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Evaluation of Cooling Techniques for Personal Cooling Garments in Hot and Humid Climates

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***Abstract*— Personal cooling garments have become a major requirement to cater thermal discomfort, caused mainly due to the rise in global temperatures. Various cooling techniques have been used for specific applications, mainly focused on thermal protection than thermal comfort. Thermoelectric cooling, phase change materials, and evaporative cooling techniques were selected and further analyzed through mathematical modeling to assess their suitability for personal cooling garments. Phase change materials can provide 2 hours of cooling using 46 capsules, while evaporative cooling can provide cooling for 36.1 minutes and thermoelectric cooling can provide continuous cooling. The study concluded that a combination of thermoelectric cooling with phase change materials could remove required heat from the top part of the body which is emitted during medium level activities. Two circuits, each with three Peltier modules of the TEC1-127 series supplied with a direct current of 1.5A and supplied voltage of 9V could provide efficient heat pumping ability, with the coefficient of performance of 1.17 each. The macro capsules with eicosane as the core material act as the heat sink when used in combination with thermoelectric modules. Hence, it concludes that a combination of thermoelectric modules with phase change materials integrated into a personal cooling garment could effectively provide the required thermal comfort.**

Keywords – personal cooling garments, thermal comfort, phase change materials, thermoelectric cooling

I. INTRODUCTION

The current temperature increment due to global warming is a raising environmental issue that highly attracted the focus of almost all the nations. It is also stated by NASA that the highest temperature was marked in 2020 [1]. Due to this temperature increment, thermal comfort of humans was compromised and the heat related illnesses also increased, along with the raise in the death percentages [2]. The effect of global warming and the raise of temperature can have more effect on tropical countries compared to others. The recent COVID-19 pandemic is another severe problem for the frontline medical staff who are required to wear a sealed type of clothing for longer durations, which are mostly made with polyolefin fibres that increase thermal discomfort. Human thermal comfort depends on four environmental parameters: ambient and radiant temperature, relative humidity and air velocity and two human parameters: activity level and clothing insulation [3].

In general, a centralized cooling system is used in commercial buildings and split type air conditioners into residential units. However, the cooling effect will only be limited to the indoor environment, and it is also reported that the cooling efficiencies are comparatively lower with regards to the high energy consumption [4]. Therefore, considering the above limitations, personal cooling garments (PCG) will provide the best solution to human thermal comfort. It is also stated that PCGs can reduce up to 25% of the energy consumed for Heating, Ventilation, and Air Conditioning (HVAC) [5].

During the last nine decades research on protective garments used in high temperature environments, paving the way towards the introduction of cooling techniques namely air cooling (AC), liquid cooling (LC), phase change materials for cooling (PCM), and evaporative cooling techniques (EC). These are also known as the traditional cooling techniques which are used for garments in the fields such as military, sports, healthcare, firefighting and industrial applications. Studies on PCGs are still in progress and providing new cooling techniques such as the enhanced conductive cooling with boron nitride (BN), vacuum desiccant cooling (VDC), which is also an advanced evaporative cooling and thermoelectric cooling using Peltier effect (TEC). The effectiveness of these cooling techniques varies depending on the climate conditions they are being used. Thus, precise selection has to be made when it comes to the selection of a suitable cooling technique for PCGs.

Thermal comfort is a subjective sensation, and therefore the individual requirement towards it may also differ. Hence, providing the individual requirement on thermal comfort is possible by the use of PCGs. Considering the impacts of global warming, the limitations of centralized cooling and the capabilities of PCGs, it could be envisaged that a PCG with precise cooling technique/ techniques can create a new market segment in technical textiles which has a high potential for future growth of wearables and smart textiles.

