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Original

Comparison of regenerated bamboo and cotton performance in warm environment

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Abstract

Different materials have been used to fabricate summer (warm environment) clothing, such as cotton, nylon, neoprene, polyester and 100% synthetic fibers. However, because of their mechanical and thermal properties, nylon and polyester cloth has a tendency to rot and chafe in damp conditions. In addition, close-fitting synthetic fibers and neoprene make some wearers feel uncomfortable because of the rapidly occurring body skin sweat. However, bamboo and cotton have demonstrated to have low thermal conductivity. Hence, they are excellent materials to fabricate summer clothing. In this study, a theoretical analysis complemented with practical measurements of thermal properties of three different rib knitted structures produced from a 30 tex yarn of three blends of fibers (100% regenerated bamboo, 100% cotton and 50:50 regenerated bamboo: cotton) was realized to compare bamboo and cotton performance in warm environment. Obtained results show that garment thickness and heat storage rate in the human body can significantly be reduced by using 100% regenerated bamboo, without compromising comfort.

Keywords: Warm environment clothing; Protective materials; Bamboo garment; Modeling behavior

1. Introduction

To maintain its temperature in a safety interval, the human body needs to eliminate excessive warmth. To eliminate the excessive warmth, it changes the amount of blood circulating through the body and it increases the amount of liquid transpiration on the body skin. These actions are commonly self-activated once its average internal temperature overpasses the 98.6 °F (37 °C) (Jessen, 2012; Hockey & Rew, 1996). Also, when the environmental temperature is close to the temperature of the body skin, the internal temperature regulation becomes more difficult. If the air temperature is equal to or higher than the temperature of the body skin, the blood that circulates close to the body skin cannot help to decrease the human body temperature (Widmaier, Raff, & Strang, 2013). In addition, if the environmental humidity increases, the evaporation of the liquid transpiration on the body skin decreases. Hence the effort of the body to maintain a safety temperature is affected, excessive blood arrives to the body skin and less arrives to the active muscles, the brain, and the other internal organs (Marieb & Hoehn, 2012). As a consequence, the body capacity to work decreases and a premature exhaustion due to the heat stress is experienced.

The previously described conditions are commonly found in seaside cities and also in many jobs in industrialized countries (Auliciems & Szokola, 2007). Different approaches have been used to prevent and minimize the effects of premature exhaustion due to heat stress in hot and warm environment. On the one hand, supplements such as drinks specially designed to replace body fluids and electrolytes have been used. They may be of benefit for workers who have very physically active occupations but they may add unnecessary sugar or salt to the diet (Jones, 1992). On the other hand, protective clothing has been used to reduce the effects of environmental stress factors. The materials used in clothing which has been designed for warm and hot weather must be able to give comfort and durability. It must allow air to circulate freely across the skin, which can help to keep the body cool. In addition, the material needs to resist the sun's rays in order to help delay the onset of sunburn.

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Materials such as cotton, nylon 6, nylon 6.6, neoprene, polyester, and 100% synthetic fibers have been used for warm and hot environment clothing fabrication. However, pure nylon and polyester cloth have a tendency to rot and chafe in damp conditions. In addition, even a close-fitting and lightweight garment made of 100% synthetic fiber and neoprene make some wearer feel uncomfortable because of the rapidity of body skin sweat. On the other hand, cotton and bamboo are a tribe of flowering perennial evergreen plants in the grass family Poaceae (Das & Chakrabarty, 2008) which is an excellent candidate for warm environment clothing fabrication due to its mechanical and thermal properties (Mounika, Ramaniah, Prasad, Rao, & Reddy, 2012; Prakash, Ramakrishnan, & Koushik, 2013; Raimundo & Figueiredo, 2009).

In this study, the thermal properties of three different rib knitted structures produced from a 30 tex yarn of three blends of fibers (100% regenerated bamboo, 100% cotton and 50:50 regenerated bamboo: cotton) were used to compare the performance of regenerated bamboo and cotton in warm environment. Standardized values for metabolic rate, for different physical activities, were used in the calculations. The heat storage rate in the human body *vs* clothing insulation for the considered yarn blends was calculated. In addition, the relation of clothing thickness and clothing isolation was established. Theoretical results show that the garment thickness as well as the heat storage rate can significantly be reduced in the human body by using 100% regenerated bamboo, without compromising comfort.

