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Cooling garments—A review

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Thermal discomfort is one the major challenges during work in hot and/or humid environments like mines, foundries and arid/desert regions. Heat and moisture management is the key to prevent the workers from heat stress. Personnel protective garments alone are not sufficient to provide thermal neutrality. Auxiliary cooling garments are required to aid the process of human body cooling. This review consists of human thermoregulation, followed by different types of cooling garments, and their advantages and disadvantages.

Keywords: Cooling garment, Core body temperature, Evaporative cooling, Liquid cooled garments, Phase change material

1 Introduction

With the rapid technological advancement human has accepted the challenges of working in increasingly hostile and adverse conditions. Despite the growth of technology, the places still exist where we have to work in hot or/and humid conditions. Two stress generators act simultaneously in such cases, viz work load and hot environmental condition. Examples of such work areas include aerospace, firefighting, chemical warfare conditions, working in foundry and mines, working in arid/ desert regions, etc.

Exposure to high temperature during working is a potentially fatal occupational hazard[1]. Personnel who work in such harmful conditions are prone to suffer from heat strain or even heat stroke in extreme cases[2]. To prevent the personnel from such physiological disorders, mostly a two-step approach is adapted[3]. Firstly, a heat protective suit is worn by the worker which can act as a shield against the incoming radiative heat from the hot environment outside. Unfortunately, such types of protective clothing impede dissipation of metabolic heat generated due to work[4]. To remove this metabolic heat, cooling garments have proved to be a powerful tool. Cooling garments play an important role in alleviating the thermal discomfort experienced by the individuals working in hot environmental conditions. Figure 1 shows different types of cooling apparels[5].

The operating principle of such cooling garments is to create a cooler microclimate to facilitate the removal of metabolic heat and block heat exchange between the user and the environment[6]. The cooling garments can be broadly classified in two groups based on their working principle, namely active and passive cooling garments. The operating principle of active cooling garments is to circulate cold air or liquids through tubing networked inside the garment. The mode of heat transfer is mainly conduction and convection[7]. Passive cooling garment uses either phase change materials like ice-pack, polymer gels, paraffin waxes or chemically frozen gels[8] or evaporation of cooling liquids[9].

2 Human Thermoregulation

The literal meaning of homeostasis is same state, and it refers to the control of internal body

Fig. 1—Different types of cooling apparels – vests, headgear, wristband, and neckband[5]

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temperature within tolerable limits, when the external environment is changed. One of the largest examples of homeostasis is human thermoregulation of body temperature within a very narrow range. Human thermoregulation controls the internal body temperature as well as the external heat dissipation[10]. The overall requirement is a balance between heat input and heat output from the body. Any imbalance between heat gain and heat loss will lead to thermal discomfort. However, the thermal comfort is not dependent on the energy balance alone. Along with the energy balance of the body, a secondary requirement is the combination of skin temperature and core body temperature to provide thermal neutrality[11]. When body temperature is controlled with minimum physiologically regulated efforts, a sensation of thermal comfort occurs.

From clinical perspective, the core body temperature is controlled within a very narrow range of approximately 36.7 ± 0.3 °C (ref. 12). Human thermoregulatory failure can occur if the core body temperature varies more than 2°C on either side of 37°C, resulting in either hyperthermia (> 39°) or hypothermia (< 35°C). If the core body temperature reduces by 10°C or rises by 5°C it may lead to possibility of death[13, 14].

Heat stress is a result of thermal imbalance between input energy and output energy of the body. Apart from health disorders, heat stress during work causes reduction in productivity and increase job related accidents[1]. With increasing amount of forced heat storage in the body psychomotor capacity reduces and may eventually collapse causing death[15]. The physiologically tolerable heat storage can be maximum (630 kJ) (ref. 3) or a mean body temperature of 40°C (refs 2, 16). Heat storage of 316.8kJ or rise in body temperature by 1.2 °C can guarantee complete physiological and mental participation in work[17]. During work or exercise, chemical potential energy stored in the body as carbohydrates and lipids are transformed to kinetic energy and heat. Around 80% of this converted chemical energy contributes to the generation of heat inside the body. Heat storage rate of 800 J/s can cause body temperature rise by 1°C in about 5 min for a 70kg person performing 200W external work load[18].

