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ALTEC-7012 THERMOELECTRIC DEVICE FOR COOLING OF THE HUMAN HEAD

The results of computer simulation of thermophysical processes in the human head at given heat fluxes on its surface have been presented. The disadvantages of the existing physical models of the human head have been established and the ways for their improvement have been proposed. A prototype ALTEC-7012 thermoelectric device for cooling the human head has been designed and manufactured. The device is promising for human brain hypothermia.

Keywords: computer simulation, thermoelectric cooling, human head cooling, and brain hypoxia.

Brain hypoxia is among the most relevant medical problems [1—8]. It accompanies disorders of cerebral blood circulation, depressed cases, acute cardiovascular insufficiency, complete transverse heart block, head injury, poisoning with carbon monoxide, and asphyxia of various origin. Brain hypoxia may also occur as a complication of surgeries on heart and major blood vessels and in early recovery period. It is accompanied with various neurological syndromes and psychiatric disorders.

If hypoxia lasts longer than 3—4 minutes, brain recovery is impossible. However, local hypothermia is known to reduce brain need in oxygen, to enhance its resistance to hypoxia and to minimize or even to remove risk of temporary brain ischemia, thereby extending permissible duration of hypoxia [9—10]. For instance, cooling by 5 °C increases brain lifetime several times. Hypothermia is recommended in the case of various head injuries, cardiac surgeries, and during recovery period, in the case of hypoxic cerebral edema, intoxication, and CNS injuries.

Usually, the equipment for cooling of human head is associated with bulky fixed hardware based on compressor refrigerators [11—17]. Recently, engineers have deigned devices based on thermoelectric cooling, however, they have not been widespread yet [18—20].

Therefore, this research is aimed at assessing the prospects for the application of thermoelectric equipment to cooling of human head and at designing a device for human brain hypothermia.

PHYSICAL MODEL OF HUMAN HEAD

The physical model of human head is based on the existing models. It is a hemisphere having a radius R that is equal to average radius of the adult human being (Fig. 1). The sphere has near-surface layers *1—3* whose thickness is equal to average thickness of scalp q_{meti} (i = 1—4) generated in each, uniformly across the spherical volume, and each exchanging heat with circulating blood described by blood perfusion factor ω_{bi}. The brain is considered a biological tissue having a high blood perfusion; blood temperature is fixed at T_b = 37 °C. Temperature at the boundaries of respective layers is T_1, T_2, T_3, T_4. Thermophysical properties of these biological layers are given in Table 1 [21].

The upper part of the hemisphere exchanges heat with environment (by irradiation and convection) or with cooling helmet (with given integral heat exchange coefficient). Here, q_1 is density of heat flux dissipated from the human head to the environment. The lower part of the hemisphere has a temperature of T_5 = 37 °C.

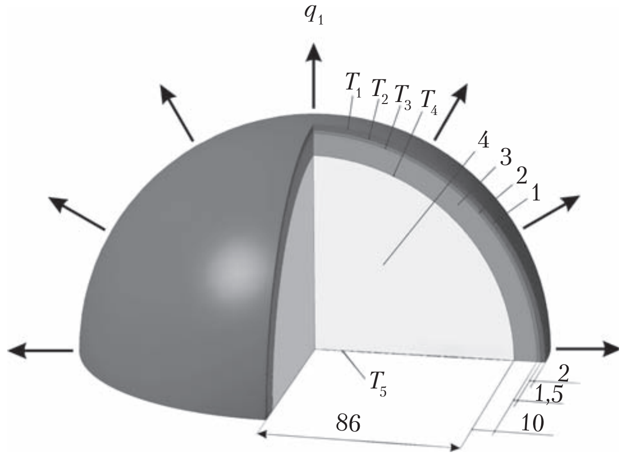


Fig. 1. Physical model of human head

MATHEMATICAL DESCRIPTION OF PHYSICAL MODEL

The general heat exchange equation in the biological tissue is as follows [21–26]:

$$\rho_i \cdot C_i \cdot \frac{\partial T}{\partial t} = \nabla(\kappa_i \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_{b_i} \cdot (T_b - T) + q_{met_i}, \quad (1)$$

where i = 1—4 are respective layers of the physical model of the human head; ρ_i is density of the respective layer of the biological tissue, kg/m^3; C_i is specific heat capacity of the respective layer of the biological tissue, J/kg·K; ρ_b is blood density, kg/m^3; C_b is specific blood heat capacity, J/kg·K; ω_{bi} is rate of blood perfusion of the respective layer of the biological tissue, m$^3 \cdot$ s$^{-1} \cdot$ m^{-3}; T_b is human blood temperature, K; q_{meti} is heat of metabolism of the respective layer, W/m^3; T is absolute temperature, K; κ_i is heat conductivity coefficient of the respective layer of the biological tissue, W/m · K; t is time, s.

