

Theoretical Prediction and Measurement of the Fabric Surface Apparent Temperature in a Simulated Man/Fabric/Environment System

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Aeronautical and Maritime Research Laboratory**

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ABSTRACT

Theoretical analysis is presented to predict the fabric surface apparent temperature in a simulated man/clothing fabric/environment system. The predicted outcomes have been validated by comparison with the experimental results using a sweating hotplate in an environmental chamber. An air gap of approximately 9mm between the fabric and the hotplate surface was found to be the optimum for controlling the fabric surface temperature. The apparent temperature of the fabric can match its surrounding objects by further adjusting its surface emissivity depending on the ambient temperature. A Disruptive Pattern Combat Uniform (DPCU) fabric was used in the experimental assessment of the theoretical predictions which were in good agreement with the theoretical predictions. A sweating hotplate with dry and wet states was also used to assess the influence of evaporative heat on the fabric surface temperature. No significant difference was found in the fabric surface apparent temperature between the dry and wet states.

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Executive Summary

The temperature difference between a clothed man and his surrounding objects can be easily detected and recognised by using a thermal camera. To thermally camouflage a clothed man, the apparent surface temperature pattern of the clothing fabric under a thermal camera should satisfy two criteria: these are temperature and spatial similarity to the surrounding natural objects. Temperature similarity can be achieved by either reducing the actual fabric surface temperature and/or reducing the fabric surface thermal emittance.

In this study, theoretical analysis has been used to predict the fabric surface apparent temperature in a simulated man/clothing/environment system. An air gap of approximately 9 mm between the fabric and the hotplate surface was found to be the optimum for controlling the fabric surface temperature. The apparent temperature of the fabric matched its surroundings by adjusting its surface emissivity depending on the ambient temperature. Disruptive Pattern Combat Uniform (DPCU) fabric was used in the experimental assessment of the theoretical predictions which were in good agreement with the theoretical predictions. A sweating hotplate was used in the dry and wet states to assess the influence of evaporative heat on the fabric surface temperature. No significant difference was found between the dry and wet states of the sweating hotplate.

This study recommends that a spaced structure fabric with an air gap thickness around 9 mm be developed for reducing the clothing fabric surface temperature. It is also recommended that the apparent temperature of natural foliage and other field objects, in hot harsh environment, be investigated in order to determine the appropriate fabric surface emissivity.

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1. Introduction

Soldiers are vulnerable to detection through electro-optic (EO) surveillance systems, in particular the thermal imaging camera. To reduce the thermal IR (infra-red) signature of a combat soldier operating in the open, the thermal image needs to match the thermal patterns of the background. Similarities in apparent surface temperatures and their spatial patterns between the soldier and background are an essential requirement for effective thermal camouflage.

Fabric surface temperature is one of the key measures of thermal signature for a clothed man/environment system. The temperature measured through a non-contact radiometric instrument can be termed as the radiometric temperature or apparent temperature. There are a number of factors that influence the apparent temperature on the fabric surface. They can be classified into three groups.

These are:

1. Environmental factors, such as ambient temperature, solar and ground radiation and wind speed;
2. Human body heat, such as skin temperature and sweating rate;
3. Fabric thermo-physical properties and geometric structures, such as fabric surface thermal emissivity and weave structures.

It becomes apparent that the thermal IR signature of a clothed man can only be changed through appropriate design of the thermal emissivity of the clothing surface and its geometric structure for any given environmental condition and personal physical activity level.

The existence of a temperature gradient across the thickness of a textile ensemble provides an opportunity to disguise the body temperature from the temperature of the surrounding objects, although the temperature gradient between the body and the clothing surface will be strongly dependent on the ambient conditions. In a laboratory study of the thermal radiative properties of thin fabrics, Cain and Farnworth [1] found that the distance between the fabric and hotplate surface had a significant impact on the fabric thermal resistance and this was attributed to the influence of a static air layer attached to the surface of the fabric. The effect of this air gap becomes insignificant once the gap thickness exceeds about 13 mm at which point the convective heat exchange process become significant [1]. Fabric thickness also influences the thermal resistance as the static air volume trapped within the fabric structure normally determines the fabrics thermal resistance[2].

To study the effect of geometric structures of fabric ensembles on the fabric surface apparent temperature, a theoretical analysis has been carried out to investigate the influence of various parameters. In this report, a sweating hotplate/fabric/environmental chamber system was used to simulate the interactions between the man, his clothing and his environment at night. An inframetrics

radiometer (see Appendix A) was used to measure the fabric apparent temperature inside the environmental chamber, which was set at 20, 25, 30 and 40°C respectively. The relative humidity was maintained at 60% in all cases. The surface temperature of the sweating hotplate, which was used to simulate body temperature was maintained at 34°C. The sweating hotplate was operated in both the dry and sweating modes.

2. Theoretical Analysis

To simplify the complex process of heat exchange involving the human body, clothing fabric and the environment, a flat surface sweating hotplate was used. This simulates the surface temperature of the human body, which attempts to maintain a constant surface temperature regardless of the ambient conditions. The hotplate is placed in an environmental chamber under controlled conditions of ambient temperature and humidity (Figure 1). This system simulates a night time setting as there is no solar radiation involved in the heat exchange. To determine the effect of heat exchange between the hotplate surface and the fabric, the fabric was kept at a predetermined distance (D) from the hotplate surface.

