Anatychuk L.I. *acad. NAN Ucraine*[1,2],
Kobylianskyi R.R. *cand. phys.– math sciences*[1,2],
Fedoriv R.V.[1,2]

[1]Institute of Thermoelectricity of the NAS and MES of Ukraine,
1, Nauky str., Chernivtsi, 58029, Ukraine, *e-mail:* anatych@gmail.com
[2]Chernivtsi National University, 2 Kotsiubynskyi Str.,
Chernivtsi, Ukraine, 58012,

COMPUTER SIMULATION OF CYCLIC TEMPERATURE EFFECT ON THE HUMAN SKIN

This paper presents the results of computer simulation of cyclic temperature effect on the human skin in a dynamic mode. A three-dimensional computer model of biological tissue was built with regard to thermophysical processes, blood circulation, heat exchange metabolic and phase transition processes. As an example, the case is considered when on the skin surface there is a work tool whose temperature varies in the temperature range [-50 ÷ +50] °C. Temperature distributions in different layers of the human skin in heating and cooling modes have been determined. The results obtained make it possible to predict the depth of biological tissue freezing and heating with a given temperature effect. Bibl. 46,Fig. 10, Tabl. 2.
Keywords: temperature effect, human skin, dynamic mode, computer simulation.

Introduction

It is well known in medical practice that temperature exposure is an important factor in the treatment of many diseases of the human body [1-3]. However, the devices used for this purpose are in most cases bulky, without proper temperature control and thermal reproduction capabilities. To obtain lower temperatures, systems with liquid nitrogen are used [4-8], which significantly limits the possibilities of their use in medical institutions, where the provision of liquid nitrogen is problematic. In addition, the use of liquid nitrogen or the Joule-Thomson effect in the expansion of gases does not allow for the exactly required temperature regimes, and generally reduces the efficiency of using cold in treatment.

This problem can be solved by using thermoelectric cooling (heating) [3, 9-12]. Studies of the thermal effect on biological tissue carried out for many years, the creation of thermoelectric devices on their basis and the use in medical practice confirm their effectiveness. Thermoelectric devices are promising in such areas of medicine as cryotherapy, cryosurgery, ophthalmology, traumatology, neurosurgery, plastic surgery, urology, dermatology, etc. [1-3].

However, the experience of using thermoelectric medical devices has revealed a number of their disadvantages. Among them, the most important is the lack of the ability to control the cooling and heating processes in time. The latter significantly narrows the possibilities of treatment with heat and cold.

Studies show that cooling rates (their dynamics) play a decisive role in treatment [7, 13-25]. Thus, very rapid cooling does not lead to the destruction of biological tissues at all. On the contrary, moderate but cyclic cooling promotes vigorous destruction of tumors. Time cooling and heating functions are also important in the treatment of other diseases.

Thus, the general problem is to develop a fundamental scientific basis for creating a new generation of thermoelectric medical devices, which reproduce the specified functions of cooling and heating in biological tissue. In most cases, it is very difficult to control the cyclic processes of cooling and heating of biological tissue [26, 27]; therefore, it is necessary to learn to predict the depth of freezing and heating of skin layers at a given temperature effect at different points in time.

So, the *purpose of this work* is to determine, using computer simulation, the temperature distributions in different layers of the human skin in a dynamic mode at a given cyclic temperature effect.

Physical model

According to a physical 2D model with axial symmetry (Fig.1), the area of biological tissue of the human body is a structure of three layers of skin (epidermis 1, dermis 2, subcutaneous layer 3) and the internal biological tissue 4 and is characterized by the following thermophysical properties [28-34]: thermal conductivity κ_i, specific heat C_i, density ρ_i, blood perfusion rate ω_{bi}, blood density ρ_b, blood temperature T_b, blood heat capacity C_b and specific heat release Q_{meti} due to metabolic processes and latent heat of phase transition L. Thermophysical properties of skin and biological tissue of the human body in normal [35-39] and frozen states [40, 41] are shown in Tables 1, 2. The respective layers of biological tissue 1-4 are considered as bulk heat sources qi, where:

$$q_i = Q_{met\,i} + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T), \quad i = 1..4 . \tag{1}$$

The geometric dimensions of each such layer 1-4 are a_i, b_i. On the surface of the skin is a round work tool 5, the geometric dimensions of which are as follows: thickness $d = 1$ mm and diameter $c = 10$ mm. According to medical recommendations and analysis of known cryoprobes used for cryodestruction, it was determined that the diameter of such probes is from 5 mm to 15 mm [42, 43]. Therefore, in this work, as an example, we took the average value of the probe diameter, which is $c = 10$ mm. The temperatures at the boundaries of the respective layers 1-4 and the work tool 5 are T_1, T_2, T_3, T_4, T_5, T_6. The temperature inside biological tissue is $T_1 = +37$°C. The temperature of the work tool varies in the range $T_7 = [-50 \div +50]$ °C. The ambient temperature is $T_8 = +22$°C. The surface of human skin with a temperature of T_6 is in a state of heat exchange with the environment (heat transfer coefficient α and radiation coefficient ε) at a temperature of T_8. The lateral surface of the skin is adiabatically isolated.

