БІОЛОГІЧНІ ТА МЕДИЧНІ ПРИЛАДИ І СИСТЕМИ

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DEVELOPMENT OF A MATHEMATICAL MODEL OF THE THERMAL FIELD OF AN INTEGRAL STRUCTURE IN THE IMPLEMENTATION OF SENSORS FOR BIOMEDICAL RESEARCH

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Анотація. В статті розглянуто реалізація комплексної методики для електротеплового моделювання вимірювальних перетворювачів теплових сенсорів потоку, який поєднує синтез кола заміщення імпульсної температурної релаксації та спосіб формування ВАХ перетворювачів в режимі їх самонагріву струмом живлення. Розглянуто питання оцінювання нестабільності ітераційних процесів при аналізі ВАХ вимірювальних перетворювачів з від’ємним диференційним опором, що обумовлено самонагрівом цих перетворювачів. Розроблено експрес-метод визначення меж, в яких забезпечується коректний електротепловий DC аналіз для застосування в біомедичних приладах та системах.
Ключові слова: електротеплове моделювання, вимірювальні перетворювачі, самонагрів перетворювачів, біомедичні прилади та системи.

Abstract. The paper deals with the implementation of a complex technique for electrothermal modeling of measuring transducers of thermal flow sensors, which combines the synthesis of the impulse temperature relaxation substitution circuit and the method of forming the I-V converters in the mode of their self-heating by the supply current. The issue of assessing the instability of iteration processes in the analysis of I/V measuring converters with negative differential resistance, which is caused by self-heating of these converters, is considered. An express method for determining the limits in which correct electrothermal DC analysis is provided for use in biomedical devices and systems has been developed.
Keywords: electrothermal modeling, measuring transducers, self-heating of transducers, biomedical devices and systems.

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Introduction

Information signal of the primary thermal flow sensors converters is their temperature that depends on the intensity of the heat exchange between the structure of the converter and the flow medium (gas or fluid). Modeling studies of the circuits of the above-mentioned measuring converters, carried out for the optimization of their structure and supply modes, require the combination of the analysis of the electric and thermal processes in a single complex.

Unfortunately, known packages of circuit modeling, in particular, PSpice and MicroCAP, do not allow combining electric and thermal analysis - in the course of such modeling studies the temperature of the elements cannot change if the electric power, released in these elements, varies. That is why, the problem of the development of the adaptation method of the circuit modeling procedure in the given packages for the realization of the possibility of the complex analysis of electric and thermal processes in the circuits of primary thermal flow sensors converters, was put forward. The realization of this task requires the creation of the model (equivalent circuit) of the elements, volt-ampere characteristic of which is influenced in the process of self-heating of these elements.

Techniques and models of calculation of the temperature fields of the electronic equipment and, in particular, solid-state and hybrid integrated circuits have already been adequately discussed in numerous publications. A number of specialized programming products are available , namely: WinTherm (developer ANALYSIS TECH; www.analysistech.com), T3Step and Thermodel (developer MICRED; www.micred.com), BETAsoft Board (developer DYNAMIC SOFT ANALYSIS; www.betasoft-thermal.com), etc. [54-65]. Taking into consideration, that the scientific aspects of the greater part of thermal calculations are comprehensive, at least, from the point of view of the tasks, put forward in the given research, further we will suggest only the description of the thermal model in general form and partial examples of the results of thermal fields of the integrated structures of the thermal hot-wire anemometers calculations . The material of the given subsection should be considered only as the initial data for the developed new approaches of the electric thermal modeling, presented in the next parts of the monograph, where the dynamic, thermal and circuit calculations of elements, the temperature of which is the informative value of the signal converter of the thermal flow are combined.

