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A Review On: Analysis Of The Properties Of Thermal Insulation Materials

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ABSTRACT

Clothing insulation is one of the important factors of human thermal comfort assessment. Thermal insulation is the reduction of heat transfer (i.e., the transfer of thermal energy between objects of differing temperature) between objects in thermal contact or in range of radioactive influence. Thermal insulation can be achieved with specially engineered methods or processes, as well as with suitable object shapes and materials. Heat flow is an inevitable consequence of contact between objects of different temperature. Thermal insulation provides a region of insulation in which thermal conduction is reduced or thermal radiation is reflected rather than absorbed by the lower-temperature body. The term thermal insulation can refer to materials used to reduce the rate of heat transfer, or the methods and processes used to reduce heat transfer. Heat energy can be transferred by conduction, convection, radiation or when undergoing a phase change. For the purposes of this discussion only the first three mechanisms need to be considered. The flow of heat can be delayed by addressing one or more of these mechanisms and is dependent on the physical properties of the material employed to do this. Predicting the pattern of clothing adjustment to climate change can provide important basis for thermal comfort and energy consumption analysis. To achieve reliable results, it is necessary to provide precise inputs, such as clothing thermal parameters. These values are usually presented in a standing body position and scarcely reported locally for individual body parts. Moreover, as an air gap distribution is both highly affected by a given body position and critical for clothing insulation, this needs to be taken into account.

KEYWORDS

Thermal insulation, Cold-weather PPC, Clothing insulation, Clothing layers, Heat and mass transfer.

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INTRODUCTION

Clothing can be described in physical term of thermal insulation for the heat exchange of man with his immediate thermal environment [1]. In thermal comfort theory, clothing insulation is an important factor that affects thermal sensation [2]. People can adjust their clothing insulation to suit their own thermal comfort requirement [3,4] and reduce energy consumption in buildings [5]. Therefore, clothing adjustment is a powerful behavioural adaption mode to weather change [6,7]. Predicting the pattern of clothing adjustment to weather change provides important basis for thermal comfort and energy consumption analysis [8,9].

Outdoor temperature is an important climatic factor to the change of indoor clothing. Various models were developed to predict the change of indoor clothing insulation with outdoor temperature, based on different regression functions. De Dear and Brager used an exponential decay function to fit the change of the mean clothing insulation for occupants of each building with the mean outdoor effective temperature at the time of the survey, based on ASHRAE RP-884 database. According to this model, 40% of the variance in clothing insulation was explained by variations in the outdoor climatic index [10]. Thermoregulation of human body aims at maintaining body core temperature in a narrow range and depends on metabolic heat production and the exchange of heat between skin and environment. When the human body is covered with clothing, it affects human physiological regulation mechanisms. Thus, the design and material aspects of functional clothing (e.g. protective or sport clothing) requires a detailed understanding of heat transfer processes. In the clothing research, heat transport is usually assessed by hot plates, thermal cylinders or thermal manikins in steady-state measurements. The experimental methods of assessing heat transfer require the availability of prototypes and testing facilities (e.g. climatic chambers) [11], which can be costly and time consuming.

Nowadays, global climate is changing and extreme cold spell incidents are becoming increasingly frequent and intense in recent years. During extreme cold spell incidents, people have a much greater chance to suffer from cold stress, which endangers human health, wellbeing and safety. Long-time exposure to cold stress could induce cold-related illnesses and injuries, e.g., cracked skin, chilblain, frostbite, trench foot, cognitive impairments, hypothermia or even deaths [12-14]. Clothing governs heat and mass transfer between the human body and the ambient environment. Local clothing thermal properties may vary considerably over the body, thus, having a major impact on the development of skin temperatures, sweating, and perception of thermal sensation and comfort [15]. Therefore, clothing, intended as a functional necessity to protect against harsh climate conditions and not as an ornamental accessory, has always been one of the main primary needs of mankind to adapt to the thermal outdoor environment. Indeed, variety in clothing is attributable also to the different local climate conditions where populations were living [16].

