ARPN Journal of Engineering and Applied Sciences

IMPACT OF NON-CONTACT ELECTROMAGNETIC RADIATION ON LIVING ORGANS AND TISSUES

A. Yu. Prosekov[1], I. L. Vasilchenko[2,3], A. M. Osintsev[2], V. I. Braginsky[4], E. S. Gromov[2] and N. V. Vasilchenko[2]

[1]Department of Bionanotechnology, Institute of Food Science and Technology, Kemerovo State University, Kemerovo, Russia
[2]Department of General and Experimental Physics, Institute of Food Science and Technology, Kemerovo State University, Kemerovo, Russia
[3]Oncology Department (Head and Neck Tumors) of the State Budgetary Institution of Health Care Regional Clinical Oncological Dispensary, Kemerovo, Russia
[4]Department of Automation of Production Processes and ICS, Institute of Food Science and Technology, Kemerovo State University, Kemerovo, Russia
E-Mail: a.yu.prosekov@bk.ru

ABSTRACT

This study aims to create a laboratory unit for induction heating and assess how possible it is to use local induction heating in solving problems related to biotechnology and medicine. This article contains a description of a method for non-contact local hyperthermal heating of biological tissues using inductive electromagnetic radiation. The method is based on the introduction of a composite material consisting of a polymer base and incorporated ferromagnetic particles into living tissues. The authors present a simplified mathematical model of physical processes occurring during the heating of a polymer sample-implant. The results of mathematical modeling are further used to approximate the data obtained in experiments on a specially built laboratory unit. The materials for building the applicator included a mixture of a plastic polymer and a hardener. The plastic polymer was modified by adding finely dispersed ferromagnetic particles and thoroughly mixed. Since the further use of the polymer applicator will occur in the field of biotechnology and medicine, the material for the manufacture of the applicator was Speedex putty silicone impression mass. The authors have calculated the physical parameters of the simplest model of the heated applicator. The nature of the dependence of the efficiency of induction heat release has been established. An increase in the efficiency of induction heating with an increase in the size of electrically conductive particles has been proven. Another series of experiments has been organized with double power consumption. The authors see the prospect of further development of studies in the chosen area in the development and creation of an automated control system and long-term maintenance of the temperature of heated samples at the target level. To do this, it is necessary to compare various methods for controlling the thermal power: control of the duty cycle of the master oscillator pulses, frequency shift near the resonant frequency, periodic on/off switching of the master oscillator, etc. Besides, it is necessary to develop a technique and technology for monitoring the uniformity of the sample temperature, which is especially important due to the complexity of using conductors in the induction heating zone. Finally, an important task for further studies is the development of different inductors for different applications. The authors assume that an open external inductor with a ferrite core may become the most probable model.

Keywords: induction heating, hyperthermia, polymer matrix, ferromagnetic filler.

INTRODUCTION

The larynx is a complex anatomical and physiological complex consisting of various tissue structures, with a developed network of blood, lymphatic vessels, and nerves. The larynx is an organ consisting of a cartilaginous skeleton, connected by fibrous ligaments and lined with a mucous membrane. The upper 2/3 of the epiglottis and the area of the vocal folds are covered with stratified squamous epithelium, while the rest of the mucous membrane is covered with multilayered ciliated epithelium. The lamina propria of the mucous membrane is represented by loose fibrous tissue, protein-mucous glands, and accumulations of lymphoid tissue. All cartilages of the larynx, except for the epiglottis, are hyaline. All muscles of the larynx are striated and can contract both voluntarily and reflexively [1].

In 2017, 7,148 cases of newly diagnosed laryngeal cancer were registered in Russia. In 2017, 9.52 cases per 100,000 population were diagnosed in men, the average annual growth rate was 0.1%, while the increase equaled minus 1.03%. In 2017, 0.65 cases per 100,000 of the population were diagnosed in women, the average annual growth rate was 2.4%, and the increase equaled 25.22%. The average age of diagnosed men is 61.8 years, and the average age of diagnosed women is 63.1 years. The number of cases of larynx cancer rises sharply from the age of 50, reaching the highest peak at 55-75 years. The mortality of patients within a year since the diagnosis of laryngeal cancer in Russia in 2017 amounted to 23.0%. The average age of deceased men in 2017 was 64.2 years, and the average age of deceased women was 64.1 years. Among all newly established diagnoses, stages I-II were found in 36.5% of patients, stage III in 43.2%, and stage IV in 18.7%. Only 5% of patients were diagnosed during preventive examinations [2].