Method

In the process of the thermal calculation of the integral structures, they are divided into the sections, in particular, into layers and parallelograms, each of them is described by the independent system of parameters - thermal conductivity factor, heat capacity, heat release power, etc. The system of heat conduction equations in the Cartesian coordinate system x, y, z for the i-th layer of the multilayer structure (assuming that the bottom boundary of the i-th layer corresponds to the coordinate $z_i = \delta_i$, and the upper – $z_i = \delta_i$, , where δ_i – is the hickness of the i-th layer) has the form [172, 173]:

$$\partial^2 T_i / \partial x^2 + \partial^2 T_i / \partial y^2 + \partial^2 T_i / \partial z^2 = 0$$

Boundary conditions are:

- on lateral edges if $x = 0$, $x = L_x$, $y = 0$, $y = L_y$:

$$\partial T_i / \partial x = 0; \quad \partial T_i / \partial y = 0;$$

- on the boundary of the *i*-th and (*i*+1)-th layers if $z_i = \sigma_i$, $zi+1 = 0$:

$$T_i = T_{i+1}; \quad \lambda_i \left(\partial T_i / \partial z_i \right) = \lambda_{i+1} \left(\partial T_{i+1} / \partial z_{i+1} \right);$$

- on the surface *S* if z1 = 0

$$\frac{\partial T_1}{\partial z_1} = -\frac{1}{\lambda_1} \sum_{j=1}^{k} \frac{P_j}{a_j b_j} h_j(x) h_j(y) h_j(z) + \frac{\alpha_0}{\lambda_1} T_1;$$

- on the surface S_N if $z_N = \delta_N$:

$$\frac{\partial T_N}{\partial z_N} = \frac{1}{\lambda_N} \sum_{j=1}^{k} \frac{P_j}{a_j b_j} h_j(x) h_j(y) h_j(z) - \frac{\alpha_N}{\lambda_N} T_N,$$

where *Ti* – is the excessive temperature (temperature of overheating) of the i-th layer over the ambient temperature (*i* = 1, 2, 3... *N*); *N* – is a number of layers; *λi* – is the thermal conductivity of the i-th layer; *Pj* – is the power of the j-th source of heat (*j* = 1, 2, 3... *k*); *k* – is the number of heat sources; *aj*, *bj* – are dimensions of the heat sources with the number j on axes x and y, correspondingly; *hj*(*x*), *hj*(*y*) – are coordinate-dependent functions which take the value of 1 in the area of the source and 0 outside the area of the j-th source of heat; *hj(z)* – are coordinate-dependent functions, which take the value of 1 on the surface S_N and 0 - on the surface S_0, correspondingly; α_0, α_N – are heat transfer coefficients from the surfaces S_0, S_N.

Calculation of the temperature field, stipulated by the location of the source of heat on the surface SN, can be performed by means of numerical methods, applying series:

$$\frac{T_{ij}}{P_j}=\frac{(1-k_i)Z_c\alpha_0+1}{Z_c\alpha_0\alpha_N+\alpha_0+\alpha_N}\frac{1}{L_xL_y}+\frac{8L_x}{\pi^2a_ia_jL_y}\times$$
$$\times\sum_{n=1}^{\infty}\frac{W(n,0,k_i)}{n^2}\cos n\pi\frac{\varphi_i}{L_x}\cos n\pi\frac{\varphi_j}{L_x}\sin n\pi\frac{a_j}{2L_x}\sin n\pi\frac{a_i}{2L_x}+$$
$$+\frac{8L_y}{\pi^2b_ib_jL_x}\sum_{m=1}^{\infty}\frac{W(0,m,k_i)}{m^2}\cos m\pi\frac{\psi_i}{L_y}\sin m\pi\frac{b_i}{2L_y}\cos m\pi\frac{\psi_j}{L_y}\times$$
$$\times\sin m\pi\frac{b_i}{2L_y}+\frac{64L_xL_y}{\pi^4a_ia_jb_ib_j}\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\frac{W(n,m,k_i)}{n^2m^2}\cos n\pi\frac{\varphi_i}{L_x}\cos n\pi\frac{a_i}{2L_x}\times$$
$$\times\cos n\pi\frac{\varphi_i}{L_x}\sin n\pi\frac{a_j}{2L_x}\sin m\pi\frac{\psi_i}{L_y}\sin m\pi\frac{b_i}{2L_y}\cos m\pi\frac{\psi_j}{L_y}\sin m\pi\frac{b_i}{2L_y},$$