This model does not take into account the thermal contact resistance between the work tool and the human skin, since it is estimated to be insignificant and is $R_c = 2 \cdot 10^{-3}$ m^2·K/W [44].

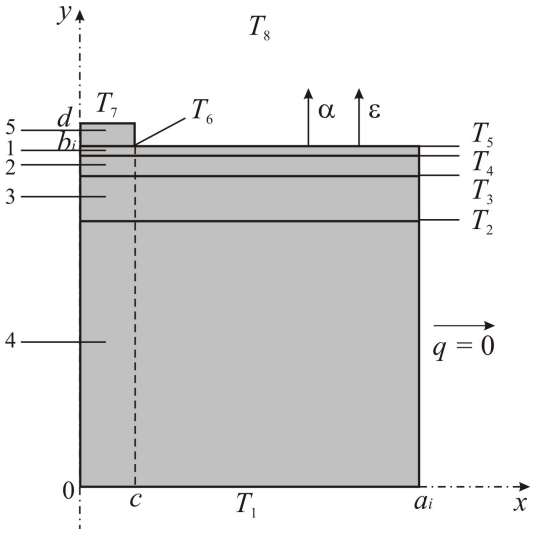

Fig.1. Physical 2D model of the human skin with axial symmetry: 1 – epidermis, 2 – dermis, 3 – subcutaneous layer, 4 – internal biological tissue, 5 – work tool

Table 1

Thermophysical properties of biological tissue of the human body [35-39]

Layers of biological tissue	Epidermis	Dermis	Subcutaneous layer	Internal tissue
Thickness, l (mm)	0.08	2	10	30
Specific heat, C ($J \cdot kg^{-1} \cdot K^{-1}$)	3590	3300	2500	4000
Thermal conductivity, κ ($W \cdot m^{-1} \cdot K^{-1}$)	0.24	0.45	0.19	0.5
Density, ρ ($kg \cdot m^{-3}$)	1200	1200	1000	1000
Metabolism, Q_{met} (W/m^3)	368	368	368	368
Blood perfusion rate, ω_b (ml/s·ml)	0	0.0005	0.0005	0.0005
Blood density, ρ_b ($kg \cdot m^{-3}$)	1060	1060	1060	1060
Blood heat capacity, C_b ($J \cdot kg^{-1} \cdot K^{-1}$)	3770	3770	3770	3770

Table 2

Thermophysical properties of biological tissue of the human body in the normal and frozen states [40, 41]

Thermophysical properties of biological tissue	Value	Measurement units
Heat capacity of normal biological tissue (C_1)	3600	J/m^3 °C
Heat capacity of frozen biological tissue (C_2)	1800	J/m^3 °C
Thermal conductivity of normal biological tissue (κ_1)	0.5	W/m °C
Thermal conductivity of frozen biological tissue (κ_2)	2	W/m °C
Latent heat of phase transition (L)	$250 \cdot 10^3$	J/m^3
Upper temperature of phase transition (T_1)	-1	°C
Lower temperature of phase transition (T_2)	-8	°C

Mathematical model

In general, the equation of heat exchange in biological tissue is given by [45]:

$$C_i \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\kappa_i \cdot \nabla T) + \rho_b \cdot C_b \cdot \omega_{bi} \cdot (T_b - T) + Q_{meti}, \quad i = 1..4, \tag{2}$$

where C_i, κ_i is specific heat and thermal conductivity of respective skin layers, ρ_b is blood density, C_b is specific heat of blood, ω_{bi} is blood perfusion of respective layers, T_b is blood temperature, T is temperature of the biological tissue; Q_{meti} is heat released due to metabolic processes in each layer.

The term on the left side of equation (2) is the rate of change of thermal energy contained in a unit volume of biological tissue. The three terms on the right side of this equation represent, respectively, the rate of change of thermal energy due to thermal conductivity, blood perfusion and metabolic heat.

The equation of heat exchange in the biological tissue (2) is solved with the corresponding boundary conditions. The temperature on the surface of the work tool varies according to the given law in the temperature range T_7 = [-50 ÷ +50] ° C. Inside the biological tissue, the temperature T_1 = + 37 ° C. The lateral surfaces of biological tissue are adiabatically isolated (q = 0), and the upper surface of the skin is in a state of heat exchange (heat exchange coefficient α and radiation coefficient ε) with the environment at a temperature of T8.

$$q_i(x,y,t)\Big|_{\substack{c\le x\le a \\ y=b_i}} = \alpha \cdot (T_8 - T_5) + \varepsilon \cdot \sigma \cdot (T_8^4 - T_5^4), \tag{3}$$

where $q_i(x,y,t)$ is the heat flux density of the i-th layer of the human skin, α is the coefficient of convective heat exchange of the skin surface with the environment, ε is the radiation coefficient, σ is the Boltzmann constant, T_5 is the temperature of the human skin surface, T_8 is the ambient temperature (T_8 = + 22 ° C).