Thus, the human body covered in garments constitutes a complex system of thermal exchange, where heat and vapor produced by skin are first transferred to the gap between skin and the clothes and then throughout the textile material of the cloth, which is porous, towards the external environment [17]. Therefore, heat is transferred by means of conduction, convection and radiation phenomena, while water vapor by means of evaporation, absorption, condensation, de-absorption and transpiration (Fig. 1) [18].

Taken together, in cold-humid climates in winter, both moist clothing and high air humidity have profound effects on clothing performance and human thermal comfort. However, what are the thermal behaviours in the clothing microenvironment under actual wearing situations, and how to evaluate the clothing moisture effects caused by cold-humid environments on human thermal comfort remain unknown [19].

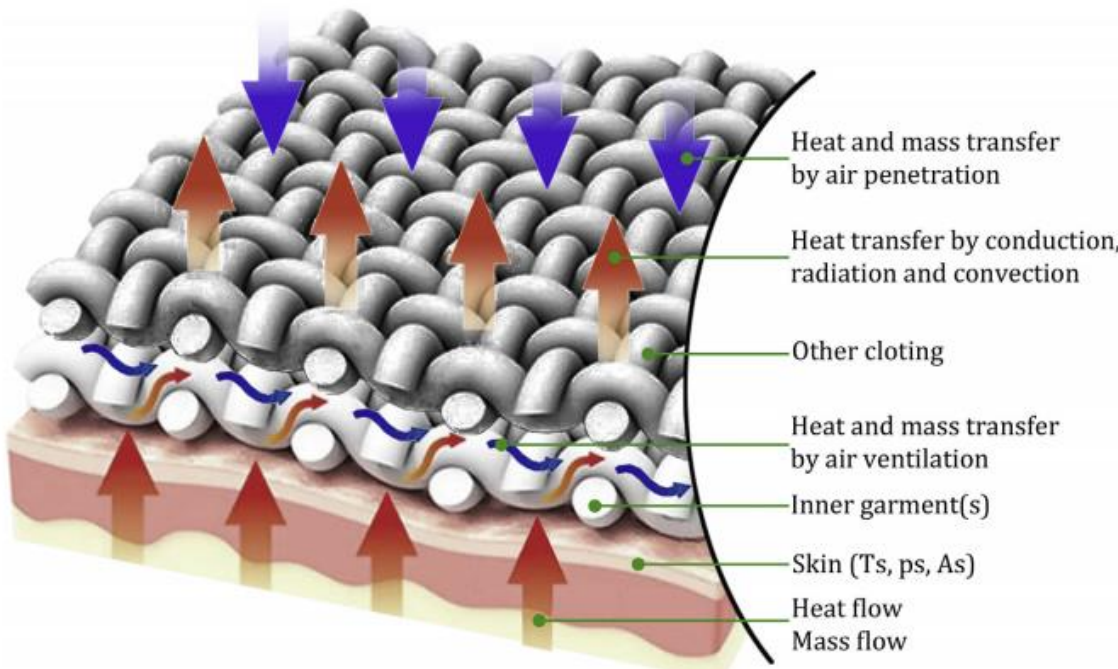

Fig.1. Heat and water vapor exchanges between the human body and the environment throughout clothes.

Effect of clothing insulation

The effect of various clothing insulation values on the time course of core temperature, mean skin temperature, mean trunk temperature and mean heaters' temperature is illustrated in Fig.2. All simulations were carried out at metabolic rate of 1.6 met under the ambient temperature of 15 °C and the PHCS's heating power was 20 W. All the four studied temperatures, as expected, increased with the increasing clothing insulation. Though core temperatures at the four clothing insulation levels rose from 37.28 °C to 37.81 °C during the 60-min simulations, clothing insulation had no pronounced effect on the increment of core temperature among the four simulation cases.

Regarding the mean skin temperature, it dropped from 32.65 °C to about 32.10 °C during the initial 20 min and then was relatively stable throughout the remaining 40 min under the four clothing insulation levels (i.e., 1.0, 1.5, 2.0 and 2.5 clo). This revealed that all the four simulation cases could be able to help occupants maintain mean skin temperature in the thermoneutral range, despite those values were quite close to the lower limit (i.e., 32.0 °C [20]). Similarly, the mean trunk temperature at the four levels of clothing insulation decreased from 33.67 °C to 32.90 °C within the initial 20 min and it became stabilized throughout the remaining 40 min of the simulation. For the mean heaters' temperature, it was maintained at 36.19, 36.32, 36.40 and 36.46 °C under clothing insulation levels of 1.0, 1.5, 2.0 and 2.5 clo, respectively. It might be argued from Fig.2 that clothing insulation had a limited impact on the further improvement of thermophysiological responses when the minimal insulation to attain occupant thermal comfort has been reached.