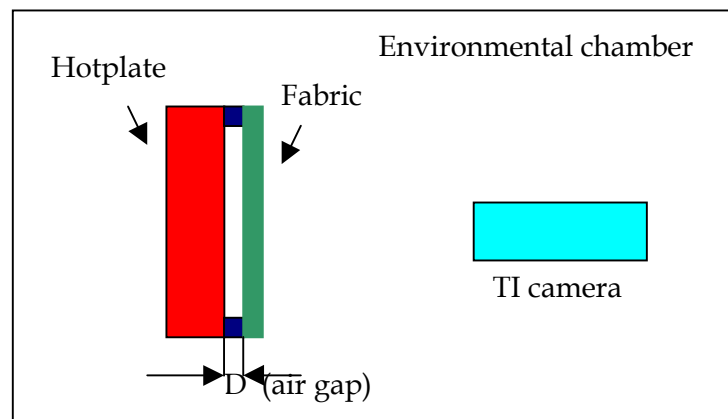


Figure 1. Schematic diagram of hotplate/fabric/environmental chamber set up

The apparent radiometric temperature of the fabric surface will depend on the ambient temperature, its “true” temperature and surface thermal emissivity. It follows the Stefan-Boltzmann’s law as follows:

$$M = \epsilon\sigma T^4 \quad (1)$$

where M is the radiance emittance of the target, ϵ is the emissivity of the target; and σ is the Stefan-Boltzmann’s coefficient, $\sigma = 5.672 \times 10^{-8} \text{ Wm}^{-2}\text{k}^{-4}$. T is the “true” temperature or black body temperature of the target.

If the air gap between the hotplate and the fabric is less than 13 mm it is valid to assume that there is an insignificant amount of convection involved in the heat transfer from the hotplate to the fabric [1]. In this case heat transfer will occur primarily by conduction and radiation. According to equation 1, and assuming that the fabric is an opaque object, the radiative energy exchange ($M_{\text{rad-gain}}$) between the blackened surface of the hotplate and the fabric can be expressed as

$$M_{\text{rad-gain}} = \epsilon_f \sigma (T_{\text{hotplate}}^4 - T_f^4) \quad (2)$$

where T_{hotplate} is the surface temperature of the hotplate and T_f is the surface temperature of the fabric.

Kirchhoff's law states that absorptivity is equal to its emissivity, that is $\alpha_f = \epsilon_f$, and consequently the fabric will absorb all emitted energy from the hotplate as shown in equation 2.

Since the fabric is at a stand-off distance from the surface of the hotplate heat will also transfer by conduction through the air gap. The transmitted conductive energy is expressed as

$$M_{\text{cond-gain}} = U_{\text{air}} * (T_{\text{hotplate}} - T_f) / D \quad (\text{W m}^{-2}) \quad (3)$$

where U is the conductivity of air, $0.025 \text{ Wm}^{-1}\text{k}^{-1}$, and D is the air gap between the fabric and the hotplate, in metres (m).

When the ambient temperature is below 34°C , the only source of heat is the hotplate, as shown in Figure 1. Under this condition the heat loss through the fabric is a combination of convection and radiation. Convective exchange occurs between the fabric and the circulating air in the chamber and radiative heat is emitted from the fabric. The convective loss due to airflow can be expressed as:

$$M_{\text{cov-loss}} = (T_f - T_{\text{air}}) / I_a \quad (4)$$

where I_a is the insulation value of the fabric (Km^2W^{-1}) and depends on the air flow speed. At an air movement velocity of 0.2 ms^{-1} , it is $0.124 \text{ Km}^2\text{W}^{-1}$ (or 0.8 Clo) [3].

Radiative heat exchange within the chamber can be expressed as

$$M_{\text{rad-loss}} = \epsilon \sigma (T_f^4 - T_{\text{air}}^4) \quad (5)$$

When the heat balance is reached, the amount of heat gained by the fabric will equal the amount of heat lost by it. That is:

$$M_{\text{rad-gain}} + M_{\text{cond-gain}} = M_{\text{rad-loss}} + M_{\text{cov-loss}} \quad (6)$$

In the case of a chamber temperature above 35 °C, the hotplate must be operated in the wet condition for thermal equilibrium to be maintained. In this mode water evaporates from the surface of the hotplate through the fabric in an attempt to keep its surface temperature at 34 °C. In this case, the heat gain of the fabric is through both radiative and conductive exchange with the chamber air. The heat loss from the fabric to the sweating hotplate is through radiative and conductive exchange. When a heat balance is reached, the heat loss from the fabric to the hotplate equals the evaporative heat loss from the hotplate.

3. Prediction of Fabric Surface Apparent Temperature

3.1 Air Gap

Based on the above theoretical analysis, the fabric surface apparent temperature can be predicted. Figure 2 shows the calculated relationship between the air gap thickness and fabric surface temperature at different ambient temperatures. The fabric surface emissivity is assumed to be unity.

