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Fabric Cooling by Water Evaporation

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Abstract

Clothing can provide safety and comfort for persons exposed to both cold and hot thermal environments. To assess the potential impact of clothing moisture and wetness on fabric cooling, a series of wind-tunnel tests was conducted to quantify the evaporative cooling capacity of selected fabric samples. Single-layer cotton, polyester, nylon and silk were evaluated. The results showed that onset and magnitude of evaporative cooling was determined by the amount of water contained in a fabric sample. The results also showed that an exposed “skin” exhibited more cooling when covered with a fabric than when it was not. The information obtained helps better understand the evaporative cooling process for fabrics and assist in the selection of garment materials that optimize worker comfort and safety.

Keywords: Evaporative Cooling; Fabrics Moisture; Protective Clothing

1 Background

Evaporation of water from the skin can provide significant cooling benefits for individuals exposed to hot and / or dry environments. However, clothing can complicate the evaporation process by creating a barrier to metabolic heat loss through the insulation created by the clothing itself. This, in turn, can create a humid microclimate that reduces the evaporative cooling efficiency of sweat from the skin [1]. Assessing the cooling effect of evaporation in clothing systems is very complex. Sweat may evaporate directly from the skin surface or wick into the fabric where evaporation takes place on the surface of the garment rather than on the skin surface. Both of these processes can occur simultaneously. Furthermore, excessive sweat may roll off the skin or remain trapped in the clothing system. It is assumed that sweat evaporated from the skin surface can deliver more cooling than when sweat evaporates from a garment [2]. When sweat evaporates from a garment, the location of the evaporative phase change is moved from the skin to the outer surface of the garment where heat is extracted from the external environment rather than from the surface of the skin. The overall cooling effects of sweat evaporation for clothed persons has been carried out on human subjects as well as using thermal manikins [3-6]. However, the outcomes have been difficult to related to clothing design and fabric selection because the

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data are confounded by heat loss due to the latent heat of vaporization which cannot be assessed separately [7]. The cooling generated by wet clothing, independent of body metabolic heat loss, and the associated latent heat of vaporization, have not been separated. To address this issue, a series of tests was carried out to measure the cooling created by evaporation not impacted by metabolic heat production or subsequent sweating.

2 Methods and Procedures

Wind-tunnel tests were conducted on cotton, polyester, nylon and silk fabric samples to determine the cooling generated by water evaporation from the fabric samples under controlled temperature, humidity, and air velocity conditions. The temperature drop due to water evaporation was measured using a thermocouple temperature probe imbedded into the surface of a mounting platform. A “control” configuration which did not include a fabric sample placed on the temperature sensor was used as a reference. All tests were performed three times and the data averaged.

2.1 Wind Tunnel

A negative pressure laminar air flow wind-tunnel was used for this study. The wind-tunnel measured 2.3 meters in length, 40.5 cm in height and 30.5 cm in width. Fabric samples were placed onto a mounting platform which was positioned in the center of the wind-tunnel 1.2 meters from the inlet. The air velocity was maintained at 1.5 m/sec. Air temperature was maintained at 22 °C (± 2 °C) and relative humidity maintained at 15% ($\pm 5\%$).

2.2 Fabric Samples

Four types of fabric materials were tested. These included 100% cotton, 100% polyester, 100% nylon, and 100% silk. Each sample was 5.0 cm $\times$ 6.0 cm in size.

2.3 Mounting Platform

Fabric samples were placed onto a convex shaped mounting platform made of water impermeable Styrofoam. Samples were placed onto the platform surface at a 45° angle relative to the horizontal and oriented into the wind-tunnel airflow. The platform allowed a fabric sample to lay smoothly on the surface. To prevent potential displacement of the fabric sample by the air flow, each sample was secured to the platform by four corner pins. The platform provided gravity run-off for all excess water. A precision type K fine-wire glass insulated thermocouple was embedded into the surface of the mounting platform which provided a temperature measurement of the underside of the fabric sample. The digital thermometer provided an accuracy of ± 0.1 °C

2.4 Test Protocol

Fabric samples were spray irrigated with water 10 seconds prior to the start of each test run. The irrigation water was maintained at room-temperature prior to application and was applied until

a fabric sample was saturated. Saturation was determined when the water was dripping freely from the mounting platform. The fabric samples tested for the “moist” condition were initially saturated with the irrigation water but then manually squeezed to remove all excess water. This procedure was subjective. No water was added to any of the samples later during the tests. The temperature drop created by each sample was measured for duration of 15 minutes. The temperature on the surface of the platform and bottom of the fabric sample was recorded at 0.5 minute, 1.0 minute, 1.5 minutes, 2 minutes, 5 minutes, 10 minutes and 15 minutes. All fabric samples, including the saturated and moist conditions, were tested three times.

