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COMPUTER SIMULATION OF THE WORKING TOOL OF A THERMOELECTRIC DEVICE FOR CRYODESTRUCTION WITH ACCOUNT OF THE PHASE TRANSITION

The paper presents the results of computer simulation of the working tool of a thermoelectric device for cryodestruction with account of the phase transition, as well as cyclic temperature effect on the human skin in dynamic mode. A physical model of the working tool, a three-dimensional computer model of the biological tissue with account of thermophysical processes, blood circulation, heat exchange, metabolic processes and the phase transition, is constructed. As an example, a case is considered when the working tool is on the skin surface, the temperature of which changes cyclically according to a given law in the temperature range [-50 ÷ +50] °C. Temperature distributions in different layers of the human skin in cooling and heating modes were determined. The obtained results make it possible to predict the depth of freezing and warming of the biological tissue at a given temperature effect.

Key words: cryodestruction, working tool, temperature effect, human skin, dynamic mode, computer simulation.

Introduction

It is well known in medical practice that temperature effect is an important factor in the treatment of many diseases of the human body [1-11]. However, the devices used for this purpose are in most cases bulky, without adequate temperature regulation and thermal regime reproduction capabilities. To obtain lower temperatures, liquid nitrogen systems are used, which significantly limits the possibilities of their use in medical institutions where the supply of liquid nitrogen is problematic. In addition, the use of liquid nitrogen or the Joule-Thomson effect during gas expansion does not allow for the implementation of precisely required temperature regimes, which reduces the overall efficiency of using cold in treatment.

The use of thermoelectric cooling (heating) can solve this problem [12-21]. The studies of thermal effects on the biological tissue conducted over many years, the creation of thermoelectric devices based on them and their use in medical practice confirm their efficiency. Thermoelectric devices are promising in such areas of medicine as cryotherapy, cryosurgery, ophthalmology, traumatology, neurosurgery, plastic surgery, urology, dermatology, etc.

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

Studies show that cooling rates (their dynamics) play a decisive role in treatment [12-27]. Thus, very fast cooling does not lead to the destruction of the biological tissues at all. On the contrary, moderate but cyclical cooling promotes energetic destruction of tumors. The time functions of cooling and heating are also important in the treatment of other diseases.

Therefore, the general problem is to develop a thermoelectric device for the destruction of the biological tissue or oncological neoplasms, which will provide the possibility of cyclic temperature effects on the tumor. This determines the relevance of the problem posed in the present work.

The importance of solving this problem is obvious, otherwise thermoelectric devices for medicine of a new generation with the possibility of cyclic temperature effects on the human skin cannot be developed.

In [28], a computer simulation of the working tool of a thermoelectric device for cryodestruction was performed without taking into account the phase transition. Therefore, the purpose of this work is computer simulation of the working tool of a thermoelectric device for cryodestruction with account of the phase transition.

1. Physical model of the working tool of a thermoelectric device for destruction the walls of which are made of steel

Fig.1 shows a physical model. It consists of housing 1, inside which substance 2 (25% alcohol solution) with a phase transition temperature T_1 is placed. Housing 1 with a hemispherical end 3 touches the skin 4 with a plane 5 with a diameter d. Housing 1 is made of medical grade stainless steel. Skin model 4 takes into account its complex structure.

The model takes into account heat inleak Q_1 at the ambient air temperature T_2=25°C, as well as heat inleak Q_2 from the ambient air. The upper part of housing 1 is adiabatically insulated (q=0). The diameter of the thermal contact 5 is 5 mm.

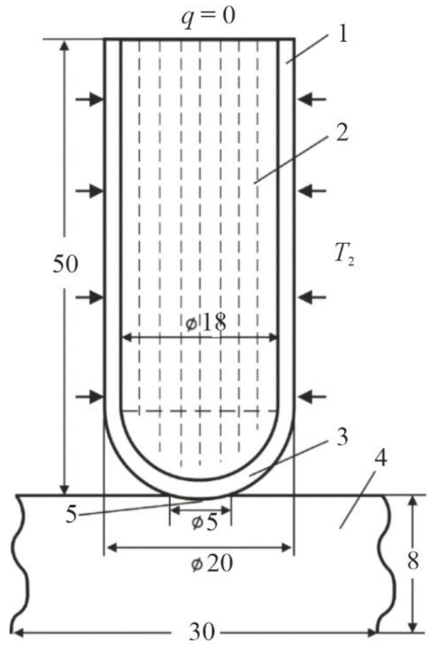

Fig. 1. Physical model of the working tool of a thermoelectric device for cryodestruction, the walls of which are made of steel.

2. Computer model

Three-dimensional computer models were created for the biological tissue in a cylindrical coordinate system, on the surface of which there is a thermoelectric medical device for local cooling. The Comsol Multiphysics package of application programs [29], was used to build computer models, which makes it possible to simulate thermophysical processes in the biological tissue, taking into account blood circulation, heat exchange, metabolic processes, and the phase transition.

The calculation of temperature distributions and the density of heat flows in the biological tissue and the cold accumulator was carried out by the finite element method, the essence of which is that the object under study is divided into a large number of finite elements and in each of them the value of the function is sought, which satisfies the given second order differential equation with the corresponding boundary conditions. The accuracy of solving the given problem depends on the level of division and is ensured by the use of a large number of finite elements [29].

Thermophysical properties of the skin and the biological tissue of the human body in normal [30-38] and frozen states are shown in Tables 1, 2.

The thermal contact resistance between the working tool and human skin is not taken into account in this model, as it is estimated to be insignificant and is $R_c = 2\cdot10^{-3}$ $m^2\cdot K/W$.

Table 1

Thermophysical properties of the biological tissue of the human body [30-38].