2. Heat balance and exchange modeling of human body and clothing

The interaction of heat with a dressed human body can be described from an arbitrary flux of heat impinging with the dressed body. Once the flux of heat is inside the front surface of the dressed body, the behavior of the flux of heat is determined by the rates of storage, production and losses. By conservation of energy, the net heat storage must balance the net production and losses within the unit volume of the dressed body. Using the nomenclature of Table 1, this can be written as: (Bartkevicius, Rackiene, & Virbalis, 2008; Holmer, 2006)

$$S = (M - W) - (R + C + E + K) - (C_{res} + E_{res}) \quad (1)$$

where S is the heat storage rate, M is the metabolic energy production rate, W is the external mechanical work, and R, C and E are the radiation, convective and evaporative heat loss from the skin, respectively. K is the conduction to the surfaces by direct contact with skin or clothing, C_{res} and E_{res} are the convective and evaporative heat losses from respiration, respectively. The units of the rate of storage, production and losses are energy per second, which are joules per second ($\mathrm{J\,s^{-1}}$) or watts (W). It is useful to standardize over persons of different sizes by using units of watts per square meter ($\mathrm{W\,m^{-2}}$) of the body surface area.

The energy balance components, M and W, describe the heat production in the human body. The other components (R, C, E, K, C_{res}, and E_{res}) describe the heat consumption. Thermal energy balance is obtained when the heat storage rate is equal to zero ($S = 0$). In addition, when the heat storage rate is positive ($S > 0$) the body temperature increases and there exists a heat gain, hence the body needs to be cooled. On the other hand, when the heat storage rate is negative ($S < 0$) the body temperature decreases and there exists a heat loss, hence the body needs to be heated.

Table 1
Nomenclature used in the theoretical modeling.

$\frac{A_r}{A_{Du}}$	Fraction of skin surface involved in heat exchange by radiation	$\frac{A_r}{A_{Du}} \approx 0.77$ n.d.
C	Convective heat loss from skin	$\mathrm{W\,m^{-2}}$
$CORR$	Correction factor to clothing insulation	n.d.
C_{res}	Convective heat loss from respiration	$\mathrm{W\,m^{-2}}$
E	Evaporative heat loss from skin	$\mathrm{W\,m^{-2}}$
E_P	Emissivity of the human body	$E_p \approx 0.97$ n.d.
E_{res}	Evaporative heat loss from respiration	$\mathrm{W\,m^{-2}}$
F_{cl}	Reduction factor for sensible heat exchange due to the clothes warm	n.d.
f_{cl}	Clothing are factor	n.d.
h_c	Convective heat transfer coefficient	$\mathrm{W\,m^{-2}\,C^{-1}}$
h_r	Radioactive heat transfer coefficient	$\mathrm{W\,m^{-2}\,C^{-1}}$
I_{cl}	Intrinsic insulation of the clothing	clo
i_{mdyn}	Dynamic permeability index for the clothing	n.d.
i_{mst}	Static permeability index of the clothing	$i_{mst} \approx 0.38$ n.d.
L_r	Lewis relation	$L_r = 1665\,^{\circ}\mathrm{C\,kPa^{-1}}$
M	Metabolic rate	$\mathrm{W\,m^{-2}}$
P_a	Vapor pressure of the environment	kPa
σ	Stefan–Boltzmann constant	$\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$
P_{sat}	Saturation vapor pressure	kPa
P_{sk}	Saturated vapor pressure at mean skin temperature	kPa
R	Radiation heat loss from skin	$\mathrm{W\,m^{-2}}$
R_a	Static insulation of boundary air layer	$R_a \approx 0.11\,\mathrm{m^2\,^{\circ}C\,W^{-1}}$
R_{etdyn}	Dynamic total water vapor resistance of the clothing system	$\mathrm{m^2\,kPa\,W^{-1}}$
RH	Relative humidity	(%)
R_{tdyn}	Dynamic thermal resistance of the clothing system	$\mathrm{m^2\,^{\circ}C\,W^{-1}}$
R_{tst}	Static insulation of the clothing	$\mathrm{m^2\,^{\circ}C\,W^{-1}}$
S	Rate of body heat storage	$\mathrm{W\,m^{-2}}$
T_a	Air temperature	°C
T_G	Globe temperature	°C
T_{mrt}	Mean radiant temperature	°C
T_S	Dry temperature	°C
T_{sk}	Skin temperature	°C
V_a	Air velocity	$\mathrm{m\,s^{-1}}$
W	Mechanical power	$\mathrm{W\,m^{-2}}$
WS	Walking speed	$\mathrm{m\,s^{-1}}$

2.1. Heat production components

In heat production components, the metabolic rate M is defined as the rate at which the body utilizes food to produce energy. The unit of metabolic rate is the Met, where