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Some Riddles in Clothing Thermal Behaviors

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ABSTRACT

Cloth wearing seems so natural that everyone is self-deemed knowledgeable and has some expert opinions about it. However to clearly explain the physics involved, and hence to make predictions for clothing design or selection, turns out as demonstrated below to be quite challenging even for experts. Cloth is a multiphased, porous and anisotropic material system and usually in multilayers. Unlike ordinary engineering heat transfer problems, the human body acts as an internal heat source in a clothing situation, thus forming a temperature gradient between body and ambient, and the sign of this gradient often changes as the ambient temperature varies. Our body also perspires and the sweat evaporates, an effective body cooling process via phase change. To bring all the variables into analysis quickly escalates into a formidable task. This work attempts to unravel the problem from a physics perspective, focusing on several rarely noticed yet critically important mechanisms involved so as to offer a clear and accurate depiction of the principles in clothing thermal comfort.

Key Words: *Cloth thermal comfort; Heat transfer between body, cloth and ambience; Changing sign of temperature gradient; Body sweating and phase change; Non-affinity between the behaviors of cloth and fibers.*

INTRODUCTION

In our discussions herein, the terms cloth and apparel are used synonymously, referring to the 3D structure formed by 2D fabrics, whereas textile as a more general term denotes to the materials made of fibers (natural or manmade). The term clothing is used to represent the act/status of wearing cloth.

So cloth can be defined as a designed 3D textile structure made of 2D fabrics that are networks of yarns formed in turn by spinning fibers. Cloth wearing is a behavior unique to human beings of virtually all societies, and it seems so natural that everyone is self-deemed knowledgeable and has some expert opinions about it. In fact, cloth has become such an indispensible part of our body and is often referred to as our "second skin" [1,2].

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In order to serve our body with multifaceted functions, clothes as materials are hierarchal, porous, and flexible with friction-induced system integrity so as to possess at least the following attributes [3,4]:

- Flexible and pliable to conform to human body, yet with desirable durability and resistance to various physical impacts for body protection;
- Soft and smooth to touch but with considerable resistance to abrasion and punctuation;
- Permeable for body perspiration and skin breathing, while with certain proof to external liquid penetration;
- Biocompatible to human body, yet chemically active for dying and printing;
- Light in weight to reduce wearing burden but rigid enough for body shaping;
- …

One of the major functions of clothing is for body protection against various hazards such as chemical, physical and hygienic perils, and thermal protection is one of the essentials. Cloth has been with us for thousand years, and we all wear clothes incessantly and keep such intimacy through our entire life. Even so cloth has seldom been taken as a materials system for thorough scientific research, as stated by Pan in [3]

> *"It is, therefore, surprisingly puzzling that the materials are so critically indispensable to us and, yet, have been so taken for granted that many rarely pause to think about textiles from a materials science point of view. Textiles, in fact, remain to be poorly understood in terms of materials sciences rigor".*

There have been some books with systematic treatment of the cloth thermal comfort [2,5] [6,7]. However when coming to current research activities in this area, what one may find is the utter rarity of the publications on the topic: typing the key phase "cloth thermal comfort" into the Web of Science generated a mere 23 articles, and very few of them deal with the fundamental principles of clothing, and none of those appears sufficiently comprehensive. Of the 23 papers, one with highest citations [8] is on an attempt to mimic the wool fiber structure into a manmade fiber, by assembling multi-scale fibrils into a tree-like channel net, thus providing an efficient heat transfer property. Another one [9] is on the theoretical analysis of water vapor diffusion through porous semi-permeable barrier textile material, to evaluate its applicability for sport applications.

One of the major causes in this situation may be attributed to the scientific intricacy of the topic. However incredible it may sound to many including scientists, investigation of the physics

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pertaining to clothing is rather complex: it involves several sub-systems including human body, the surrounding environment and the multilayered cloth, jointly forming a triad system with such influencing parameters as temperature, humidity, air flow, phase change dynamics and random causes, on top of the aforementioned complex material behaviors of cloth. This at least partly explains why comprehensive analysis of the clothing process dealing with those complications has rarely been done by researchers [1,10].

