Fabric Heat Transfer by Conduction and Radiation

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Abstract

Persons exposed to solar heat radiation in hot and dry climates are at increased risk of heat illnesses. Clothing can reduce such exposure. The effectiveness of clothing to reduce such heat loading depends on the ability of the fabric to reflect this heat radiation. However, incomplete reflection results in fabric heating which will heat the body by conduction. The protection against heat radiation by a garment can be offset by the retention of metabolic heat due to insulation. This will counteract the IR attenuation benefits offered by the clothing. An accurate understanding of such a trade-off is needed in order to optimize the selection of clothing when managing heat stress resulting from exposure to solar IR heat radiation. Laboratory experiments were performed on multiple layers of Cotton, Nylon, Wool and Polyester fabric to evaluate their heat insulation characteristics and IR heat attenuation properties. The relationship between fabric layers and IR attenuation properties was examined under controlled laboratory conditions. The results of this study showed that fabric insulation heat gain and corresponding IR radiation attenuation was proportional to the number of fabric layers used. However, the IR heat radiation attenuation was significantly greater with each additional fabric layer than the heat gain penalty associated with fabric insulation. Additionally, heat transfer by condition was seen to contribute about 18% of the radiant heat transfer to the body. Separating the fabric from the body using a spacer will reduce this amount of heat transfer to the skin. The results of this study show that multiple fabric layers can significantly reduce the risk of IR heat radiation overexposure while limiting the metabolic heat build-up inside protective clothing. The study also confirms that by selecting the appropriate number of fabric layers, it is possible to optimize the IR heat radiation protection while limiting metabolic heat build-up inside clothing.

Keywords: Solar Heat Stress; IR Heat Radiation Attenuation; Multi-layered Clothing; Fabric Insulation, Heat Transfer by Conduction

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1 Introduction

Workers exposed to outdoor solar heat radiation are at increased risk of suffering heat related disorders [1-3]. Use of tents, hats, and other protective equipment are frequently used to reduce such exposures. However, these measures are often impractical when employees must change postures or are required to move to new locations. Innovative use of clothing materials and creative approaches to garment design can help reduce clothing heat stress during exposure to outdoor solar environments [4-5].

While clothing can offer a barrier to solar heat radiation, protective garments can also lead to physiological heat stress by limiting the dissipation of body metabolic heat [5-8]. The goal of this study is to identify the cost - benefit of multiple garment fabric layers that balance garment insulation with garment heat radiation attenuation. To pursue this objective, experiments were conducted to evaluate the heat insulation characteristics and the associated IR heat radiation attenuation properties of four different fabric types.

In evaluating clothing induced heat stress, it must be recognized that the human body is a heat producing system that attempts to maintain a balance between heat gain and heat loss. Environmental parameters such as air temperature, air velocity, radiant heat, and humidity can all affect this balance. Clothing material and garment design can influence this heat balance also by promoting or reducing heat exchange via sweat evaporation, convection, conduction, and heat radiation [9-10]. The specific performance during heat radiation exposure can also be linked to the chemical and physical structure of the garment materials itself including thickness and weight [11-16].

Previous research evaluating the impact of heat radiation on protective clothing has shown that fabric thickness is an important factor affecting the IR protective performance of a garment [17-18]. Additionally, these studies have shown that a multi-layer system can provide high levels of protection [19, 20].

2 Methods and Procedures

2.1 Fabric Samples

Four fabric types were evaluated that included six samples of Wool (100%), Nylon (100%), Cotton (100%) and Polyester (88%). Insulation characteristics and IR radiation attenuation properties were evaluated for 1, 2, 4, and 6 layer combinations. Each fabric sample was 10 cm x10 cm in size. The Wool sample had a thickness of 1.0 mm and weighed 2.0 grams, the Nylon sample had a thickness of 0.8 mm and weighed 1.6 grams, the Cotton sample had a thickness of 1.0 mm and weighted 1.7 grams , the Polyester sample had a thickness of 3.0 mm and weighted 1.9 grams. The four combinations of each fabric type were measured to determine their insulation heat gain characteristics and IR radiation heat attenuation properties separately under controlled laboratory temperature conditions. The dimensions of the fabric samples used in this study are illustrated in Fig. 1.