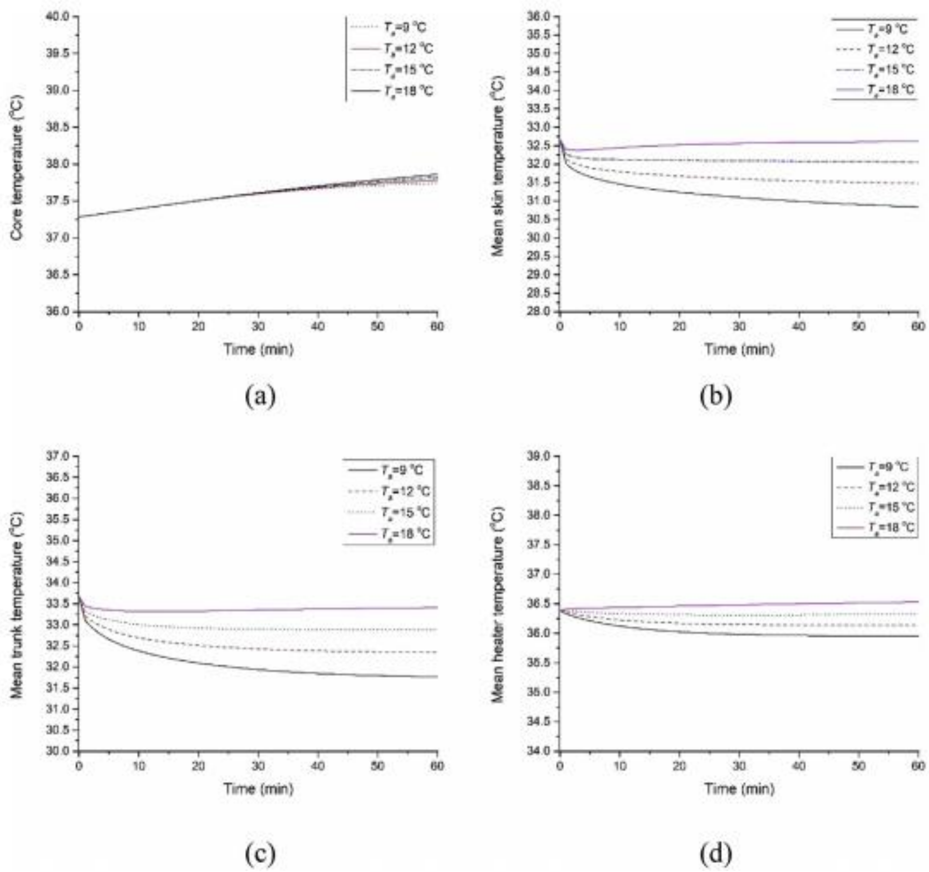

Fig. 2. Temporal variations of core temperature (a), mean skin temperature (b), mean trunk temperature (c) and the mean heaters' temperature (d) under four levels of clothing insulation (i.e., 1.0, 1.5, 2.0 and 2.5 clo) at 15.0 °C indoor temperature. Input parameters in the simulations: Icl= 1.5 clo, P= 20 W, M = 1.6 met.

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Obviously, wearing a set of personal heating clothing with thermal insulation of 1.0 clo and heating power of 20 W could help occupants attain thermal comfort at an indoor temperature of 15.0 °C with a metabolic rate of 1.6 met. If no heating was supplied, the mean skin temperature would drop to 31.73 °C (see Fig. 3), which obviously fell outside of the thermoneutral skin temperature range. Thus, clothing incorporated with auxiliary heating is effective to help occupants attain indoor thermal comfort in such a low indoor temperature. More important, the bulkiness of clothing did almost not change even six thin heaters were being embedded to the PHCS because the thickness of heaters is negligible (i.e., 1.2 mm).