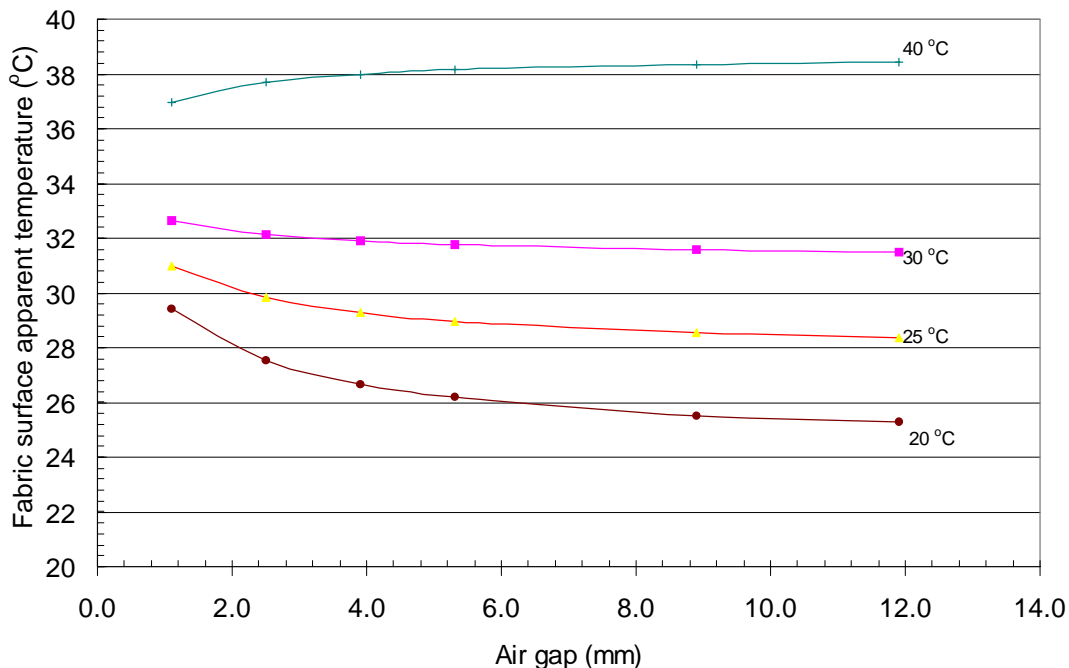


Figure 2. The influence of the air gap at different ambient temperatures

From Figure 2, it can be observed that the fabric surface temperature decreases with an increase in the air gap between the hotplate and fabric when the ambient temperature

is below 34 °C. It increases when the ambient temperature is above 35°C. There is a general trend as shown in Figure 2 for the fabric surface temperature to become almost constant when the air gap is greater than 9 – 12 mm. The rate of temperature drop or rise becomes insignificant as shown in Table 1. This is probably due to the onset of the convective effect, which is in agreement with the finding of other workers [1].

It is noted from Table 1 that when the air temperature is 25°C or above and the air gap is greater than 8.9 mm, the ratio of fabric surface temperature to the air gap is about 0.05 °Cmm⁻¹ or less. This indicates that any further reduction of fabric surface apparent temperature cannot be achieved effectively by increasing the air gap.

Table 1. Relationship between the rates of increment in air gap and the fabric surface temperature

°C/mm	1.1mm	~2.5mm	~3.9mm	~5.3mm	~8.9mm	~11.9mm
20 °C	-	-1.324	-0.618	-0.354	-0.180	-0.089
25 °C	-	-0.840	-0.395	-0.226	-0.114	-0.057
30 °C	-	-0.356	-0.175	-0.099	-0.051	-0.025
40 °C	-	0.499	0.211	0.117	0.057	0.028

Figure 3 shows the variation in the apparent temperature of the fabric with changing air gap thickness at the ambient temperature of 20 °C. These results have been plotted for a variety of fabric surface emissivity. It can be seen from the graph that at an air gap thickness of approximately 7 mm, an emissivity of 0.4 is required to match the ambient temperature.