Fig. 1: Wool, Nylon, Cotton and Polyester fabric samples evaluated in the study. Each sample was 10 cm × 10 cm in size. Insulation characteristics and IR radiation attenuation properties were evaluated for 1, 2, 4, and 6 layer combinations

2.2 Temperature Platforms

2.2.1 Configuration #1

A 0.01 mm thick steel base-plate located on top of platform configuration #1 is illustrated in Fig. 2. It was used to simulate human skin temperature of 35 °C. Three thermocouple sensors were attached to the top of the base-plate and recorded changes in base-plate temperature resulting from fabric insulation and heat radiation exposure from the IR heat lamp positioned above the base-plate. All tests were conducted with an ambient air temperature of 21 °C (±1 °C) and a relative humidity of 24% (±3%). Each fabric exposure period was 5 minutes in duration.

2.2.2 Configuration #2

The base-plate used in heat platform configuration #1 was also used to measure the heat transfer by conduction only. The base-plate in configuration #2 was used without the heat chamber as illustrated in Fig. 3. In addition, a 15 mm removable spacer-frame was mounted onto the base-plate. The base-plate remained at room temperature prior to heat radiation exposure, i.e. at 21 °C. The fabric samples were placed directly onto the base-plate during exposure to Infrared radiation. Afterwards, each fabric sample was placed onto the 15 mm spacer-frame and exposed to Infrared radiation.

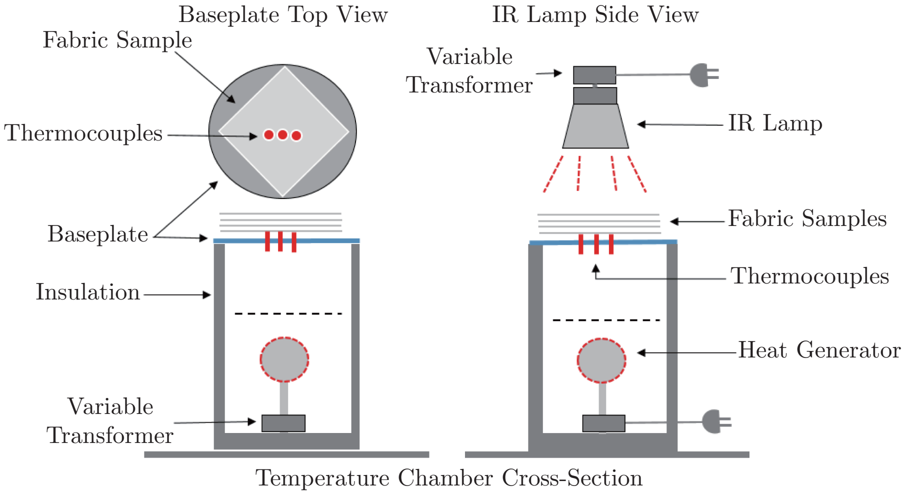

Fig. 2: Temperature platform configuration #1 showing placement of internal heat generator, base-plate location, thermocouple and IR heat lamp positions

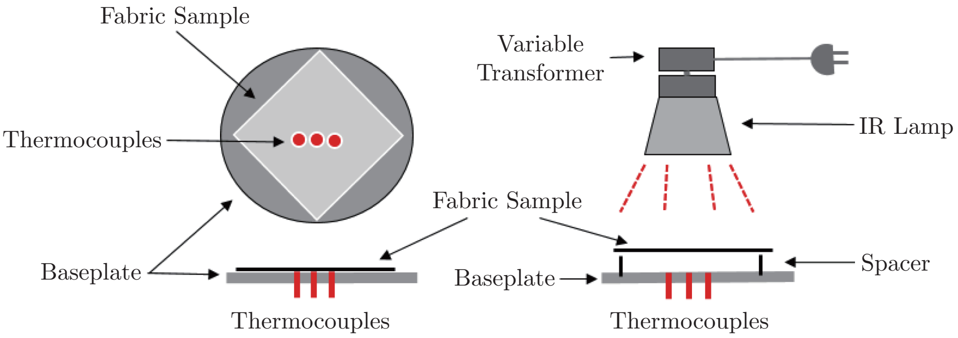

Fig. 3: Temperature platform configuration #2 showing placement of the base-plate, thermocouple, IR heat lamp position and the spacer-frame placed on top of the un-heated base-plate

2.3 Heat Gain Measurements

Insulation heat gain for each fabric type was evaluated for a 1 layer, 2 layers, 4 layers and 6 layers combinations. The temperature changes resulting from layering was determined for a single layer first, then followed by 2, 4 and 6 layers. IR radiation heat gain was evaluated in reverse, beginning with 6-layers followed by 4 layers, 2 layers and 1 layer.

