5. Advanced materials for thermal protection

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5.1 Introduction

Textiles for thermal protection may be used against exposure to extreme high or low temperatures, for mitigation of health hazards by long term exposure to temperatures outside the human thermophysiological temperature limits or for avoiding discomfort, usually under intense physical activity. The main mechanisms for thermal protection textiles are thermal insulation and regulation of heat transfer. Advanced and smart materials may incorporate temperature sensors as well as 3D structures and properties changing textiles responding to different conditions. Extreme temperature protecting wearables are mostly based on insulating properties, aiming to maintain body heat, produced by metabolic activity, from escaping to the environment or avoid environmental heat from reaching the body.

The human body generates heat through metabolic activity and needs to maintain a quasi-constant temperature of 36.6±5 °C. Depending on the ambient conditions, humans need to retain or to discharge body heat. The comfort zone for humans lies at temperatures between 22 °C to 27 °C and relative humidity (RH) between 40% and 60% [1]. Evolution has deprived the human body of the fool body fur, which acts as a heat transfer regulator for most mammals. This function is more or less substituted by the use of garments for entrapping body heat and sweating for discharging excess heat.

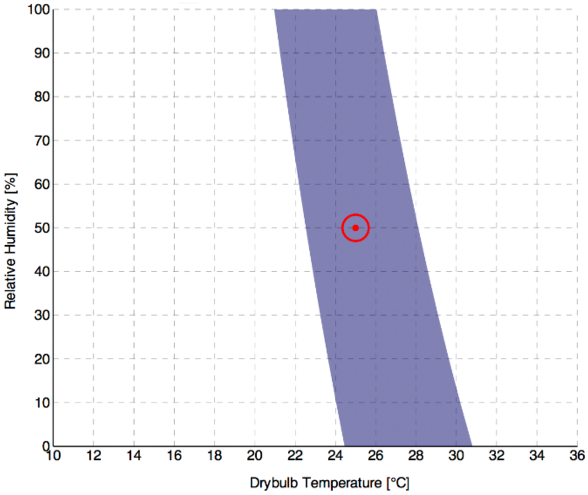

Figure 5.1 *Comfort zone of the human boby. Center for the Built Environment, University of California Berkeley, CC BY-SA 3.0, via Wikimedia Commons*

Heat transfer may occur mainly through three mechanisms: thermal conduction, thermal convection and thermal radiation. Thermal conduction occurs between solid bodies or entrapped fluids that remain still. The rate of heat that can be transferred by conduction is highly depended on the nature of the materials. Metals have a very high thermal conductivity, while most materials used for fabrics have a low thermal conductivity. Entrapped air exhibits very low thermal conductivity, thus most insulating materials use air trapped in bubbles or between fibers as the main mechanism for prohibiting heat transfer. Water exhibits high thermal conductivity; thus, a wet cloth will not protect from low temperatures. Thermal convention occurs when heat is transferred by the flow of a fluid. Heat transfer by convention may be verry effective, as one may know from experience when is hit by a cold breeze or entre a building that uses central heating. Thermal radiation occurs when temperature difference between the radiating body and the environment is high. The heat from the sun reaches the earth by radiation, same is the mechanism for the heat we feel when facing a fire or a red-hot metal. A different way for heat transfer to occur is phase transition and key role in temperature regulation of the human body plays water evaporation. When water, ether fresh water or sweat, evaporates, molecules pass from liquid to gas state and this lowers the temperature of the remaining water that is still in contact with the body, thus acts as a cooling mechanism.

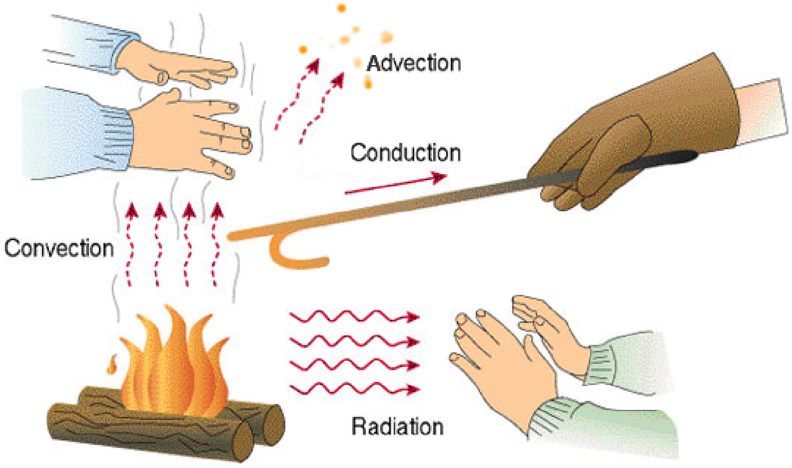

Figure 5.2 *Heat transfer mechanisms. Kmecfiunit, cmglee, CC BY-SA 4.0, via Wikimedia Commons*

The heat equilibrium of the human body depends on the balance between the heat that is generated by metabolism and the heat that is exchanged with the environment. Heat in most cases is not transferred by a single mechanism but by a combination of mechanism which run in series or in parallel. Design of textiles and wearbles for thermal protection requires understanding of both heat transfer mechanisms and the heat regulating mechanism of the human body, as to achieve the desired properties, in relation to the environmental conditions that the wearables will be used.

In addition to regulating heat flows, advance textiles may also incorporate heat generating or cooling components which actively interact with the heat transfer equilibrium in order to achieve the desired temperature for the human body. These technologies will be discussed in the next chapter.

