L. Thigh	28.18	28.42	27.41	31.40
R. Thigh	28.20	28.84	27.02	30.90
Pelvis	30.85	31.65	29.35	38.50

Head	26.85	27.09	25.68	26.75
L. Hand	22.89	22.61	24.01	23.38
R. Hand	23.78	24.00	24.01	23.97
L. Forearm	25.36	25.11	25.80	25.58
R. Forearm	24.92	25.05	25.50	25.36
L. Upper arm	28.09	27.89	27.80	30.60
R. Upper arm	28.20	28.34	27.07	27.70
Chest	31.15	31.35	30.09	35.64
Back	32.51	33.11	29.41	41.90
All	28.45	28.65	28.61	31.49

Table C2: Manikin skin temperature at steady state conditions during testing of radiant heaters

Manikin Body Section	$t_{sk,i}$ **(°C)**						
	Ra-1-L	**Ra-1-H**	**Ra-2-H**	**Ra-3-H**	**Ra-4-H**	**Ra-5-L**	**Ra-5-H**
L. Foot	37.99	45.91	28.24	36.13	32.46	28.30	28.50
R. Foot	37.38	45.01	27.60	29.34	28.43	27.85	28.30
L. Low leg	31.17	35.32	27.30	39.00	33.63	27.44	27.10
R. Low leg	31.22	34.74	27.60	30.90	28.92	27.80	27.70
L. Thigh	26.56	27.99	27.05	30.64	27.69	27.70	27.34
R. Thigh	26.97	28.20	26.71	29.33	27.14	27.70	27.85
Pelvis	29.41	30.74	29.37	32.18	28.34	30.73	31.80
Head	25.20	27.64	30.90	26.30	25.56	35.77	43.30
L. Hand	23.80	24.18	32.33	24.38	24.30	29.54	30.30
R. Hand	25.10	25.34	25.58	24.37	23.90	26.01	27.39
L. Forearm	26.20	26.55	31.88	26.35	25.85	30.97	32.78
R. Forearm	25.90	25.80	26.40	25.52	25.01	28.80	29.69
L. Upper arm	27.65	28.61	31.74	28.20	27.20	32.80	34.71

R. Upper arm	27.51	28.41	28.17	27.49	26.73	29.60	31.15
Chest	30.16	31.32	34.13	31.10	29.11	36.40	39.62
Back	29.63	31.05	30.98	30.61	28.69	32.41	33.65
All	28.61	30.52	29.23	30.10	27.94	30.44	31.85

Table C3: Manikin skin temperature at steady state conditions during testing of convective heaters

Manikin Body Section	$t_{sk,i}$ **(°C)**						
	Cv-1-L	**Cv-1-H**	**Cv-2-H**	**Cv-3-L**	**Cv-3-H**	**Cv-4-H**	**Cv-4-L**
L. Foot	28.81	29.67	28.16	28.79	28.20	33.11	30.63
R. Foot	28.00	29.10	27.55	27.93	27.38	29.39	28.54
L. Low leg	30.89	29.10	27.31	28.66	27.46	34.97	32.22
R. Low leg	29.80	29.34	27.60	28.62	27.30	30.13	29.50
L. Thigh	35.78	28.84	27.17	36.43	30.31	36.00	34.18
R. Thigh	33.91	29.52	26.97	33.93	28.24	29.14	28.40
Pelvis	32.72	31.06	30.01	34.81	30.06	31.01	30.38
Head	27.00	27.17	30.67	26.92	27.30	26.58	26.00
L. Hand	25.10	24.63	24.58	23.99	24.63	26.28	24.82
R. Hand	24.51	25.30	23.96	24.41	24.82	25.08	24.30
L. Forearm	27.66	27.20	31.58	29.00	34.50	30.16	28.47
R. Forearm	27.97	26.76	25.05	27.53	28.57	26.48	25.70
L. Upper arm	29.30	28.77	29.40	30.21	29.33	29.30	27.91
R. Upper arm	29.47	28.87	27.18	28.84	28.68	27.40	26.70
Chest	31.98	31.79	31.10	32.09	31.50	30.83	30.04
Back	30.82	31.40	30.41	30.98	30.04	30.21	29.43
All	30.87	29.28	28.50	30.98	29.05	30.38	29.29