There are exophytic, endophytic, and mixed forms of laryngeal tumor growth. The exophytic form of growth has the appearance of a papilloma, papillary growths, or a large, lumpy formation on a broad base, growing into the lumen of the larynx. The borders of the tumor are clear, the infiltration of the underlying tissues is insignificant, and the course is favorable compared to other types of cancer. An endophytic tumor infiltrates and destroys tissues, while the mucous membrane can be slightly changed. The infiltrate has no clear boundaries, ulcerates, and early causes immobility of the affected half of the larynx. The mixed form of the tumor combines exophytic and endophytic growth. Exophytic cancer calculates slowly and forms metastases rarely and late. Endophytic forms of cancer are more aggressive, and they metastasize early and often [2].

The well-known induction heating procedure is used to efficiently heat objects without contact with them and without penetrating objects [1]. An indispensable material property of such objects is their high electrical conductivity, which, as a rule, is ensured by the manufacture of objects from ferromagnetic materials. The use of induction heating in medicine and other scientific and practical fields dealing with living biological tissues has an important limitation. Organic tissues do not have magnetic properties and have extremely low electrical conductivity. Therefore, direct induction heating directly to tissues is practically impossible [2].

Our study aims to create a laboratory unit for induction heating and assess how possible it is to use local induction heating in solving problems related to biotechnology and medicine.

The study is based on the assumption that controlled non-contact local heating of a selected small area of a significant array of living tissues can be carried out by placing a special applicator consisting of a polymer base and ferromagnetic particles inside organic tissues [3]. When analyzing scientific literature and research and technical patent documentation, we failed to find any analogs of the proposed method for induction heating of mixtures of a polymer with ferromagnetic materials [4].

The developed method can be applied, in particular, for local non-contact heating of selected fragments of frozen organic objects. This will help to carry out sampling to study the properties of a sample frozen for long-term storage without its complete thawing and/or destruction. Besides, the developed method can be used to create local intraoperative hyperthermia in combination with radiation therapy in the treatment of cancer using induction heating of a tissue-equivalent applicator [5-8].

Induction heating acts on the following types of tumors and tissues:

a) Epithelial tumors. (Benign: squamous cell papilloma, oxyphilic adenoma. Malignant: intraepithelial carcinoma (carcinoma in situ), squamous cell carcinoma; squamous cell carcinoma; squamous cell non-keratinizing cancer; spindle cell squamous cell carcinoma; adenocarcinoma; adenoid cystic cancer; neuroendocrine cancer, mucoepidermoid cancer; undifferentiated cancer).
b) Soft tissue tumors (Benign: lipoma, hemangioma, leiomyoma, rhabdomyoma, granulosa cell tumors, neurofibroma, neurilemmoma (schwannoma), paraganglioma (chemodectoma). Malignant: fibrosarcoma, rhabdomyosarcoma).
c) Tumors of bone and cartilage tissue. (Benign: chondroma. Malignant: chondrosarcoma).
d) Tumors of the hematopoietic and lymphoid tissues.
e) Tumors of mixed genesis.
f) Secondary tumors.
g) Unclassified tumors.

Tumor-like lesions. (1. Pseudoepithelial hyperplasia. 2. Epithelial anomalies: keratosis-hyperplasia (keratosis without atypia), dysplasia (keratosis with atypia) 3. Oncocytic metaplasia and hyperplasia. 4. Cysts 5. Intubation granuloma or contact ulcer 6. Vocal fold polyps: fibrous, vascular, hyalinized, myxoid. 7. Amyloid deposits. 8. Infectious granuloma 9. Plasma cell granuloma. 10. Stewart's granuloma 11. Wegener's granuloma. 12. Osteochondroplastic tracheopathy) [3, 4].

MATERIALS AND METHODS

The developed method should allow uniform heating of the polymer applicator as a result of the absorption of the energy of the alternating electromagnetic field by ferromagnetic elements, which are evenly distributed in the body of the polymer applicator [9].