The thermodynamics between human body and environment is better described by the steady-state energy balance model developed by Fanger[11]. This model assumes the human body to be in a thermal equilibrium and it stores negligible energy. According to this model heat exchange between human body and environment can be presented by the following equation:

$$M - S = W + R + C + K + E \qquad \dots (1)$$

where M is the metabolic heat production; S, the heat storage (zero at equilibrium); W, the external work; R, the radiative heat loss; C, the convection by moving fluid (air or water) surrounding the body; K, the conduction (generally negligible); and E, the evaporative heat loss. All quantities in Eq. (1) are having unit in W/m^2.

Thermal balance therefore involves the interaction among metabolic heat generation, heat gain from the environment and heat loss from the body by means of physiological control such as sweating. Total heat stress can be defined as:

Total heat stress = metabolic heat + environmental heat – heat loss from body

Sweating, shivering, vasodilation and vasoconstriction are the four major human thermoregulatory mechanisms. With rising environmental temperature, the skin becomes warmer, resulting in a decrease in the core-skin temperature gradient and increased conduction due to increase in blood flow. Vasodilation causes an increase in diameter of the blood vessels near the skin which helps in increased blood flow and heat dissipation from the body by means of convection and radiation. When ambient temperature becomes higher than the body temperature, then heat loss by means of convection and radiation is not enough to maintain the thermal balance. In such condition sweating is the main mode of heat loss from the body. Evaporation of sweat is a highly efficient heat removal process. Under heat stress, complex physiological mechanisms encourage evaporation to reduce the thermal discomfort. But high sweat rate can cause fluid and electrolyte imbalance in the body and eventual collapse due to dehydration[19].

Occupational Safety and Health Administration (OSHA) informs that if these cooling mechanisms fail, the body stores heat instead of releasing it. As a result the body core temperature rises and the heart rate increases. As the body continues to store heat, the individual begins to loose concentration and has difficulty focusing on a task, may become irritable or sick and often loses desire to drink. The next stage is most often fainting, and death is possible if the person is not removed from the heat stress.

3 Active Cooling Garments

As discussed earlier, active cooling garments work on the principle of circulating cool air or liquid through tubings spread in the garment. Active cooling garments are also known as fluid cooling garment or FCG. Active cooling garments are further classified in two categories, namely air cooled garments and water / liquid cooled garments.

Air Cooled Garments

In air cooled garments, compressed air is supplied from an external air supply system and heat removal takes place both by convection as well as evaporation of sweat. At the end of each distribution pipe, miniature jets are provided to break up the boundary air layers and promote the sweat evaporation process. Depending on the application, these garments can employ ambient air or pre-cooled air.

The Gemini and Apollo space suits used this concept of body cooling. Different researches have shown that the Gemini space suits have a very limited cooling capacity and the cooling was marginal for work rates over 348.9 Watt (refs 20, 21). Minor improvement in cooling efficiency caused uncomfortable wind and noise levels[22].

In comparison to the liquid cooled garment, air cooled garments have advantages such as (i) it is a positive pressure system, a small leak or tear in the garment is less likely to contribute to contamination of the wearer and (ii) it is easier to connect and disconnect than a liquid-cooled system[23]. But the major disadvantages of this cooling technique are (i) cooling efficiency is inferior due to low heat capacity of air (ii) it needs continuous power supply, it is heavy and bulky and (iii) non-portable[24]. These garments are found to be inadequate in applications like space suits, hot industrial trades.

Liquid Cooled Garments

Failure of air cooled garments to provide desired cooling efficiency in specific applications like space suits leads to the development of liquid cooled garments. Liquid cooling garments are the most commonly used active cooling garments in today's applications. In liquid cooling garments, cooling liquid is circulated inside the tubes embedded in the garment by means of a battery operated pump as shown in Fig. 2. As the liquid becomes warmer by the body heat, it is carried away to a heat sink or cooler for recooling purpose[25].

In 1958, Billingham[27] first suggested the concept of the water cooled garment and it was first prototyped at the Royal Aircraft Establishment in 1962 (ref. 2). Higher heat capacity of water in comparison to air provides certain engineering advantages like reduced pumping power, lesser weight and lesser bulk.