In normal circumstances energy from the human body is transferred to the environment in different modes. Accordingly, out of the total energy transferred, more than 70% is through convection and radiation, 2% through respiration and conduction, and the remaining percentage by the evaporation of sweat [6]. Even though the heat is getting transferred to the environment, there is a huge percentage of heat getting stored as thermal energy in the microclimate between the body and the clothing contributing to increase in temperature. The functionality of the PCG is primarily to remove the stored thermal energy while providing the required thermal comfort for personal wear in daily activities. The main heat transfer modes can be described mathematically as stated by Equation (1) the Fourier's law of heat conduction, Equation (2) the convection by Newton's law of cooling, and Equation (3) the evaporative heat transfer.

$$q_{conduction} = -K\frac{dT}{dx} \tag{1}$$

$$q_{convection} = h(T_\tau - T_\infty) \tag{2}$$

$$q_{evaporation} = \varepsilon(P_\tau - P_\infty) \tag{3}$$

where, T is the temperature and K is the thermal conductivity of the material, h is the convective heat transfer coefficient, T_τ is the outer surface temperature of the clothing and T_∞ is the temperature of the ambident environment, ε is the evaporative heat transfer coefficient, P_τ – partial pressure of the ambient water vapor and P_∞ - partial pressure of the water vapor at the skin.

Even though there are different cooling techniques used for specific heat protection applications as mentioned above, out of those, only a few could effectively be used for PCGs. The air cooling garments (ACG) functions with the circulation of the air through the porous tubing arrangements. The cold air gets blown to the body through the pores and increases the convective heat transfer. Similarly, the liquid cooling garments (LCG) functions by circulating the coolant or liquids in place of air in ACGs. However, the tubing arrangement is of sealed type restricting any leakages. This liquid circulating around absorbs the energy stored in the microclimate through conduction. Meanwhile, garments incorporating PCM (PCMG) functions according to the theory of latent heat where the temporary cooling is provided during the phase change: energy is transferred from human body to the PCM via conduction. Similarly, in evaporative cooling garments (ECG) the cooling is due to the result of evaporation of the liquid which is mostly water, where the liquid absorbs the energy in the microclimate and thereby change its phase to vapour.

Considering the novel cooling techniques, conductive clothing can enhance efficient heat removal from the microclimate through BN/PVA composite [7], also VDC can function more efficiently in any environmental condition [8]. The TEC is a technique, where the temperature difference can be created when the current goes through the module (Peltier effect) and provide cooling [4]. A critical comparison of these cooling techniques for the suitability of use in a PCG, by considering the requirements in a daily wear are described in Table 1. The AC and LC techniques have shown the highest cooling efficiencies during the long time of wearing opposed to other traditional cooling techniques. Nevertheless, the flexibility and freedom of movement, low weight and less bulkiness which are the major requirements in PCGs , get compromised in AC and LC techniques due to the auxiliary equipment used to obtain its functionality [6]. a similar difficulty is also observed in VDCs as the thickness and bulkiness of cooling pads used in VDC are high.

This shows that the AC and LC techniques are not suitable for the PCG even though they provide high cooling efficiencies in long duration of wearing. The PCGs also need to have the properties similar to a garment that is used as daily wear and these are worn in normal environments for a short period of time, unlike the garments worn in hostile environment. Similarly, the bulkiness and the resistance to movements of VDCs makes it less desirable for PCGs. The remaining four techniques listed in Table 1 can be selected for the PCGs, out of which enhanced conductive cooling with BN/PVA is still under research. Also, with BN/PVA it is possible that there are more chances in tropical countries where the radiant temperature gets increased more than skin temperature resulting the reverse heat flow from the environment to the human body.

Focusing on PCM, the main limitation is related to the duration of cooling. To provide a longer duration of cooling, it required to incorporate larger mass of PCM into the PCG. Researchers have used microcapsules, macro capsules and macro packets to incorporate PCMs to the garments. Out of these, the mostly used type is the microcapsules. Nevertheless, due to the micro scaled size of the capsule, it was not an effective method of cooling for longer durations due to the less amount of PCM mass in the garment. As a solution, to incorporate more PCM in the garment, some researchers have used macro packets of PCM, which resulted in increase in weight and limited the freedom of movement[9]. Considering these limitations, the new area of research have focused on the macro capsules which are in the scale of 3mm – 5mm [10]. Usage of these macro capsules can have higher mass of PCM compared to the micro capsules thus support the longer duration of cooling. The other major issue with respect to PCM is the durability of the capsules. Due to the external forces, it was found that there are more chances for the capsules to get damaged.