where T_{ij} – is the average temperature of the i-th section, heated by the j-th source of heat; a_i, a_j, b_i, b_j – are dimensions of the sections; ϕ_i, ϕ_j – are the coordinates of the centers of sections on the axis x; ψ_i, ψ_j – are the coordinates of the centers of sections on the axis y; Lx, Ly – are the dimensions of the structure on the

$$Z_C=\sum_{l=1}^{N}\delta_l/\lambda_l$$

axes x and y; – is thermal resistance; δ_l, λ_l – thickness and thermal resistance of the l-th layer (l = 1, 2, 3,

$$W(n,m,k_i)=\left(G_N(1-k_i)+k_i\right)\frac{Z_N}{Z_N\alpha_N+1}$$

…N); N – is a number of the structure layers.

Variable k_i takes the value 1 in the point, located on the surface S_N, and 0 – on the surface S_N. Functions G and S_N are calculated in the consecutive order, passing the layers of the structure, starting from the first and ending with $N = m$, using the recurrent expressions:

$$Z_i=\frac{\nu\lambda_iZ_{i-1}+1+(\nu\lambda_iZ_{i-1}-1)e^{-2\nu\delta_i}}{\nu\lambda_iZ_{i-1}+1-(\nu\lambda_iZ_{i-1}-1)e^{-2\nu\delta_i}};\ G_i=\frac{G_{i-1}2\nu\lambda_iZ_{i-1}e^{-\nu\delta_i}}{\nu\lambda_iZ_{i-1}+1+(\nu\lambda_iZ_{i-1}-1)e^{-2\nu\delta_i}},$$

where i – is the number of the layer $\nu=\sqrt{n^2\pi^2/L_x^2+m^2\pi^2/L_y^2}$.

In addition to the above-mentioned equations systems of mathematical description of the temperature fields, in the thermal flow sensors it is necessary to calculate the interaction of the heated structure of the primary converter of the flow sensor. In general case the dependence between the temperature parameters of thermoanemometric primary converter and parameters of the flow can be written in the form of the equation [1-5]:

$$P_н=K_1\alpha F\Delta t,$$

where $K1$ – is the coefficient, which is introduced, as in greater part of cases it is not the difference of the temperature of the heat exchange surface and the fluid that is measured but another value Δt; α – is the coefficient of the convective heat transfer; F – is heat exchange surface; Δt – is the temperatures difference.

Main parameter of the thermal model is Nusselt criterion Nu, which characterizes the heat exchange between the surface of the heater and flow medium:

$$Nu=A\,Re^n\,Pr^b\,Gr^c\left(\frac{Pr_p}{Pr_c}\right)^d,$$

where Re – is Reynolds criterion, which characterizes the ratio of the inertia and viscosity forces and determines the character of fluid (gas); Pr – is Prandtl number, which characterizes the physical properties of the fluid (gas); Gr – is Grashof number, which characterizes the lifting force, which appears in the fluid (gas) as a result of densities difference.

Prandtl similarity criterion is a physical parameter, which characterizes the properties of the flow. Grashof number also does not contain the velocity of the flow and only characterizes the interaction of the molecular friction and lifting force, this is stipulated by the densities difference in separate points of the flow due to its non-isothermality. Only Reynolds criterion Re contains the flow velocity, we are interested in. That is why, in general case the connection between Nusselt criterion, which contains the coefficient of the convective heat transfer and Reynolds criterion, which contains flow velocity V, can be written in the form:

$$Nu = C\,Re^{n},$$

where *C* – is specific heat of the measuring environment; or:

$$\frac{\alpha d}{\lambda} = C\left(\frac{vd\rho}{\mu}\right)^{n},$$

It follows:

$$\alpha = C\frac{\lambda d^{n-1}\rho^{n}}{\mu^{n}}v^{n} = C\frac{\lambda d^{n-1}}{\mu^{n}}G_{м}^{n},$$