At the initial time moment t = 0 s, it is assumed that the temperature in the entire volume of the skin is T = + 37 °C, i.e. the initial conditions for solving equation (2) are as follows:

$$T_i(x,y,0) = T_b, \qquad i = 1,...,4. \tag{4}$$

As a result of solving the initial-boundary value problem (2) - (4), the distributions of temperature $T_i(x,y,t)$ and heat fluxes $q_i(x,y,t)$ in the corresponding layers of the skin at any time are determined. As an example, in this paper we consider the case in which the temperature of the work tool varies according to a given law in the temperature range T_7 = [-50 ÷ +50] °C. However, it should be noted that the proposed technique allows us to consider cases where the temperature of the work tool $T_f(t)$ changes in any temperature range or according to a predetermined function.

During the freezing process, the cells will undergo a phase change at the freezing point, with the loss of heat of the phase transition (L) and the temperature in these cells will not change. The phase transition in the biological cells occurs in the temperature range (-1 ÷ -8) °C. The properties of the skin and biological tissue in normal and frozen states are given in tables 1, 2 [35-41]. In the temperature range (-1 ÷ -8) °C, when the cells are frozen, the heat of the phase transition is absorbed, which can be

modeled by adding the appropriate value to the heat capacity [40, 41].

When freezing the human skin, vasoconstriction occurs in the capillaries until all blood freezes in the capillaries, and the value ω_{bi} tends to zero. In addition, cells will not be able to generate metabolic heat when frozen and Q_{meti} will be zero at temperatures below zero.

In the frozen state, the properties of the skin and biological tissue will have the following values (5) – (8):

$$C_i = \begin{cases} C_1 & T \geq -1°C \\ \dfrac{L}{-1-(-8)} + \dfrac{C_1 + C_2}{2} & -8°C \leq T \leq -1°C \\ C_2 & T \leq -8°C \end{cases} \tag{5}$$

$$\kappa_i = \begin{cases} \kappa_1 & T \geq -1°C \\ \dfrac{\kappa_1 + \kappa_2}{2} & -8°C \leq T \leq -1°C \\ \kappa_2 & T \leq -8°C \end{cases} \tag{6}$$

$$Q_{met_i} = \begin{cases} 368 & T \geq -1°C \\ 0 & -8°C \leq T \leq -1°C \\ 0 & T \leq -8°C \end{cases} \tag{7}$$

$$\omega_{b_i} = \begin{cases} 0,0005 & T \geq -1°C \\ 0 & -8°C \leq T \leq -1°C \\ 0 & T \leq -8°C \end{cases} \tag{8}$$

Computer model

A three-dimensional computer model of biological tissue was created in a cylindrical coordinate system on the surface of which is a medical work tool. Comsol Multiphysics software package [46] was used to build a computer model, which allows modeling of thermophysical processes in biological tissue, taking into account blood circulation, heat exchange, metabolic processes and phase transition.

The distribution of temperature and heat flux density in biological tissue was calculated by the finite element method, the essence of which is that the object under study is divided into a large number if finite elements and in each of them a function value is sought for that satisfies given second order differential equations with the corresponding boundary conditions. The accuracy of solving the problem posed depends on the level of partitioning and is ensured by a large number of finite elements [46].

As an example, Fig. 3-10 shows the distributions of temperature and isothermal surfaces in the bulk of the human skin, on the surface of which a work tool is located, the temperature of which varies

cyclically according to a predetermined law in the temperature range [-50 ÷ +50] ° C at different points of time.

Results of computer simulation of cyclic temperature effect on the human skin in a dynamic mode

According to the known methods of cryodestruction and coagulation of biological tissue [7, 13, 18-20] the rate of cooling should be at least (40-50) °C/min, and the rate of heating (20-25) °C/min. Therefore, in this paper, as an example, we consider the case when the work tool temperature $T_f(t)$ varies in the range of operating temperatures [-÷+50]°C as follows. First, a cooled work tool is used to carry out cryodestruction of skin at a temperature $T=-50°C$ for t=120 c, then the work tool temperature changes from $-50°C$ to $+50°C$ for the next 240 s, following which skin coagulation is carried out with the heated work tool at $T=+50°C$ for t=120 s. A subsequent temperature reduction to $T=-50°C$ occurs for 120 s, then this temperature effect is repeated cyclically for a better destruction of the human skin. The indicated cyclic temperature effect on the human skin is shown in Fig.2.