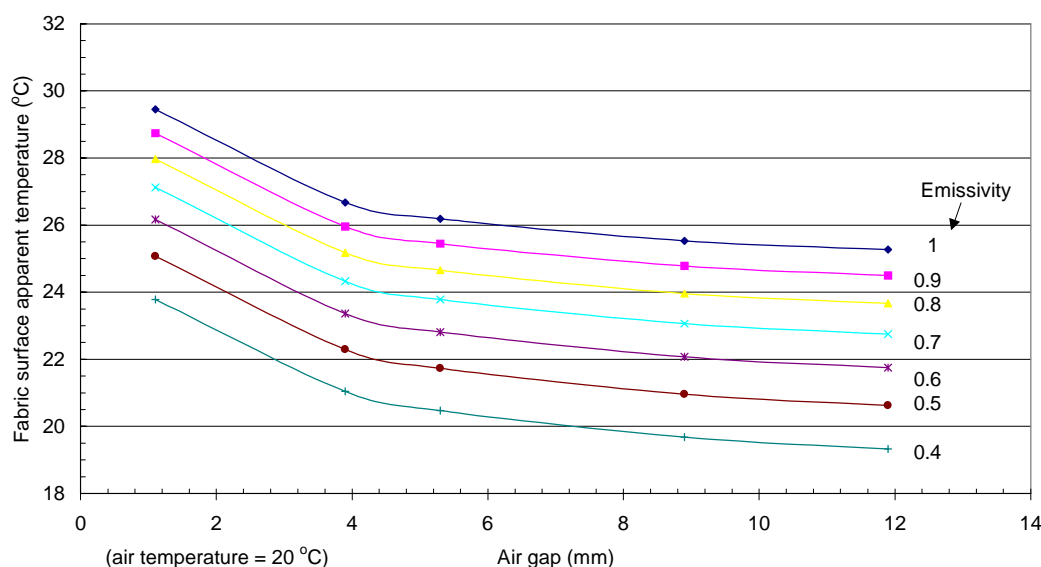
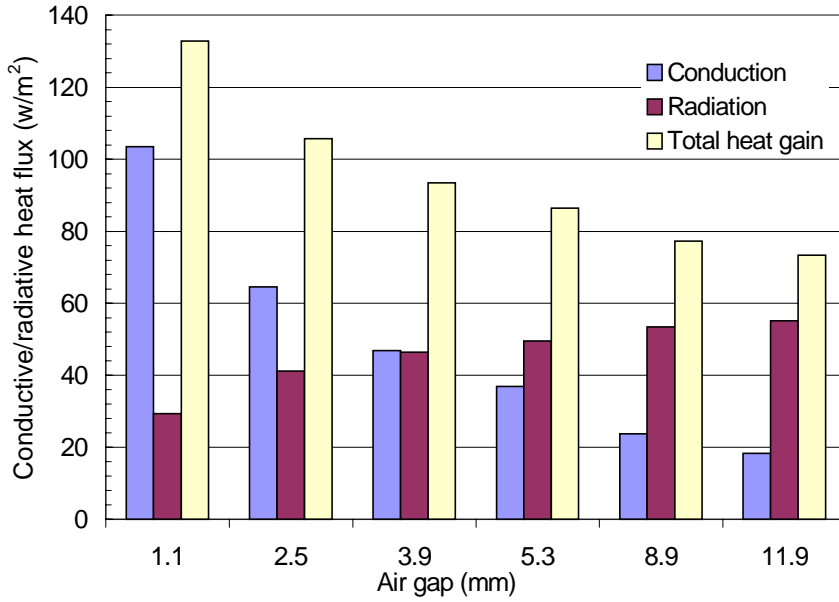
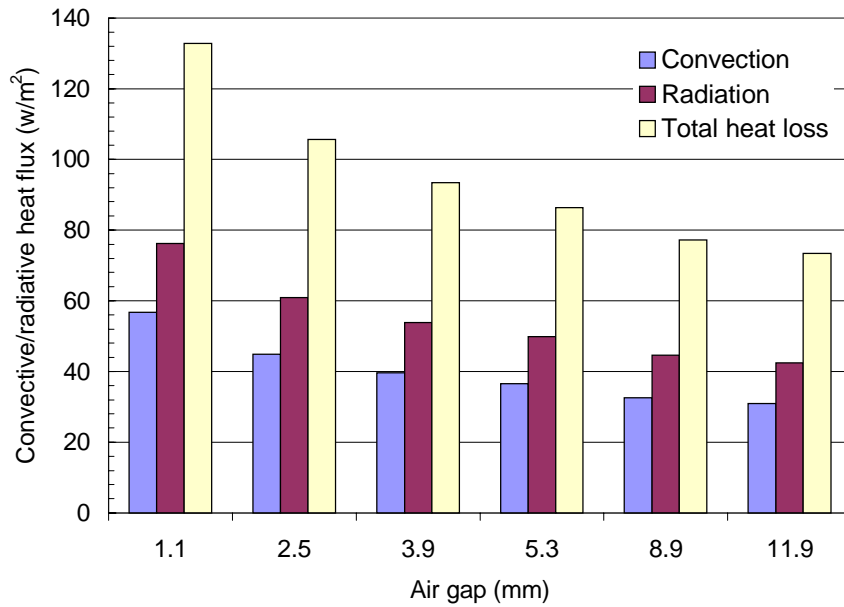


Figure 3. Effects of the air gap thickness and thermal emissivity

Figures 4 and 5 show the details of heat transfer components in the heat exchange between the fabric, hotplate and the environment at ambient temperatures of 20°C and 40°C respectively. These heat flux components include the radiative and conductive heat gain towards the fabric, and radiative and convective heat loss from the fabric.