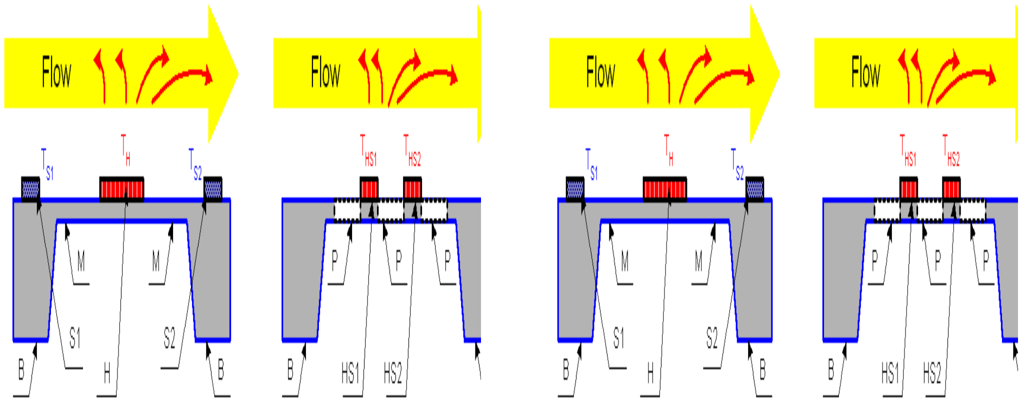
where *d* – is the diameter of the tube, where the flow velocity is measured; *v* – is the flow velocity *ρ*, *μ*, *λ* – is the density, viscosity, heat conduction of the measured medium; $G_м$ – is a mass flow rate.

It should be noted, that for practical realization, as a rule, criterion equations, obtained as a result of the experimental research, are used.

Modeling

A number of the results of the thermal calculations of two typical constructive solutions of the integral structures of the thermal flow sensors, carried out by us, are given below. The first of them (Figure 1a) - it is the crystal (B) of the silicon integrated circuit, in the centre of which on the membrane (M) one heater (H) is formed, and on the periphery - two or four sensors (S1, S2) of the difference temperature $\Delta T = T_{S2}-T_{S1}$. To minimize the heat transfer from the heater to the sensors the thermal resistance of the membrane must be as high as possible - in ideal case the heat transfer must be performed only through the medium (gas or fluid) of the measuring flow. That is why, the thickness of the membrane is minimal, typically - not more than 0.05 mm.

The sensors of the difference temperature must also have maximum heat resistance relatively the structure of the integrated circuit, that is why, they are formed with dielectric sublayer with low thermal conductivity (figure 1). Instead the thermal resistance of the integrated circuit structure on the whole must have minimal thermal resistance with the heat sink on which this circuit is mounted. It provides the fixed temperature of the structure and the lack of the temperature gradients, stipulated by the direct heat transfer across the membrane to the sensors.



a) b)

Figure 1 – Typical constructive solutions of the thermal flow sensors

The realization of the above-mentioned requirement is not a problem as the thermal conductivity coefficient λSi of the silicon (basic semiconductor of the solid-state integrated circuits) and eutectic alloy gold-silicon $\lambda_{Si\text{-}Au}$ (the layer that connects the crystal of the integrated circuit with the radiator) is rather high – λ_{Si} = 120 W/(m·K), $\lambda_{Si\text{-}Au}$ = 150 W/(m·K), correspondingly. Instead, thermal conductivity coefficient of the majority of the dielectric layers, on which temperature sensors are formad (oxide or silicon nitride) is several tens of times less that provides good thermal insulation of the temperature sensors from the crystal of the integrated circuit of the primary converter of the flow sensor.

The examples of the calculations results of the temperature field of the flow sensor structure without the available flow are shown in Figure 2a in the process of heat transfer across the flow (at various values of the normalized flow rate 1 ... 4) - in Figure 3. Temperature field has three characteristic sections: B - crystal of the integrated circuit, temperature of which is practically stable, M - peripheral part of the membrane and H - central part of the membrane, where the heater is located.