A further alarming sign is from a high profile paper [11] on clothing thermal comfort published in a prime journal, accompanied by an invited review article [12] and even an animated video clip. The paper itself dealt with the topic in an overly simplified frame and the analysis conducted is conceptually flawed, as disclosed in our e-letter to the editor [13] and detailed here in next section. This exposes an astonishing ignorance about this common human activity, even among some veteran physicists, and thus prompted the initiation of this article.

So this work represents an attempt, through examining the work by Hsu et al [11], to uncover several critical yet so-far-largely-ignored issues including, change sign in temperature gradient between body and ambience; the behavior non-affinity between cloth and its components; cloth as a porous composite, etc. Still it is not intended to be a comprehensive review of the topics, as there are, nonetheless, books [2,5 6] and a few published articles [1,14-16] for that. In the discussions below, to maintain focus on the targeted issues, even though there may be various improved forms of the original theories, we only use the one sophisticated enough, not necessarily the most updated/accurate, to facilitate our analysis.

A DUBIOUS NEW CLOTH

To reveal the hidden issues in clothing thermal comfort, we will first examine and discuss the idea and related flaws in the work by Hsu et al [11] of facilitating body heat radiative dissipation using a polyethylene (nanoPE) fabric. The nanoporous nanoPE used is a nonwoven piece with specified nano-sized holes that, according to the authors [11,12,17], allow the infrared radiation from the human body to dissipate through the new cloth easily, but shields the external visible light, thus eliminating the associated incoming heat while making the body visibly opaque to human eyes. The test results indicated that the nanoPE fabric swatch is “2.0°C lower than a cotton sample” [11].

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Most recently, the same group extended their idea of IR-transparent nanoPE further and developed a dual-mode fabric with an asymmetrical (dual) thermal emitter embedded in the asymmetrical thickness of nanoPE so that flipping the fabric will switch between the radiative cooling and heating functions [18]. This new extension however inherits the same faults in the first paper [11].

Acceding to their assumed validities of existing heat transfer theories to this case, for a piece of fabric swatch in contact with body skin in a steady state and ignoring the convection as in [11], the specific heat flux (energy per time per area) P transferred through the swatch is caused by both radiation (P_1) and conduction (P_2) as

$$P = P_1 + P_2$$

In the steady state, the temperature inside the cloth surface equals to the skin temperature T_s, yet the temperature T of outside cloth surface can be any point between $T_a \le T \le T_s$, depending on the value of the thermal Biot Number of the swatch [19], where T_a is the ambient temperature. In clothing cases at this temperature range, the radiation part is much more dominant [1,10], i.e., $P_1 >> P_2$, we can limit our discussion to thermal radiation, adopting the same symbols and formulation in [11], so that

$$P \approx P_1 = \varepsilon\sigma A(T_s^{\ 4} - T_a^{\ 4}) \qquad (1)$$

where σ in the equation is the Stefan–Boltzmann constant, A the radiating surface area, and ε the emissivity factor. T_s is again the skin temperature at = 33.5 °C (isothermal) and T_a the ambient temperature.