In many liquid cooling garments the tubings are sewn to one layer of fabric so that the tubings can be in direct contact of the skin. However, for better wearer comfort a three layer structure where the tubings are sandwiched between the inner and outer fabric layer is preferred[28]. The inner layer needs to carry away the sweat in liquid or vapour form. For better performance, the inner layer must have good thermal conductivity, good moisture management and good tactile properties.

The cooling efficiency of liquid cooling garments depend on environmental conditions, tubing type and length, liquid inlet temperature, flow pattern(single-loop or multi-loop) and flow rate[2]. External heat may directly reach the tubings or can indirectly be absorbed by the garment. Apart from air temperature, humidity plays a great role in controlling the cooling capacity of the liquid cooling garments. Studies showed that despite cooling, sweat rate increased due to damp environment[29]. Tubing characteristics like tubing material and thickness[30], the diameter of the tube (the surface volume ratio controls the conductive heat transfer from the skin to the convective liquid)[31], total tubing in contact with the skin and tubing length

Fig. 2—Liquid cooling garment with tubings embedded inside[26]

which affects temperature gradient along the tube[30] control the heat transfer process from the body. Heat extraction is related to the flow rate in a non-linear fashion[30]. However, Frim *et al.*[32] has reported that cooling is dependent on flow rate only at lower levels. At higher flow rates, heat extraction is independent of flow rate. Absolute limits for inlet water temperature are 0°C (frostbite) and 45°C (pain threshold), but practical limits are much narrower depending on the area of application[22].

Different physiological characteristics like heat rate, rectal temperatures of personnel using liquid cooling garments in hot environments such as cockpits, military applications were studied by Semeniuk *et al.*[33], Katsuura *et al.*[34] and Nunneley *et al.*[35]. According to these studies, liquid cooling garment has proved to provide sufficient cooling in hostile environment. Figure 3 shows the comfort zone for water cooled garments. For each heat load there is a range of skin temperature which interacts with human thermoregulation and minimises sweat secretion. Heat discomfort means heat storage and sweating. Cold discomfort implies shivering. The dashed line indicates the lower limit of active sweating.

Circulating liquid used normally in liquid cooled garments is water with 10% ethylene glycol. The amount of water available in the reservoir and the build up of inlet water temperature restricts the usage time of liquid cooling garments. A reservoir of one-half litre is sufficient enough to provide considerable amount of body cooling. Studies have shown that using ice packs for double layered reservoir maintain the circulating water temperature between 15°C and 18°C for ambient dry bulb temperature of 40°C over two hours[4]. Water cooled jackets can provide 160 - 170W cooling per square metre of body area. This level of cooling has proved to be more than sufficient for persons performing light physical activity in hot environment.

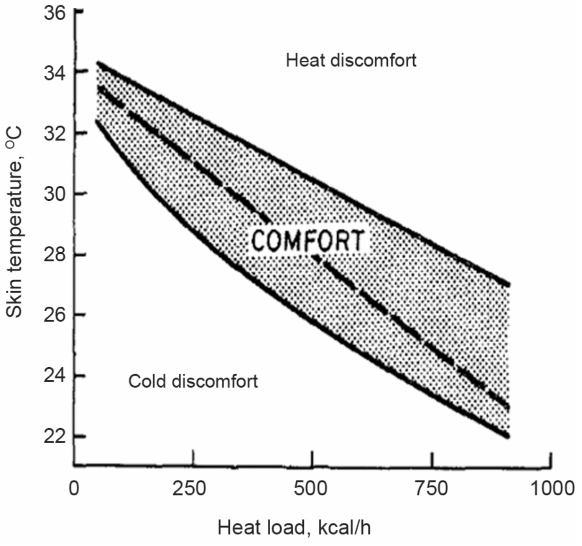

Fig. 3—Comfort zone for water cooled garments[22]

Human body consists of different regions having different thermoregulation characteristics. These regions can be listed as hands and feet, limbs, torso and head. The heat exchange depends on surface area, local heat generation, conductivity of the tissue, etc. So, different cooling is required for different areas of the body.

Liquid cooling garments have also found their application in medical field for certain illness such as multiple sclerosis to alleviate the symptoms. Kraft *et al.*[36] showed that the controlled microclimate due to the liquid cooling garment increases the motor functions of a patient suffering from multiple sclerosis. The water inlet temperature in this study was 7°C and 26.6°C.