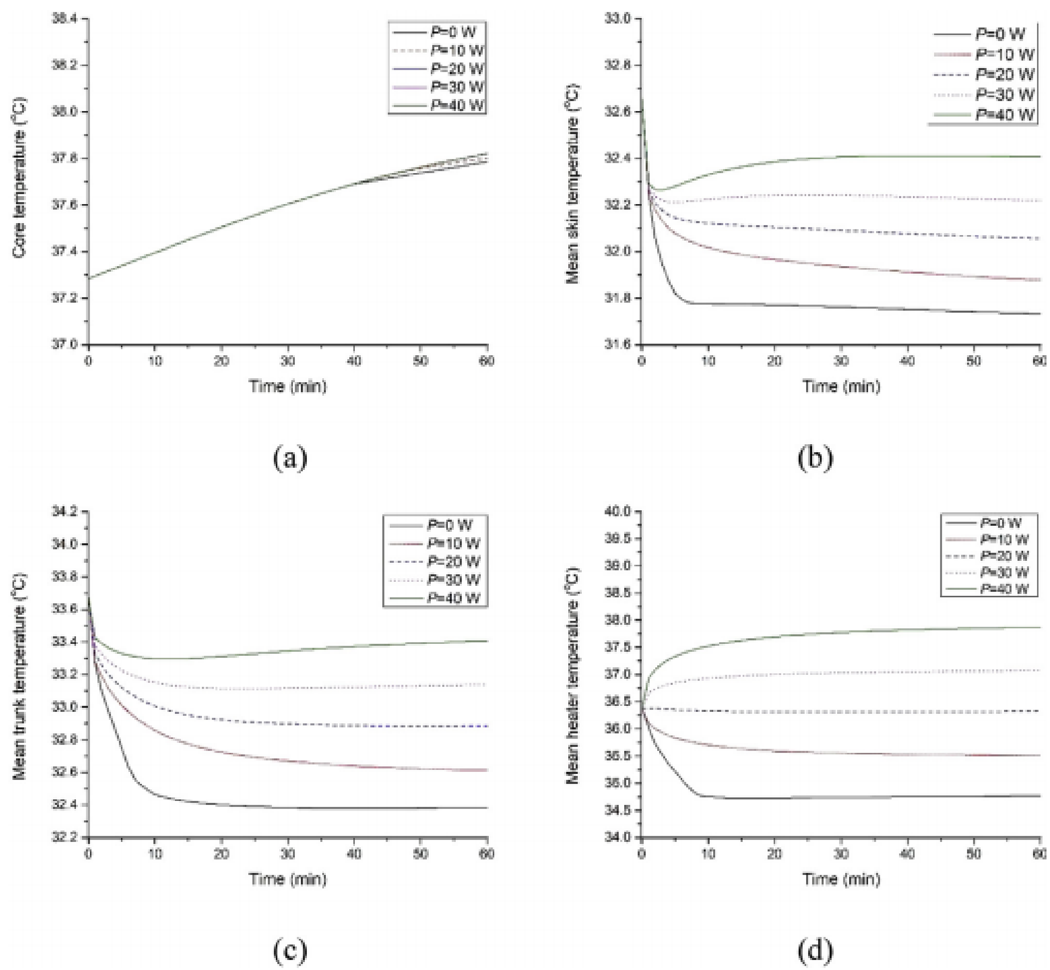

Fig.3. Temporal variations of core temperature(a), mean skin temperature (b), mean trunk temperature (c), and mean heaters' temperature (d) under four heating powers (i.e., 10, 20, 30, and 40 W) and the control condition (i.e., P= 0 W). Input parameters in the simulation: Icl=1.5 clo, Ta=15.0 °C, M=1.6 met.

Cold-weather PPC

Wearing cold-weather PPC influenced all measured physiological responses compared to wearing only a base layer. The 3-layer PPC increased MR by 8.8% and 10.0% during level and inclined walking respectively Fig.4. This corresponds to a 2.3% and 2.6% increase in MR per additional kg of clothing during level and inclined walking respectively. The same pattern was also observed for VO2 and HR (Table 1). Wearing the 3-layer PPC decreased GE (Table 1) and increased muscle activation in all three muscles, seen as an increase in % RMSmax by 9–29% compared with that wearing a base layer ensemble Fig.5. Walking with the 3-layer PPC ensemble was rated as more strenuous than walking with a base layer during both level and inclined walking (Table 2). The PCC did not alter stride frequency (Table 1) [21-28].