The materials for building the applicator included a mixture of a plastic polymer and a hardener. The plastic polymer was modified by adding finely dispersed ferromagnetic particles and thoroughly mixed. Since the further use of the polymer applicator will occur in the field of biotechnology and medicine, the material for the manufacture of the applicator was Speedex putty silicone impression mass, well-established in dental practice [10].
The high-frequency current required for induction heating of the applicator was obtained in the course of experiments using a laboratory inverter, schematically shown in Figure 1. Its principle of operation is as follows. Two powerful field-effect transistors, functioning as the keys of the two arms of the power half-bridge, receive a rectified stabilized voltage from a powerful regulated mains electrical supply (laboratory autotransformer). The transistors open and close alternately by a signal applied to their gates from the driver. The switching frequency, and hence the current frequency, is determined by the driver pulse generator (PG). The inductor (60 mm long air coil for 10 turns with a diameter of 45 mm and a compensating capacitor connected in parallel) is connected to the bridge through a matching transformer (not shown in Figure 1). The resonant frequency of the inductor corresponds to the frequency of the PG due to the selection of the capacitance of the capacitor [11-13].

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

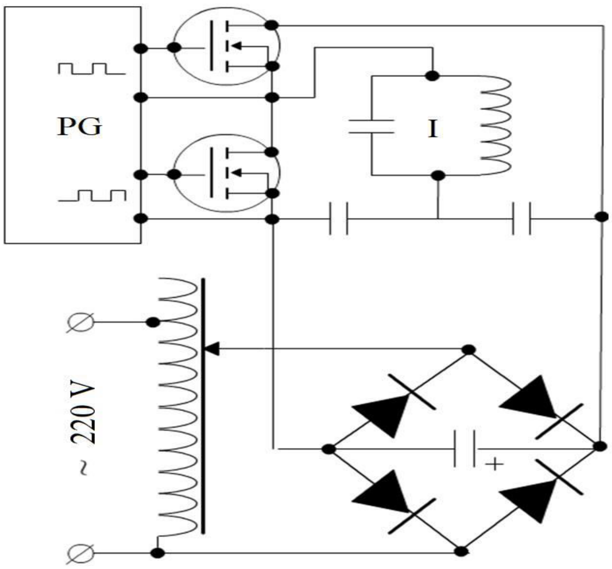

Figure-1. Schematic diagram of the laboratory unit.

In the course of the experimental study, heating by induction occurred in the frequency range of 120 ± 60 kHz. Such a wide range is determined by the need to adjust the resonant inductor adequate to the specified parameters. Two important advantages of the selected frequency range should be pointed out. Firstly, a strong electromagnetic field in this range can be obtained using common electronic devices. Secondly, the field of this frequency range is hardly absorbed directly by organic substances, which means that the tissues surrounding the applicator will not be exposed to excessive and unnecessary heating [14].

The power of the laboratory unit used to create an alternating magnetic field was calculated from the values of the voltage and current drawn from the electrical mains. The electronic part of the unit allows switching currents up to 1 kW. However, with an increase in power consumption (starting from 100 W), the need for additional forced cooling of the heating coil of the inductor increases. The experiments described below were carried out at two different powers (20 and 40 W), not requiring coil cooling [15].

To test the possibility of induction heating, we made samples of a polymer applicator of the approximately spherical shape of the same size and 20 mm in diameter. When making prototypes, a hole was formed in their central part for introducing a thermometer. The function of ferromagnetic fillers was performed by (1) a mixture of ultrafine powders of nickel (80%) and aluminum (20%) with a particle size of 10-100 nm, (2) steel balls with a diameter of 0.5-1 mm, as well as (3) reduced iron in the form of small turnings with a size of about 0.1×1×3 mm. The filler mass fraction varied in the range of 10-60%. The composition of samples with different filler mass fraction is presented in Table-1.

Table-1. Sample composition.

Filler mass fraction, %	Filler weight, g	Polymer base weight, g	Sample volume, cm^3
10	0.59	5.34	4.19
20	1.31	5.22	4.19
30	2.18	5.08	4.19
40	3.27	4.90	4.19
50	4.67	4.67	4.19
60	6.53	4.35	4.19

Without exception, all samples containing more than 50% filler were difficult to mold, and many of them had defects in the form of fractures. The least homogeneous samples were obtained by mixing the polymer base with iron turnings, the unevenness of the shape and size of the pieces of which made it difficult to uniformly distribute the filler. Even at mass fractions above 30%, many samples contained protruding elements of the iron turnings, which is unacceptable for medical use due to the possibility of injury to tissues adjacent to the heated applicator.

The use of steel balls as a ferromagnetic filler gave satisfactory uniformity to the finished samples in the absence of traumatic protrusions on the surface of the latter.

The highest degree of homogeneity of the finished samples was, as expected, observed when using ultrafine fillers.