Table 1. Comparison of cooling techniques

Description	**ACG**	**LCG**	**PCMG**	**ECG**	**BN/PVA Composite**	**TEC**	**VDC**
Requirement of external equipment	For the circulation of air	For the circulation of liquid	No	No	No	For cooling purposes and to power the modules	For cooling
Uniqueness	No	Highest efficiency and best for longer durations	Quick response & high efficiency for short term cooling	Best suitability for less humid environment	Only technique to use conductive heat transfer efficiently	Shortest response time and quickest cooling	Functions in any environment
Major limitation to be used for cooling in PCG	High weight, bulkiness due to external elements	High weight, bulkiness due to external elements	Duration of cooling time, and durability of the PCG	Not suitable in high humid environment	Under research, heat from environment can transfer towards the body..	Current flow in the garment	Bulkiness and the increased thickness of the pads.

Considering this problem, the researchers have investigated the strength and durability with the different core to shell ratios. With the increase of the core to shell ratio, the encapsulation efficiency is not as expected due to possibility of incomplete coating [11]. Nevertheless, in decreasing the ratio, the heat capacity is also compromised. Thus the best core to shell ratio suggested in the literature is 3:1 [12]

TEC is a new cooling technique when it comes to textiles, the problem related to this method is possibility of current leakages. It is also stated the temperature difference between the two sides of the TEC depends on the current that flows through it [4], [13]. Therefore, a precise calculation on the current that can provide cooling without harm, need to be carried out and accordingly the suitable module should be selected [4].

Focusing on the evaporative cooling, the functionality highly depends on the relative humidity of the environment [14]. Therefore, it can efficiently function in lower humid environments. For the tropical countries where the humidity is higher [15], this technique is not highly efficient.

The critical review of the available techniques suggested the possibility to use three main techniques for cooling garments, as listed below.

- PCM technique
- Liquid Mediate EC technique
- TEC using Peltier modules

II. OBJECTIVES

Hence, this study focuses on qualitative and quantitative analysis of different cooling techniques, and their combinations to evaluate the suitability to be used in personal cooling garments for hot and humid climatic conditions. This study aims to achieve following objectives,

- to review different cooling techniques and evaluate their effectiveness for the use in personal cooling garments,
- to evaluate the effectiveness of combined cooling techniques for personal cooling garments, using analytical/ numerical methods,
- to propose suitable combination of cooling techniques for personal cooling garments for hot and humid climates.

III. METHODOLOGY

With the identification of the cooling techniques, that can be incorporated in the cooling garments through the review, separate mathematical models were developed, for the combined cooling techniques by adopting the available heat transfer equations for individual cooling techniques by considering the enhanced performance of each technique separately.

A. Human thermoregulation

According to [3], thermodynamics between the environment and the human body is described with the steady-state energy balance model, where heat transfer between the body and the environment can be expressed using Equation (4).,

$$0 = M_r - W_r - C_{res} - E_{res} - C_b - R_b - E_b - S_t \qquad (4)$$

where, M_r - metabolic rate, W_r - work rate performed on the environment, C_{res} - convection respiratory heat transfer, E_{res} - latent respiratory heat transfer, C_b - body convection heat transfer, R_b - body radiation heat transfer, E_b-body evaporative heat transfer, S_t - heat storage rate by the body. The heat storage S_t in Equation (4) defines the temperature of the microclimate between the body skin and the fabric. The thermally comfortable skin temperature in tropical countries varies in the temperature range of 304.5K to 305.5K [16].