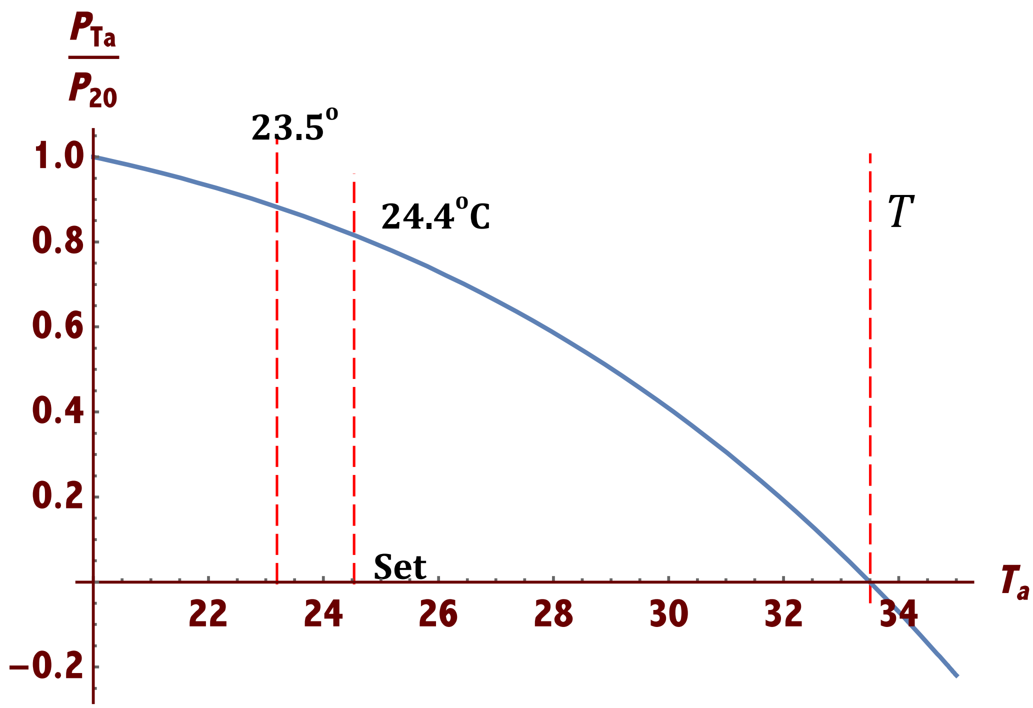

Fig. 1 The radiation heat loss as a function of ambient temperature

A simple plot based on Equation 1 is shown in Fig. 1, where for easy comparison the vertical axis represents the relative heat dissipation - the heat dissipation P at any given ambient temperature T_a normalized by the maximum value achieved when the ambient temperature is at the minimum, say T_a = 20.0 °C. It is clear from the result that at the practically fixed skin temperature T_s, a smaller T_a will generate a larger P value, **i.e., a more effective radiation heat release in a cooler environment.** This will be more apparent if the thermal conduction P_2 is included as it is also a decreasing function of the ambient temperature T_a.

In the study [11], the authors took all the measurements at the ambient temperature T_a = 23.5 °C (74.3 °F). However, at this level, body heat would unlikely be a concern for many people, after all it is still not warm enough for air conditioning (AC) whose set point is nearly 2 °F degree higher at T_a =76.0°F, according to ANSI/ASHRAE standards [20].

Once the ambient temperature T_a is beyond 76.0°F (24.4 °C), the AC is on and the relative heat dissipation in Fig. 1 is reduced, close to 0.70 of that when T_a = 20.0 °C, versus 0.76 when T_a = 23.5 °C. So the nanoPE will no longer be 2.0°C cooler than the cotton at this higher T_a. If the ambient temperature T_a further increases to around the skin temperature T_s =33.5 °C, this nanoPE will completely stop functioning! **In other words, once the weather is really hot,**

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exceeding the body temperature, this nanoPE will loose all its cooling power! That is, this nanoPE fabric indeed promotes body chilling, but only in cool days when $T_a < T_s$, or it resolves an imaged problem.

THE CULPRITS IN THE PROBLEM

Upon examining the topic to further expose the blunders in this IR-transparent nanoPE work, several causes are found responsible, as discussed below.

- Changing sign of the temperature gradient

The problem above shows how little we really understand the physics in clothing, and more importantly, it also divulges a rarely-noticed-yet-very-critical fact. Note again in Fig. 1, once we extend the ambient temperature T_a along the *x* axis further beyond the skin temperature T_s =33.5 °C (92.3 ºF), the relative heat dissipation will change its sign and turn into negative, meaning once the ambient temperature exceeds the skin temperature, instead of dissipating body heat to the ambient, this nanoPE approach will induce the heat from the ambience to the body. This new clothing would actually exacerbate the scorching of human body in hot days!