Appendix D

HEF Variability and Error Analysis

Table D1: HEF test variability analysis, across four repetitions of Test Ra-5-L

Manikin Body Section or Region	Test 1 HEF (°C/kW)	Test 2 HEF (°C/kW)	Test 3 HEF (°C/kW)	Test 4 HEF (°C/kW)	Average HEF (°C/kW)	HEF Max Deviation (°C/kW)	HEF Max % Variability
L. Foot	1.78	1.34	1.55	1.34	1.50	0.45	25%
R. Foot	2.61	1.83	1.59	1.27	1.82	1.33	51%
L. Low leg	1.36	1.18	0.88	0.65	1.02	0.71	52%
R. Low leg	1.56	1.11	0.44	0.22	0.83	1.34	86%
L. Thigh	3.94	3.50	1.94	2.59	2.99	2.00	51%
R. Thigh	4.30	3.67	2.32	2.54	3.21	1.98	46%
Pelvis	7.28	6.30	5.10	5.60	6.07	2.18	30%
Head	22.92	22.39	30.25	29.45	26.25	7.86	26%
L. Hand	13.32	12.91	7.82	7.01	10.27	6.31	47%
R. Hand	5.63	5.43	7.09	6.09	6.06	1.66	23%
L. Forearm	12.70	12.40	13.21	12.72	12.76	0.81	6%
R. Forearm	9.58	9.13	7.73	7.14	8.40	2.43	25%
L. Upper arm	13.79	13.11	13.70	13.82	13.60	0.71	5%
R. Upper arm	7.68	7.01	7.00	6.36	7.02	1.32	17%
Chest	17.46	16.56	15.09	15.27	16.10	2.37	14%
Back	9.69	8.59	9.35	9.49	9.28	1.10	11%
Lower Body	3.04	2.56	1.61	1.74	2.10	1.43	47%
Upper Body	4.17	3.53	2.50	2.69	3.03	1.67	40%
Extremities	13.33	12.69	13.78	13.42	12.99	1.09	8%
Core	12.29	11.53	11.91	11.79	11.57	0.75	6%
All	8.64	8.06	7.98	7.99	8.17	0.66	8%

Table D2: Instruments used for the study and instrumental precision

Instrument	Count	Accuracy
PT Teknik Thermal Manikin	1	1%
Split globe thermometer	1	0.25 °C
Hobo temperature sensors	4	0.25 °C
WattsUp 57777 power meter	1	1.8%
AirDistSys 5000 global anemometer	4	0.02 m/s + 1% of reading

Table D3: Calculated percent uncertainty (95% certainty) of the PHE of all heaters tested. Uncertainty was calculated based on the calculated personal heater efficiency and accuracy of instrumentation and measurements taken.

Test ID	Instrumental Uncertainty (95%)	Combined Instrumental and PHE Uncertainty (95%)
Cd-1-L	20.9%	26.6%
Cd-1-H	18.3%	19.5%
Cd-2-H	17.5%	6.8%
Cd-3-L	6.6%	7.4%
Ra-1-L	17.2%	3.5%
Ra-1-H	8.7%	1.9%
Ra-2-H	12.7%	1.0%
Ra-3-H	9.3%	1.5%
Ra-4-H	29.1%	1.9%
Ra-5-L	8.8%	0.7%
Ra-5-H	6.4%	0.4%
Cv-1-L	7.7%	0.4%
Cv-1-H	13.4%	0.2%
Cv-2-H	18.4%	1.4%
Cv-3-L	7.5%	0.4%
Cv-3-H	14.2%	0.2%
Cv-4-H	8.8%	0.2%