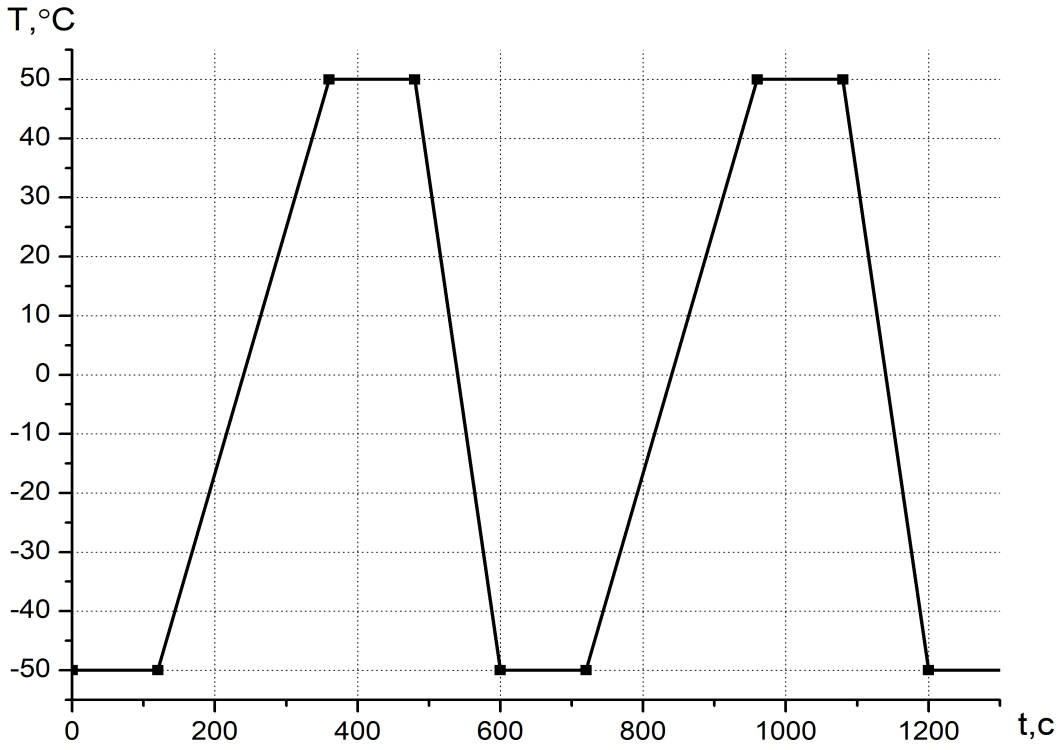

Fig.2. The plot of work tool temperature versus time

Figs. 3-10 show the distributions of temperature and isothermal surfaces in the cross section of biological tissue on the surface of which the work tool is placed, the temperature of which varies according to the above law in the operating temperature range [-50 ÷ +50] ° C at the initial and final moments of cooling-heating cycle.

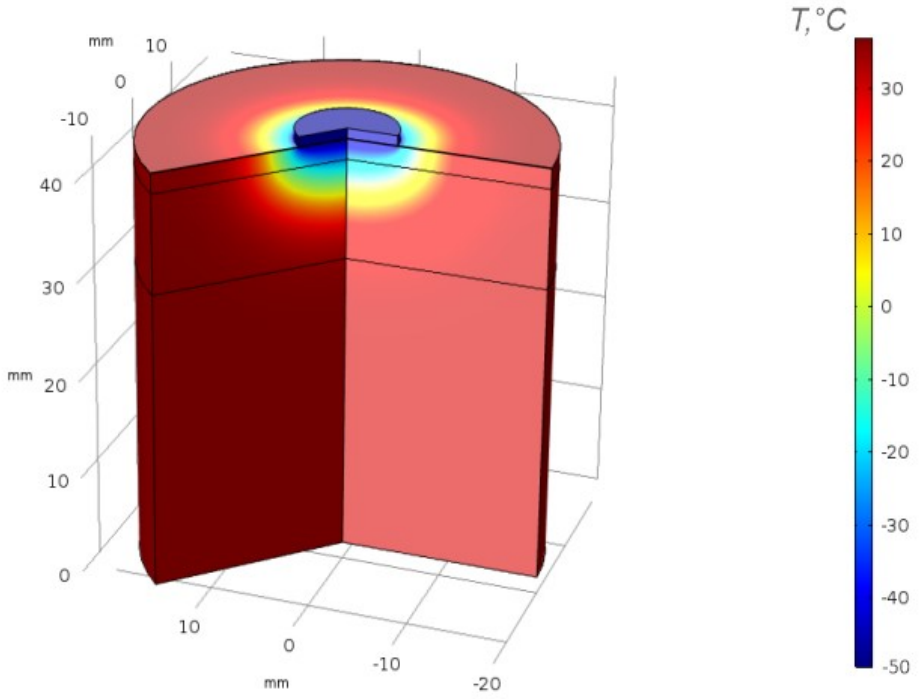

Fig.3. Dostribution of temperature in the bulk of the skin the surface of which accommodates a work tool at a temperature of T=50°C at point of time t=210s