Biological tissue layers	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
Heat capacity of blood, C_b ($J\cdot kg^{-1}\cdot K^{-1}$)	3770	3770	3770	3770

Table 2

Thermophysical properties of the biological tissue of the human body in normal and frozen states [30-38].

Thermophysical properties of biological tissue	Value	Units of measurement
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)	$250\cdot10^3$	J/m^3
Upper temperature of phase transition (T_1)	-1	°C
Lower temperature of phase transition (T_2)	-8	°C

3. Computer simulation results

Fig. 2 shows temperature distributions in the human skin, directly under the center of action of the working tool.

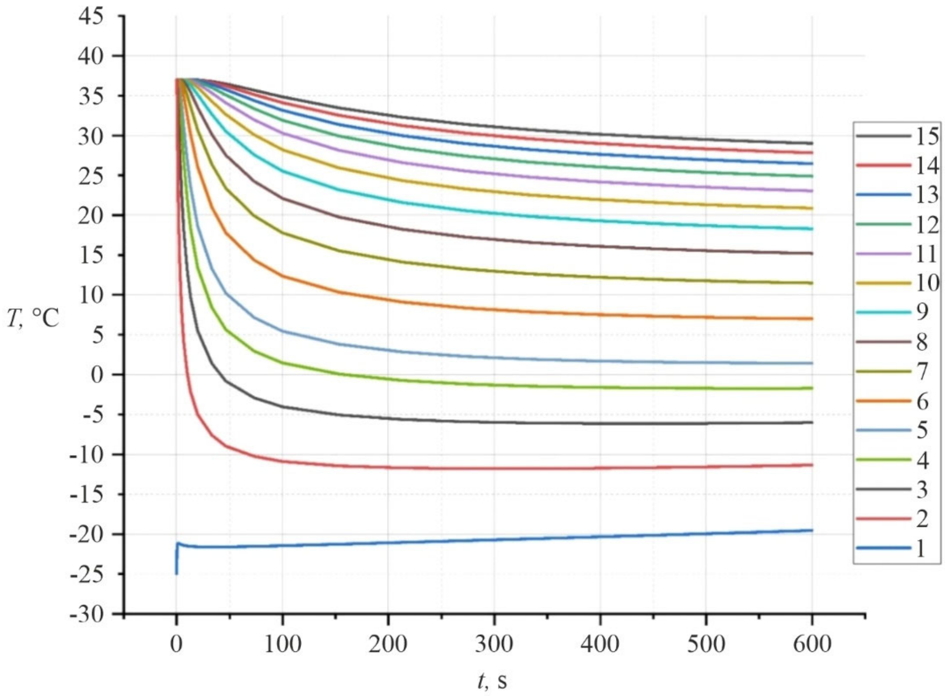

Fig. 2. Dependences of temperature on time in the human skin at different depths: 1 – point of contact between working tool and skin; 2 – 0.5 mm; 3 – 1 mm; 4 – 1.5 mm; 5 – 2 mm; 6 – 2.5 mm; 7 – 3 mm; 8 – 3.5 mm; 9 – 4 mm; 10 – 4.5 mm; 11 – 5 mm; 12 – 5.5 mm; 13 – 6 mm; 14 – 6.5 mm; 15 – 7 mm.

Fig.3 shows temperature distributions in the skin directly under the centre of action of the working tool at time moments: *10 s, 60 s, 140 s, 200 s, 600 s.*

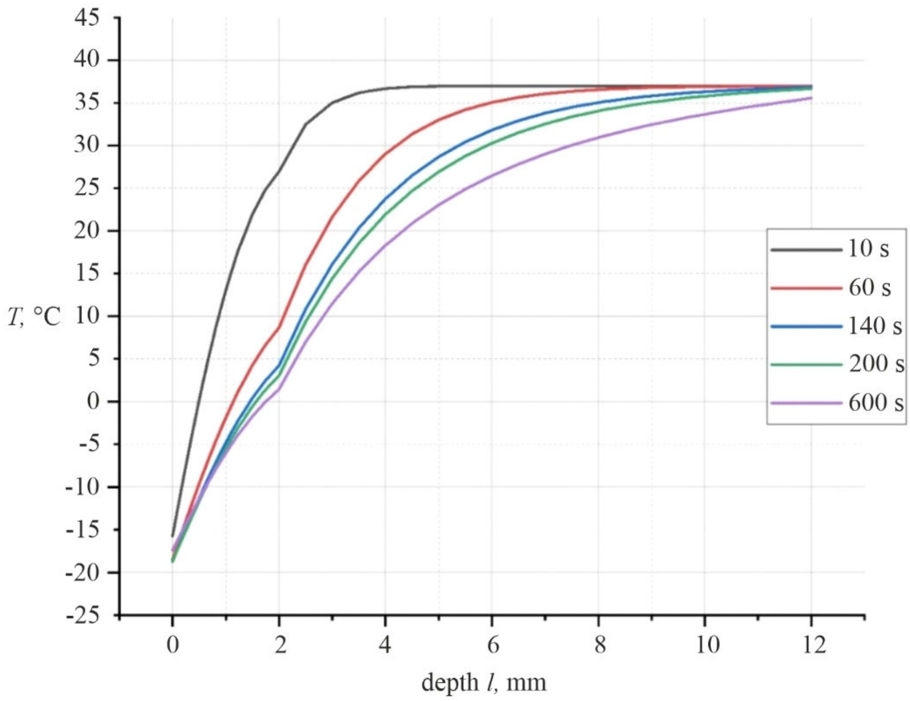

Fig. 3. Dependences of temperature on skin depth at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

Fig. 4 represents temperature distributions in the cold accumulator at different depths.