B. *Mathematical representation of PCM technique*

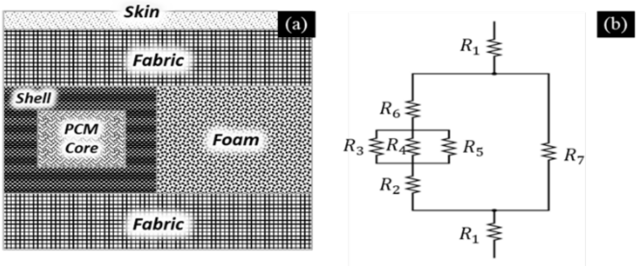

Fig. 1 – Model of a garment incorporated with PCM (a) Schematic representation (b) Equivalent thermal resistance diagram. (R1 -6, represent the thermal resistance of each component).

Mathematical equations were derived from the basic heat transfer equation available in the literature, for a sandwiched structure that contains PCM macro capsules embedded in flexible foam material in between two fabric layers. The heat stored in the microclimate gets reduced during the phase changing period of PCM, and during this period the wearer feels comfortable. The proposed mathematical model, for the heat transfer calculations of this system, was developed based on the schematic presented in Fig. 1.

During the heat transfer calculations, the following assumptions were made,

- The phase change of PCM occurs uniformly (No temperature gradient and moving boundary problem)
- The spherical capsules are assumed to be cube shaped to reduce the complexity of modelling.
- The heat transfer is assumed to be in one dimension (perpendicular to the fabric surface).

Therefore, the total heat flow per unit area Q_{Tot} through the design could be calculated as,

$$Q_{Tot} = \frac{(T_b - T_e)}{R} \quad (5)$$

where, T_b - Temperature of the body, T_e-Temperature of the environment, R - equivalent thermal resistance of resistors R_1 to R_7, where $R_2 = R_6$ and $R_3 = R_5$ as shown in Fig. 1.

Substituting the expression for R in the Equation (5), the Q_{Tot} could be expressed as;

$$Q_{Tot} = \frac{2(T_b - T_e)\{R_1[(R_3+2R_4)(2R_2+R_7)+R_3R_4]+2R_2R_7(R_3+2R_4)+R_3R_4R_7\}}{(R_3+2R_4)(2R_2+R_7)+R_3R_4} \quad (6)$$

The time period of cooling t can be obtained by Equation (7),

$$t = n * \frac{V\rho L_f}{Q_s} \quad (7)$$

where, n - no. of capsules required, V - volume of a capsule, ρ - density of the core material, Q_s - heat flux to the core and L_f - latent heat of fusion.

C. *Mathematical representation for water-mediate EC technique*

Fig. 3 shows the schematic representation and the illustration of the thermal resistance for the water-mediated EC model. The sweat evaporated from the skin and the evaporation of moisture present on the fabric contributes to the cooling effect produced. The fabric layer consists of a three-layered structure as shown in Fig. 2.

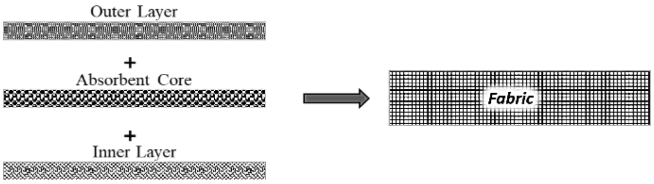

Fig. 2. – The model representing the sandwiched fabric layer.

This cooling technique functions after the liquid water is introduced to the absorbent core. The cooling effect is created by the evaporation of the liquid water which occurs at any temperature, if the air is unsaturated. Accordingly, when the fabric is worn near to the skin, the energy stored within the microclimate is absorbed, which results in evaporation. Evaporation of one liter of water takes away approximately 2400 kJ, which can effectively reduce the heat stress as described in Equation (4).

During the model formulation, the following assumptions were made

- The three-layered fabric has been modelled as one fabric layer.
- The system behaves in isothermal conditions.
- The fabric surface is covered by a continuous water film.
- The partial pressure of water vapor at the skin surface reaches the saturated level.

The first assumption to represent a ‘three-layered fabric as one layer of fabric’ was due to the fact that the inner layer and the outer layer do not contribute to holding water, thus, the effect created towards the water film is negligible.