3 Results

3.1 Control

Table 1 summarizes the evaporative cooling observed for the “control” condition in comparison to the saturated cotton fabric sample. The temperature drop seen for the control condition was 5.1 °C during the first five minutes and declined to 4.4 °C afterwards. However, the temperature drop observed for the cotton sample was 8.6 °C during the first 10 minutes but showed no decline afterwards.

Table 1: Temperature drop observed for the “control” condition and saturated cotton sample. Values represent the average of three trials

Exposure Time (Minutes)	“Control” Configuration (°C)	Cotton Sample (°C)
0	0	0
0.5	3.4	4.2
1.0	4.4	6.2
1.5	4.7	7.3
2	4.8	7.9
5	5.1	8.5
10	4.5	8.6
15	4.4	8.6

3.2 Water Content

Table 2 summarizes the evaporative cooling observed for the “moist” and the “saturated” cotton samples. During the first 1.5 minutes of exposure, cooling created by the “moist” sample was substantially greater than by the “saturated” sample. However, after two minutes of exposure, the “saturated” cotton sample exhibited substantially greater cooling than the “moist” cotton sample.

3.3 Fabric Materials

Table 3 summarizes the evaporative cooling for the cotton, polyester, nylon and silk saturated fabric samples. During the first 1.5 minutes the temperature drop measured was greater for

Table 2: Cotton sample temperature drop observed for the “moist” and “saturated” conditions. Values represent the average of three trials

Exposure Time (Minutes)	Cotton Sample (Moist) (°C)	Cotton Sample (Saturated) (°C)
0	0	0
0.5	6.7	5.7
1.0	7.8	7.4
1.5	8.3	8.2
2	8.4	8.5
5	8.5	8.8
10	8.5	8.8
15	8.5	8.8

Table 3: Evaporative cooling observed for the saturated cotton sample, polyester sample, nylon sample, and silk sample. Values represent the average of three trials

Exposure Time (Minutes)	Cotton Sample (°C)	Polyester Sample (°C)	Nylon Sample (°C)	Silk Sample (°C)
1.5	8.5	8.3	9.1	9.2
2	9.1	8.9	9.2	9.3
5	9.6	9.5	9.3	9.4
10	9.7	9.6	9.2	9.4
15	9.7	9.6	9.0	9.4

the Nylon and silk samples in comparison to the temperature drop measured for the cotton and polyester samples. However, this relationship was reversed after five minutes when the cotton and polyester cooling was observed to be greater than that for the nylon and silk samples.

4 Analysis

Comparing the temperature drop created by the cotton sample with the temperature drop created by the “control” condition suggests that the improved cooling for the saturated cotton fabric sample was due to the water contained in the fabric sample. Since the testing platform was made of non-absorbing material, water applied to the platform flowed off the surface freely with only a surface layer of water remaining due to the surface adhesion. This condition provided only a limited amount of water for evaporation. As shown in Fig. 1, the “control” cooling decreased over time while the cotton fabric sample exhibited no such decrease. This difference in cooling suggests that the amount of water retained by the fabric sample determined the final cooling capacity as well as the duration of the cooling process. The T-test applied to the equilibrium conditions, i.e., the 2-15 minute time segments, yielded $p = 0.001$.