RESULTS

Let us calculate the physical parameters of the simplest model of the heated applicator. If, under the influence of induction heating, heat q_1 is released inside the applicator per unit of time, while part of the heat q_2 is emitted by the surface of the sample, then approximately we can assume that

$$q_2 = \sigma(T - T_0)\,, \tag{1}$$

where T is the sample temperature; T_0 is the ambient temperature; σ is a constant proportional to the surface area, identical for all samples. The excess of heat release over the loss of heat by the sample leads to an increase in the temperature of the latter:

$$q_1 - q_2 = (c_1 m_1 + c_2 m_2)\frac{dT}{dt}\,, \tag{2}$$

where $c_1 = 0{,}5\ \frac{\mathrm{J}}{g \cdot K}$ and m_1 are the specific heat and mass of the filler, respectively, and $c_2 = 1{,}5\ \frac{\mathrm{J}}{g \cdot K}$ and m_2 are the same values for the polymer base.

Expression (2), considering equality (1), is transformed into a differential equation of the form:

VOL. 17, NO. 13, JULY 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

$$\frac{dT}{dt}+\alpha T=\beta \ , \tag{3}$$

where $\alpha=\frac{\sigma}{c_1m_1+c_2m_2}$ and $\beta=\frac{q_1}{c_1m_1+c_2m_2}+\alpha T_0$.

The solution to this equation is well known. Given the initial condition $T(0)=T_0$, it takes the form:

$$T=T_0+\frac{q_1}{\sigma}\left(1-\exp(-\alpha t)\right), \tag{4}$$

To establish the nature of the dependence of the efficiency of induction heat release q_1 on the size of the filler particles, let us study a single spherical particle of radius *R*, located in an alternating uniform magnetic field $B=B_m\cos\omega t$. At the initial stage of calculations, it is advisable to consider the particle as a nonmagnetic conductor. This assumption will help to avoid complications, considering the violation of the uniformity of the magnetic field near the curved surface of the ferromagnet, and exclude from the calculations the work spent on remagnetization of the sample.

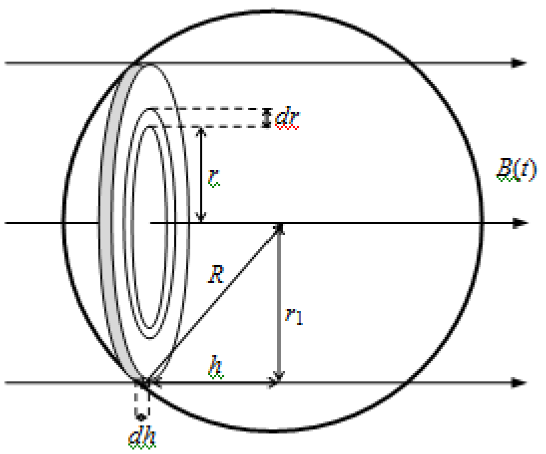

Figure-2. Calculation of heat release in the sample.

Let us split the ball into disks of variable radius r_1. Let us select one of such disks of thickness *dh* at a distance *h* from the center of the ball (Figure-2). To calculate the amount of heat released in the volume of this disk per unit time, we select in it an annular segment of radius *r* and thickness *dr*. The electromotive force of the induction arising in this segment is directly proportional to the rate of change of the magnetic flux passing through it:

$$\varepsilon_i=-\frac{d\Phi}{dt}=\pi r^2\omega B_m\sin\omega t \ , \tag{5}$$

The intensity of the vortex electric field in the ring is described by the following expression:

$$E_i=\frac{\varepsilon_i}{2\pi r}=\frac{1}{2}r\omega B_m\sin\omega t \ , \tag{6}$$

According to the Joule-Lenz law, the power of the heat released per unit volume of the conductor $w=\frac{E^2}{\rho}$. Therefore, for the heat released, on average, per unit time in the selected ring, we obtain:

$$dW=\langle w\rangle dV=\langle w\rangle\cdot 2\pi r\cdot dh\cdot dr=\frac{1}{4}\frac{\pi\omega^2B_m^2}{\rho}dh\cdot r^3dr \ , \tag{7}$$

Expression (7) considers the mean value of the sine square $\langle\sin^2\omega t\rangle=\frac{1}{2}$ over the period.