The component in the left part of the equation (1) is rate of varying heat energy in the volume unit of biological tissue. The three components in the right part are rate of varying heat energy due to heat conduction, blood perfusion, and metabolic heat, respectively.

The heat exchange equation in the biological tissue shall be solved for the following boundary conditions (2)—(3):

$$\begin{cases} q_1 = q_{rad} + q_{conv} = \varepsilon \cdot \sigma \cdot (T^4 - T_0^4) + h_{conv} \cdot (T - T_0) \\ \text{або} \\ q_1 = h_{fluid} \cdot (T - T_{fluid}), \end{cases} \quad (2)$$

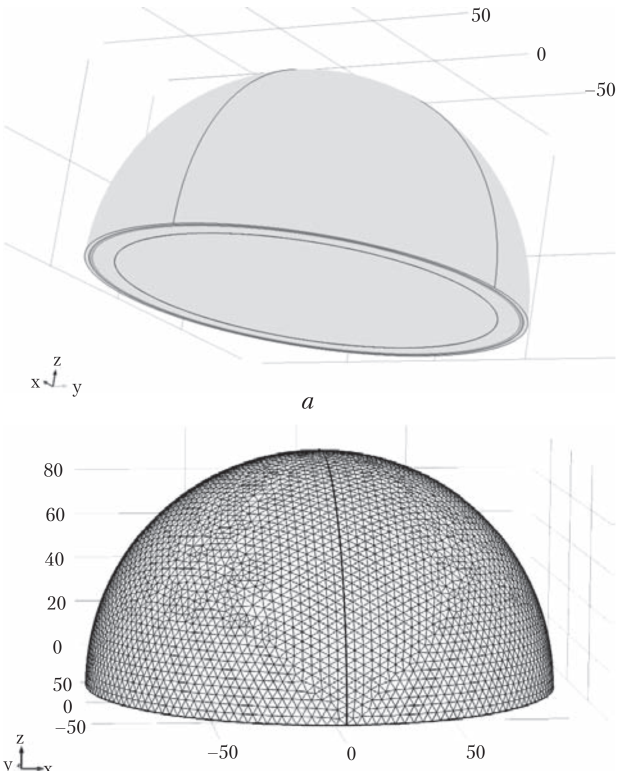
$$T_5 = 310\ K, \quad (3)$$

where q_1 is density of heat flux dissipated from the human head to environment; q_{rad} is emission

Table 1

Thermophysical Properties of Biological Layers of the Human Head [21]

Anatomic structure of the human head	Heat conductivity k, W/m·K	Density ρ, kg/m^3	Specific heat capacity C_p, J/kg·K	Perfusion W_b, l·s^{-1} m^{-3}	Metabolism q_{met}, W/m^3
Scalp	0.47	1000	3680	1.5	363
Subcutaneous layer	0.16	850	2300	0.2	130
Skull	1.16	1500	1591	0.15	130
Brain	0.49	1080	3850	8.5	10437
Blood	0.5	1069	3650	—	—



b

Fig. 2. Grid of finite element method in COMSOLE MULTIPHYSICS computer program

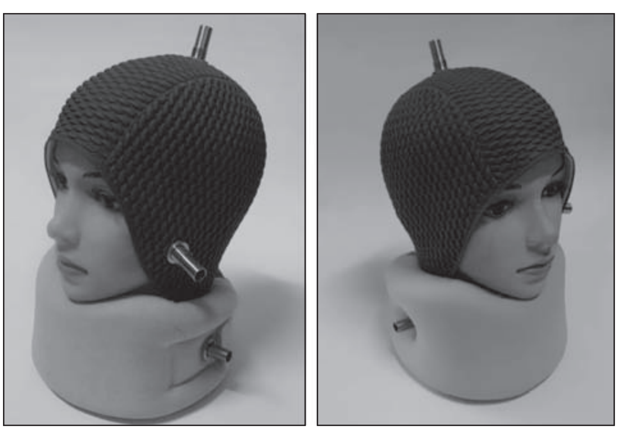


Fig. 5. Cooling helmet for head and collar for neck

heat flux density; q_{conv} is convection heat flux density; ε is emissivity coefficient; σ is Boltzmann constant; T is absolute temperature; T_0 is environment temperature; h_{conv} is convective heat ex-

Fig. 6. Thermoelectric cooling unit

change coefficient; h_{fluid} is coefficient of heat exchange with fluid; T_{fluid} is fluid temperature.