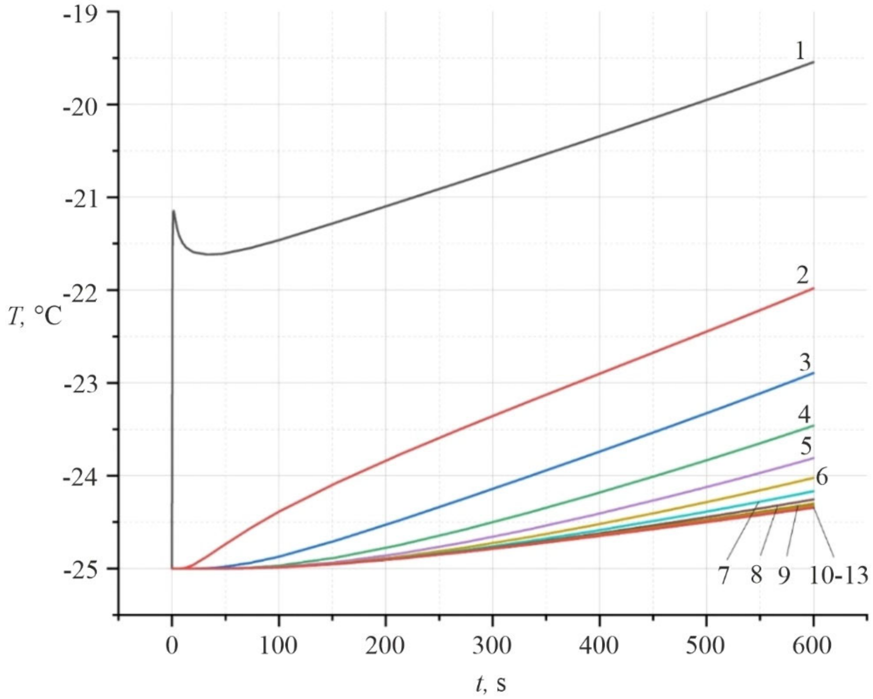

Fig. 4. Dependences of temperature on time in the cold accumulator at different depths: 1 – point of contact between working tool and skin: 2 – 4 mm; 3 – 8 mm; 4 – 12 mm; 5 – 16 mm; 6 – 20 mm; 7 – 24 mm; 8 – 28 mm; 9 – 32 mm; 10 – 36 mm; 11 – 40 mm; 12 – 44 mm; 13 – 48 mm.

Fig. 5 shows the distribution of temperatures in the cold accumulator at the following moments: 10 s, 60 s, 140 s, 200 s, 600 s

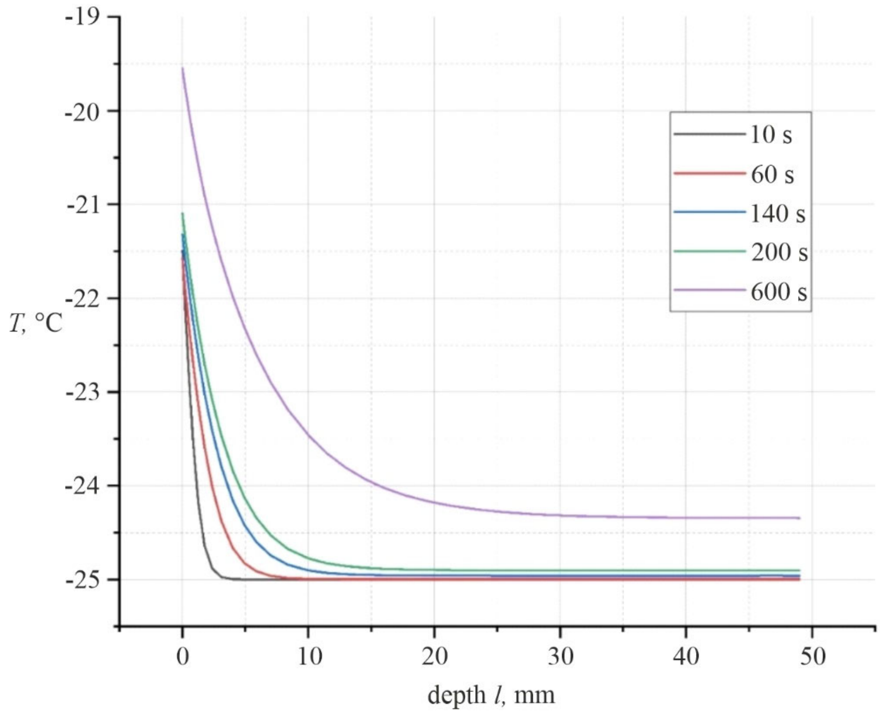

Fig. 5. Dependences of temperature on time in the cold accumulator at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

4. Physical model of the working tool of a thermoelectric device for destruction the walls of which are made of copper

Fig. 6 shows a physical model. It consists of a housing 1, inside which a substance 2 (25% alcohol solution) with a phase transition temperature T_1 is placed. Housing 1 with its hemispherical end 3 touches skin 4 with a plane 5 of diameter d. Housing 1 is made of copper. The complex structure of skin 4 is taken into account in the model.

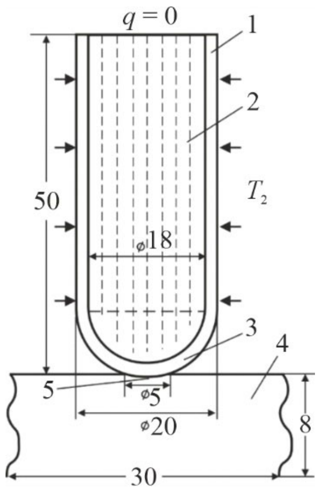

Fig. 6. Physical model of the working tool of thermoelectric device for cryodestruction the walls of which are made of copper.

The model takes into account the heat inleak Q1 at the ambient air temperature T_2 = +25ºC, as well as the heat inleak Q_2 from the ambient air. The upper part of the housing 1 is adiabatically insulated (q=0). The diameter of the thermal contact 5 is 5 mm.