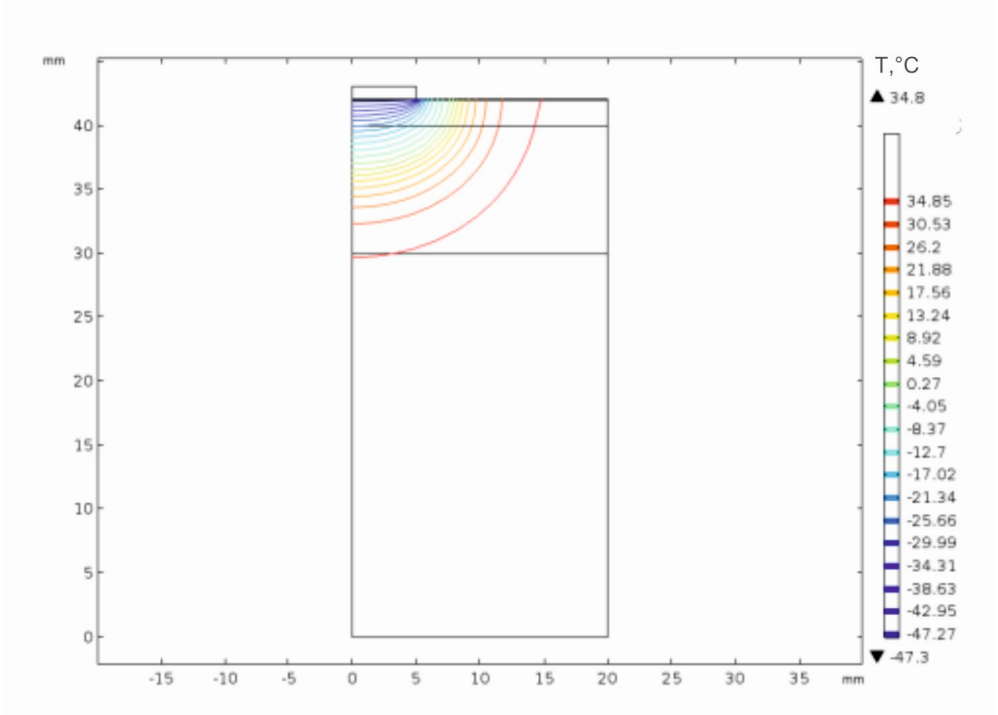

Fig.4. Distribution of isothermal surfaces in the bulk of the skin the surface of which accommodates a work tool at a temperature of T=-50°C at point of time t=120 s

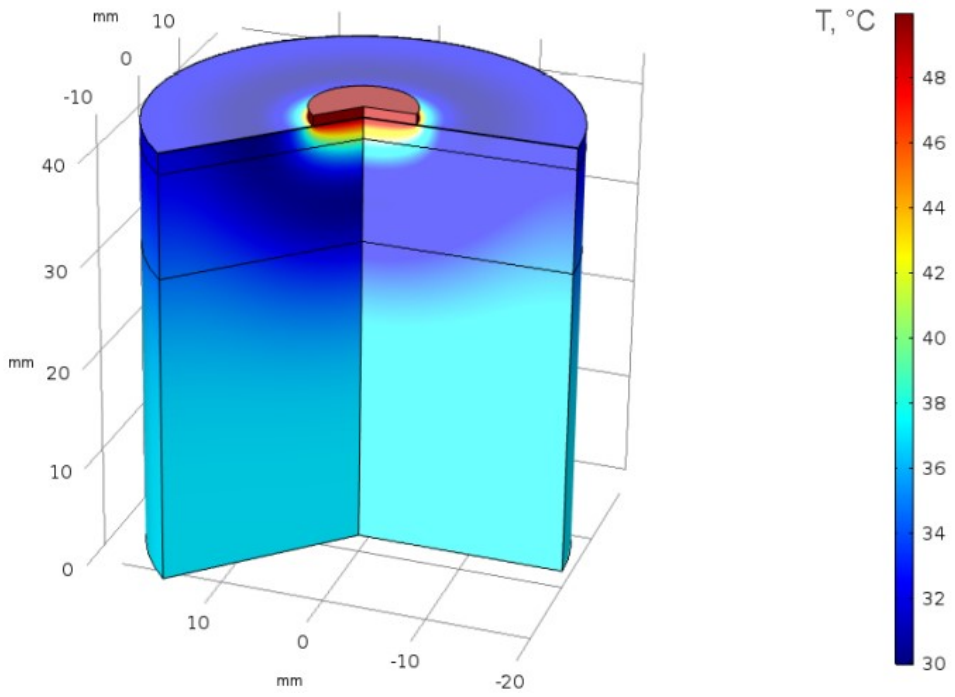

Fig.5. Ditsribution of temperature in the bulk of the skin the surface of which accommodates a work tool at a temperature of T=+50°C at point of time t=480 s