COMPUTER MODELLING RESULTS

In order to determine the heat impact on the human head, a 3D computer model of the human head whose surface contacts with cooling helmet has been developed. For designing the computer model, *Comsol Multiphysics* [27] software package has been used. This enables modelling the thermophysical processes in the human biological tissue with blood circulation and metabolism taken into account. The temperature and heat flux density distributions were calculated by the finite elements method (Fig. 2).

Using object-oriented computer modelling the temperature distribution inside the human head has been determined. For instance, Fig. 3 (see color inset) shows the temperature distribution in the axial cross section of the human head at a total heat flux from its surface Q = 10 W.

Magnitude of heat fluxes from the human head ranges within Q = 10÷100 W and is limited with minimum permissible temperature of human head surface (+2 °C). For the convenience of comparing the mentioned heat regimes, Fig. 4 (see color

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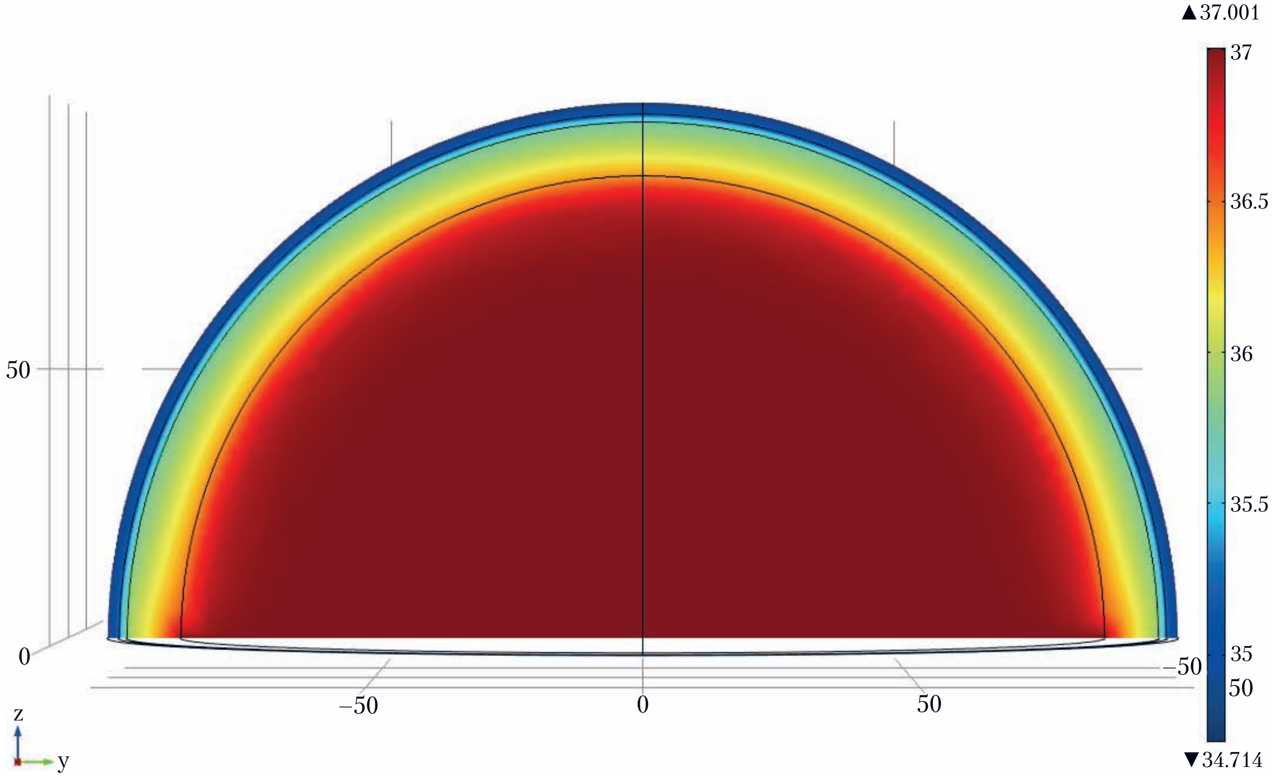

Fig. 3. Temperature distribution in axial cross section of human head at total heat flux from its surface Q = 10 W