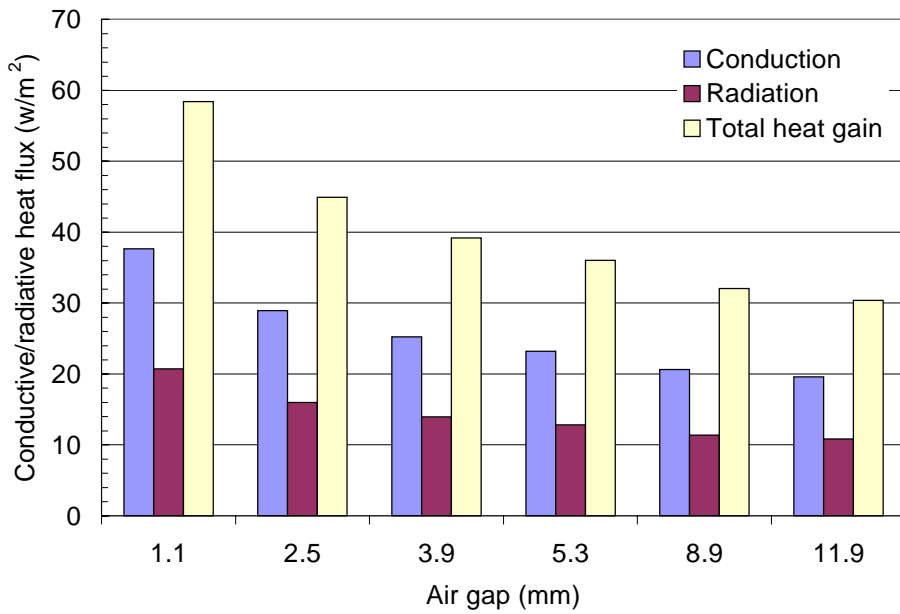


(a) Heat gain

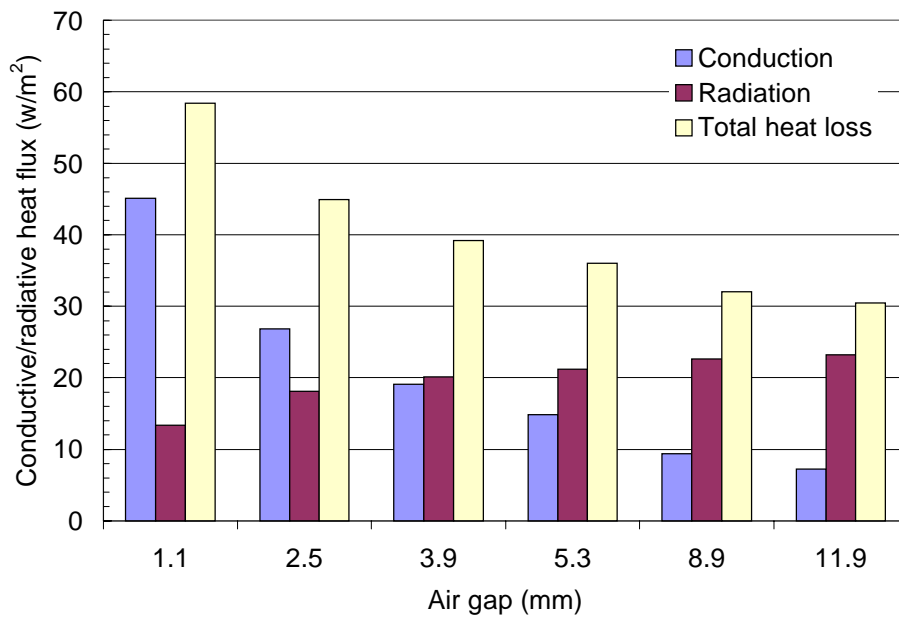


(b) Heat loss

Figure 4. Components of heat flux at ambient temperature of 20 °C



(a) Heat gain



(b) Heat loss

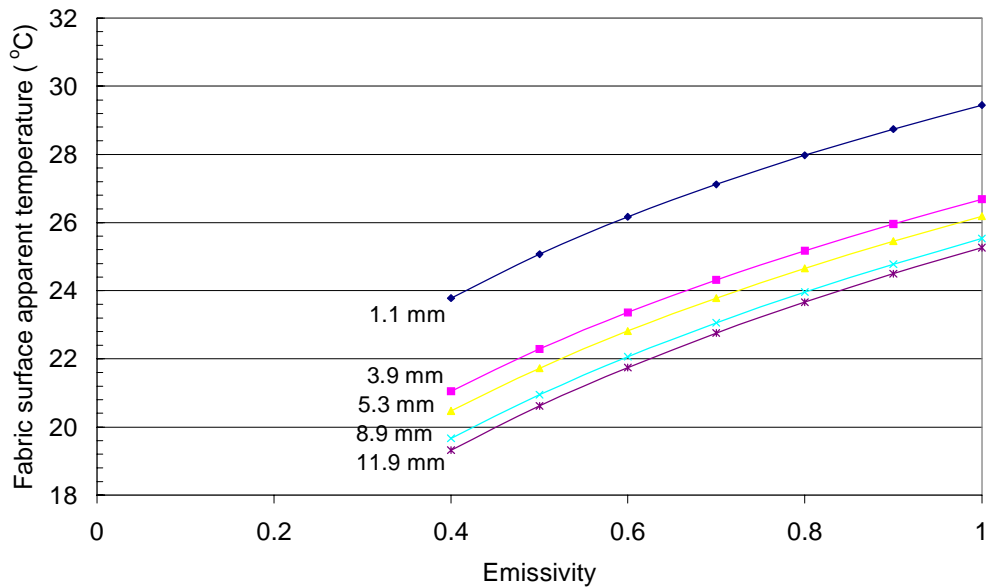
Figure 5. Components of conductive and radiative heat flux at ambient temperature of 40 °C

As shown in Figures 4(a) and (b), the total heat flux transfer decreases as the air gap increases. It can be seen that the conductive heat transfer from the hotplate to the fabric is much greater than the radiative component when the air gap is less than 4 mm. As the air gap increases, the conductive component falls below the radiant component. This indicates that the air gap starts to act as an effective insulation layer and reduces the heat gain by the fabric. The greater rate of reduction in the conductive gain component leads to the reduction of total heat gain as shown in Figure 4(a). In Figure 4(b), radiative and convective heat losses decrease as the air gap increases in a similar trend. It is worth noting that at a given ambient temperature, increasing the convective heat exchange will lead to greater total heat loss.

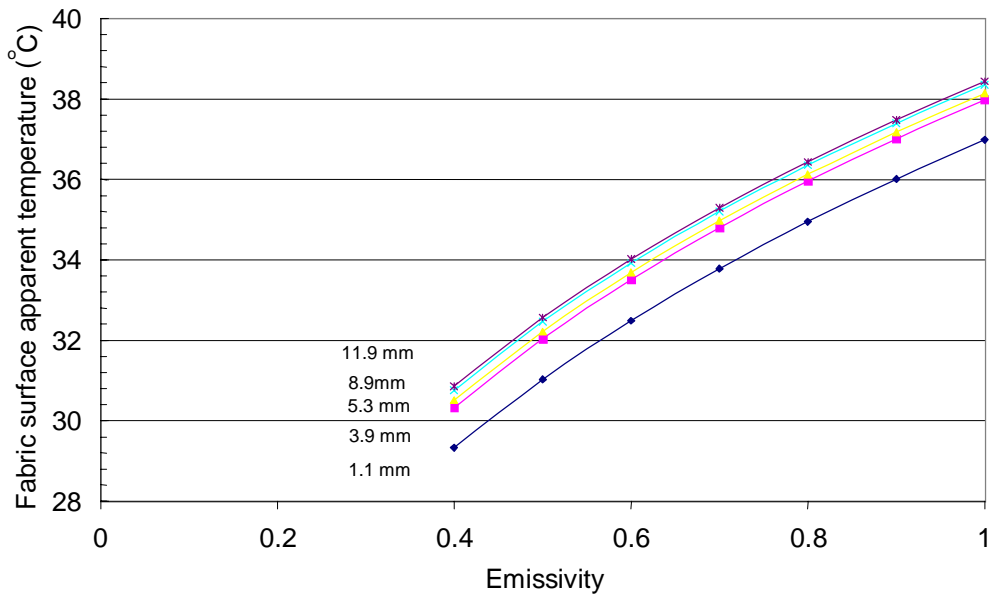
When the ambient temperature is higher than 35°C, the heat gained by the fabric is from the air and surroundings. As shown in Figures 5(a) and (b), the total heat gained by the fabric decreases as the air gap increases. The conductive heat loss component drops as the air gap increases and falls below the radiative loss when the air gap is greater than about 4mm. It is evident that the reduction of total dry heat loss is due to the reduction of the conductive component, which in turn is due to the air gap.