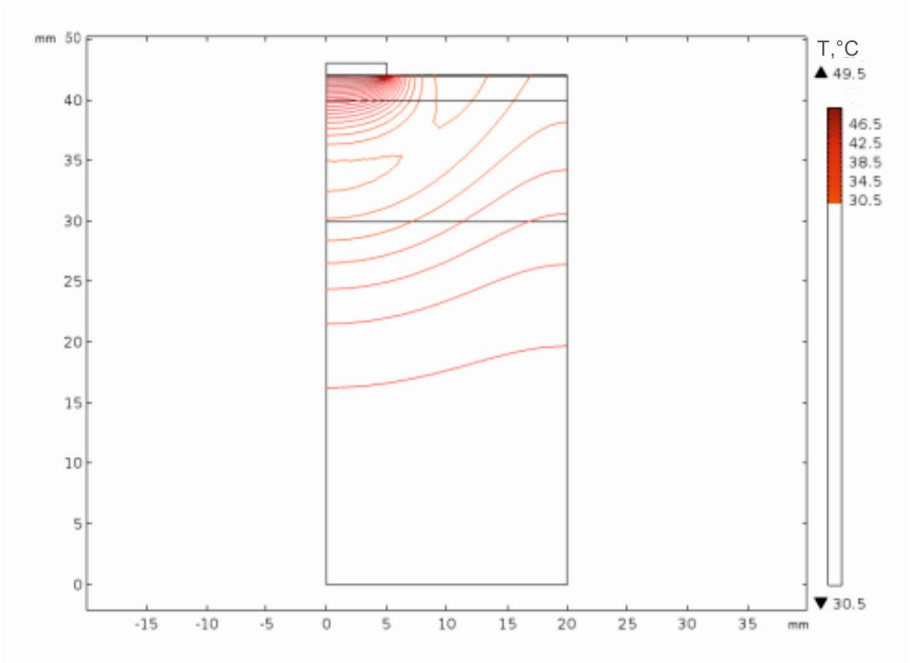

Fig.6. Distribution of isothermal surfaces in the bulk of the skin the surfaces of which accommodates a work tool at a temperature of T=+50°C at point of time t=480 s

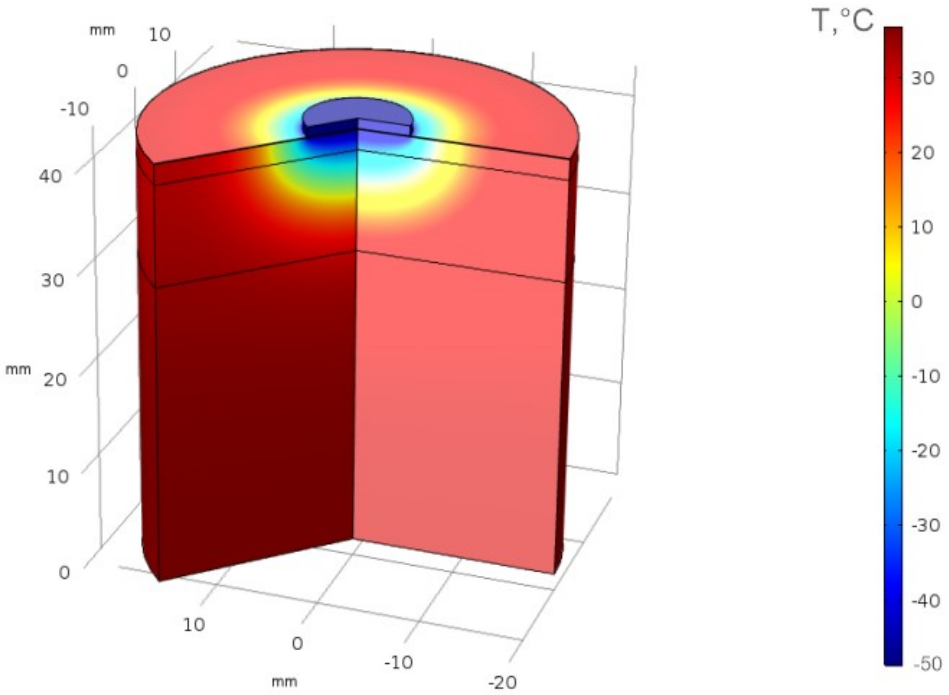

Fig.7. Distribution of temperature in the bulk of the skin the surface of which accomodates a work tool at a temperature of T=-50°C at point of time t=720 s

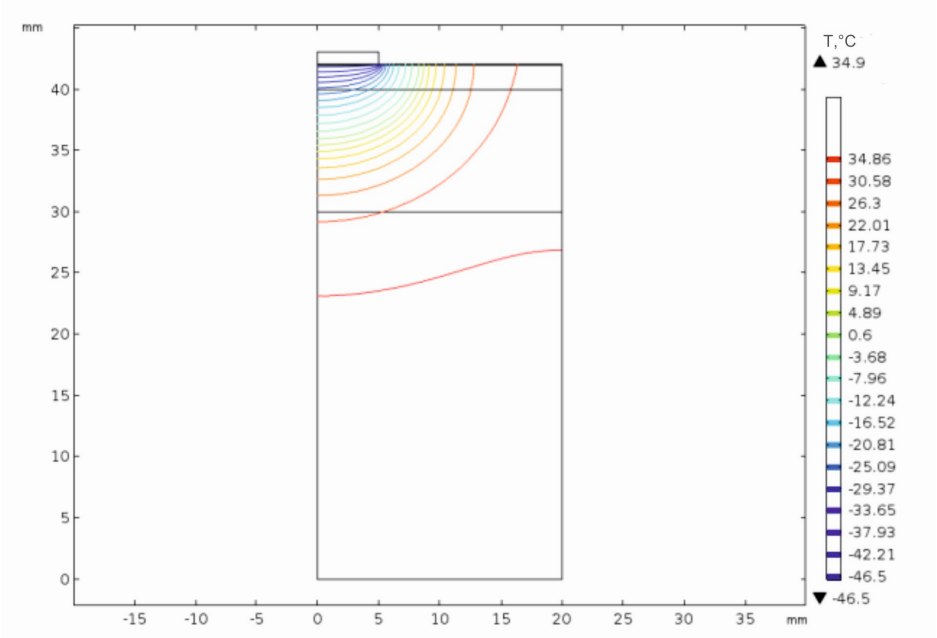

Fig.8. Distribution of isothermal surfaces in the bulk of the skin the surface of which accommodates a work tool at a temperature of T=-50°C at point of time t=720 s