Thermal transfers via conduction, convection and radiation are all temperature gradient dependent. In this case, the temperature gradient is

$$\Delta T = T_s - T_a \qquad (2)$$

As the skin temperature T_s = 33.5 °C is practically fixed, and the ambient temperature T_a may be lower, equal to or greater than T_s. That is, the sign of the temperature gradient, hence the direction of heat transfer, will be reversed accordingly. That is, the entire system will experience a reversal in heat transfer direction around $T_a = T_s$.

According to the heat energy conservation equation, a complete form for Eq. 1 for a clothed body can be, for steady state and within certain limit, expressed as [21]

$$P = M - W - E - [Q] \qquad (3)$$

where *P* = the total heat flux,

M = metabolic rate energy generated by body, always positive;

W = mechanical work done by body to the ambience, always – W;

E = rate of total latent heat loss due to respiration and sweat evaporation,

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always - E ;
[*Q*] = total rate of sensible heat loss from skin (dry heat exchange), can be positive or negative as discussed below;

When the total heat flux *P* = 0, the heat body received and dissipated cancelled out so the body is in a steady heat balance; otherwise when *P* > 0, body receiving more heat, or *P* < 0, body loosing more heat. Of the parameters on the RHS of Eq. 3, the metabolic body rate *M* and the work performed by body *W* remain virtually constant so the body thermal comfort depends only on the remaining two factors now; the evaporation of the latent sweat *E*, which is always negative, i.e., sweating always promoting body cooling, and the sensible heat exchange *[Q]*. The signs of *[Q]* follow the sign of the temperature gradient; the positive sign represents the sensible heat from the ambient added to the body, while negative sign is the heat released from the body to the ambient, i.e.,

$$[Q] = \begin{matrix} Q \quad if\, \Delta T > 0, \quad a\, cool\, day \\ -Q \quad if\, \Delta T < 0, a\, hot\, day \end{matrix} \qquad (4)$$

In practice, improving body cooling would be necessary only in hot days when the ambient temperature exceeds the skin temperature, i.e., $T_a \geq T_s$ or ΔT < *0*, so that [Q] = - Q, fetching additional heat to the body. There will be

$$P = M - W - E + Q \qquad (3a)$$

So that *P* increases. Actions must be taken (e.g., body sweating more to raise – *E* or taking off cloth to reduce +*Q*) to return the body to the original thermal equilibrium. When weather is too hot T_s << T_a, we have to resort to other external means including a fan or air conditioner. Whereas in cold days,

$$P = M - W - E - Q \qquad (3b)$$

Note the subtlety of [Q]. In a hot day ΔT < *0*, so that [Q] = - Q: the body is gaining more heat in a hot day because of [Q]. While in a cold day ΔT > *0*, so that [Q] = Q: the body is loosing more heat due to [Q]. In other words, regardless in winter or summer, except at temperatures close to skin temperature, [*Q*] **is always working against body comfort, as illustrated in Fig. 2.**