The relationship between water retention in a fabric and the evaporative cooling capacity of the sample is illustrated in Fig. 2. The saturated (high water content) cotton sample exhibited the greatest overall cooling than the moist sample. However, the moist sample exhibited a greater temperature drop during the first 1.5 minutes while the saturated sample exhibited a greater temperature drop afterwards. The dynamics of the relative cooling advantages offered over time

Fig. 1: Evaporative cooling for the saturated cotton sample in comparison to the “control” over a 15 minute period

Fig. 2: Evaporative cooling observed for the saturated and the moist cotton samples. The moist sample generated a greater temperature drop during the first 1.5 minutes while the saturated sample generated a greater temperature drop afterwards

by each of the fabric samples is illustrated in Fig. 3. This suggests that the maximum cooling does not always occur when the water retained in a sample is high. The T-test applied to the equilibrium conditions, i.e., the 5-15 minute time segments, yielded $p = 0.007$.

A comparison of the cooling dynamics exhibited by the cotton, polyester, nylon, and silk samples is illustrated in Fig. 4. It is seen that the cotton and polyester samples offered greater evaporative cooling overall than the silk and nylon samples. It is important to note, however, the nylon and silk samples initially provided greater evaporative cooling. These differences were statistically significant. The T-test was again applied to the equilibrium conditions. The cotton/polyester comparison yielded $p = 0.05$, the cotton/silk comparison yielded $p = 0.001$, and the cotton/nylon comparison yielded $p = 0.006$. This finding again supports the concept illustrated in Fig. 2 and Fig. 3 where the moist sample exhibited greater initial evaporative cooling than the saturated sample.

Fig. 3: Illustration of the relative evaporative cooling advantage offered by the moist sample relative to the saturated sample during the first 1.5 minutes followed by a cooling disadvantage afterwards

Fig. 4: Evaporative cooling observed for the cotton, polyester, silk and nylon fabric samples after 1.5 minutes of air flow exposure

5 Discussion

The water introduced into a fabric is dispersed and also retained in response to the interaction of water molecule surface tension, cohesion and adhesion to the fabric fibers. These forces interact

with the water droplets and the fabric fibers which influence the total amount of water that is stored in the fabric and also determines the surface area over which the water can evaporate. The ability of a fabric to capture water and distribute the water over the material will dictate the evaporation capacity of the material. The distribution of the water over the fabric material determines the evaporation capacity of the fabric material which will be greater than the evaporation capacity of the skin where the water remains attached to the skin in the form of droplets as illustrated in Fig. 5. Fig. 6 illustrates the mechanism by which fibers promote the spread of water over a larger area in a fabric that increases the overall cooling capacity through evaporation. This is illustrated in Fig. 3 showing the cooling advantage offered by wet fabrics. However, the evaporation efficiency of water from a fabric can also be influenced by the total amount of water that is retained within the fabric. As seen in Table 2 and Fig. 3, the cooling efficiency is optimal at lower “wetness“ levels, i.e., moist conditions, while cooling over an extended period of time is promoted by higher water content levels.

Fig. 5: Sweat droplets accumulating on the surface of the human skin as a result of water molecule cohesion and adhesion. This limits the spread of water over the skin and reduces the potential of evaporative cooling from the skin

Fig. 6: Interaction of water droplets with fabric fibers that increases the available surface area for evaporation and subsequent skin cooling

The results of this study suggest that a person wearing an appropriate garment experiences better cooling and more comfort than a person without a garment. Such an approach is observed for experienced athletes who wear a shirt when engaged in athletic competitions. This is illustrated in Fig. 7.

Fig. 7: Runner wearing a T-shirt to maximize cooling through garment sweat evaporation (Hong Kong Sports Photography Association Photo)

6 Conclusions

Based on the results obtained in this study, the following conclusions can be reached:

- Wet clothing can create cooling that is significantly greater than cooling generated by water evaporating directly from the skin
- Initial cooling by wet fabrics is greatest when a fabric contains a minimal amount of water (moist) while cooling is optimal over a longer period of time when the fabric contains high levels of water (saturated).
- The level of cooling created by wet clothing over time is dictated by the total water content in the fabric. The greater the amount of water, the longer the cooling effect over time.

This study also helps explain why persons frequently report improved comfort in hot environments when wearing single-layered clothing that does not absorb much sweat. The materials that absorb little water such as nylon and silk provide immediate cooling while cotton provides better cooling later. Application of this information can help in the design and development of future clothing systems that create both immediate and long-term improvements in comfort and safety for the users.

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