Another important category of thermal protecting textile material are not wearables, such as insulation panels and upholstery.

5.2 Advanced textiles for thermal insulation and body heat regulation

Textiles for thermal insulation aim to minimize heat transfer from the human body to a cold ambient environment or decrease heat transfer from a hot environment towards the body, while allowing heat transfer from the body to the environment.

In the first case the main mechanisms of protection against cold consist in using low thermal conductivity materials (usually making use of air entrapped between fibers), preventing water from wetting the textile and prohibiting airflows from reaching inner layers, where these could induce water evaporation from near the body or replace warm entrapped. In the latter case, for protection against heat, insulating properties are also desired, but -especially in case of body heat regulation- quick water evaporation from near the body is sought.

These results may be achieved by using materials and fabrication technics, both in yarn production and in textile making, to create novel products. Recent bibliography is rich in scientific publications that propose solutions using different approaches. N. Khadse et al. [2] exploit the difference in thermal expansion coefficient between two materials, Hytrel® and Crastin®, to produce a bi-component fiber which curves in low temperatures entrapping air. The fiber was produced by co-extrusion/melt-spinning and was originally assessed for producing non-woven paddings. Y. Chen et al. [3] developed a wearable membrane, based on recycled PET polymer, for regulating sweat transfer and enhance thermal insulation. To this end they used vacuum filtration and magnetron sputtering to create a multi-layer membrane incorporating carbon nanotubes/manganese oxide nano wires (CNTs-MnO_2 nanowires) for sweat transfer regulation and silver nanoparticles (Ag) for increased antibacterial properties. Y. Xu et al. [4], inspired by polar animals' hair and feathers, used wet spinning in ethanol/water/ammonia mixture to develop biomimetic fiber with internal -hidden- nano porous (HNPF) using alginic acid/quaternary chitosan as precursors. This way they achieved to produce a fiber with very low thermal conduction coefficient and biomimetic solar energy harvesting properties for woven textiles for cold resistance. L. Wang et al. [5], inspired by the same animal hair, produced hollow porous thermoplastic polyurethane (TPU)/polyacrylonitrile (PAN) composited fibers by wet spinning in water.

5.3 Advanced textiles for fire protection

Fire protection is a distinct case in thermal protection equipment due to the specific characteristics of fire with can deliver very large amount of thermal energy, produce very high temperatures and induce rapid oxidizing reactions, when an object is “set on fire”. Thus, fire protecting textiles should retain certain properties such as, excellent thermal insulation, resilience to thermal shock and rapid heat transfer, stability in high temperatures i.e material should not melt, loose functionalities or ignite when they come in contact with flames, burning objects (e.g. flammable liquids) or when the temperature rises by hot fluid flows or as a result of thermal radiation. Also, fire protecting textile should not sustain fire and in case they are ignited, fire should be extinguished on its own. Traditionally fire protecting fabrics were fabricated by woven asbestos fibers and when the carcinogenic nature of asbestos was understood were replaced by other inorganic fibers such as fiberglass and rockwool, which are also toxic.

J. Sulivan et al. [5] makes use of the anisotropy of thermal conduction of carbon nanotubes to model a textile that would be flame resistant and highly insulating towards heat coming from a perpendicular direction, but at the same, but proper alignment of the carbon nanotubes, directing the heat coming from the fire away from the body and towards the environment, reducing the temperature of the protective textile. G.M. Gonzalez et al. [6] created semi structured nonwoven para-Aramid fiber sheets, which exhibit both mechanical and thermal protection properties, due to the use of continuous ultra-thin para-aramid fiber achieving low compactness similar to an aerogel. This novel material can be used for protective equipment against explosive environments. The need for combining thermal protection and electromagnetic shielding properties in one fabric, lead M. Li et al. [7] to produce conductive composite aramid nanofibers for creating ultralight, flexible yet robust aerogel textiles. This was achieved by adding carbon nanotubes and mixing by mechanical stirring and ultrasonication of the precursor mix for wet spinning and frieze drying. A microporous yarn comprised of nanofiber aerogel was thus produced.

Sensorial textiles often exhibit poor stretchability, limiting their potential applications. S. Zou et al. [8] created a flame resistant stretchable hierarchical yarn for temperature monitoring and strain sensor applications. The yarn consists of three parts: a flexible spandex core covered by two layers of aramid fibers. The inner layer is a conductive layer of complex aramid/carbon nanotubes fiber, and the outer layer is plain aramid. Both aramid fiber layers are produced wrapping the fiber around the core using friction rollers. The perpendicular direction of the aramid fiber layers, with respect to the spandex core, allows the yarn to be elastic, while the air entrapped between the fibers diminish heat transfer and provide insulation.

A different approach was followed by L. Wang et al. [9] who created a smart fabric system by weaving a shape memory filament in para-aramid fabric. The shape memory filament (nickel/titanium alloy) can be “trained” to convert from a linear to a sinusoidal (wavy) from at a given temperature. The shape memory fabric can be introduced in a 2D multi-layer smart fabric system. When the shape transformation temperature is reached, the filament will bend and curve, creating a 3D structure with large areas of air and act effectively as a heat transfer barrier.

Summary

Cutting edge technology is used for designing novel fibers, yarns and textiles that can be used for thermal protection and comfort. Eco-design, use of recycled and recyclable materials, as well as substitution of toxic and carcinogenic materials is another key issue in research and production innovative products. Example from resent bibliography presented in this chapter provide an insight of the trends in materials use, production technologies and design. Both 2D and 3D design may be used for creating advanced wearables tailored for specific environments providing protection and comfort.

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