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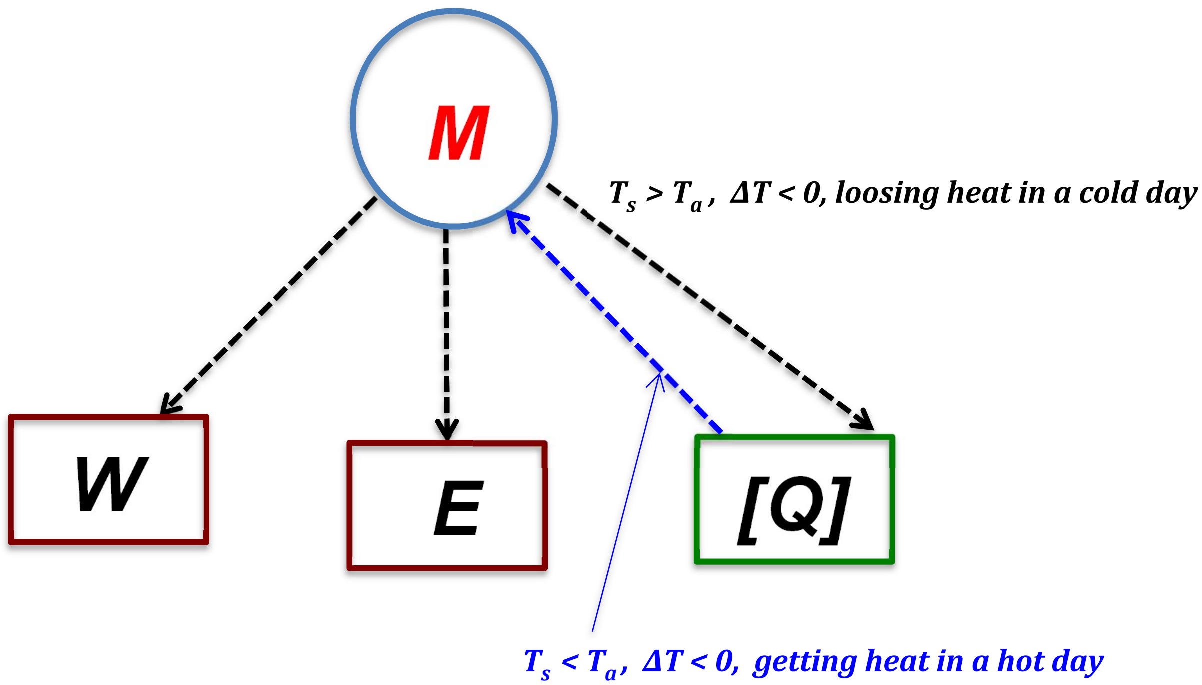

Fig. 2 body heat energy balance and temperature gradient effect

The implication of this reversing nature of [*Q*] can be profound; any scheme attempting to alter the cloth thermal comfort by controlling the sensible heat loss [*Q*], i.e., changing the thermal conductivity, convectivity and radiativity, could lead to unexpected and opposite result. This is exactly the problem when using the methodology in [11]. **Therefore, when assessing the efficacy of fabric thermal properties, the sign of the temperature gradient has to be such that it is consistent with the cloth wearing situation.**

By the way, among the three sensible heat loss mechanisms, usually heat radiation is by far the most effective [1,10]. In severe cold weather, e.g., in the arctic area $T_s \gg T_a$, as our body heat is still escaping via the direct heat loss – Q, a shield layer made by materials with high irradiativity such as metals is often adopted, preferably as a liner inside the cloth, to retain the body heat. Whereas in a severely hot case $T_s \ll T_a$, e.g., on-site viewing a live volcano, the sign of the temperature gradient still dictates the direct heat dumping +*Q* from the ambient to the body. It is desirable to put on a metallic sheet yet on top of the cloth to fend off the external heat.

It is also apparent now the evaporation heat loss *E*, being independent of the temperature gradient, is the only mechanism that provides an indispensible and effective route for body cooling.

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- The non-affinity phenomenon

Another intriguing thermal phenomenon in clothing, very puzzling for alert consumers, is the seemingly disconnection between the thermal properties of a cloth and its constituent fibers. The same (e.g., cotton) fibers can be made into a T-shirt to keep body cool in summer; or into a thick coat to keep body warm in winter, i.e., the thermal properties of the constituent fiber seem to have no connection with the thermal properties of the cloth system. We call this disconnection a non-affinity [3] between the behaviors of the system and its constituents.

This problem of the relationships between the micro constituents and the macro system is typical in statistical physics. The secret in this case lies in the fact a cloth is a porous composite and the fibers in the cloth are not the most essential element in determining the system thermal performance. Giving the excellent thermal insulation capacity of the air in the pores, the fibers only serve as the medium building the pores where air stays still and thus dominates the cloth thermal properties. That is, when coming to cold weather, it is the air in the cloth that keeps our body warm. A more theoretical analysis of this issue is given in [22], concluding that our tactilely sensed warmth is actually related to a compound parameter termed thermal effusivity ε, defined as

