

The Body Cooling System Integrated into the Clothes

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Introduction

Body temperature is one of the most important human physiological parameters. Human state of health and all physiological processes bounding in the organism depends on it. High ambient temperature has a very big influence upon the human body temperature and upon his behavior, efficiency and feeling. For these reasons it is important to cool human body to ergonomic temperature. Body cooling is actual for the soldiers who serve in the desert, people who work in the high temperature environments (metal melting, glass manufacturing factories, firefighters), sportsmen. To optimize the body cooling system is useful to integrate it into human wearing clothes. Requirements for this system are:

- insensibility to the body movement;
- minimal weight;
- reliability;
- effectiveness;
- minimal system power input;
- minimal cost.

Body cooling system

The external heat transfer mechanisms are radiation, conduction, convection and evaporation of perspiration. The human must lose heat at a basal rate of about 90 watts as a result of his basal metabolism [1, 2, 4].

The basic heat transfer equation for conduction is

$$G = \frac{Q}{t} = \frac{\kappa A (T_H - T_C)}{d}, \quad (1)$$

where A – area of the human body, κ – thermal conductivity of the air surrounding the body, T_H, T_C – hot and cold temperatures ($^{\circ}\text{C}$). Typical human body area is $A = 2 \text{ m}^2 = 2 \times 10^4 \text{ cm}^2$. Thermal conductivity of the still air $\kappa = 5,7 \cdot 10^{-5} \text{ cal / s / cm} \cdot ^{\circ}\text{C}$, d – distance between the cooling skin and ambient surface.

Heat transfer equation for convection:

$$C = h \cdot A \cdot (T_H - T_C), \quad (2)$$

where h – heat transfer coefficient ($\text{W}/(\text{m}^2 \cdot ^{\circ}\text{C})$).

Heat transfer for radiation:

$$R = \frac{Q}{t} = e \sigma A (T_H^4 - T_C^4), \quad (3)$$

where $\sigma = 5,6703 \cdot 10^{-8} \text{ W}/\text{m}^2 \text{ K}^4$ (Stefan's constant), e – emissivity of the skin.

Heat transfer for evaporation:

$$E = \frac{Q}{t} = h_e \cdot (p_H - p_C), \quad (4)$$

where h_e – evaporative heat transfer coefficient, p_H – ambient water vapour pressure (kPa), p_C – water vapour pressure at the skin.

When ambient temperature is higher than body temperature all three standard heat transfer mechanisms: convection, conduction, radiation work against heat loss by transferring heat into the body. In this way body cooling function is played only by evaporation of perspiration.

Human body heat balance shown in the (5) equation.

$$S = M - C - R - E - H, \quad (5)$$

where S – rate of change in body heat content, M – metabolic heat production, C – convective heat exchange, R – radioactive heat exchange, E – evaporative heat exchange, H – airway heat loss.

Clothing influence upon thermoregulation of the human body must be evaluated. The heat transfer in clothes involves heat convection, conduction and radiation as the latent heat of various phase changes in clothing materials. Two principal properties determine this effect: thermal insulation (I_T) and evaporative resistance (R_{eT}).

Thermal insulation defines the resistance to the heat transfer by convection and radiation by clothing layers:

$$I_T = \frac{T_C - T_H}{R + C}. \quad (6)$$

Evaporative resistance defines the resistance to heat transfer by evaporation and vapour transfer through clothing layers:

$$R_{eT} = \frac{p_C - p_H}{E} \quad (7)$$

Using (6) and (7) equations we can find energy balance equation of the human body skin with clothing:

$$S = M \frac{T_C - T_H}{I_T} - \frac{p_C - p_H}{R_{eT}} - H \quad (8)$$

Only certain values for the physiological variables (M , T_C , p_C) are compatible with acceptable and tolerable conditions. These conditions can be analyzed in terms of various scenarios for activity, climate and clothing.

Suppose, the body cooling system integrated into clothes is meant for people who are in the desert or in the steppe. Cooling system is structural scheme is given in the Fig. 1. In this case, ambient temperature rises till 60 °C in the day time.

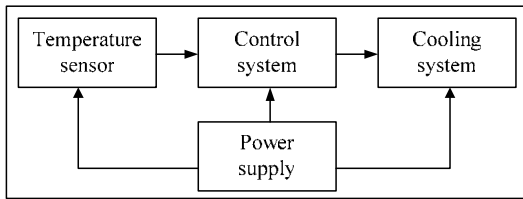


Fig. 1. Structural scheme of body cooling system

For the body cooling system first of all needs to choose minimal power energy consumption requiring cooling method.