5. Computer simulation results

Fig. 7 shows temperature distributions in the human skin, directly under the center of action of the working tool.

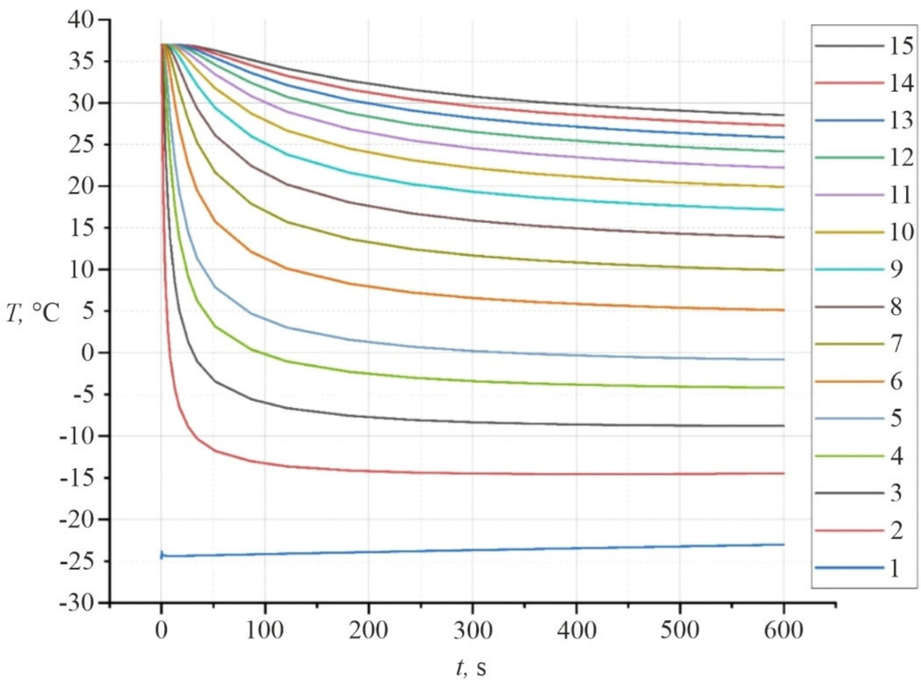

Fig. 7. Dependences of temperature on time in the human skin at different depths: 1 – point of contact between the working tool and skin; 2 – 0.5 mm; 3 – 1 mm; 4 – 1.5 mm; 5 – 2 mm; 6 – 2.5 mm; 7 – 3 mm; 8 – 3.5 mm; 9 – 4 mm; 10 – 4.5 mm; 11 – 5 mm; 12 – 5.5 mm; 13 – 6 mm; 14 – 6.5 mm; 15 – 7 mm.

Fig. 8 shows temperature distributions in the skin directly under the center of action of the working tool at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

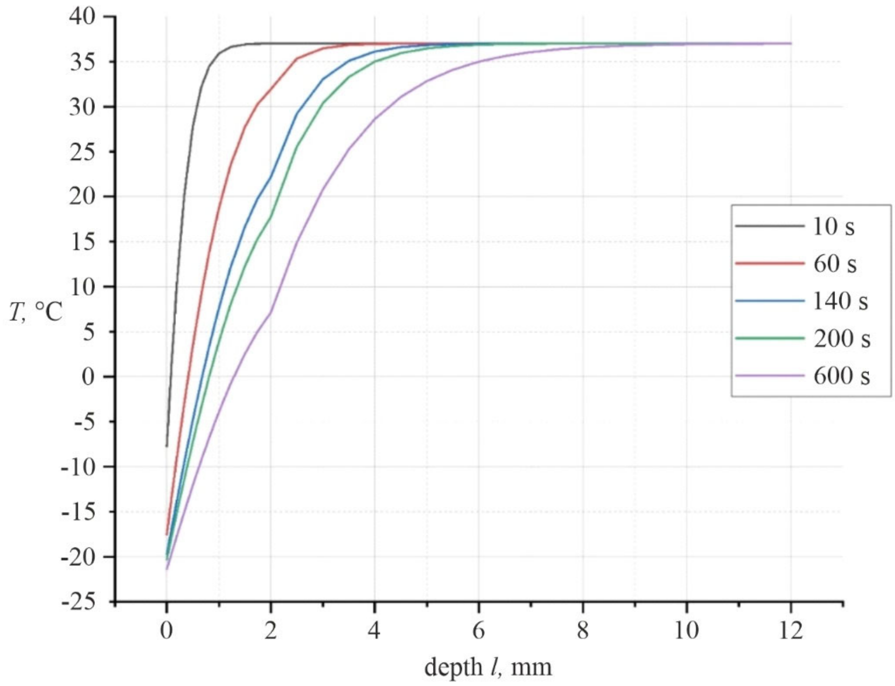

Fig. 8. Dependences of temperature on the skin depth at time moments: 10 s, 60 s, 140 s, 200 s, 600 s.

Fig. 9 shows temperature distributions in the cold accumulator at different depths.