3.2 Thermal Emissivity

Figures 6 (a) and (b) show the effect of fabric surface thermal emissivity on the fabric surface apparent temperature at different air gap thicknesses at ambient temperatures of 20 and 40°C respectively.



(a) Air temperature at 20°C



(b) Air temperature at 40°C

Figure 6. Relationship between fabric surface apparent temperature and surface emissivity

3.3 Ambient Temperature

Figure 7 shows the relationship between the fabric apparent surface temperature and the ambient temperature with an air gap of 8.9mm.

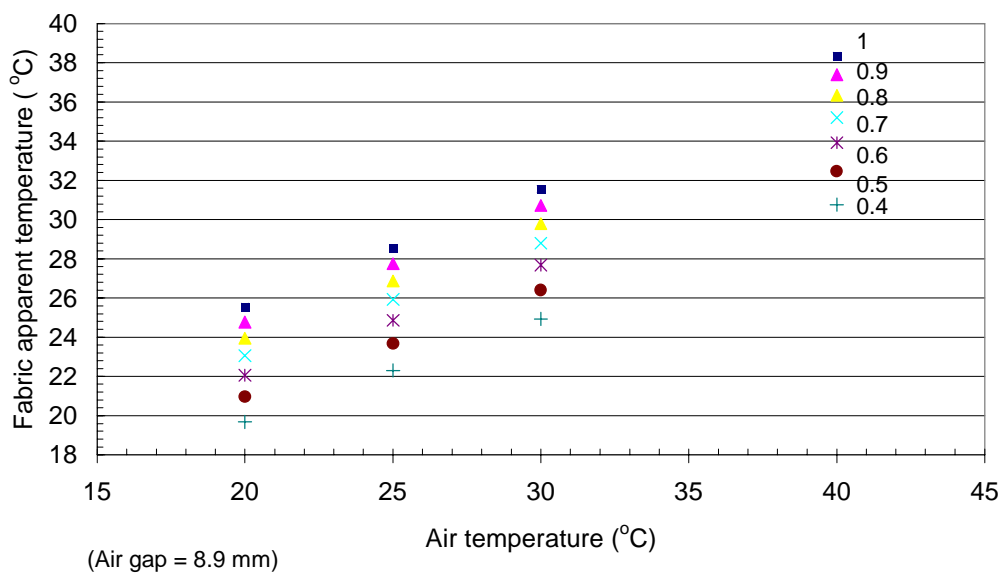


Figure 7. Relationship between ambient temperature and fabric surface apparent temperature

It is worth pointing out that there exists a linear relationship between the fabric apparent surface temperature and the ambient temperature. As shown in Figure 7, the fabric apparent temperature can match the ambient temperature of 25°C when its emissivity is 0.6 and the air gap is 8.9 mm.

4. Experimental Validation

4.1 Material

The Disruptive Pattern Combat Uniform (DPCU) fabric was used as the test fabric in the investigation. The fabric sample was cut into a circular shape of 0.02 m² in area and glued into a spacer which was larger than the outer diameter of the hotplate surface.

4.2 Experimental Set-up

To simulate the interactions between man, his clothes and the environment, a sweating hotplate/fabric/environmental chamber system was set up as shown in Figure 1. This system enabled the maintenance of a constant hotplate temperature of approximately 34°C and a sweating rate that could be varied from zero up to 0.5 gm²s⁻¹. These conditions simulate a range of conditions of the human body under different physiological conditions. The environmental chamber allows the control of the air temperature and the relative humidity within the chamber.

An infrared radiometer (8 - 14 μm) [4] was used to measure the radiometric temperature of the fabric and hotplate surfaces. An airflow meter and two RTD (thermometer) probes were also used to monitor the air current speed and the temperature in the vicinity of the fabric external face.

4.2.1 Sweating Hotplate

The sweating hot plate contains 24 small apertures, which, when required, supply water to the surface of the hot plate from a reservoir through a computer controlled stepper motor. Water in the reservoir is pre-heated to the hotplate surface temperature (nominal 35°C) before being transported to the hotplate surface. The hotplate surface was painted in a low gloss black colour to increase its emissivity.

4.2.2 Infrared Radiometer (Inframetrics 760)

A commercially available Inframetrics 760 infrared radiometer is the principal instrument used in this study. Details of the main feature of the radiometer are included in the Appendix A. The measured temperature data was taken on average over a defined area every 5 seconds, and transferred to a computer system and averaged each minute, then stored in the hard drive as a text file.