At very small flow rates (Flow 1) the temperature field remains practically unchanged and temperature difference between the sections of temperature Sensors 1 and Sensor 2 location is small. Increase of flow rate 2 and flow rate 3 leads to the transfer of heat in the direction of its motion and corresponding increase of temperature difference $\Delta T = T_{S2} - T_{S1}$. The temperature of the heater decreases, this stipulates nonlinearity of the flow sensor conversion function.

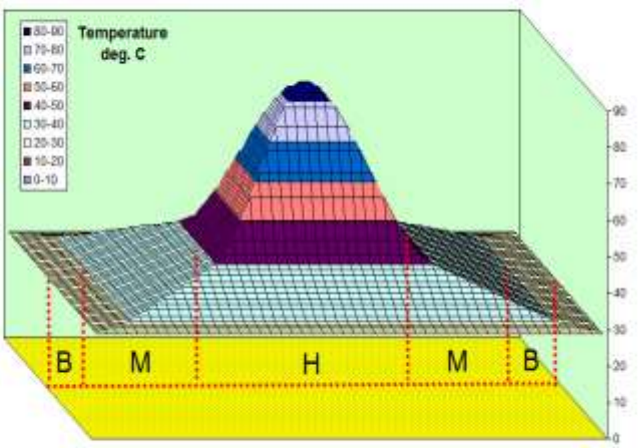


Figure 2 – Temperature field of the integrated structure (Figure 1a) without the impact of the heat transfer across the flow

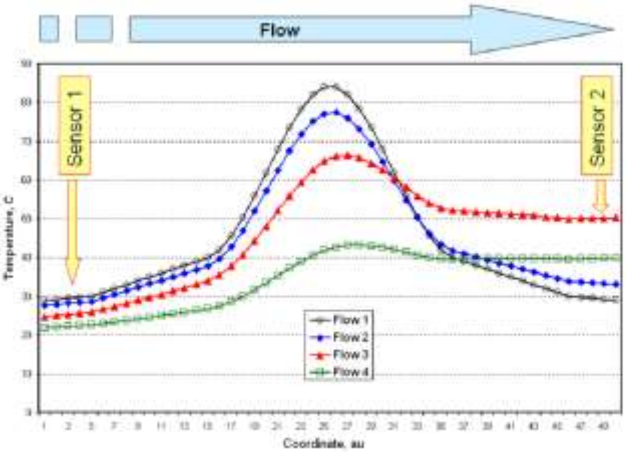


Figure 3 –Temperature field of the integrated circuit (see Figure 1a) at different flow rates (in normalized units – Flow1…4)

Further increase of the flow rate (Flow 4) leads to considerable cooling of the heater at non-sufficient heating of the flow medium, this stipulates the decrease of the structure heating in the section where temperature Sensor 2 is located and the decrease of temperature difference ΔT. Figure 4 shows typical dependence of the temperature difference ΔT on the flow rate. This dependence is the determining for the development of the structure of the primary flow sensor converter and determines the linearity of the conversion function and admissible measurement range.

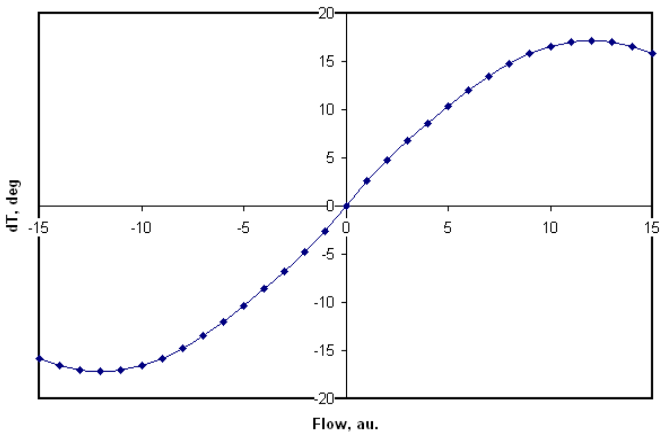


Figure 4 – Dependence of temperatures difference $\Delta T = T_{S2}–T_{S1}$ on the flow rate

Similar calculations were carried out also for the second typical construction of the primary converter of the thermal flow sensor structure (see Figure 1b), which contains two integrated elements (HS1, HS2), each of these elemends serves both as a heater and temperature sensor. In order to minimize the heat transfer these elements are made in the form of bridges, contacting with the structure of the crystal only in two points. Lateral sides of the elements are suspended, i.e., heat exchange is carried out only across the medium (P) of the flow.