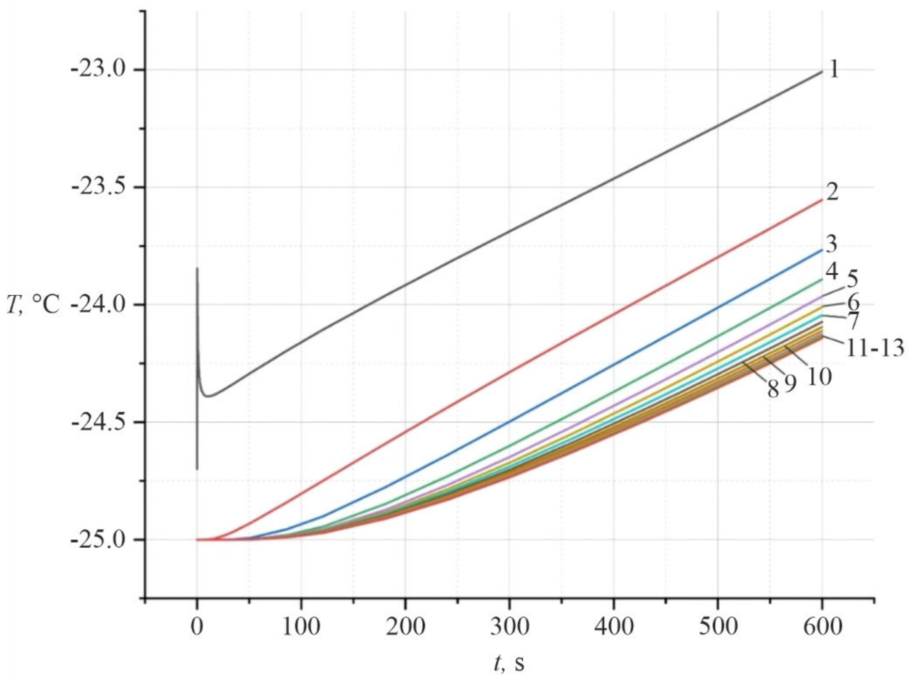

Fig. 9. Dependences of temperature on time in the cold accumulator at different depths:1 – point of contact between working tool and skin; 2 – 4 mm; 3 – 8 mm; 4 – 12 mm; 5 – 16 mm; 6 – 20 mm; 7 – 24 mm; 8 – 28 mm; 9 – 32 mm; 10 – 36 mm; 11 – 40 mm; 12 – 44 mm; 13 – 48 mm.

Fig. 10 shows temperature distributions in the cold accumulator at time moments: *10 s, 60 s, 140 s, 200 s, 600 s.*

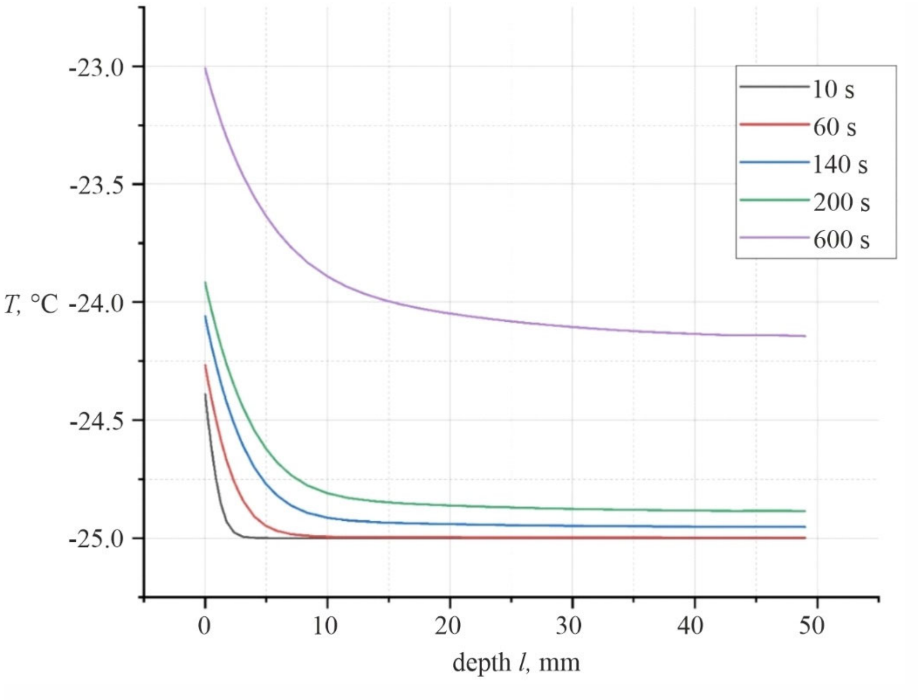

Fig. 10. Dependences of temperature on time in the cold accumulator at time moments:10 s, 60 s, 140 s, 200 s, 600 s.

Conclusions

1. A method for computer simulation of temperature distribution in the human skin in a dynamic mode, with account of the phase transition, has been developed, which makes it possible to predict the results of local temperature effects on the skin and determine at any moment in time the temperature distribution in different layers of the skin for a given arbitrary time function of change in the temperature of the working tool $T_f(t)$.

2. A computer model was developed and computer simulation of the working tool of a thermoelectric device for destruction was carried out for two design options in order to determine the temperature in the skin and the cold accumulator, taking into account the phase transition: the working tool is made of medical steel without an inner cylinder; the working tool is made of copper without an inner cylinder.

3. Using computer simulation, temperature distributions in different layers of the skin and in the cold accumulator of the working tool of a thermoelectric device for destruction at an initial temperature of -25 °C were determined, taking into account the phase transition. The results obtained make it possible to predict the depth of freezing of biological tissue.

4. With the aid of computer simulation, it was established that account of the phase transitions increases the accuracy of temperature determination in the biological tissue and the cold accumulator.

5. Using a tool design with an inner cylinder made of copper has been found to increase cooling efficiency by 10%.

References

1. Anatychuk L.I. (2003). *Thermoelectricity. Vol. 2. Thermoelectric power converters*. Kyiv, Chernivtsi: Institute of Thermoelectricity.