4.2.3 Experimental Procedure

The hotplate surface was set vertically and its surface temperature was measured using a radiometer and several thermocouples. Temperatures in the configurations of bare plate and plate with a layer of filter paper were measured separately. Chamber ambient temperature was set at 20, 25, 30, and 40°C respectively with 60% relative humidity. Air gap thickness between the fabric and the hotplate was set from zero to 11.9 mm. Each condition was measured for about 1 hr. The hotplate was used in both dry and sweating configurations. In the wet surface condition, an $0.3 \text{ g}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ constant sweating rate was used to ensure the filter paper wicking layer remained wet throughout the test. When testing against the transfer of moisture vapour and not liquid water a cellophane membrane was used to cover the filter paper. The cellophane was designed to allow only moisture vapour to diffuse through while stopping the passage of liquid water.

5. Results and Discussion

Figure 8 shows typical results measured with the above experimental set up. The sudden fluctuations which are apparent occurred when new air gaps between the test sample and the hotplate were set. This shows the disruption of the steady state conditions in the environmental chamber. Data recorded during these periods was excluded from the mean calculations.

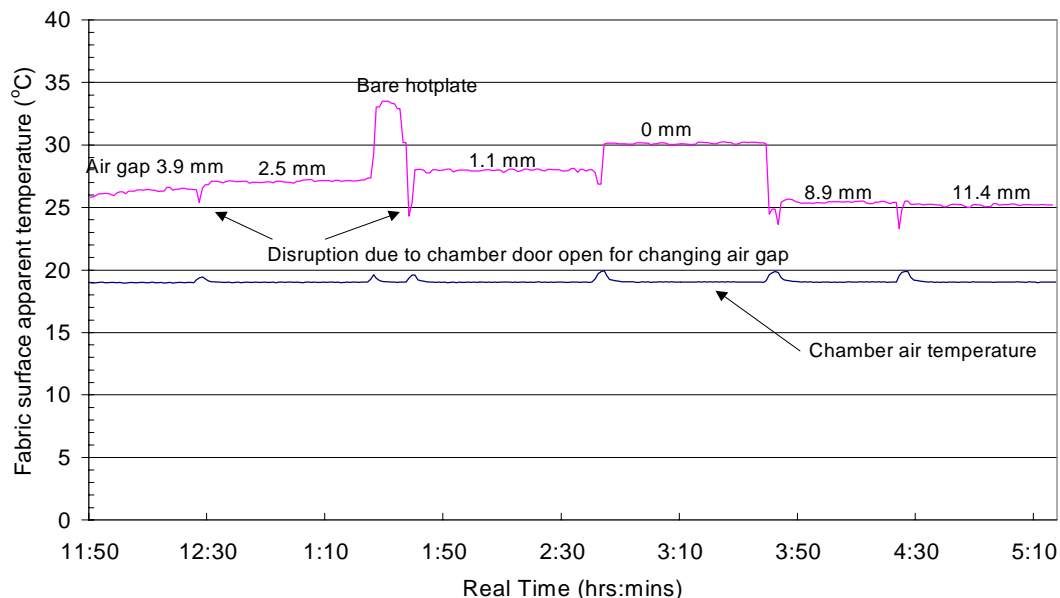


Figure 8. Variation in the fabric surface apparent temperature due to different air gap settings

5.1 Effect of Water Vapour Evaporation

Table 2 shows the fabric surface apparent temperature measured at chamber air temperatures of 20°C and 60% relative humidity. The hotplate was set in three different states: dry, wet and water vapour.

Table 2: Fabric surface apparent temperature at 20 °C and 60% R.H.

°C	Bare plate	0 mm	1.1 mm	2.5 mm	3.9 mm	5.3 mm	8.9 mm	11.9 mm
Dry	33.22	30.13	27.98	27.09	26.33	--	25.41	25.19
Wet	32.37	30.89	27.59	--	--	25.96	25.39	25.22
Water vapour	32.96	29.65	27.91	27.16	26.46	25.94	25.31	--

When the hotplate was in the dry state no water was pumped from the reservoir. The electrical power consumption by the hotplate was due to the loss of dry heat to the surroundings through the fabric sample. When the hotplate was set in the wet state its surface was covered with a layer of filter paper to provide a uniform wicking of the water across the surface. Throughout the course of the test the filter paper was kept in a fully saturated state by maintaining a sweating rate of 0.3 gm².s⁻¹. Power consumption in this case was used to compensate for both the loss of dry heat and water vapour evaporation. When water vapour transmission only was required, the filter paper was covered by a cellophane membrane. This was to prevent the fabric sample under test from being in contact with the liquid water at the hotplate surface, yet allow moisture vapour to permeate through it and into the atmosphere.

As shown in Table 2, although there are some slight variations in temperature in the case of bare plate and zero mm air gap among the dry, wet and water vapour states in the hotplate, no significant difference can be found among these three states. Table 2 also indicates that once an air gap exists between the fabric under test and the hotplate surface, the fabric surface apparent temperature does not seem to be affected by wet heat transfer.

5.2 Effect of Air Gap

Figure 9 shows the apparent fabric surface temperature plotted against the air gap at different ambient temperatures as determined by theory and by experiment. The dotted lines refer to theoretical predictions and solid lines indicate the experimental results.

As shown in figure 9, most experimental points fit well into the theoretical predictions, although some data points are slightly lower than theoretical predictions at ambient temperature below 25°C and with the air gap less than 2.5mm. This discrepancy probably arises due to experimental difficulties in keeping a uniform air gap thickness when the air gap thickness is small.