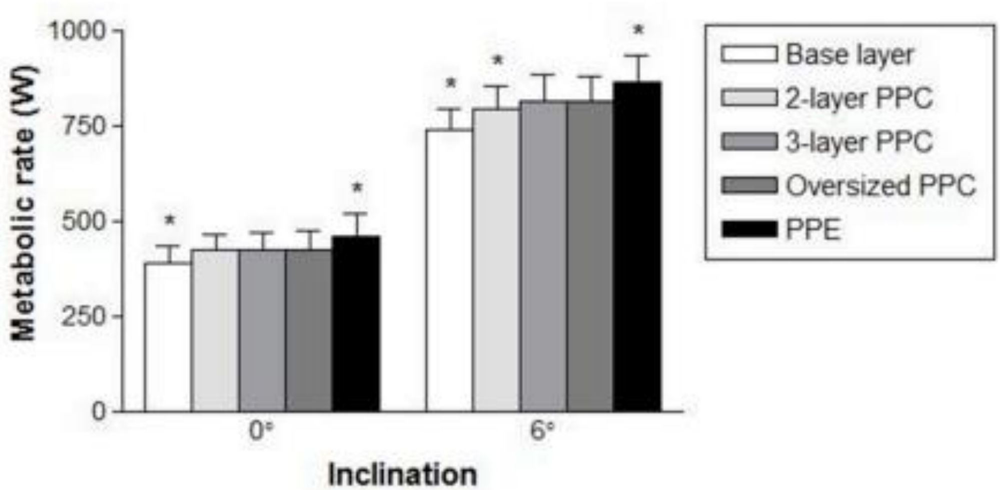

Fig.4. Mean (± SD) metabolic rate during level (0°) and inclined (6°) walking (5.0 km h-1) while wearing five different clothing ensembles. Significantly different from that wearing 3-layer PPC for level or inclined walking is indicated by asterisks.

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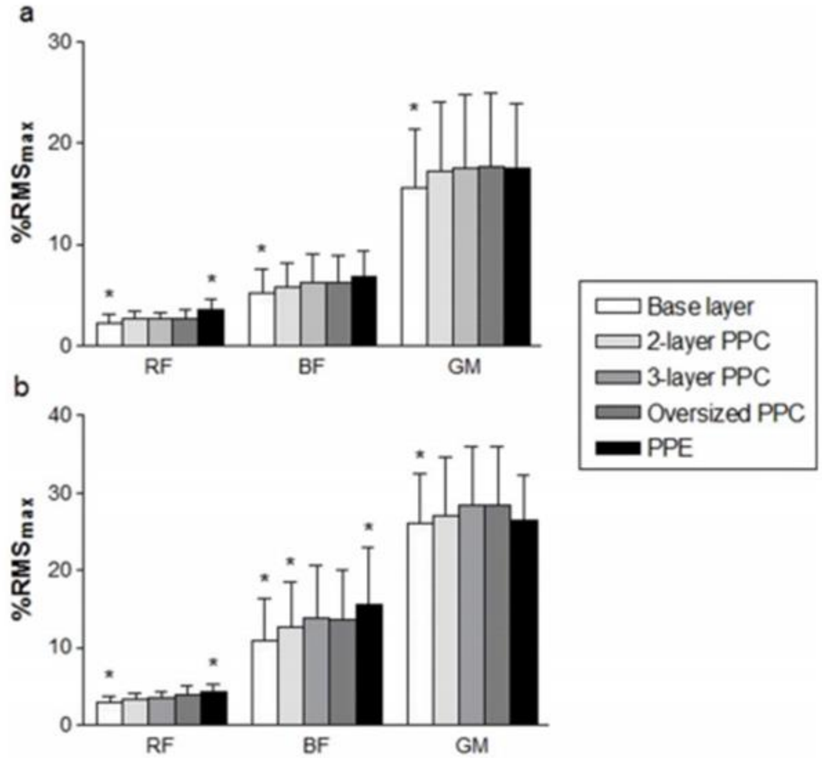


Fig.5. Mean (± SD) muscle activation level (%RMSmax) for rectus femoris (RF), biceps femoris (BF) and gastrocnemius medialis (GM) during (a) level (0°) and (b) inclined (6°) walking (5.0 km h-1) while wearing five different clothing ensembles. Significantly different from that wearing 3-layer PPC for level or inclined walking is indicated by asterisk.