Typical picture of the temperature field of such structure without the impact of the heat transfer across the flow is shown in Figure 5.

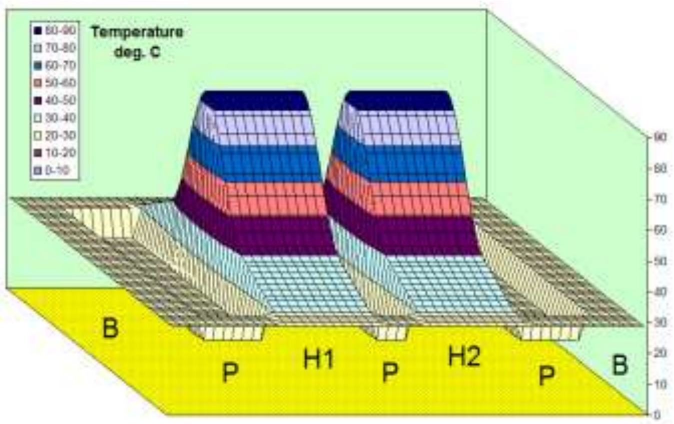


Figure 5 – Temperature field of the integral structure (see Figure 1b) without the impact of the heat transfer across the flow

The temperature of the medium between the integrated elements (HS1, HS2) we assume to be a stable value (in the Fig. it is represented by the lowered sections P). Information value of the primary converter of the flow sensor is the temperatures difference of the integrated elements $\Delta T = T_{HS2}–T_{HS1}$.

The example of the calculation of the temperature field of the structure with two integrated elements at certain flow rate is shown in Figure 6. Similarly to the above-mentioned calculations the increase of temperatures difference

$\Delta T = T_{HS2}–T_{HS1}$, is observed in case of flow rate increase, it is stipulated by the decrease of the convective heat exchange between the heaters and the flow in the direction of its propagation. In the given case it is stipulated by the increase of the medium temperature of the flow while its passage above the heaters (taking into account the large gradients of the temperatures in the flow, its temperature is not presented in the figure- it is assumed to be the fixed value T_A = 20°C). As in the previous case with one heater at certain critical rate of the flow the function of temperature difference takes the extreme value, after that the temperatures difference decreases. This limits the range of the flow rate measurement.

The analysis, carried out, confirms the data, published in literature [1-5], that the function of thermal flow sensors conversion is nonlinear and at certain value of the flow rate there comes the mode at which the gradient of the temperatures ceases to increase and starts to decrease at the increase of the flow rate.

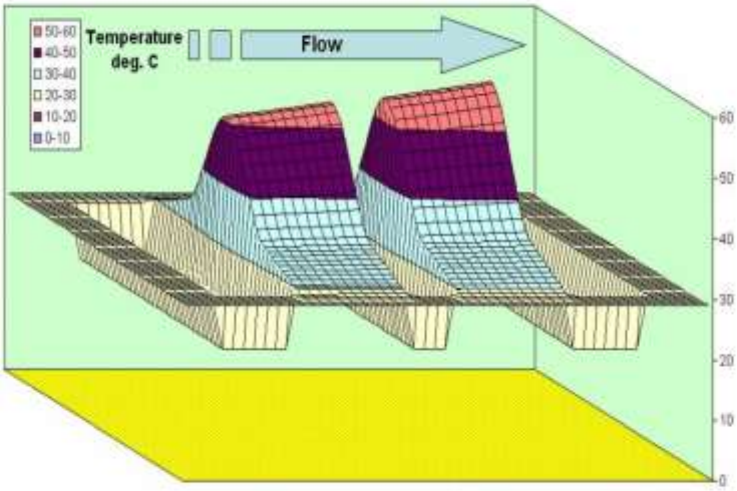


Figure 6 –Temperature field of the integrated circuit (see Figure 1b) at a certain flow rate

Conclusions

1. A complex method of electro-thermal modeling of measuring transducers of thermal flow sensors has been developed, which includes the synthesis of a substitution circuit for pulsed temperature relaxation and a method of forming I-V converters in the mode of their self-heating by the supply current.
2. Considered problems of instability of iterative processes in the analysis of I/V measuring converters with negative differential resistance due to self-heating of these converters. An express method of determining the limits in which correct electrothermal DC analysis is provided has been developed.