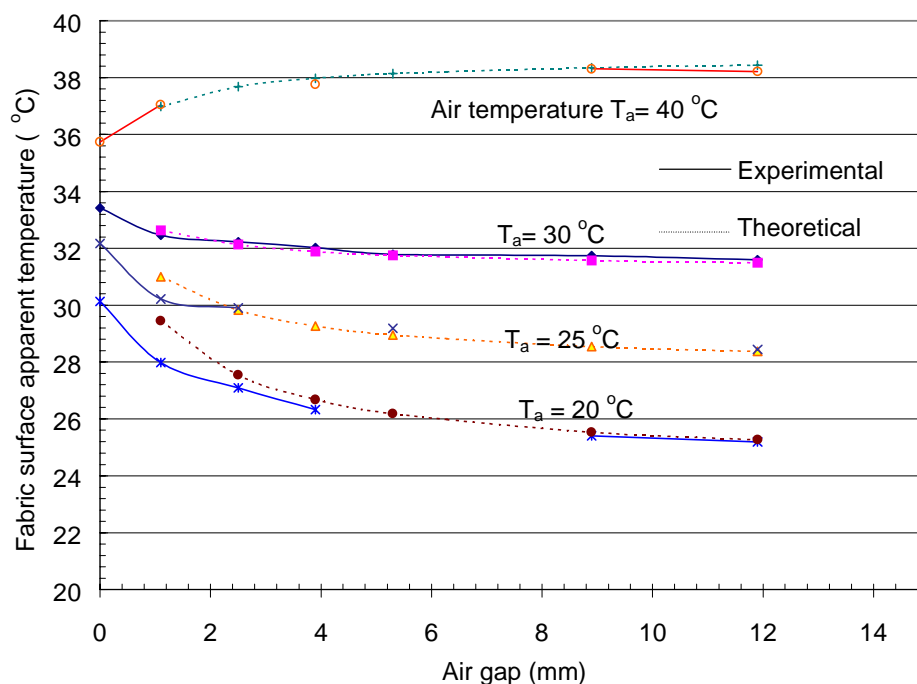


Figure 9. Comparison between theoretical and experimental results

6. Conclusions

Theoretical analyses have been presented in this report to predict the clothing fabric surface apparent temperature in a simulated man/clothing/environment condition. An insulation air gap between the clothing fabric and the hotplate has been shown to have a significant effect in reducing or increasing the fabric surface temperature in air temperatures either lower or higher than 35°C . The minimum air gap with maximum effect in reducing or increasing fabric surface temperature is identified to be around 9 mm where the conductive heat gain or loss component by the fabric is at its optimal minimum. Fabric surface apparent temperature can be further changed to match its surrounding objects or air temperature by reducing its surface emissivity.

A sweating hotplate, DPCU fabric and environmental chamber were set up to simulate man/clothing/environment interactions under steady-state conditions. A thermal camera (Inframetrics 760) was used to measure the fabric surface apparent temperature inside the environmental chamber. Tests were carried out to verify the theoretical prediction in the ambient conditions of air temperature over the range from 20 to 40°C and relative humidity of 60%. Different air gaps ranging from 1.1 mm to 11.9 mm were

used to assess the effect of air gap on the fabric surface temperature. The experimental results were in good agreement with theoretical predictions.

A spaced fabric structure with air gap around 9 mm is to be developed as a result of this study. It is predicted that this will reduce the thermal image signature of a clothed soldier. The apparent temperature of natural foliage and objects such as tree trunk, leaves, soils, rocks etc under various weather conditions in hot harsh environment also needs to be investigated to provide a database for the determination of fabric surface emissivity.

7. Acknowledgment

The author wishes to acknowledge the contribution of Mr David Robinson for his technical assistance in TIR measurement.

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Appendix A: Specifications of Inframetrics 760 (IR Imaging Radiometer)

Spectral Bandpass (Nominal)	8 – 12 μm
Detector	Mercury Cadmium Telluride (HgCdTe); @77K
Minimum Detectable Temperature Difference (typical)	
@ 30 °C	0.1 °C
Noise Equivalent Temperature Difference (typical)	
@ 30 °C	less than 0.2 °C
@ 30 °C (with image averager, 16 fields)	less than 0.05 °C
Horizontal Resolution at 50% Slit Contrast (typical)	
	1.8 mRad, 194 IFOVs/Line 256 Pixels/Line
Accuracy (worse case)	± 2 °C or $\pm 2\%$
Scan Rate (International)	7812 Hz Horizontal; 50 Hz Vertical
Output Rate (International)	15,625 Hz Horizontal; 50 Hz Vertical
Field of View (FOV)	15 ° Vertical X 20 ° Horizontal
Output format (Dynamic Range)	8 Bit, 256 Levels, 48 dB
Temperature Spans	2, 5, 10, 20, 50, 100 Normal range
Temperature Measurement Range	-20 to +400 °C normal range 20 to +1500 °C extended range
Temperature Readout Resolution	3 Digits
Power Requirements (System)	11-17 VDC, 30W
AC Power Supplies	95-250 VAC, 47-63 Hz
Ambient Operating Temperature	-15 to +50 °C

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19. ABSTRACT Theoretical analysis is presented to predict the fabric surface apparent temperature in a simulated man/clothing fabric/environment system. The predicted outcomes have been validated by comparison with the experimental results using a sweating hotplate in an environmental chamber. An air gap of approximately 9mm between the fabric and the hotplate surface was found to be the optimum for controlling the fabric surface temperature. The apparent temperature of the fabric can match its surrounding objects by further adjusting its surface emissivity depending on the ambient temperature. A Disruptive Pattern Combat Uniform (DPCU) fabric was used in the experimental assessment of the theoretical predictions which were in good agreement with the theoretical predictions. A sweating hotplate with dry and wet states was also used to assess the influence of evaporative heat on the fabric surface temperature. No significant difference was found in the fabric surface apparent temperature between the dry and wet states.					