$$\varepsilon = \sqrt{c_p \rho k} \qquad (5)$$

where κ is the thermal conductivity, ρ the specific density, and c_p the specific heat capacity of the material. Hence a material with higher effusivity ε value will render a warmer touch feeling. For cloths made of the same fibers, the cloth density ρ can vary by several orders of magnitude [23] [24], while the κ and c_p values change only mildly. Therefore we adjust the thermal behaviors of the cloth by controlling its density; for the same fiber type, when fabric density is high as in a *T*-shirt, it can keep us cool in summer, whereas in winter we wear cloth made of low density fluffy fabric as in a coat to maintain the body warmth. That is, when coming to thermal behavior of the cloth, the air in pores, no longer an unintended entity, plays the dominant role in determining the cloth thermal performance.

In other words, this non-affinity in clothing thermal comfort suggests that the primary factor impacting cloth thermal comfort is the structure (or the porosity) of the cloth, and the fiber type plays a negligible role. Such non-affinity exists only in porous structures not in

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continuum. For instance, pulling a fiber out of a cloth results in a single fiber that lost all the cloth characteristics, whereas a gold particle from a nugget is still gold.

Further, this non-affinity exists between any two links along the hierarchy of a cloth system, e.g., the properties of **a single fabric swatch tested ex-situ may not be taken directly as the properties of a cloth on a human body** as did in [11].

- Fiber sorption heat

Another often ignored, nonetheless important mechanism in cloth thermal comfort has to do with the fiber sorption heat. Except in absolutely dry or wet cases, a cloth is a composite formed by fiber, air and moisture. There are two potential sources for moisture, the ambient relative humidity and the body sweating [25]. Consequently, any property of the cloth is a contested result of the contributions from all three constituents.

Once polymeric fibers absorb water, the interactions between polymer chains and water molecules are largely exothermic **so that the sorption heat is generated**, exerting significant thermal effect on the cloth, as reported by Mordon and Hearle [26]:

> *"For example, on going from an atmosphere of 18 °C, 45% r.h., indoors to one of 5 °C, 95% r.h., outdoors, the regain of wool would change from 10 to 27%. A man's suit, weighing 1.5 kg, would give out 6000 kJ owing to this change, that is, as much heat as the body metabolism produces in 12 h."*

- The cloth fitness and air gap between cloth layers

Clothing is only physiologically necessary in cold weather when $T_s > T_a$, whereas wearing cloth in summer is largely a societal propriety. Usually we have to wear additional undergarments, thus introducing the air gap between cloth layers even if we assume the cloth is a perfect fit so that the heat leaking via sides is negligible. As the still air possesses the highest thermal insulation [10], the inter-layer air gap will influence the system thermal balance drastically. Unfortunately, due to the complex nature of the inter-layer air gap in the cloth, e.g., its scale, distribution, physical state etc., incorporating this effect into theoretical analysis is still a pending challenge [27].

- Contact comfort vs. steady heat insulation

Then it has to be admitted that different fabric surface do cause different thermal sensation. Possible reasons for this are due mainly to the transient effect, not related to sensible heat loss

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Q. First, in any thermal transfer process, particularly in porous materials like textiles, there are essentially two distinctive stages involved; the transient and the steady stages; the system state including temperature distributions between the two stages are very different [28]. The study in [11] however **failed to differentiate them, e.g., no specification of the stage was given on the data measured**. Two different clothes may lead to the same thermal performance at the steady state; still they can cause distinctive transient thermal behaviors and hence our sense of warmth towards the cloth.

HOW TO DO IT RIGHT

The supreme question remains on how to appropriately evaluate the efficacy of a new material in improving the cloth thermal comfort. As in dealing with any phenomena, there are different types of method.

- Experimental approach

The first logical experimental approach to assess the efficacy of a new cloth is to actually wear it [29,30]. Wearing trial by human subject is the most direct. However like in many human sensory processes, the inherent bias in human preference often render the method ineffective [31]. Also it won't be allowed to employ human subject when the temperature is at extreme levels.

Then full scale manikins have been developed for evaluating the cloth performance including thermal behaviors [25,30,32]. How to scale the human size and to imitate closely the human metabolic and sweating functions remain to be the challenging issues.