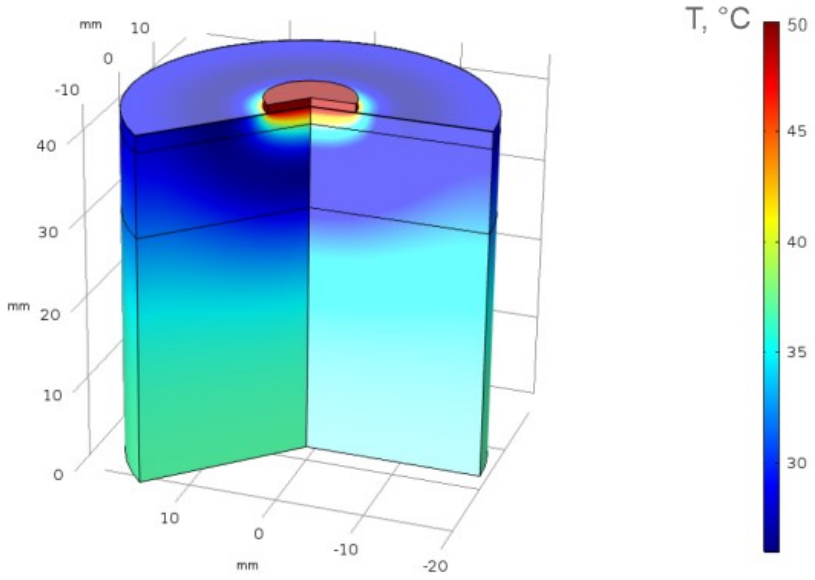

Fig.9. Distribution of temperature in the bulk of the skin the surface of which accommodates a work tool at a temperature of T=+50°C at point of time t=1080 s

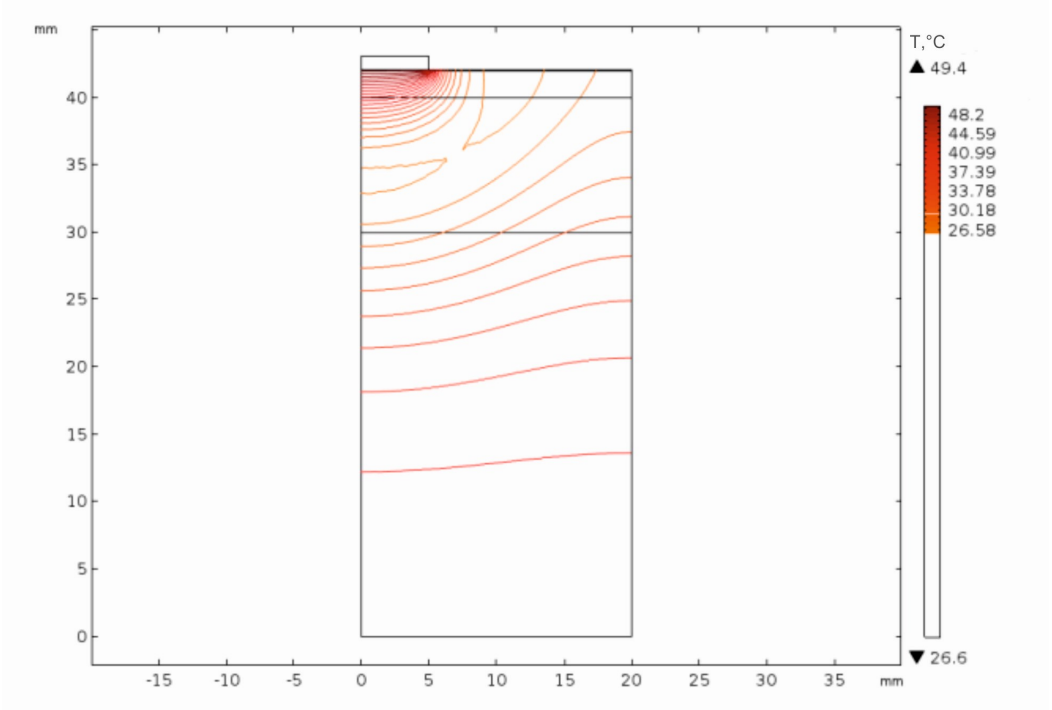

Fig.10. Distribution of isothermal surfaces in the bulk of the skin the surface of which accommodates a work tool at a temperature of T=+50°C at point of time t=1080 s