Based on the literature, the heat flow that causes the skin cooling $q_{fabw,sk}$ can be expressed as,

$$q_{fabw,sk} = \frac{\beta(P_{sat,fab} - P_{air})}{(1 + \alpha R_{ct}(1 - kU) + \alpha R_{gap})} \quad (8)$$

where, β - convection mass transfer coefficient, $P_{sat.fab}$ - saturated water vapour pressure on the fabric surface, P_{air} - water vapour pressure of the environment, α – convective heat transfer coefficient which increases with air velocity, R_{ct} - the thermal resistance of fabric in the ultra-dry state, k - experimentally determined constant characterizing the decrease of thermal resistance caused by the increased moisture of the fabric and U - relative mass increase of the fabric with moisture content (%), R_{gap} - evaporative resistance of the air layer.

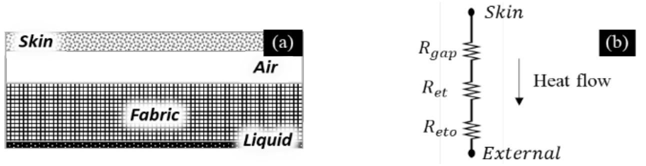

Fig. 3 - Model of a water-mediate EC garment (a) Schematic representation (b) Equivalent resistance diagram (R_{gap}, R_{et}, R_{eto}, represent the thermal resistance of each component).

The heat flow coming from the skin q_{skin}, can be described by Equation (9),

$$q_{skin} = \frac{P_{sat} - P_{air}}{(R_{gap} + R_{et} + R_{eto})} \quad (9)$$

where, P_{sat} - saturated vapour pressure in the skin surface, R_{et} - experimentally determined constant for evaporative resistance of the fabric, R_{eto} - evaporative resistance of the boundary layer.

The total heat flow q_{tot} through the fabric surface can be calculated by the addition of Equations (8) and (9).

$$q_{tot} = \frac{P_{sat} - P_{air}}{R_{gap} + R_{et} + R_{eto}} + \frac{\beta(P_{sat.fab} - P_{air})}{1 + \alpha R_{ct}(1 - kU) + \alpha R_{cgap}} \quad (10)$$

D. *Mathematical model for TEC technique*

Fig. 4 shows the schematic representation and the representation of the thermal resistance circuit created for the model on Peltier arrangements. According to the model, one Peltier element is considered, which is sandwiched in between two fabric layers. A flexible Peltier is considered since it is worn closer to the skin in a personal cooling garment, and therefore it should support the body movements.

The Peltier effect occurs if and only if a current passes through the thermoelectric module. Due to this current, heat energy gets absorbed from the connective points of thermoelectric pillars to the external circuits. Since the heat gets absorbed in these positions, the temperature gets reduced. The absorbed heat flows through the doped *p* and *n* type semiconductors and gets released at the next end, therefore the temperature in those places gets increased. The resultant cooling will depend on the balance of the cooling power, heating power, and heat produced due to the current flow (due to charge carrier movement), etc. Therefore, according to the literature [20], resultant cooling of a Peltier module can be described using Equation (11),

$$Q_{RC} = IT_c(\alpha_P - \alpha_n) - (T_H - T_C)(K_p + K_n)\left(\frac{A}{l}\right) - \frac{I^2}{2}(R_p + R_n) \quad (11)$$

where, I - current through the Peltier, α_P & α_n - Seeback coefficients of branches and T_c - temperature of cooler side of Peltier module, T_H - temperature of the hotter side of the Peltier module and K_p & K_n - thermal conductivity of the branches, A - cross-section of a leg, l - height of leg in the module, R_p & R_n - Thermal resistance of the branches

For the cooling to occur, the power supplied to the Peltier should be large enough to cater the Joule heating and to create the temperature difference. Accordingly, Equation (12) describes the required power W for the Thermoelectric module to create the Peltier effect [20].