- Theoretical consideration

Unfortunately the energy conservation relation in Eq. 3 is insufficient yet to be used for design optimization because of lacking the established relationships between the ambient temperature T_a and all the thermodynamic variables in the equation. For instance, at given metabolic rate M, the performed work W, and even the rate of sensible heat loss [Q], it is still not clear exactly how the rate of total latent heat loss E will change as a function of ambient T_a and the relative humidity.

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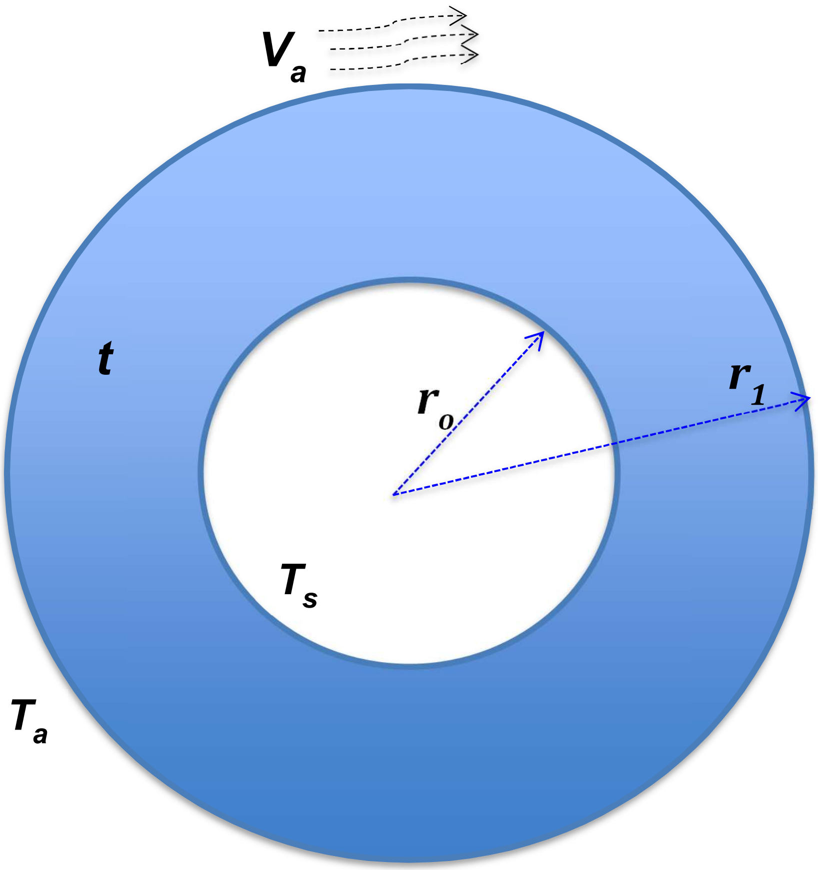

Fig. 3 Cross section of heat transfer through a clothed model.

However, we may use some known physical laws to tackle easier or local questions. For instance, consider the sensible heat case only so we know all the physics involved. We can choose the thickness of cloth t to minimize the body heat loss in a cold day at a given temperature gradient $T_s > T_a$. We assume the body-cloth system to be represented by a cylinder of the inner (equivalently body) radius r_0 and outer radius $r_1 = r_0 + t$ in Fig. 3. Then from [19] for steady state and an isotropic system, the total sensible heat lose Q per unit length through the cloth of total thickness t is the sum of all 3 mechanisms for sensible heat transfer:

$$Q = q_c + q_v + q_r = \Delta T \left(\frac{2\pi k}{\ln\left(\frac{r_o + t}{r_o}\right)} + 2\pi h_v (r_o + t)^2 \right) + 2\pi\varepsilon\sigma (r_o + t)^2 \left(T_s^{\,4} - T_a^{\,4} \right) \quad (6)$$

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where k is the thermal conductivity and h_v the cloth surface convectivity at wind speed V_a. The only variable in the equation is the cloth thickness t and its critical value t_c to minimize the heat lose can be derived as in thermal engineering [19] i.e., when $t = t_c$, there is

$$\frac{dQ}{dt} = 0 \qquad (7)$$

Furthermore, there are additional considerations related to cloth thermal comfort, such as the cloth mechanical behaviors, fabric finishes and washings etc. **Another additional concern is the interconnections among the thermal properties** of cloth: when changing one of them all others may be impacted. For more information, there is a recent review article on the complex and restrictive requirements for cloth comfort [4].