According to Nunneley[2], water cooled garments can provide virtually unlimited cooling at no physiological cost and also a higher level of wearer comfort. The liquid cooled garments have certain engineering advantages over air cooled garments from design point of view. Another advantage of liquid cooled garments is good compatibility with other protective garments. However, there are certain disadvantages of liquid cooling garments. The suits are expensive and need a very close fit to the wearer. Also there are inherent safety problems like water spillage leading to short circuits, steam burns and discomfort related to wet clothing.

4 Passive Cooling Garments

Passive cooling garments use either phase change materials like ice, paraffin wax, chemically frozen gels or evaporation of a cooling liquid, normally water. Based on the type of material being used, passive cooling garments are mainly classified in two groups, viz. (i) garments with phase change material and (ii) evaporative cooling garments.

Phase Change Cooling Garments

Phase change cooling garments generally uses dry ice or ice as the coolant. Body core-skin temperature gradient is formed due to the cooling effect of ice or dry ice by latent heat of melting and latent heat of sublimation. Body cooling thus takes place mainly by conduction[37]. For the use of any phase change material in cooling garments, it is very important to have the knowledge of the enthalpy in the working zone, since the amount of thermal energy that can be stored depends on the enthalpy variation around the phase change. Figure 4 shows the enthalpy – temperature curve of a phase change material and the considerable amount of change in enthalpy during phase change can easily be noticed.

Based on the materials used, phase change cooling garments can also be classified in two major categories, viz. inorganic compounds and organic compounds. Inorganic phase change materials can be salt hydrates, salts, metals and their alloys, whereas organic phase change materials can be paraffin waxes (or *n*-alkanes), polyethylene glycols and fatty acids[39].

Dry Ice Cooling Garments

Dry ice needs 573 kJ/kg thermal energy as latent heat to sublimate i.e. to change from solid to carbon di oxide (CO_2) gas. In dry ice cooling garments the latent heat for sublimation is taken from the body by conduction, and thus giving the body a cooling sensation. Chauhan[37] has mentioned in his review paper that during step tests of 2 h, this type of garment helped in reducing heart rate by 5- 10 bpm and skin temperature reduces by 2°C. However, no changes in core body temperature were reported.

Certain disadvantages related with the dry ice cooling garments are as follows: dry ice sublimes at -78°C and therefore can cause cold burns, the garments are expensive, not readily available and can become poisonous if CO_2 build up is in an enclosed area.

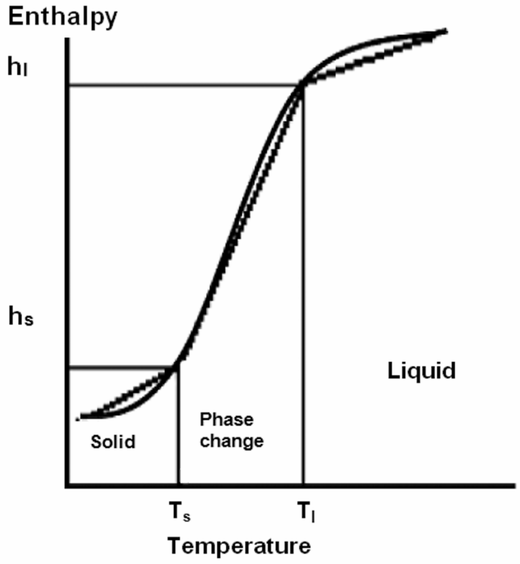

Fig. 4—Enthalpy variation with temperature[38]

Ice Cooled Garments

Mostly available phase change cooling garment in the market is the ice cooling garment which can provide cooling for 2-4 h in moderate to heavy heat loads. Latent heat of melting of ice is 343 kJ/kg at 0°C. This type of cooling garment is normally sleeveless jackets with pockets for containing ice or containing water packets which are frozen thereafter for 6-8 h. Figure 5 shows one such system.

Several studies have found that the working efficiency of ice cooled garment at different environment and work loads, as summarised below:

(i) Strydom *et al*.[41, 42] found out that 4.8 kg ice cooled vest can provide effective cooling for 2.5 h during normal mine work in an environmental condition of 35.5°C/ 33.8-37.2°C / 35.6°C dry bulb/ wet bulb temperature.