2. Moskalyk I.A., Manyk O.M. (2013). On the use of thermoelectric cooling in the practice of cryodestruction. *J.Thermoelectricity*,6, 84-92.
3. Moskalyk I.A. (2015). On the use of thermoelectric devices in cryosurgery. *Physics and Chemistry of the Solid State,* 4, 742-746.
4. Anatychuk L.I., Denisenko O.I., Kobylianskyi R.R., Kadeniuk T.Ya. (2015). On the use of thermoelectric cooling in dermatology and cosmetology. *J.Thermoelectricity*, 3, 57-71.
5. Kobylianskyi R.R., Moskalyk I.A. (2015). Computer simulation of local thermal effect on the biological tissue. *J.Thermoelectricity*, 6, 59-68.
6. Kobylianskyi R.R., Kadeniuk T.Ya. (2016). On the prospects of using thermoelectricity for treatment of skin diseases with cold. *Scientific bulletin of Chernivtsi University: collected papers. Physics. Electronics. – Vol. 5, issue. 1.* – Chernivtsi: Chernivtsi National University, 67-72.
7. Anatychuk L.I., Denisenko O.I., Kobylianskyi R.R., Kadeniuk T.Ya., Perepichka M.P. (2017). Modern methods of cryotherapy in dermatological practice. *Clinical and Experimental Pathology*. Vol. XVI, 1 (59), 150-156.
8. Anatychuk L.I., Denisenko O.I., Shulenina O.V., Mykytiuk O.P., Kobylianskyi R.R. (2018). Results of clinical application of a thermoelectric device for treatment of skin diseases. *J.Thermoelectricity*, 3, 52-66.
9. Kobylianskyi R.R., Manyk O.M., Vyhonnyi V.Yu. (2018). On the use of thermoelectric cooling for cryodestruction in dermatology. *J.Thermoelectricity*, 6, 36-46.
10. Anatychuk L.I., Denisenko O.I., Kobylianskyi R.R., Stepanenko V.I., Svyryd S.G., Stepanenko R.L., Perepichka M.P. (2019). Thermoelectric device for treatment of skin diseases. *J.Thermoelectricity*, 4, 62-73.
11. Anatychuk L.I., Todurov B.M., Kobylianskyi R.R., Dzhal S.A. (2019). On the use of thermoelectric microgenerators for powering electric pacemakers. *J.Thermoelectricity*, 5, 60-88.
12. Anatychuk L.I., Vikhor L.M., Kotsur M.P., Kobylianskyi R.R., Kadeniuk T.Ya. (2016). Optimal control of the time dependence of cooling temperature in thermoelectric devices. *J.Thermoelectricity*, 5, 5-11.
13. Anatychuk L.I., Kobylianskyi R.R., Kadeniuk T.Ya. (2017). Computer simulation of local thermal effect on the human skin. *J.Thermoelectricity*, 1, 69-79.
14. Anatychuk L.I., Vikhor L.M., Kobylianskyi R.R., Kadeniuk T.Ya. (2017). Computer simulation and optimization of the dynamic operating modes of a thermoelectric device for treatment of skin diseases. *J.Thermoelectricity*, 2, 44-57.
15. Anatychuk L.I., Vikhor L.M., Kobylianskyi R.R., Kadeniuk T.Ya., Zvarych O.V. (2017). Computer simulation and optimization of the dynamic operating modes of a thermoelectric device for reflexotherapy. *J.Thermoelectricity*, 3, 68-78.
16. Anatychuk L.I., Vikhor L.M., Kobylianskyi R.R., Kadeniuk T.Ya. (2017). Computer simulation and optimization of the dynamic operating modes of a thermoelectric device for cryodestruction. *Physics and Chemistry of the Solid State*, 18(4), 455-459.
17. Anatychuk L., Vikhor L., Kotsur M., Kobylianskyi R., Kadeniuk T. (2018). Optimal control of time dependence of temperature in thermoelectric devices for medical purposes. *International Journal of Thermophysics,* 39:108. https://doi.org/10.1007/s10765-018-2430-z.
18. Anatychuk L.I., Kobylianskyi R.R., Fedoriv R.V. (2019). Methodology for taking into account the phase transition in the biological tissue during computer simulation of cryodestruction process. *J.Thermoelectricity*, 1, 46-58.

19. Anatychuk L.I., Kobylianskyi R.R., Fedoriv R.V. (2019). Computer simulation of cryodestruction process of the human skin with thermoelectric cooling. *J.Thermoelectricity*, 2, 21-35.
20. Anatychuk L.I., Kobylianskyi R.R., Fedoriv R.V. (2020). Computer simulation of cyclic temperature effect on the human skin. *J. Thermoelectricity*, 2, 48-64.
21. Anatychuk L.I., Kobylianskyi R.R., Fedoriv R.V. (2020). Computer simulation of cyclic temperature effect on the oncological neoplasm of the human skin. *J.Thermoelectricity*, 3, 29-46.
22. Miller P., Metzner D. (1969). Cryosurgery for tumors of the head and neck - *Trns. Am.Ophthalmol. Otolaringol. Soc*., 73(2), 300-309.
23. D'Hont G. (1974). La cryotherapie en ORL - *Acta. Otorhinolaringol. Belg*., 28(2), 274-278.
24. Mazur P. (1968). Physical-chemical factors underlying cell injury in cryosurgical freezing. In:*Cryosurgery* ed. by R. W. Rand, A. P. Rinfret, H. Leden - Springfield, Illinois, U.S.A.32-51.
25. Gill W., Fraser I. (1968). A look at cryosurgery. - *Scot, Med*, I., 13, 268-273.
26. Van Venrjy G. (1975). Freeze-etching: freezing velocity and crystal size at different size locations in samples. *Cryobiology*, 12(1), 46–61.
27. Bause H. (2004). Kryotherapie lokalisierter klassischer, Neues Verfahren mit Peltier-Elementen (–32°C) Erfahrungsbericht Hamangiome. *Monatsschr Kinderheilkd*, 152:16–22.
28. Anatychuk L.I., Kobylianskyi R.R., Fedoriv R.V. (2022). Computer simulation of the working tool of a thermoelectric device for cryodestruction without taking into account the phase transition. *J.Thermoelectricity*, 2.
29. *COMSOL Multiphysics User's Guide* (2010). COMSOLAB.
30. Jiang S.C., Ma N., Li H.J., Zhang X.X. (2002). Effects of thermal properties and geometrical dimensions on skin burn injuries. *Burns*, 28, 713-717.
31. Cetingul M.P., Herman C. (2008). Identification of skin lesions from the transient thermal response using infrared imaging technique. *IEEE*, 1219-1222.
32. Ciesielski M., Mochnacki B., Szopa R. (2011). Numerical modeling of biological tissue heating. Admissible thermal dose. *Scientific Research of the Institute of Mathematics and Computer Science*, 1(10), 11-20.
33. Filipoiu Florin, Bogdan Andrei Ioan, Carstea Iulia Maria (2010). Computer-aided analysis of the heat transfer in skin tissue. *Proceedings of the 3rd WSEAS Int. Conference on Finite Differences* - Finite Elements - Finite Volumes - Boundary Elements, 53-59.
34. Carstea Daniela, Carstea Ion, Carstea Iulia Maria (2011). Interdisciplinarity in computer-aided analysis of thermal therapies. *WSEAS Transactions on Systems and Control*, 6(4), 115-124.
35. Deng Z.S., Liu J. (2005). Numerical simulation of selective freezing of target biological tissues following injection of solutions with specific thermal properties. *Cryobiology*, 50, 183-192.
36. Han Liang Lim, Venmathi Gunasekaran (2011). *Mathematical modeling of heat distribution during cryosurgery*. https://isn.ucsd.edu/last/courses/beng221/problems/2011/project10.pdf.
37. Shah Vishal N., Orlov Oleg I., Orlov Cinthia, Takebe Manabu, Thomas Matthew, and Plestis Konstadinos (2018). Combined cryo-maze procedure and mitral valve repair through a ministernotomy. *Multimed Man Cardiothorac Surg*. doi: 10.1510/mmcts.2018.022.
38. Rykaczewski Konrad (2019). Modeling thermal contact resistance at the finger-object interface. *Temperature*, 6 (1), 85-95.