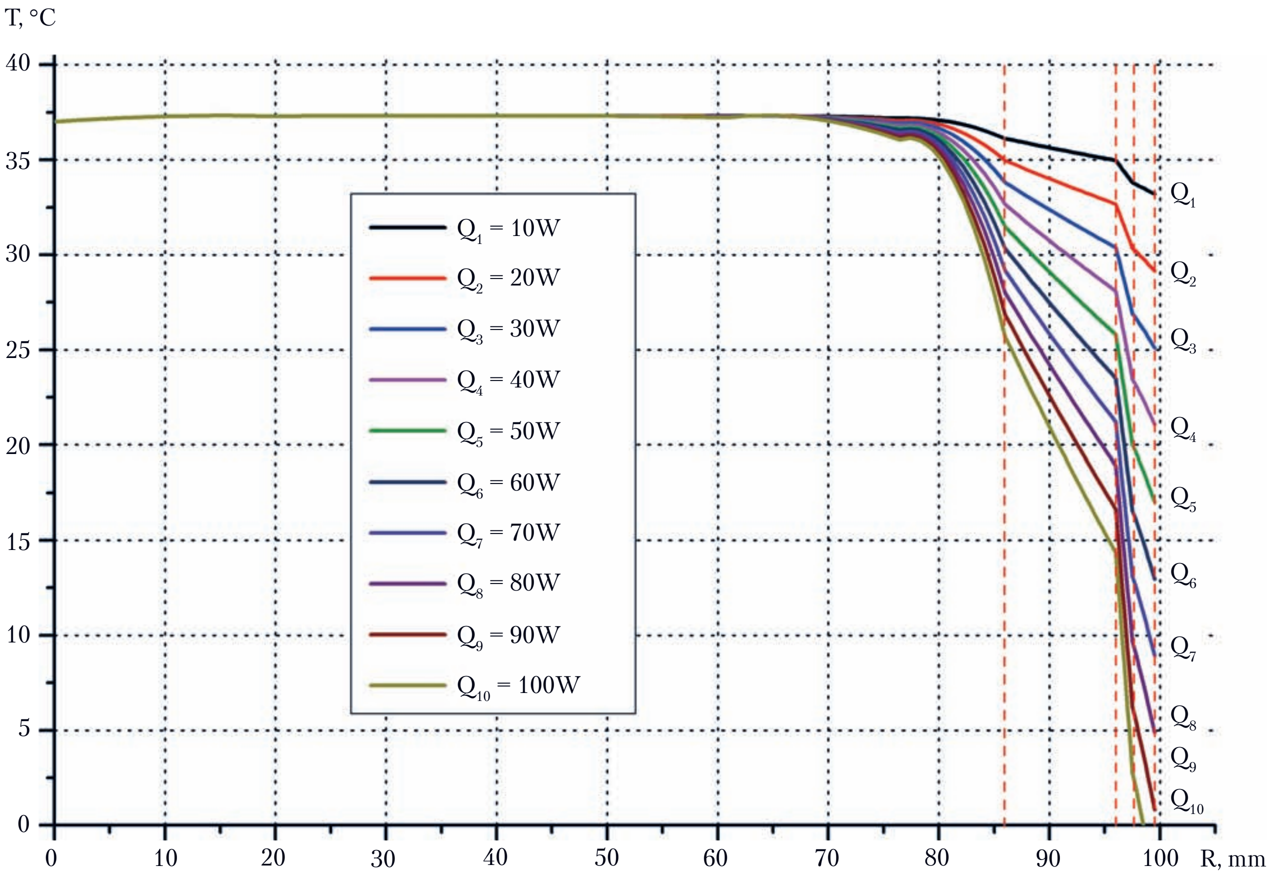

Fig. 4. Influence of intensity of cooling Q on temperature T distribution along radius R of human head hemisphere

Fig. 7. Thermoelectric device for cooling of human head ALTEK 7012

inset) features the temperature distribution along the hemisphere radius for the respective heat fluxes from the surface of human head.

Fig. 4 shows that provided temperature of external surface of the human head is kept at the minimum permissible level (+2 °C), only 3 mm of near-surface layer of the human brain can be cooled down to required +32 °C, with temperature of the brain core remaining fixed (+37 °C). In this case, 90 W heat is withdrawn from the human head, which according to [28], corresponds to 90% of heat generation of the whole human organism. However, in fact, the human brain should cool down, since heat withdrawal of 90 W 6 times exceeds the total heat generation by the human head. As a result, blood passing through the head gets cooler and when passing through the human organism, cools the whole organism. Having returned to the head the blood has temperature slightly lower than +37 °C, which in the existing models is given as constant. Obviously, this fact is the key weak spot of the existing physical and computer models of the human head.

Hence, the existing approaches to designing physical models and computer modelling of the human head with arterial blood temperature fixed at T_{blood} = +37 °C should improve due to taking into consideration a gradual cooling of the circulating blood and heat capacity of the whole human organism.