The heat released per unit of time in the entire selected disk is obtained through integration:

$$dq=\int_0^{r_1}dW=\frac{1}{4}\frac{\pi\omega^2B_m^2}{\rho}dh\int_0^{r_1}r^3dr=\frac{1}{16}\frac{\pi\omega^2B_m^2}{\rho}r_1^4dh \ , \tag{8}$$

Considering the obvious connection between r_1 and *h* (Figure-2), let us determine the amount of heat released in the volume of one ball:

$$q_0=\frac{1}{16}\frac{\pi\omega^2B_m^2}{\rho}\int_{-R}^{R}\left(R^2-h^2\right)^2dh=\frac{1}{15}\frac{\pi\omega^2B_m^2}{\rho}R^5 \ , \tag{9}$$

Thus, if we assume that all ferromagnetic particles are in the same conditions, for a sample with a volume of conducting particles *V*, the heat release will be:

$$q_1=Nq_0=\frac{3V}{4\pi R^3}q_0=\frac{V}{20}\frac{\omega^2B_m^2}{\rho}R^2 \ , \tag{10}$$

Calculations indicate an increase in the efficiency of induction heating with an increase in the size of conductive particles. Formula (10) serves as an extremely rough and approximate estimate of the ongoing processes, since (1) the particles are considered as isolated, which excludes their mutual influence; (2) the particles are considered non-magnetic; (3) the skin effect that occurs when alternating current flows in a conductor is not considered. However, the theoretically substantiated position on the increase in the efficiency of induction heating with increasing particle size is also confirmed by the experimental data presented below.

Thus, at a power consumption of 20 W, the samples with the nanodispersed filler practically did not heat up. An increase in the power to 40 W led to noticeable heating only for samples with a mass fraction of a filler of 60%. This is explained by the formation of conglomerates of nanoparticles at their high concentration, which ensures their direct contact and thus increases their effective size.

ARPN Journal of Engineering and Applied Sciences

The data obtained in experiments with samples containing a filler made of steel balls with a diameter of 0.5 mm heated at a power consumption of 20 W are shown in Figure-3. With such an inductor power, heating the samples to a hyperthermal temperature at ambient room temperature turned out to be possible only for samples with a mass fraction of a ferromagnetic material above 50%. Modeling parameters using formula (4): σ = 0.020 W/K; q_1 = 0.150 W for a 20% mass fraction, q_1 = 0.225 W for a 40% mass fraction, and q_1 = 0.375 W for a 60% mass fraction.

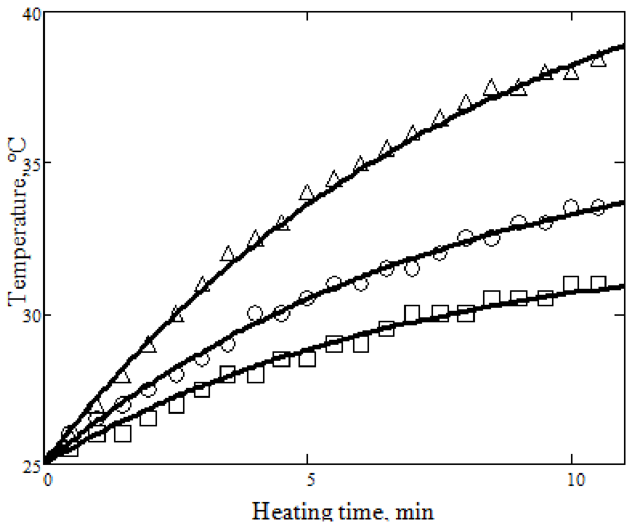

Figure-3. Experimental results and their model approximation (solid lines). Heating power: 20 W. Filler: balls with a diameter of 0.5 mm:
□: 20% mass fraction
○: 40% mass fraction
Δ: 60% mass fraction

The power of the generated heat does not increase in direct proportion to the increase in the mass of the filler, as, in theory, should follow from formula (10). A comparison of the q_1 values obtained by approximating the experimental data with the values calculated using formula (10) is shown in Table-2.

Table-2. Comparison of experimental and theoretical estimates for Figure-3.

Filler mass fraction, %	q_1 values	
	Estimated from experimental data, W	Estimated using formula (10), W
20	0.150	0.150
40	0.225	0.374
60	0.375	0.748

The slower (in comparison with the theoretical prediction) increase in the thermal power is mainly due to the significant in homogeneity of the magnetic field in the sample volume.

The data obtained in experiments with samples containing a filler made of steel balls 1 mm in diameter are shown in Figure-4.