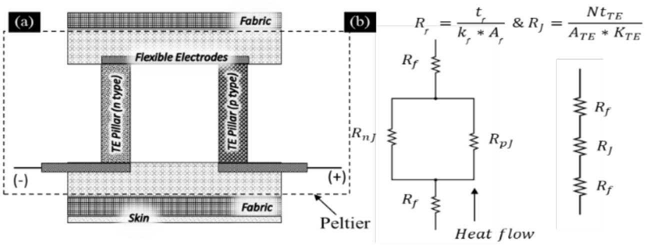

Fig. 4 – Model of TEC using Peltier - Modules (a) Schematic representation (b) Equivalent resistance diagram (R_f, R_{pj}, R_{nj}, R_j, represent the thermal resistance of each component).

$$W = (\alpha_P - \alpha_n) * I * (T_H - T_c) + \frac{I^2}{2} * (R_p + R_n) \quad (12)$$

Considering the function of the Peltier modules, it functions as the heat pump and therefore the term efficiency is not appropriate. Based on the second law of thermodynamics the suitable term to assess the performance of the Peltier is the coefficient of performance (COP) and can be calculated using Equation (13).

$$COP = \frac{Q_{Res\ Cooling}}{W} \quad (13)$$

IV. RESULTS AND DISCUSSION

The results of this study fall under two categories: the analytical model results, and the suitability of the cooling techniques, which have been carried out with the physical boundary conditions suited for a high humid high temperature environment.

A. *Results of the Mathematical analysis*

1) *Results of the study of the PCM cooling*

According to the model described in Fig. 1, in an environment with a temperature in the range of 303K to 306K, nonadecane can be used as the PCM core encapsulated by melamine formaldehyde as the shell material. The core to shell ratio of the PCM capsule used was 3:1 with the length and width of 3 mm on each side. These capsules were included in the flexible polyurethane foam which gets sandwiched by high density polyethylene (HDPE) fabric. The analysis was made with relation to a repeat unit where the fabric thickness considered was 0.5 mm.

Thermal conductivity values of HDPE, polyurethane foam, and melamine formaldehyde were 0.481, 0.028, 0.5Wm^{-1}K^{-1}, respectively. The core of the macro capsule has the latent heat of fusion of 222 kJ/kg. According to the analysis with the one-dimensional heat flow, it was found that the heat that passes through the shell material of a PCM capsule was 5.197 mW, when temperatures T_b = 306K and T_e = 303K. Furthermore, it was calculated that 46 macro capsules of diameter 3mm can provide 2 hours of sufficient cooling.

However, it was found that the temperature of the skin was maintained at 305K (the phase change temperature of the nonadecane) during the long period of wearing. Therefore, with respect to the tropical countries where the radiant temperature is higher, selected PCM alone can only provide the cooling with limited temperature reduction in the microclimate

2) Theoretical results based on the study of the water mediate evaporative cooling technique

Considering the environmental parameters in high temperature and high humid environments the following were used for the analysis,

- the environmental temperature is $304 \pm 3\ K$ [17],
- relative humidity varies between $60\ \% - 100\ \%$ [17],
- wind speed varies between $2\ ms^{-1} - 5\ ms^{-1}$ [18].

At the above stated environmental parameters, considering a three-layered fabric with 20ml of water absorbed in the core layer, the calculation results showed that the total heat flux going through the fabric was around 330 W/m^{-2}. Furthermore, it was found that the composite structure was able to cool for 35 minutes through the evaporation of the water available in the middle layer.

3) Results based on the study of thermoelectric cooling using Peltier modules.

When a person is performing a light activity, the energy emitted by the body to the environment is 87W/m^2 [3]. The average surface area of the human body is 1.8m^2 and it is also stated that the upper back part of the body between the neck and waist, emits a larger amount of heat to the environment and has a surface area of 0.3m^2 [19]. Considering the function of a TEC as a heat pump/refrigerator, by pumping the heat emitted by the body which is stored on the microclimate (colder side) to the environment (hotter side), thermoregulation can be achieved. To pump the heat emitted by the body to the environment, a Thermoelectric module (model no: TEC1-12706), with its parameters such as conductivity of branches $K_{TE} = 1.50 Wm^{-1}K^{-1}$, Seeback coefficients α_m = 0.200VK-1, the temperature of the hotter side T_H = 300K, resistance R_{module} = 1.98Ω was considered for the analysis.