Body cooling system integrated into clothes can apply different cooling principals: thermodynamic methods – Carnot, Stirling, Ericsson cycle; thermoelectric effects: Peltier, Thomson effect; magnetocaloric cooling, electrocaloric cooling, optical cooling.

Reverse thermodynamic cycle

Cooling cycle path can be displayed in the plane temperature – entropy (T - s diagram). Basic thermodynamic cooling cycles are shown in Fig. 2.

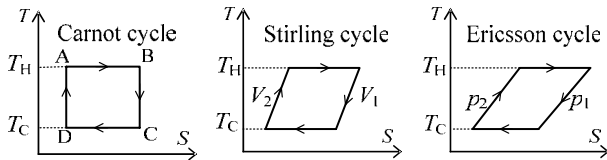


Fig.2. Temperature – entropy diagrams a) Carnot cycle, b) Stirling cycle and c) Ericsson cycle

All three cycles are different in the way in which the hot and cold isotherms are connected [5]. In the Carnot cycle an adiabatic path (no heat exchange) is used, in the Stirling cycle an isochoric path (constant volume) and in the Ericsson cycle an isobaric path (constant pressure). Common for all three cycles is that the entropy of the working medium can be changed significantly at (nearly) constant temperature to take up or give away heat. Heat dQ

absorbed at a temperature T is related to an entropy change of the working medium, dS_{medium} , by: $dQ \leq T dS_{medium}$.

Comparative analysis of these cooling cycles has shown that Carnot cycle has the best efficiency:

$$\eta_{max} = \frac{(T_H - T_C)}{T_H} = 1 - \frac{T_C}{T_H} \quad (9)$$

here T_H and T_C are absolute hot and cold reservoirs temperature.

One of the main advantages of reverse thermodynamic cycle, regarding its application for the body cooling system integrated into clothes – it has the best efficiency compared with other cooling principles, i.e. 40-60 %.

Disadvantages: mobile, lot of energy and space requiring mechanical parts – compressor, evaporator, either necessary cooling reagent (refrigerant) – this liquid is toxic and has effects on the ozone layer, the negative influence of greenhouse gases and can take affect on the human.

Thermoelectric cooling method based on Peltier effect

Peltier effect is reversible to Seebeck effect. In this process electrical energy changes into thermal energy [3].

Electrons in a conductor or a semiconductor behave as a Fermi fluid with Fermi temperature:

$$T_F = \frac{h(3\pi^2 n)^{2/3}}{2km^*} \quad (10)$$

where n is the electron density, k – Boltzmann's constant, m^* - effective mass of the electron. Significantly below the Fermi temperature T_F the entropy is proportional to T .

The Fermi temperature T_F is relatively large in electron systems (in metals typically $T_F \approx 6 \cdot 10^4$ K). It can be lowered by reducing the electron density as depicted in Fig. 3. At fixed temperature T_0 a reduction of T_F means an increase in entropy (ΔS_0 in Fig. 3).

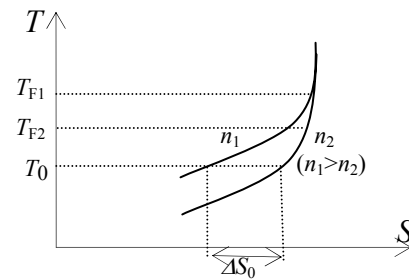


Fig. 3. Entropy of electron systems with high and low electron densities (n_1 respectively n_2)

In practical thermoelectric coolers an n -type semiconducting material is combined with p -type material. In this way a current can be established with a double Peltier effect: one for the electrons that leave the junction through the n -type material and one for the holes that leave via the p -type material:

$$Z_{12} = (\alpha_1 - \alpha_2)^2 \left[\sqrt{\frac{\kappa_1}{\sigma_1}} + \sqrt{\frac{\kappa_2}{\sigma_2}} \right]^{-2} \quad (11)$$

This effect is defined as absorption of heat on the junction of two conductors through which a *d.c.* electric current passes (Fig. 4). The absorption of this heat depends on the direction of the electric current, and per unit time it is equal to

$$Q_{\Pi} = (\Pi_1 - \Pi_2) \cdot I, \quad (12)$$

where $\Pi_{1,2}$ are the Peltier coefficients of the conducting materials ($\Pi = \alpha T$, where α - Seebeck coefficient, T - temperature), I is the electric current.