From Figs. 3-6 it is seen that at *t*=120 s the epidermis is cooled to -48,9°C, the temperature at the epidermis-dermis boundary is -48.3°C, the temperature at the dermis-subcutaneous fat is -25.5°C. And at $t = 480$ s the temperature in the epidermis rises to +49,8°C, at the epidermis-dermis boundary the

temperature is +49.5°C, at the dermis-subcutaneous fat the temperature is +40.3°C. As long as the upper skin layer (epidermis) has the lowest thickness and blood perfusion $\omega_b = 0$, then the temperature inside this layer is close to the work tool temperature. Later, with repeated cyclic temperature exposure (Fig. 7-10), it is observed that at $t = 720$ s after cooling, the temperature inside the skin, for example, at the dermis-subcutaneous fat boundary, reaches -28 ° C, and at $t = 1080$ c after reheating, the temperature at the dermis-subcutaneous fat boundary is + 38 ° C.

It was found that with an increase in the exposure (number of cycles) of temperature effect, a deeper cooling of skin layers and approximately the same heating of the skin are achieved. That is, with a prolonged temperature exposure in the range [-50 ÷ +50] °C one can achieve destruction and coagulation of superficial skin neoplasms.

The results obtained make it possible to predict the depth of freezing and heating of the human skin layers at a given cyclic temperature exposure to achieve the maximum effect during cryodestruction or coagulation. The developed method of computer simulation in a dynamic mode enables one to determine the temperature distribution in different skin layers with a predetermined arbitrary function of changing the work tool temperature with time $T_f(t)$.

Conclusions

1. Computer simulation was used to determine the distributions of temperature in different skin layers in heating and cooling modes with a change of work tool temperature by the predetermined law in the temperature range [-50÷+50]°C. The results obtained give an opportunity to predict the depth of freezing and heating of biological tissue at a given cyclic temperature effect.
2. The method of computer simulation of the distribution of temperature in the human skin is developed, which enables one to predict the results of local temperature effect on the skin and determine at any point of time the distributions of temperature in different skin layers at a predetermined arbitrary temporal function of change in work tool temperature $T_f(t)$.

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Анатичук Л.І., *акад. НАН Украини*[1,2]
Кобилянський Р., *канд. физ.-мат. наук*[1,2]
Федорів Р.В.[1,2]

[1]Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
e–mail: anatych@gmail.com
[2]Чернівецький національний університет ім. Юрія Федьковича,
вул. Коцюбинського 2, Чернівці, 58012, Україна

КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ЦИКЛІЧНОГО ТЕМПЕРАТУРНОГО ВПЛИВУ НА ШКІРУ ЛЮДИНИ

У роботі наведено результати комп'ютерного моделювання циклічного температурного впливу на шкіру людини у динамічному режимі. Побудовано тривимірну комп'ютерну модель біологічної тканини з врахуванням теплофізичних процесів, кровообігу, теплообміну, процесів метаболізму та фазового переходу. Як приклад, розглянуто випадок, коли на поверхні шкіри знаходиться робочий інструмент, температура якого змінюється циклічно за наперед заданим законом у діапазоні температур [50 ÷ +50] °С. Визначено розподіли температури у різних шарах шкіри людини в режимах охолодження та нагріву. Отримані результати дають можливість прогнозувати глибину промерзання і прогрівання біологічної тканини при заданому температурному впливі. Бібл. 46, рис. 10, табл. 2.

Ключові слова: температурний вплив, шкіра людини, динамічний режим, комп'ютерне моделювання.

Анатычук Л.И., *акад. НАН Украины*[1,2]
Кобылянский Р.Р., *канд. физ.-мат. наук* [1,2]
Федорив Р.В.[1,2]

[1]Институт термоэлектричества НАН и МОН Украины,
ул. Науки, 1, Черновцы, 58029, Украина,
e–mail: anatych@gmail.com;
[2]Черновицкий национальный университет им. Юрия Федьковича,
ул. Коцюбинского, 2, Черновцы, 58012, Украина

КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ ЦИКЛИЧЕСКИХ ТЕМПЕРАТУРНЫХ ВОЗДЕЙСТВИЙ НА КОЖУ ЧЕЛОВЕКА

В работе приведены результаты компьютерного моделирования циклического температурного воздействия на кожу человека в динамическом режиме. Построено трехмерную компьютерную модель биологической ткани с учетом теплофизических процессов, кровообращения, теплообмена, процессов метаболизма и фазового перехода. В качестве примера, рассмотрен случай, когда на поверхности кожи находится рабочий инструмент, температура которого меняется циклически по заранее заданному закону в диапазоне температур [50 ÷ +50] ° С. Определены распределения температуры в различных слоях кожи человека в режимах охлаждения и нагрева. Полученные результаты дают возможность прогнозировать глубину промерзания и прогревания биологической ткани при заданном температурном воздействии. Библ. 46, рис. 10, табл. 2.

Ключевые слова: температурное воздействие, кожа человека, динамический режим, компьютерное моделирование.

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