(ii) Sweetland and Love[43] found that 6 kg ice cooled vest can provide effective cooling for only 1 h during carrying of wood blocks in an environmental condition of 40°C/ 39 - 54°C/39°C dry bulb/wet bulb temperature.

(iii) De Rosa and Stein[44] found that 4.5 kg ice cooled vest can provide effective cooling for 2 h during treadmill walking at 5.6 km/h in an environmental condition of 30.1°C/ 26.7- 45°C / 31.7°C dry bulb/ wet bulb temperature.

Kamon *et al*.[45] pointed out that ice cooled garments can be really useful in reducing thermal stress for personnel working in nuclear industry. Pasternack[46] found that ice cooled garments can be useful in hot working environments like mines, coking plants, metallurgical plants and power stations. Both Kamon and Pasternack have suggested that ice cooling garments are easily compatible with other protective garments.

The disadvantages related to ice cooled garments can be listed as follows. Bulkiness of the garment

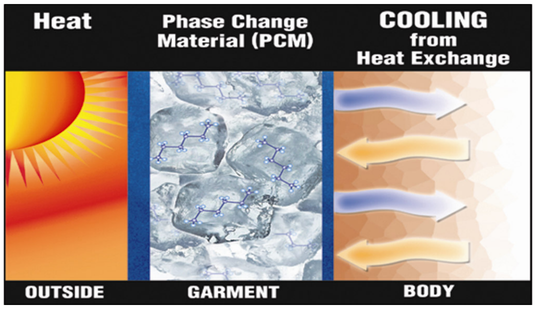

Fig. 5—Phase change cooling garment[40]

reduces wearer's mobility, extended cold exposure can cause harm to skin and develop flu like symptoms, the regeneration of ice pack requires freezer. Research is going on for microencapsulation of organic phase change materials to be used in cooling garments.

5 Evapourative Cooling Garments

Cooling from water-soaked garments has probably been discovered shortly after clothing become standard for human beings. The effect of cooling from wet clothing may be a pleasing one, but for daily use there are certain drawbacks. The wet clothing dries up very fast in the sun or a dry breeze, even though it is fully saturated with water. Clinging of the water-soaked fabric with the body gives uneasy feeling during outdoor activities. Water drips off from the fabric, thus reducing the cooling potential and inconveniencing the user. In numbers of research works Lubos Hes[47, 48] has experimentally found that total cooling heat flow through fabrics, in wet conditions, is influenced by moisture evaporation from fabric surface along with heat flow through the fabric. Relative water vapour permeability has been found to increase with moisture content in the fabric. In these studies, air gap also plays an important role as it inversly affects water vapour permeabilty and thus affects cooling.

With some simplifying assumptions, a quantitative relationship has been established[47] for the total heat flow (q_{tot}) transferred through the boundary layer of the fabric, which is given by the sum of heat flow passing from the skin through the permeable fabric and heat flow caused by temperature gradient between the skin and fabric surface, which is cooled by evaporation of water from the fabric surface, as shown below:

$$q_{tot} = \frac{P_{sat} - P_{air}}{R_{egap} + R_{et} + R_{eto}} + \frac{\beta\left(P_{sat.fab} - P_{air}\right)}{1 + aR_{ct}\left(1 - kU\right) + aR_{cgap}} \quad \ldots (2)$$

where p_{sat} is the saturated water vapour pressure on the skin surface (Pa) which is tabled and depends on the skin temperature; p_{air} the water vapour pressure of the environmental air (Pa) which is given and is determined by measurement; R_{egap} the evapourative resistance of the air layer (Pa.m^2/W) which can be measured or calculated; R_{et} the evapourative resistance of the fabric (Pa.m^2/W) which should be determined experimentally; R_{eto} the evapourative resistance of the boundary layer (Pa.m^2/W) can be determined experimentally, or its approximate value can be calculated for the known velocity of the parallel air flow; β the convection mass transfer coefficient $\beta \approx \sqrt{v}$ related to water vapour partial pressure and heat flow (W/Pa.m^2); $p_{sat,fab}$ the saturated water vapour pressure on the fabric surface (Pa), depending on the fabric surface temperature, which can be determined by the iteration procedure; α the heat transfer coefficient (W.m^2/K), which increases with the air velocity; R_{ct} the thermal resistance of a fabric in ultra-dry state (K.m^2/W), to be determined experimentally; k the experimentally determined constant characterizing the decrease of thermal resistance caused by the increased moisture U of the fabric; U the relative mass increase of the fabric with moisture content (%), determined by weighing; h the thickness of air gaps between the measuring surface and the fabric (m), determined by measurement; D_p the diffusion coefficient related to water vapour partial pressure and heat flow (W/Pa.m), available in literature on heat transfer; and R_{cgap} the thermal resistance of air layer (K.m^2/W), which canbe measured or calculated.