According to the calculations carried out, to cater the stated requirement with achieving a temperature difference of 10K between the two sides of the module, using 6 Peltier modules with 3 in one circuit is more realistic. It is calculated that 1.5A current with a supply voltage of 9V for one circuit will be required. The calculated COP of one module was 1.17 for this mentioned situation as calculated from (13).

B. Suitability of these cooling techniques in hot and humid environments.

All these cooling techniques are suitable to be used in a PCG. A comparison of the theoretical calculations made based on models derived from heat transfer principles discussed in section B, are summarised and tabulated in Table 2, which depicted that PCM could provide 2 hours of cooling by simply having 46 macro capsules. This has the advantage as the capsule can be restored back to its initial state with the reduction of temperature. Thus, there is no requirement of any additional inbuilt energy source to be incorporated into the PCG. Nevertheless, the temperature reduction during the cooling period by PCM is lesser compared to the other cooling techniques. The water mediate evaporative cooling technique also does not require any additional elements to power or any additional energy sources. As shown in Table 2, this can provide cooling for 36 minutes by simply evaporating 20 ml of water. However, this evaporation is dependent on the relative humidity and in humid environments, the effect created by this cooling technique is comparatively low. Thermoelectric cooling using Peltier modules is an advanced method that uses current, and can reduce the temperature to any required temperature range within a very short time period. The heat can be pumped effectively out to the environment even by using small currents and voltages, yet with a higher COP value. Nevertheless, the disadvantage of this method is that at lower temperature differences created, the back heating gets more prominent. Also, looking at the combinations possible, it is clear that there are three combinations, where, the TEC and EC methods are impossible as it uses water and electricity together. Comparing the other two combinations, the PCM and EC methods could provide lesser cooling compared to the combination of the Pelter & PCM technique. The back heating effect created by the TEC could be absorbed by the PCM, which can act as a heat sink when eicosane is used. As the phase change temperature of the material is 309K which is closer to the temperature of the hot side of the Peltier, it can provide an efficient heat sinking process. Using more than one Peltier and placing them on the backside of the cooling panel could help in removing larger amounts of heat as well as to avoid effects due to the back heating, thus providing the optimum cooling.

Table 2. Analysis of cooling techniques

Cooling technique	Dependent	Cooling duration
PCM	46 capsules	2 hours
EC	20 ml	36.1 minutes
TEC	1.5A/3V	continuous

V. CONCLUSION

The temperature recording by NASA and the consensus related to the heat related illnesses shows that there is no proper thermal comfort achieved in clothing globally and when it comes to the tropical countries this effect is severe. This proves the requirement for a personal cooling system in clothing since it is considered as the second skin. The requirement of PCG was further proven by the survey conducted in Sri Lanka. Hence this study investigated the suitability of different cooling techniques and their combinations to use in personal cooling garments in tropical countries.

To provide thermal comfort via PCG, the qualitative analysis made on the available cooling techniques suitable for textiles concluded that cooling using Phase Change Material

(PCM), Evaporative Cooling (EC) and Thermoelectric Cooling (TEC) was found to be more effective in both cooling and to cater the requirements from the day-to-day wear. The mathematical analysis of these three techniques showed that TEC provided continuous cooling with a 10 ℃ temperature difference between the two sides of it, while having problems with the back heating as it functions as the heat pump. PCM was able to provide 2 hours of cooling with 46 capsules, although the temperature reduction it can provide in the microclimate was not adequate. EC was having a limitation in cooling due to the barrier caused for the water to evaporate in high humid environments. Therefore, considering the pros and cons of each of these three techniques, it is recommended that the combination of PCM & TEC can provide optimum cooling for a PCG in tropical climates. These results obtained from the mathematical analysis are further required to validate with experimental evidence, which would be the next phase of this research. Also, the final garment design should consider other factors such as heaviness of the cloth, energy consumption etc.

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