Maximal temperature difference between two conductors depends upon electrical current density, electrical specific conductivity and thermal specific conductivity:

$$(T_H - T_C)_{\max} = \frac{1}{8} (\Pi_1 - \Pi_2)^2 \sigma / \kappa, \quad (13)$$

where σ - specific electrical conductivity, κ - specific thermal conductivity.

Regarding to equation (13) cooling effect is the stronger the bigger specific electrical conductivity is and the less as possible specific thermal conductivity is.

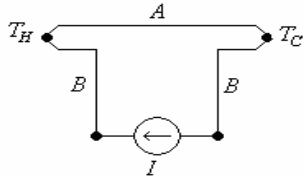


Fig. 4. Principal scheme of Peltier effect

Optimal Peltier efficiency, when the current optimal is shown in equation:

$$\eta = \left(\frac{T_{ave}}{\Delta T} \right) \left(\frac{\left(\left(1 + Z^* T_{ave} \right) \frac{1}{2} - 1 \right)}{\left(\left(1 + Z^* T_{ave} \right) \frac{1}{2} + 1 \right)} \right) - \frac{1}{2}, \quad (14)$$

where $T_{ave} = \frac{1}{2}(T_H + T_C)$, $\Delta T = T_H - T_C$.

Low efficiency determines low coefficient of the figure of merit of material

$$Z^* = \frac{\alpha^2 \sigma}{\kappa} T, \quad (15)$$

where α - Seebeck coefficient, σ - specific electrical conductivity, κ - specific thermal conductivity, T - temperature. Thermoelectric coolers with coefficient $Z^* = 1$ operate only 10% of Carnot efficiency. Using new conductors processing technology it could be reached, that Z^* is equal to 4, and this should be about 30% of Carnot efficiency.

Correct description of the Peltier effect is based on the equation of energy balance:

$$\frac{\partial \varepsilon}{\partial t} = -divq + \frac{j^2}{\sigma} - \left(\frac{\partial \Pi}{\partial T} - \alpha \right) (j \nabla T), \quad (16)$$

where $q = q_{dr} + q_{dif}$ generalized heat flux; $q_{dif} = -\kappa \nabla T$ - thermal diffusion flux, $q_{dr} = \Pi j$ - thermal drift flux (a heat flux which is carried out by charge carriers during the process of their drift in the electric field), ε - energy, σ - electrical conductivity, j - electric current density, α - Seebeck coefficient.

In the linear approximation and in a steady state which describes the Peltier effect energy balance equation is reduced to the following equation:

$$div(\kappa \nabla T - \Pi j) = 0 \quad (17)$$

This equation shows, that the heat bulk sources and sinks are absent in linear approximation in electric current.

Fig. 5 shows dependence between temperature difference and the transferred power. The bigger temperature difference is the less power is transferred. We need temperature difference about 40 °C, in this case transferred power is about 19 W.

Peltier effect is reversible to Seebeck effect. Using this effect we can make body heating system from the same system when the ambient temperature falls down.

Selection of the thermoelectric cooling method determines these factors: 1) safety for the human; 2) very high reliability of cooling elements and ease of use; 3) consideration of size, space, weight; 4) possibility to use the same elements for heating, too.

Mostly, cooling process is required where a lot of sun is in the desert or steppe. In this case for the power supply of the thermoelectric elements we can use solar batteries. Matching them with accumulators we can use the same system for body heating at the time when the sun is absent.

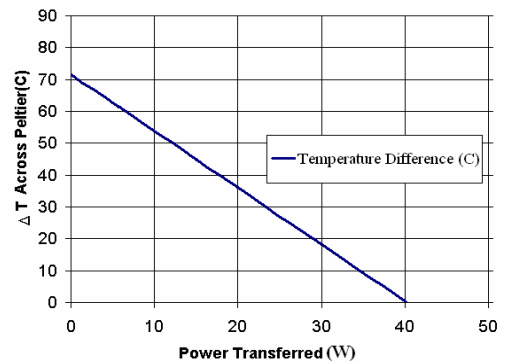


Fig. 5. Transferred power dependence from the temperature difference

Magnetocaloric cooling and other principles

One of the newer cooling methods is magnetocaloric cooling [5]. By demagnetizing a paramagnetic material, the magnetic domains become disordered and entropy increases. Thus heat can be absorbed. The magnetocaloric cycle is schematically depicted in the T - s diagram of Fig. 6. The curve for the magnetized state (i.e., $B > 0$) has lower entropy than that of the demagnetized state (i.e., $B = 0$). This method is strong investigating in these latter years. Magnetocaloric cooling advantages are: 1) green technology (no use of conventional refrigerants); 2) noiseless technology (no compressor); 3) high thermodynamic efficiency; 4) lower energy consumption; 5) simple construction; 6) low maintenance costs; 7) low pressures.