With the invention of superabsorbent polymer particles, the popularity for its use in evaporative cooling garment has increased considerably due to the relative simplicity and cheapness of manufacturing items that contains them. The common approach is to use this polymer to fill small pockets or channels provided in the garment (Fig. 6).

Evapourative cooling garments are relatively new developments in the area of personal cooling systems. The advantage of evapourative cooling garment is that it employs the large latent heat of water evapouration, which is around 2430 kJ/kg at 30°C more than seven times of the heat of ice fusion. The latent heat of evaporation (λ) of water can be calculated from the following equation[50]:

$$\lambda = 0.001(2.792\times10^{6} - 160\mathrm{T} - 3.43\mathrm{T}^{2}) \quad \ldots (3)$$

where λ is the latent heat of evaporations of water (J/g); and T the temperature in Kelvin.

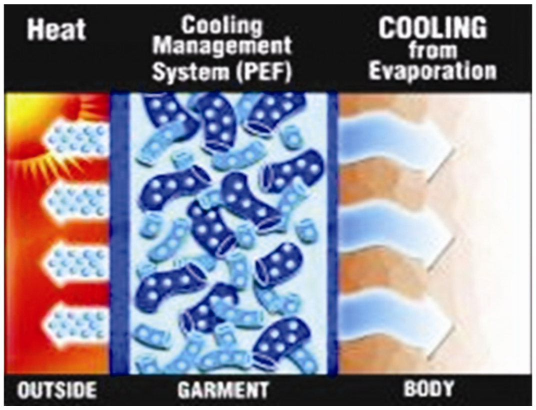

Fig. 6—Evapourative cooling garment[49]

The concept of evaporative cooling garment is to reduce the heat gained from the environment by evaporating the excess amount of water reserved in the cooling fabric. The latent heat of evaporation of water is taken from the environment and thus the amount of heat reaching to the body is reduced in cases where vest are used for thermal protection. It is normally assumed that moisture vapour that actually leaves the clothing contributes to the cooling of the body and hence the evaporative heat loss is calculated from the mass change of the human clothing system (corrected for metabolic heat losses and respiratory heat losses). This mass change rate multiplied by the latent heat of evaporations gives the rate of energy loss due to evaporations.

In 1972, Craig[51] has reported the effect of evaporative cooling of men in wet clothing. The atropine treatment used in anticholinesterase poisoning has unwanted side effects of excessive sweating. Craig has experimentally proved that initial wetting of the fabric reduces the amount of sweat generated, an effect attributed to the cooling of skin due to the evaporations from the wet clothing.

In 2008, Rothmaier *et al.*[52] designed a textile based laminate that allows making up of light weight cooling garments based on evaporative cooling principle. The concept was evaporations of water from skin-contacting reservoir, using the body temperature. The three layer textile laminate structure was made by laminating two layers of Sympatex membranes on both side of a woven polyester fabric. Sympatex membranes are made of polyetherester and are impermeable to air and liquid water yet permeable to water vapour. Both the membranes and the fabric define a confined space for holding little amount of water. Rothmaier *et al.*[52] has shown that with the rise in ambient temperature the environmental heat will assist in evaporation and thus will reduce the duration of cooling. Low level of humidity facilitates the evaporation process, whereas high amount of vapour concentration in the air constrains the evaporation process. The light weight of the laminate structure is one advantage for its use in cooling garments. The main weight load will be of water, whose volume depends on preferred cooling duration and environmental conditions.

Numerous patents are available on the design of three layer evaporative cooling garment[53-58]. In 2002, Bumbarger *et al.*[59] designed a multi-layer evaporative cooling composite consisting of an inner layer which is water impermeable but breathable, an outer layer which is permeable to both water and water vapour and an absorbent core of fibrous matrix with superabsorbent polymer particles dispersed within it. The fibrous matrix is preferably made from meltblown structure which provides a higher number of point contacts, thus facilitating to hold the dispersed polymer particles in place. The inner layer which is kept in direct contact or nearer to the skin should be thermally conductive to carry away the excess heat from the body to the absorbent core (Fig. 7).