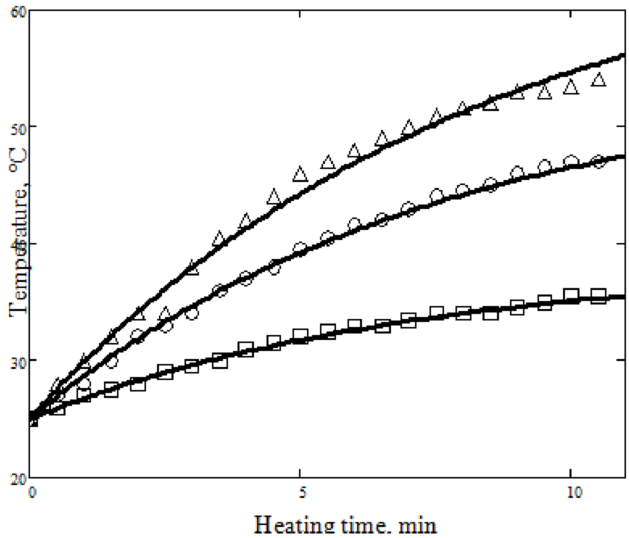

Figure-4. Experimental results and their model approximation (solid lines). Heating power: 20 W. Filler: balls with a diameter of 1 mm:
□: 20% mass fraction
○: 40% mass fraction
Δ: 60% mass fraction

The results of the experiments indicate that when balls with a diameter of 1 mm are used as a filler, all prototypes with a mass fraction of balls exceeding 20% are steadily heated to a temperature above 40 ° C even at a power of 20 W. The simulation was carried out based on the parameter σ = 0.020 W/K, as in the previous case.

Table-3 shows the q_1 values obtained for samples containing a filler of balls with a diameter of 1 mm by approximating the experimental data with the values previously calculated using formula (10). The discrepancy has narrowed slightly, but the empirical data are still very far from those predicted using formula (10).

Table-3. Comparison of experimental and theoretical estimates for Figure-4.

Filler mass fraction, %	q_1 values	
	Estimated from experimental data, W	Estimated using formula (10), W
20	0.267	0.267
40	0.585	0.667
60	0.841	1.332

If we compare the data in Tables 2 and 3 from the point of view of the dependence of the thermal power on the particle size predicted using formula (10), we can find

VOL. 17, NO. 13, JULY 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

that the experimental results do not agree with the predicted. The ratios of the corresponding q_1 values for balls with a diameter of 1 mm and 0.5 mm for three different mass fractions are 1.78, 2.6, and 2.24 (on average about 2.2), while the calculated value according to formula (10) should be exactly 4. This fits well with the above-stated judgment about the extremely evaluative nature of formula (10) derived based on several significant simplifications and assumptions. On the other hand, the nature of the dependencies revealed in the experiments is in qualitative agreement with the conclusions following from formula (10). A significant scatter of values may be initially conditioned by inaccuracy in tuning the oscillatory circuit of the inductor into resonance with the master oscillator. Even a slight detuning from resonance upon introducing samples with different ferromagnetic compositions can significantly change the current in the coil and, consequently, the magnetic field in the sample.

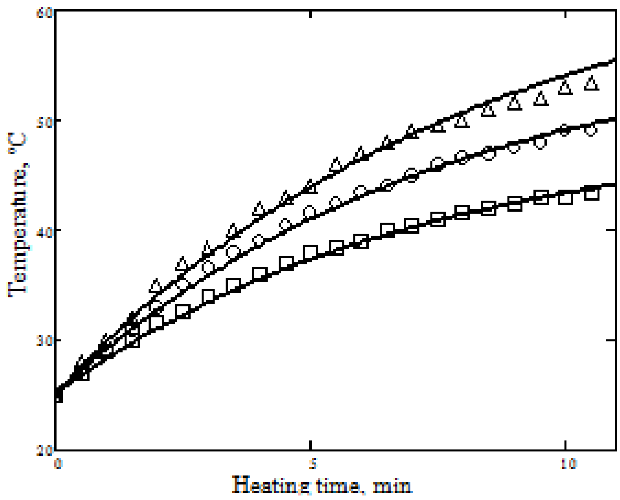

Figure-5. Experimental results and their model approximation (solid lines). Heating power: 20 W. Filler: reduced iron turnings:
□: 20% mass fraction
○: 40% mass fraction
Δ: 60% mass fraction

The results of an experiment on heating samples with reduced iron turnings as a filler are shown in Figure-5. The data are generally similar to the previous series of experiments, but the curves obtained indicate that the nature of heating corresponds to the average effective size of particles, with a diameter slightly larger than 1 mm. Curve modeling parameters using formula (4) for Figure-5: $\sigma = 0.020$ W/K; $q_1 = 0.483$ W for a 20% mass fraction, $q_1 = 1.058$ W for a 40% mass fraction, and $q_1 = 1.521$ W for a 60% mass fraction.