Conductive heat transfer associated with each fabric type was determined when one sample of each was placed first directly onto the base-plate then followed by placing the sample on top of the spacer frame which provided a 10 mm separation between the sample and the base-plate. These tests were done for single-layer configurations only.

3 Results

3.1 Insulation Heat Gain

3.1.1 Single Fabric Layer

The increase in base-plate temperature resulting from insulation created by a single layer of Wool, Cotton, Nylon and Polyester fabric sample is summarized in Table 1. The results show that the Wool fabric sample exhibited the highest increase in base-plate heat gain (+2.8 °C) while Nylon fabric exhibited the lowest increase (+0.8 °C). Cotton and Polyester exhibited an increase of 1.0 °C and 2.0 °C respectively.

Table 1: Summary of temperature increase associated with a single layer of Wool fabric, Nylon fabric, Cotton fabric and Polyester fabric

Fabric Layers	Wool (°C)	Nylon (°C)	Cotton (°C)	Polyester (°C)
0	33.4 (±0.7)	32.5 (±0.8)	34.0 (±0.7)	35.8 (±0.9)
1	36.2 (±0.8)	33.3 (±0.9)	35.0 (±0.9)	37.8 (±1.0)
Δ (°C)	+2.8	+0.8	+1.0	+2.0

3.1.2 Multiple Fabric Layers

The increase in base-plate temperature resulting from multiple layers of Wool, Cotton, Nylon and Polyester fabric samples is summarized in Table 2. The results show that when fabric layers were stacked, the resulting insulation heat gain was similar for each additional layer (+0.5 °C to +0.6°C). However, in comparison to the insulation heat gain created by the first fabric layer, the incremental increase in insulation heat gain was significantly lower.

Table 2: Summary of insulation temperature increase associated with multiple layers of Wool, Nylon, Cotton and Polyester fabric samples

Fabric Layers	Wool (°C)	Nylon (°C)	Cotton (°C)	Polyester (°C)
1	36.2 (±0.6)	33.3 (±0.5)	35.0 (±0.7)	37.8 (±0.8)
2	37.6 (±0.5)	34.0 (±0.6)	35.8 (±0.7)	38.4 (±0.6)
4	38.8 (±0.6)	35.0 (±0.5)	36.6 (±0.6)	39.6 (±0.7)
6	39.6 (±0.7)	35.7 (±0.4)	37.4 (±0.8)	40.8 (±0.8)
Δ/layer	+0.6	+0.5	+0.5	+0.6

3.2 IR Heat Radiation Attenuation

3.2.1 Single Fabric Layers

The decrease in base-plate temperature resulting from single layers of Wool, Cotton, Nylon and Polyester fabric samples is summarized in Table 3. The results show that the Polyester sample decreased radiation heating substantially more than the Wool, Nylon or Cotton samples. The Polyester samples reduced the initial heating by 42.8 °C, while the other samples reduced the heating significantly less.

Table 3: Summary of a temperature attenuation associated with the use of a single layer of fabric

Fabric Layers	Wool (°C)	Nylon (°C)	Cotton (°C)	Polyester (°C)
0	57.1 (±0.7)	57.4 (±0.6)	58.3 (±0.8)	59.6 (±0.5)
1	19.4 (±1.0)	21.6 (±0.7)	20.8 (±0.9)	16.8 (±0.7)
Δ (°C)	−37.3	−35.6	−37.5	−42.8

3.2.2 Multiple Fabric Layers

The decrease in base-plate temperature resulting from 2-6 fabric layers is summarized in Table 4. The data also show that as additional fabric layers were added, the reduction in IR radiation heat gain ranged from -1.9 °C to -1.5 °C. However, again, this reduction was significantly less than the initial decrease provided by a single layer.

Table 4: Summary of a temperature attenuation associated with multiple layers of fabric exposed to IR heat radiation

Fabric Layers	Wool (°C)	Nylon (°C)	Cotton (°C)	Polyester (°C)
1	19.4 (±1.0)	21.6 (±0.8)	20.8 (±0.7)	16.8 (±0.8)
2	16.4 (±0.8)	19.8 (±0.8)	19.3 (±0.6)	15.0 (±0.6)
4	13.4 (±0.5)	17.5 (±0.8)	16.1 (±0.9)	11.4 (±0.6)
6	9.7 (±0.7)	13.9 (±0.5)	11.9 (±0.9)	7.8 (±0.8)
Δ/layer	−1.9	−1.5	−1.8	−1.8

3.2.3 Heating by Fabric Conduction

The temperature changes associated with the use of the 10 mm spacer frame are summarized in Table 5. The data show a significant reduction in the base-plate temperature for all four fabric types with an average temperature reduction of 9.7 °C or 18.3%.