Drawbacks of using superabsorbent polymer particles can be listed as clamminess, uneven cooling, powdery deposits on skin or clothing, lumps and bulges and a little longer time of immersion.

In 2012, Frost[60] patented a novel approach to design a three layer quilted textile material suitable for use in evaporative cooling garments. The inventor claims that the product will be able to provide evaporative cooling of 8 - 10° C, below ambient. The material of this invention can be used in cooling vests, cooling blankets for people, food or equipment.

The three layer quilted structure consists of an absorbent core which is basically a nonwoven fibrous felt or batting, comprising a typical blend of three types of fibres, viz. cellulose, a cross-linked polyacrylate co-polymer (superabsorbent fibre) and polyolefin bonding fiber. The preferred composition of these three types of fibre in the nonwoven structure is 40% polyacrylate, 30% cellulose and 30% polyolefin. The nonwoven structure has a typical basis weight of 120 g/m^2. Cellulose fibres help in rapid uptake of water as well as a quick release, giving an immediate cooling effect. The polyacrylate fibre is not as efficient in wicking as cotton, but it absorbs and retains a large amount of water. The

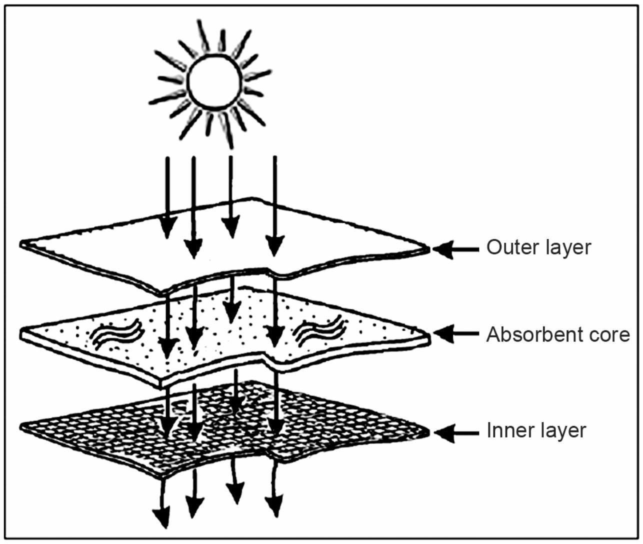

Fig. 7—Three layer evaporative cooling fabric concept[59]

strong hydrogen bonds in the polyacrylate fiber avoid draining of water from the structure due to gravity and releases water vapour at a steady rate over the period of time. On applying heat, the thermoplastic polyolefin fibres act as an adhesive binder for the other fibres to stabilise the nonwoven structure.

The inner moisture barrier layer is of woven fabric made from airjet textured yarns, which protects the wearer from dampness and provide a soft, draping surface for good thermal transfer between the wearer and the clothing. The inner fabric is inherently resistant to water and wind.

The outer layer is a nylon oxford fabric which allows free passage of water vapour and limited passage of water. Suitable thread count and thickness of the inner and outer layer fabrics provide the required properties. No coatings or surface finish treatments are used for desired results.

All types of evapourative cooling garments described above need to be dipped in water for 1-2 min prior to use, in order to reserve the cooling liquid in the absorbent core of super absorbent polymer. Then the excess water needs to be rinsed and the cooling vests are ready for use.

The great advantage of this type of cooling garment is that it is light, flexible and therefore portable. But this type of garment is not suitable for humid conditions as the effectiveness of evaporative cooling is inversely proportional to ambient relative humidity. Another limitation of this technology is that cooling takes place on the outer surface of the garment, not inner surface which is nearer to skin.

6 Conclusion

Each of the major four types of cooling garments has certain advantages as well as disadvantages. For application areas where accuracy of the work is of more concern, discomfort due to limited mobility can be neglected to certain extent. Depending on the end use it is very critical to select the personal cooling garment carefully. Liquid cooling garment or more specifically the water cooled garments remain to be the most effective personal cooling system. For light to moderate work load, evaporative cooling garments can provide the best solution if the environment is dry and hot.

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