Table 1 Mean (±SD) physiological responses and stride frequency at the end of the walking trials wearing five different clothing ensembles during level (0°) and inclined (6°) walking (5.0 km h^{-1}).

Measurement	Inclination	Clothing ensemble				
		Base layer	2-layer PPC	3-layer PPC	Oversized PPC	PPE
GE (%)	6°	15.8 ± 0.7 *	15.3 ± 0.7 *	15.0 ± 0.6	15.0 ± 0.6	14.6 ± 0.7 *
VO_2 (L·min^{-1})	0°	1.16 ± 0.13 *	1.25 ± 0.13	1.25 ± 0.13	1.26 ± 0.14	1.36 ± 0.16 *
	6°	2.18 ± 0.16 *	2.33 ± 0.17 *	2.38 ± 0.19	2.38 ± 0.18	2.53 ± 0.19 *
HR (beats·min^{-1})	0°	96 ± 15 *	98 ± 15	100 ± 16	102 ± 16	107 ± 16 *
	6°	126 ± 17 *	130 ± 18 *	134 ± 19	135 ± 18	142 ± 17 *
T_{re} (°C)	0°	37.3 ± 0.3	37.3 ± 0.3	37.3 ± 0.3	37.3 ± 0.4	37.4 ± 0.3
	6°	37.3 ± 0.3	37.3 ± 0.3	37.2 ± 0.3	37.2 ± 0.4	37.3 ± 0.3
T_{skin} (°C)	0°	30.9 ± 0.8	29.7 ± 1.2	30.5 ± 0.9	30.6 ± 0.9	31.0 ± 0.9
	6°	31.0 ± 0.8	29.8 ± 1.3	30.4 ± 1.0	30.5 ± 0.7	30.8 ± 0.7
Stride frequency	0°	55.8 ± 2.7	56.0 ± 2.7	56.2 ± 2.3	56.1 ± 2.5	54.3 ± 2.3 *
(strides·min^{-1})	6°	54.1 ± 3.3	54.9 ± 2.9	55.2 ± 3.0	54.6 ± 3.4	54.4 ± 2.9

Table 2 Median [range] subjective scores of rate of perceived exertion (RPE), thermal comfort and thermal sensation when wearing five different clothing ensembles during level (0°) and inclined (6°) walking (5.0 km h-1).

Measurement	Inclination	Clothing ensemble				
		Base layer	2-layer PPC	3-layer PPC	Oversized PPC	PPE
RPE[a]	0°	8 [6–11]*	9 [7–12]	9 [7–13]	9 [7–11]	10 [7–16]
	6°	10 [7–13]*	12 [9–14]	13 [8–16]	13 [9–15]	13 [10–17]*
Thermal comfort[b]	0°	1 [1–2]	1 [1–2]	1 [1–2]	1 [1–3]	1 [1–3]
	6°	2 [1–3]	2 [1–2]	2 [1–3]	2 [1–3]	2 [1–3]
Thermal sensation[c]	0°	0 [0–2]	0 [-1 - 1]*	1 [0–2]	1 [-1 - 2]	1 [0–2]
	6°	1 [0–2]	1 [0–2]	1 [0–2]	1 [0–2]	2 [1–3]*

Significantly different from that wearing 3-layer PPC for level or inclined walking. Multiple comparisons were used to identify possible differences between base layer and 3-layer PPC (effect of PPC), 2-layer PPC and 3-layer PPC (effect of layers), oversized PPC and 3-layer PPC (effect of fit/hobbling), PPE and 3-layer PPC (effect of PPE). n= 19.