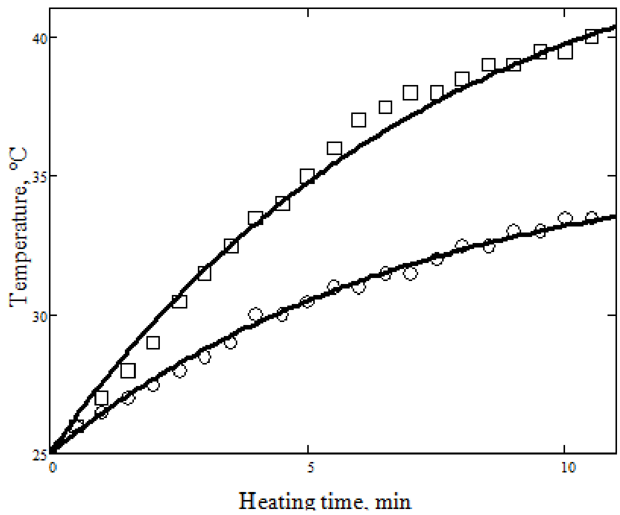

Figure-6. Experimental results and their model approximation (solid lines). Filler: balls with a diameter of 0.5 mm; 40% mass fraction:
□: heating power of 40 W
○: heating power of 20 W

To verify the dependence of the thermal power q_1 on the magnitude of the magnetic field, another series of experiments was organized at double power consumption. Figure-6 demonstrates the dependence of the temperatures of samples with a 40% filler mass fraction (balls with a diameter of 0.5 mm) on time for two powers consumed from the electrical mains. Curve modeling parameters using formula (4) for Figure 6: $\sigma = 0.020$ W/K; $q_1 = 0.225$ W for a heating power of 20 W and $q_1 = 0.40$ W for a heating power of 40 W. In this case, the experimental values differ by almost two times, as expected following formula (10).

CONCLUSIONS

The results obtained fully prove the possibility of contactless induction heating of non-conductive materials, in particular biological tissues, to hyperthermic temperatures. Hyperthermic temperatures will act on intraepidermal laryngeal cancer, which usually develops against the background of atypical papillomas or pachydermia, while clear morphological signs of the transition of these processes to cancer in situ are often not found. Among malignant neoplasms of the larynx, squamous cell carcinoma is the main group (98%). Malignant non-epithelial tumors of the larynx occur in 0.5-2% of cases. Therefore, the effect of hyperthermic temperatures on epithelial tissues (skin and muscles) is most relevant [5].

We see the prospect of further development of studies in the chosen area in the development and creation of an automated control system and long-term maintenance of the temperature of heated samples at the target level. To do this, it is necessary to compare various methods for controlling the thermal power: control of the duty cycle of the master oscillator pulses, frequency shift near the resonant frequency, periodic on/off switching of the master oscillator, etc. Besides, it is necessary to develop a technique and technology for monitoring the uniformity of the sample temperature, which is especially important due to the complexity of using conductors in the induction heating zone. Finally, an important task for further studies is the development of different inductors for different applications. We assume that an open external inductor with a ferrite core may become the most probable model.

REFERENCES

[1] Wust P., Hildebrandt B., Sreenivasa G., Rau B., Gellermann J., Riess H., Felix R. and Schlag P.M. 2002. Hyperthermia in combined treatment of cancer. Lancet Oncol. 3(8): 487-497.

[2] Vasilchenko I. L., Osintsev A. M, Glushkov A. N., Kolomiets S. A., Polikarpov A. F., Maitakov A. L., Braginskii V. I., Pastushenko D.A., Vasilchenko N.V., Osintseva M.A. and Gordeeva L.A. 2015. Sposob personalizirovannogo lecheniya mestnorasprostranennykh zlokachestvennykh novoobrazovanii na osnove lokalnoi kontaktnoi gipertermii s ispolzovaniem individualnogo tkaneekvivalentnogo applikatora [A method for personalized treatment of locally advanced malignant neoplasms based on local contact hyperthermia using an individual tissue-equivalent applicator]. Patent na izobretenie RU 2565810 [Invention patent RU 2565810], Russian Federation.