In [29—30], it has been established that in order to raise effectiveness of human brain cooling the thermoelectric device shall contain a cooling hel-

Table 2

Technical Parameters of the Device

Technical parameters	Value
Range of operating temperature	(–5÷+40) °C
Temperature stability	±0.1 °C
Resolution of measured and set temperature	±0.01 °C
Accuracy of temperature measurement	±0.2 °C
Cooling capacity	250 W
Power voltage:	
AC 50 Hz	220 ± 10 V
DC	12—14 V
Main power	450 W
Size of the cooling unit	(305 × 250 × 360) mm
Weight of the cooling unit	6 kg

met for the head and a cooling collar for the neck. These devices can be promising for emergency cases (blood stroke, coronary thrombosis, cerebral blood circulation disorder, acute cardiovascular insufficiency, head injury, and brain hypoxia).

THERMOELECTRIC DEVICE FOR COOLING OF THE HUMAN HEAD AND ITS TECHNICAL PARAMETERS

Thermoelectric device for cooling of the human head *Altec-7012* (Figs. 5—7) has been designed at the Institute for Thermoelectrics of the NAS of Ukraine and the MES of Ukraine in collaboration with the Amosov National Institute for Cardiovascular Surgery of the NAMS of Ukraine.

The device is to be used for cooling the human head in the case of brain hypoxia, cerebral blood circulation disorders, depressed cases, acute cardiovascular insufficiency, complete transverse heart block, for the heart and major vessels surgeries, in early recovery period and in emergency cases (hypoxia, blood stroke, coronary thrombosis, head injury, etc). The technical parameters are given in Table 2.

The device consists of thermoelectric cooler (Fig. 6), cooling helmet (Fig. 5), cooling neck collar (Fig. 5), ambulance cart (Fig. 7), and human brain temperature sensor. The cooler consists of thermoelectric cooling unit designed at the Institute of Thermal Electrics, control unit based on 4-channel microprocessor temperature controller, modular power source, and circulating pump.

The cooling unit contains 20 *Altec-127* thermoelectric modules (1.8×1.8×2.5) arranged among fluid heat exchangers and collectors, which create two separate fluid loops: in the cold loop, a heat carrier is circulating under the action of the pump, it withdraws heat from the human body; the hot loop is connected to the central water supply system.

With the help of hoses, the cooling helmet and the cooling neck collar are serially connected to the thermoelectric cooler. Cooling capacity enables connecting a cooling blanket to the human body, as well. For convenience of patient carriage, the device has an ambulance cart. The full-option device is showed in Fig. 7.

CONCLUSIONS

1. The existing approaches to physical modelling of the human head based on the assumption of arterial blood temperature kept constant at $T_{крові}$ = 37 °C have been established to need improvements via taking into account gradual cooling of the circulating blood and heat capacity of the human organism.

2. It has been established that for raising effectiveness of human head cooler the thermoelectric device shall contain a cooling helmet, a cooling neck collar, and, if necessary, a cooling blanket. This device is promising for emergency cases (blood stroke, coronary thrombosis, cerebral blood circulation disorder, acute cardiovascular insufficiency, head injury, and brain hypoxia).

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ТЕРМОЕЛЕКТРИЧНИЙ ПРИЛАД «АЛТЕК-7012» ДЛЯ ОХОЛОДЖЕННЯ ГОЛОВИ ЛЮДИНИ

Наведено результати комп'ютерного моделювання теплофізичних процесів голови людини при заданих теплових потоках на її поверхні. Виявлено недоліки існуючих комп'ютерних моделей голови людини та запропоновано шляхи їх вдосконалення. Розроблено конструкцію та виготовлено експериментальний зразок термоелектричного приладу «АЛТЕК-7012» для охолодження голови людини. Прилад перспективний для гіпотермії головного мозку людини.

Ключові слова: комп'ютерне моделювання, термоелектричне охолодження, охолодження голови людини, гіпоксія головного мозку.

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ТЕРМОЭЛЕКТРИЧЕСКИЙ ПРИБОР «АЛТЕК-7012» ДЛЯ ОХЛАЖДЕНИЯ ГОЛОВЫ ЧЕЛОВЕКА

Приведены результаты компьютерного моделирования теплофизических процессов головы человека при заданных тепловых потоках на ее поверхности. Выявлены недостатки существующих компьютерных моделей головы человека и предложены пути их совершенствования. Изготовлен экспериментальный образец термоэлектрического устройства «АЛТЕК-7012» для охлаждения головы человека. Прибор перспективный для гипотермии головного мозга человека.

Ключевые слова: компьютерное моделирование, термоэлектрическое охлаждение, охлаждение головы человека, гипоксия головного мозга.

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