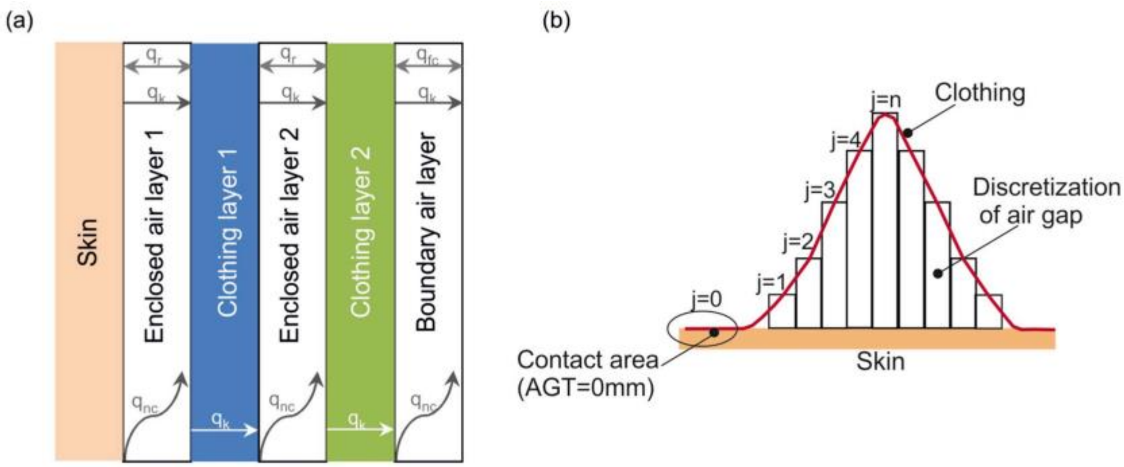
a 6, no exertion; 7, extremely light; 9 very light; 11, light; 13, somewhat hard; 15, hard; 19, extremely hard; 20, maximal exertion.

b 1, comfortable; 2, slightly uncomfortable; 3, uncomfortable; 4, very uncomfortable.

c 3, hot; 2, warm; 1, slightly warm; 0, neutral; −1, slightly cool; −2, cool; −3, cold.

Clothing layers

The thermal insulation of a fabric used to make clothing depends on thermal insulation of fibres and yarns but also on fabric thickness, since the bulk of the thermal resistance is provided by the entrapped air in fabric pores [22]. For fabrics with low porosity the type of fibre and fabric construction may play a role since the ratio of fibre material to the air will increase. The value of thermal insulation can be measured on a hot plate or obtained from the literature [24-38]. In the theoretical model it is assumed that fabric properties are constant and the thickness of the fabric is homogeneous. The porosity and air permeability of the fabric in respect to mass transfer are neglected as forced convection in an enclosed air layer is not considered in the model. To understand the heat exchange between human body and environment through the clothing, the entire system can be divided into three different segments as shown in Fig. 6.



q_k :Conductive heat transfer q_{nc} :Natural covective heat transfer
q_r :Radiative heat transfer q_{fc} :Forced covective heat transfer

Fig.6. Schematic diagram of heat transfer from human body to environment through clothing layers (a), principle of discretization of the enclosed air layer (b).

CONCLUSIONS AND FUTURE PERSPECTIVES

In the last decades, a broad research effort has been carried out on outdoor thermal comfort. The complexity of the topic, which is due to the many and rapidly changing variables, calls for the modeling of thermal comfort sensation for a normalized, standard subject. Clothing's thermal insulation is among the main variables, and it is linked to the clothes that individuals wear to defend themselves from the meteorological forcing of the outdoor environment. The wide variability of outdoor conditions does not allow hypothesizing clothing's thermal insulation as independent from the other factors characterizing climate and its daily and seasonal variability. Because, that clothing's thermal insulation preference, as expressed by an individual, depends also on personal thermal sensation linked to individual's comfort.

Thus, it appears as a necessary step to consider clothing's thermal insulation more in depth, by determining a mean preference value that also accounts for physiological factors linked to age and gender, Moreover, psychological and cultural factors influence clothing preferences, a specific population to the local climate zone. Based on the foregoing, our aim is to develop and introduce a new type of thermal insulation material for clothing in the future.

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