ON THE TRIAD OF "BODY- CLOTH- AMBIENCE"

The fundamental objective of research on the triad system of body-cloth-ambience, as stated by Parsons[21], is to establish "Thermal models integrate the principles of heat transfer, heat balance, thermal physiology and thermoregulation along with anthropometry and anatomy into a mathematical representation of the human body and its thermoregulatory systems. When presented on a computer, these 'complete' models can simulate the thermal responses of a person and provide a prediction of the dynamic response of the body to any environment."

So far we have accumulated some knowledge about the human thermoregulation, for instance, the sweating rate of human body can reach as high as 2 kg/h for a short period and 0.9 kg/h over several hours. Also it can be easily calculated that a human body of normal size would have roughly 2 m^2 total surface area, with normal 90 W/m^2 heat production capacity, yet only 0.25 kg/h sweat is needed to dissipate all the body heat generated. Therefore, the evaporation of the sweat has the potential to sufficiently dissipate the heat released from the human body to maintain the cloth heat balance [21 6 33], of course at the certain ambient conditions.

On the other hand, what we can present so far are almost all terminal or extreme values. To describe in detail the dynamics and stochastics in this complex triad system is still far beyond our reach, even though we have identified all the effective parameters in the heat exchange process, and have available of all the general physical and mathematic laws and principles. Still we know, to just name a few, very little the dynamics of sweat rate E change as a function of the ambient temperature T_a and sensible heat loss rate Q, including both temporal and spatial

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distributions; very little how the changes in sweat rate *E* will in turn alter the properties of the cloth (moisture condensation and evaporation); let alone the inter-person and intra-person body variations in thermal physiology and thermoregulation along with anthropometry and anatomy.

Challenges are daunting but there are reasons to be optimistic, chiefly that because of the arising interests to wearable technology, unprecedented efforts from industry and academia, especially non-textile fields, starting to focus on clothing science. Needless to say, as dealing with any complex problem, simplification is a necessary initial step: but it has to be done correctly. To start, a sufficiently clear understanding of the problem has to be achieved so as to decide what/how the simplification should be done.

CONCLUSIONS:

Cloth wearing is a common activity for nearly everyone, but to clearly explain the physics involved turns out to be quite challenging even for experts.

The question involves interactions at a given ambience between human body and cloth; both are highly sophisticated with many related yet still elusive issues. To understand clothing thermal comfort, one has to tackle the complex phenomena discussed in this article, including changing sign of the temperature gradient; the cloth fitness and air gap between cloth layers; contact comfort vs. steady heat insulation, and the polymer sorption issue etc., and the research tools, in experiment, computation simulation, and physics, are yet to be made available.

Also it is demonstrated in this work that a more sophisticated perspective has to be held when dealing with the seemingly intuitive problem. Clear distinction and connection between the micro constituents and the macro system has to be established. For instance, the properties of a single fabric swatch tested ex-situ may not be taken as the corresponding properties of a cloth; and there is a non-affinity between the behaviors of the system and its constituents. This non-affinity in clothing thermal comfort suggests that the primary factor impacting cloth thermal comfort is the structure (or the porosity) of the cloth, and the fiber type plays only a negligible role. Such non-affinity exists only in discrete porous structures. For instance, pulling a fiber out of a cloth results in a single fiber that lost all the cloth characteristics, whereas a gold particle from a nugget is still gold.

Finally when handling a complex problem like this, certain simplifications are necessary. Nonetheless a reasonably essential picture of the entire system physics has to be developed first so that such simplification can be done correctly.

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