[3] Vasilchenko I. L., Osintsev A. M. and Kolomiets S. A. 2015. Metod personalizirovannoi kontaktnoi gipertermii zlokachestvennykh opukholei na osnove induktsionnogo nagreva applikatora vikhrevymi tokami submegagertsovogo diapazona v sochetanii s kontaktnoi luchevoi terapiei [The method of personalized contact hyperthermia of malignant tumors based on induction heating of the applicator with eddy currents of the sub-MHz range in combination with contact radiation therapy]. Meditsina v Kuzbasse. 14(1): 21-26.

[4] Toraya-Brown S., Fiering S. 2014. Local tumour hyperthermia as immunotherapy for metastatic cancer. International Journal of Hyperthermia. 30(8): 531-539. http://dx.doi.org/10.3109/02656736.2014.968640

[5] Gao Sh., Zheng M., Ren X., Tang Ya. and Liang X. 2016. Local hyperthermia in head and neck cancer: mechanism, application and advance. Oncotarget. 7: 57367-57378. https://doi.org/10.18632/oncotarget.10350

[6] Ryan T. P., Hartov A., Colacchio T. A., Coughlin C. T., Stafford J. H. and Hoopes P. J. 1991. Analysis and testing of a concentric ring applicator for ultrasound hyperthermia with clinical results. International Journal of Hyperthermia. 7(4): 587-603. http://dx.doi.org/10.3109/02656739109034971

[7] Ito K. and Saito K. 2011. Development of microwave antennas for thermal therapy. Current Pharmaceutical Design. 17(22): 2360-2366. https://doi.org/10.2174/138161211797052538

[8] Bardati F. and Tognolatti P. 2016. Hyperthermia phased arrays pre-treatment evaluation. International Journal of Hyperthermia. 32(8): 911-922. http://dx.doi.org/10.1080/02656736.2016.1219393

[9] Stauffer P. R., Diederich C. J. and Seegenschmiedt M. H. 1995. Interstitial heating technologies, In: Seegenschmiedt, M. H., Fessenden, P. and Vernon, C. C. (ed.) Thermoradiotherapy and thermochemotherapy: Vol. 1, biology, physiology and physics, pp. 279-320. Berlin, New York: Springer-Verlag.

[10] Johannsen M., Thiesen B., Wust P. and Jordan A. 2010. Magnetic nanoparticle hyperthermia for prostate cancer. International Journal of Hyperthermia. 26(8): 790-795. http://dx.doi.org/10.3109/02656731003745740

[11] Ivkov R. 2013. Magnetic nanoparticle hyperthermia: A new frontier in biology and medicine? International Journal of Hyperthermia. 29(8): 703-705. http://dx.doi.org/10.3109/02656736.2013.857434

[12] Huang X., Qian W., El-Sayed I.H. and El-Sayed M. A. 2007. The potential use of the enhanced nonlinear properties of gold nanospheres in photothermal cancer therapy. Lasers in Surgery and Medicine. 39(9): 747-753. https://dx.doi.org/10.1002/lsm.20577

[13] Vasilchenko I. L., Vinogradov V. M., Pastushenko D. A., Osintsev A. M., Maitakov A. L., Rynk V. V. and Vasilchenko N. V. 2013. Ispolzovanie lokalnogo induktsionnogo nagreva v lechenii zlokachestvennykh novoobrazovanii [The use of local induction heating in the treatment of malignant neoplasms]. Voprosy onkologii. 59(2): 84-89.

[14] Stauffer P. R., Vasilchenko I. L., Osintsev A. M., Rodrigues D. B., Bar-Ad V., Hurwitz M. D. and Kolomiets S. A. 2016. Tumor bed brachytherapy for locally advanced laryngeal cancer: a feasibility

assessment of combination with ferromagnetic hyperthermia. Biomedical Physics and Engineering Express. 2(5): 055002. https://doi.org/10.1088/2057-1976/2/5/055002

[15] Stauffer P. R., Cetas T. C. and Jones R. C. 1984. Magnetic induction heating of ferromagnetic implants for inducing localized hyperthermia in deep-seated tumors. IEEE Transactions on Biomedical Engineering. 31(2): 235-251. https://doi.org/10.1109/TBME.1984.325334