Disadvantages are: 1) strong magnetic field with not completely known influences on living creatures; 2) protections to avoid disturbances of electronic components; 3) the field strengths of permanent magnets are still limited, superconducting magnets are too expensive; 4) temperature differences are still not so high.

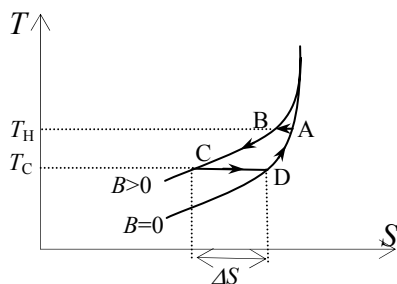


Fig. 6. Magnetocaloric cooling in T - s diagram

The magnetic field, which is necessary for effective cooling, is about 1,2 – 2 T. Under Lithuanian Republic rules effect for human safe magnetic field is till 0,2 T. This is main reason why magnetocaloric cooling method is impossible for human body cooling system.

Electrocaloric and optical coolings aren't very useful and still are in research. Electrocaloric cooling is based upon the effect of electrical field. In 2006 in the journal Science it was reported about thin film of perovskite PZT which has a strongest electrocalorific response with materials cooling down to 7 °C in a field of 25 kV/m. Optical cooling is based on anti-Stokes fluorescence. This action works by laser light. At this moment the best result is a temperature difference of 56 K. For the cooling system integrated into clothes these principles are too complicated.

Conclusions

1. There are some different principles suitable for human body cooling: reverse thermodynamic cycles, Peltier effect, magnetocaloric, electrocaloric, optical cooling and other.

2. For the body cooling system integrated in the clothes the most suitable cooling method is Peltier effect, because the reliability, "green" technology, the absence of mechanical devices and possibility to use the same system for heating.

3. The cooling is needed in the cases when the solar radiation is intensive, therefore, the power supply function can be played by solar batteries.

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Regulation of the human body temperature has a very high influence on physiological processes bounding in the human organism. The minimization and integration of this system into humans clothes became important when being in the desert or working in the environment of the high temperature. The body cooling system structural scheme, energy balance equations evaluating the human clothes are presented. Possible cooling methods for the body cooling system integrated into clothes are reviewed: thermodynamic, thermoelectric, magnetocaloric. Considering safety and convenience of integration into the clothes the cooling method based on Peltier effect was chosen. Solar battery is used instead of the power supply in the body cooling system. Ill. 6, bibl. 5 (in English; summaries in English, Russian and Lithuanian).

Р. Бансевичюс, Р. Рачкене, Ю. А. Вирбалис. Интегрированная в одежду система охлаждения тела // Электроника и электротехника. – Каунас: Технология, 2007. – № 5(77). – С. 3–6.

Регулирование температуры тела имеет большое влияние на физиологические процессы, протекающие в организме человека. Применение такой системы и ее интегрирование в одежду актуально для людей, находящихся в пустыне или работающих в высокотемпературных помещениях. Представлена структурная схема системы охлаждения тела и уравнения баланса тепловой энергии с учетом одежды. Обсуждены различные принципы охлаждения тела, пригодные для интегрирования в одежду: термодинамические, термоэлектрические, магнетотепловые. С расчетом удобства и безопасности выбран способ охлаждения основан на эффекте Пельтье. В качестве источника питания предлагается использовать солнечные батареи. Ил. 6, библи. 5 (на английском языке; рефераты на английском, русском и литовском яз.).

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Žmogaus kūno temperatūros reguliavimas turi didelę įtaką žmogaus organizme vykstantiems fiziologiniams procesams. Tokios sistemos minimizavimas ir integravimas į žmogaus dėvimus drabužius tampa aktualus esant dykumoje ar dirbant aukštos temperatūros patalpose. Pateikta kūno vėsinimo sistemos struktūrinė schema ir energijos balanso lygtys, sudarytos atsižvelgiant į žmogaus dėvimus drabužius. Aptarti galimi naudoti vėsinimo principai: termodinaminiai, termoelektriniai, termomagnetiniai. Atsižvelgiant į patogumą, saugą ir ergonomiškumą, pasirinktas Peltier efektu paremtas vėsinimo metodas. Kūno vėsinimo sistemoje kaip maitinimo šaltinis naudojamos saulės baterijos. Il.6, bibl.5 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).