Table 5: Summary of temperature changes associated with the use of a 10 mm spacer placed between the fabric samples and the base-plate

Fabric Sample	With Contact (°C)	With Spacer (°C)	Δ (°C)	(%)
Nylon	52.8 (±1.0)	45.1 (±0.9)	−7.7	−14.5
Wool	55.1 (±0.7)	46.1 (±0.8)	−9.0	−16.3
Polyester	49.2 (±1.0)	39.7 (±0.7)	−9.5	−19.3
Cotton	54.1 (±0.9)	41.5 (±1.0)	−12.6	−23.2
Average	52.8	43.1	−9.7	−18.3

4 Analysis

The following steps were used in determining the heat gain due to IR exposure alone:

1. Measurement of insulation heat gain created by the fabric layers without IR exposure.
2. Measurement of the combined heat gain resulting from fabric insulation + IR exposure.
3. Subtracting the heat gain values obtained for the fabric insulation from the heat gain values obtained for the combined IR exposure + insulation.

The temperature increase due to insulation created by Cotton, Wool, Nylon and Polyester is illustrated in Fig. 4. All of the fabric types exhibited a linear increase in insulation heat gain as fabric layers were added. Polyester showed the highest insulation values while Nylon exhibited the lowest.

The heat attenuation characteristics of Wool, Nylon, Cotton and Polyester fabric samples when placed on the temperature platform configuration #1 during IR heat radiation exposure is illustrated in Fig. 5. All fabrics exhibited a linear decrease in temperature (increased attenuation)

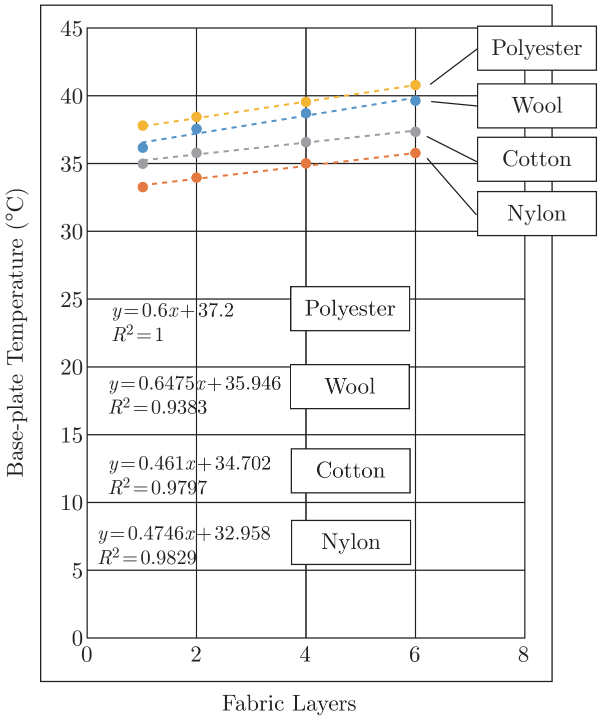

Fig. 4: Illustration of the changes in insulation heat gain associated with multiple layers of Wool, Nylon, Cotton and Polyester fabric samples without IR radiation exposures. Regression equations and R^2 correlations coefficients are presented with each graph