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КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ РОБОЧОГО ІНСТРУМЕНТУ ТЕРМОЕЛЕКТРИЧНОГО ПРИЛАДУ ДЛЯ КРІОДЕСТРУКЦІЇ З ВРАХУВАННЯМ ФАЗОВОГО ПЕРЕХОДУ

У роботі наведено результати комп'ютерного моделювання робочого інструменту термоелектричного приладу для кріодеструкції з врахуванням фазового переходу, а також циклічного температурного впливу на шкіру людини у динамічному режимі. Побудовано фізичну модель робочого інструменту, 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] °C. 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.

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

Література

1. Анатичук Л.І. Термоелектрика. Т. 2. Термоелектричні перетворювачі енергії. Київ, Чернівці: Інститут термоелектрики, 2003. – 376 с.
2. Москалик І.А., Маник О.М. Про використання термоелектричного охолодження у практиці кріодеструкції // Термоелектрика. − № 6. – 2013. – С. 84 – 92.
3. Москалик І.А. Про використання термоелектричних приладів у кріохірургії // Фізика і хімія твердого тіла. – №4. – 2015. – С. 742 – 746.
4. Анатичук Л.І., Денисенко О.І., Кобилянський Р.Р., Каденюк Т.Я. Про використання термоелектричного охолодження в дерматології та косметології // Термоелектрика. − № 3. – 2015. – С. 57 – 71.
5. Кобилянський Р.Р., Москалик І.А. Комп'ютерне моделювання локального теплового впливу на біологічну тканину // Термоелектрика. − № 6. – 2015. – С. 59 – 68.
6. Кобилянський Р.Р., Каденюк Т.Я. Про перспективи використання термоелектрики для лікування захворювань шкіри холодом // Науковий вісник Чернівецького університету: збірник наук. праць. Фізика. Електроніка. – Т. 5, Вип. 1. – Чернівці: Чернівецький національний університет, 2016. – С. 67 – 72.

7. Анатичук Л.І., Денисенко О.І., Кобилянський Р.Р., Каденюк Т.Я., Перепічка М.П. Сучасні методи кріотерапії в дерматологічній практиці // Клінічна та експериментальна патологія. – Том XVI. – №1 (59). – 2017. – С. 150 – 156.
8. Анатичук Л.І., Денисенко О.І., Шуленіна О.В., Микитюк О.П., Кобилянський Р.Р. Результати клінічного застосування термоелектричного приладу для лікування захворювань шкіри // Термоелектрика. − № 3. – 2018. – С. 52 – 66.
9. Кобилянський Р.Р., Маник О.М., Вигонний В.Ю. Про використання термоелектричного охолодження для кріодеструкції у дерматології // Термоелектрика. − № 6. – 2018. – С. 36 – 46.
10. Анатичук Л.І., Денисенко О.І., Кобилянський Р.Р., Степаненко В.І., Свирид С.Г., Степаненко Р.Л., Перепічка М.П. Термоелектричний прилад для лікування захворювань шкіри // Термоелектрика. − № 4. – 2019. – С. 62 – 73.
11. Анатичук Л.І., Тодуров Б.М., Кобилянський Р.Р., Джал С.А. Про використання термоелектричних мікрогенераторів для живлення електрокардіостимуляторів // Термоелектрика. − № 5. – 2019. – С. 60 – 88.
12. Анатичук Л.І., Вихор Л.М., Коцур М.П., Кобилянський Р.Р., Каденюк Т.Я. Оптимальне керування часовою залежністю температури охолодження в термоелектричних пристроях // Термоелектрика. − № 5. – 2016. – С. 5 – 11.
13. Анатичук Л.І., Кобилянський Р.Р., Каденюк Т.Я. Комп'ютерне моделювання локального теплового впливу на шкіру людини // Термоелектрика. − № 1. – 2017. – С. 69 – 79.
14. Анатичук Л.І., Вихор Л.М., Кобилянський Р.Р., Каденюк Т.Я. Комп'ютерне моделювання та оптимізація динамічних режимів роботи термоелектричного приладу для лікування захворювань шкіри // Термоелектрика. − № 2. – 2017. – С. 44 – 57.
15. Анатичук Л.І., Вихор Л.М., Кобилянський Р.Р., Каденюк Т.Я., Зварич О.В. Комп'ютерне моделювання та оптимізація динамічних режимів роботи термоелектричного приладу для рефлексотерапії // Термоелектрика. − № 3. – 2017. – С. 68 – 78.
16. Анатичук Л.І., Вихор Л.М., Кобилянський Р.Р., Каденюк Т.Я. Комп'ютерне моделювання та оптимізація динамічних режимів роботи термоелектричного приладу для кріодеструкції // Фізика і хімія твердого тіла. – Т.18. − № 4. – 2017. – С. 455 – 459.
17. Anatychuk L., Vikhor L., Kotsur M., Kobylianskyi R., Kadeniuk T. (2018). Optimal control of time dependence of temperature in thermoelectric devices for medical purposes. *International Journal of Thermophysics* 39, 108. https://doi.org/10.1007/s10765-018-2430-z.
18. Анатичук Л.І., Кобилянський Р.Р., Федорів Р.В. Методика врахування фазового переходу в біологічній тканині при комп'ютерному моделюванні процесу кріодеструкції // Термоелектрика. − № 1. – 2019. – С. 46 – 58.
19. Анатичук Л.І., Кобилянський Р.Р., Федорів Р.В. Комп'ютерне моделювання процесу кріодеструкції шкіри людини при термоелектричному охолодженні // Термоелектрика. − № 2. – 2019. – С. 21 – 35.
20. Анатичук Л.І., Кобилянський Р.Р., Федорів Р.В. Комп'ютерне моделювання циклічного температурного впливу на шкіру людини // Термоелектрика. − № 2. – 2020. – С. 48 – 64.
21. Анатичук Л.І., Кобилянський Р.Р., Федорів Р.В. Комп'ютерне моделювання циклічного температурного впливу на онкологічне новоутворення шкіри людини // Термоелектрика. − № 3. – 2020. – С. 29 – 46.
22. Miller P., Metzner D. (1969). Cryosurgery for tumors of the head and neck. – *Trns. Am.Ophthalmol. Otolaringol. Soc.*, 73 (2), 300 – 309.

23. D’Hont G. La cryotherapie en ORL (1974). *Acta. Otorhinolaringol*., 28 (2), 274 – 278.
24. Mazur P. (1968). Physical-chemical factors underlying cell injury in cryosurgical freezing. In:*Cryosurgery* ed. by R.W. Rand, A.P. Rinfret, H. Leden – Springfield, Illinois, U.S.A. 1968 p. 32 – 51.
25. Gill W., Fraser I. (1968). A look at cryosurgery. *Scot, Med*, I., 3, 268 – 273.
26. Van Venrjy G. (1975). Freeze-etching: freezing velocity and crystal size at different size locations in samples. *Cryobiology*, 12 (1), 46 – 61.
27. Bause H. (2004). Kryotherapie lokalisierter klassischer, neues Verfahren mit Peltier-Elementen (– 32 °C) Erfahrungsbericht Hamangiome. *Monatsschr Kinderheilkd*. 152, 16 – 22.
28. Анатичук Л.І., Кобилянський Р.Р., Федорів Р.В. Комп’ютерне моделювання робочого інструменту термоелектричного приладу для кріодеструкції без врахуванням фазового переходу // Термоелектрика. − № 2. – 2022, С. 34 – 45.
29. COMSOL Multiphysics User’s Guide (2010). COMSOLAB.
30. Jiang S.C., Ma N., Li H.J., Zhang X.X. (2002). Effects of thermal properties and geometrical dimensions on skin burn injuries. *Burns*, 28, 713 – 717.
31. Cetingul M.P., Herman C. (2008). Identification of skin lesions from the transient thermal response using infrared imaging technique. *IEEE*, 1219 – 1222.
32. Ciesielski M., Mochnacki B., Szopa R. (2011). Numerical modeling of biological tissue heating. Admissible thermal dose. *Scientific Research of the Institute of Mathematics and Computer Science,* 1 (10), 11 – 20.
33. Filipoiu Florin, Ioan Bogdan Andrei, Carstea Iulia Maria (2010). Computer-aided analysis of the heat transfer in skin tissue. *Proceedings of the 3rd WSEAS Int. Conference on Finite Differences – Finite Elements – Finite Volumes – Boundary Elements*, 53 – 59.
34. Carstea Daniela, Carstea Ion, Carstea Iulia Maria. (2011). Interdisciplinarity in computer-aided analysis of thermal therapies. *WSEAS Transactions on Systems and Control*, 6 (4), 115 – 124.
35. Deng Z.S. Liu J. (2005). Numerical simulation of selective freezing of target biological tissues following injection of solutions with specific thermal properties. *Cryobiology*, 50, 183 – 192.
36. Han Liang Lim, Venmathi Gunasekaran (2011). *Mathematical modeling of heat distribution during cryosurgery*. https://isn.ucsd.edu/last/courses/beng221/problems/2011/project10.pdf.
37. Shah Vishal N., Orlov Oleg I., Orlov Cinthia, Takebe Manabu, Thomas Matthew, and Plestis Konstadinos (2018). Combined cryo-maze procedure and mitral valve repair through a ministernotomy. *Multimed Man Cardiothorac Surg*. doi: 10.1510/mmcts.2018.022.
38. Rykaczewski Konrad (2019). Modeling thermal contact resistance at the finger-object interface. *Temperature*, 6 (1), 85 – 95.

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