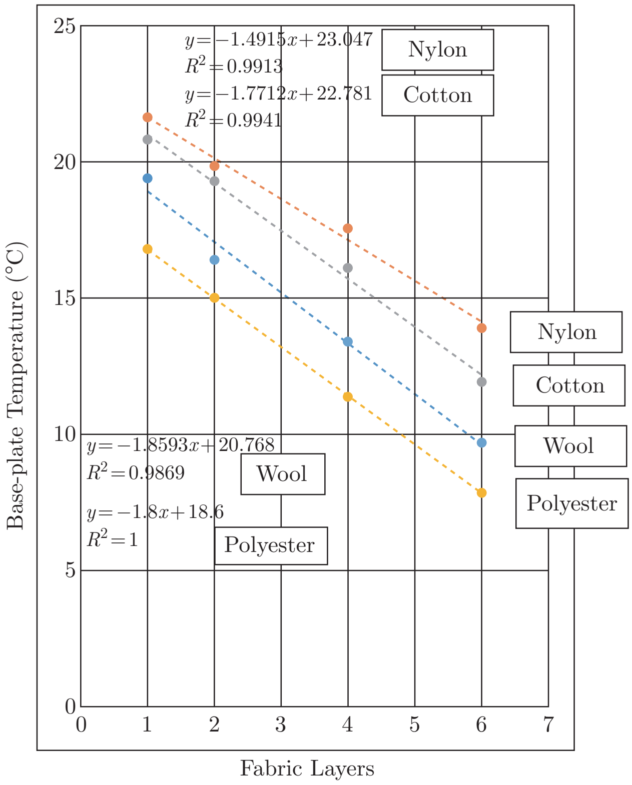

Fig. 5: Illustration of heat attenuation resulting in decreasing temperature values during IR radiation exposure for Wool, Nylon, Cotton and Polyester fabric samples. Regression equations and R^2 correlation coefficients are presented with each graph

as fabric layers were added. Polyester showed the highest attenuation while Nylon exhibited the lowest attenuation.

The spacer separating a fabric sample from the base-plate (body) offers an important additional opportunity to reduce heat loading. Fig. 6 illustrates IR heating by direct contact “A”, and a reduced heat transfer by secondary radiation only “B”, where heat transfer by conduction is eliminated. The additional 18% reduction in heat transfer that can be achieved when a fabric sample is separated from the base-plate by a 15 mm spacer (Table 5) suggests that the heat radiation attenuation offered by the fabric samples can be enhanced significantly.

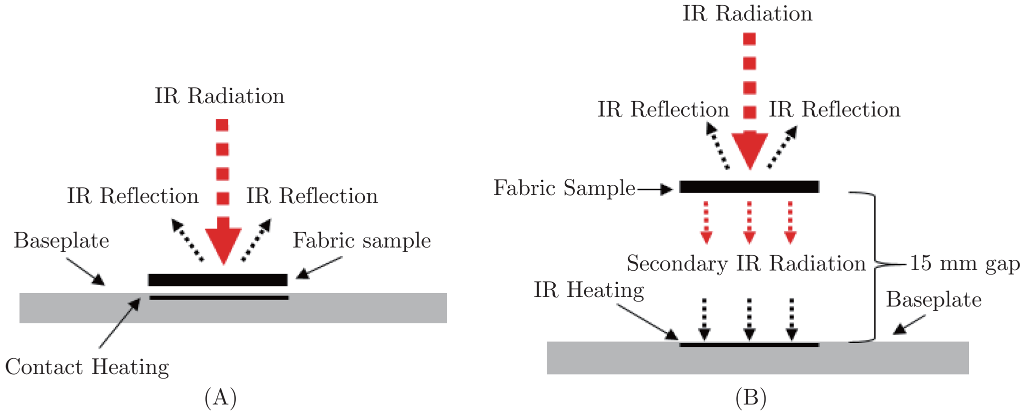

Fig. 6: Illustration of heat transfer during direct contact with the base-plate (A) and when fabric sample is separated by a spacer (B). Heat transfer during direct contact occurs by conduction while heat transfer using a spacer occurs by secondary radiation only

5 Conclusions

The results of this study demonstrate the thermal benefits associated with wearing fabrics to reduce heat stress caused by exposure to IR heat radiation. The results also show that a reduction in IR heating offered by multiple layers of fabric outweighs the potential insulation heat gain (penalty) created by metabolic heat build-up trapped inside clothing layers. Of special interest is the disproportionate benefit of a single layer of fabric in reducing IR heat radiation exposure. The use of spacers to separate the fabric form the body can improve the heat radiation attenuation properties even further.

The overall benefits associated with multiple fabric layers in reducing the heat load imposed by solar IR heat radiation should always be viewed in relation to the sweat evaporation and convective cooling capacity offered by a garment system. When multiple fabric layers are added to a garment, the cooling effects of sweat evaporation will likely be reduced, although such a negative impact will be minimal in very dry environments. Selecting the fewest number of fabric layers needed to achieve thermal comfort should always be the goal.

6 Limitations

The fabric samples evaluated in these experiments were obtained from previously worn clothing and may have been impacted by their previous use. Furthermore, the structural fiber characteristics such as yarn count, weave type and weave density could not be determined. Nevertheless, such variables may have influenced their thermal characteristics. Controlling such factors in future studies may allow a more precise differentiation of heat insulation characteristics and IR heat radiation penetration properties.

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