References

[1] Y. Fang and W. W. Liou. Computations of the Flow and Heat Transfer in Microdevices Using DSMC With Implicit Boundary Conditions // J. Heat Transfer. – 2002. – Vol. 124. – P. 338–345.

[2] W.W. Liou and Y. Fang. Implicit Boundary Conditions for Direct Simulation Monte Carlo Method in MEMS Flow Predictions // CMES. – 2000. – Vol. 1, No. 4, – P. 119–128.

[3] Y. Weiping, L. Chong, L. Jianhua, M. Lingzhi and N. Defang. Thermal distribution microfluidic sensor based on silicon // Sensors and Actuators B. – 2005. – Vol. 108. – P. 943–946.

[4] B.W. van Oudheusden. Silicon thermal flow sensors // Sensors and Actuators A: Phys. – 1992. № 30. – PP. 5–26.

[5] M. Ashauer, H. Glosch, F. Hedrich, N. Hey, H. Sandmaier, W. Lang. Thermal flow sensor for liquids and gases based on combinations of two principles // Sensors and Actuators A. – 1999. Vol. 73. – PP. 7-13.

[6] F. Jiang, Y.-C. Tai, C.-M. Ho, R. Karan, M. Garstenauer. Theoretical and experimental studies of micromachined hot-wire anemometers // International Electron Devices Meeting (IEDM), San Francisco, December 11–14. – 1994. PP. 139-142.

[7] J.J. van Baar, R.W. Wiegerink, T.S.J. Lammerink, G.J.M. Krijnen, M. Elwenspoek. Micromachined structures for the thermal measurements of fluid and flow parameters // J. Micromech. Microeng. – 2001. – № 11. – PP. 311–318.

[8] T. S. T. Lammerink, N. R. Tas, M. Elwenspoek, J. H. J. Fluitman. Micro-liquid flow sensor // Sensors and Actuators A. – 1993. – PP. 45-50.

[9] P.M. Handford, P. Bradshaw. The pulsed-wire anemometer // Exp. Fluids 7. – 1989. – PP. 125–132.

[10] Ellis Menga, Po-Ying Li, Yu-Chong Tai. A biocompatible Parylene thermal flow sensing array // Sensors and Actuators A. – 2008. № 144. –PP. 18–28.

[11] A. Margelov. Honeywell gas flow sensors [Electronic resource] / A. Margelov // Chip News. — 2005. — № 9 (102). — С.56—58. —www.chip-news.ru.

[12] Z.Yu. Gotra, R.L. Holyaka, S.V. Pavlov, S.S. Kulenko, O.V. Manus Differential thermometer with high resolution // Technology and construction in electronic equipment. - 2009. - No. 6 (84). - P. 19 - 23.3.Ю.

[13] Pavlov S. V. Information Technology in Medical Diagnostics //Waldemar Wójcik, Andrzej Smolarz, July 11, 2017 by CRC Press - 210 Pages.

[14] Wójcik W., Pavlov S., Kalimoldayev M. Information Technology in Medical Diagnostics II. London: (2019). Taylor & Francis Group, CRC Press, Balkema book. – 336 Pages.

[15] Highly linear Microelectronic Sensors Signal Converters Based on Push-Pull Amplifier Circuits / edited by Waldemar Wojcik and Sergii Pavlov, Monograph, (2022) NR 181, Lublin, Comitet Inzynierii Srodowiska PAN, 283 Pages. ISBN 978-83-63714-80-2.

[16] Pavlov Sergii, Avrunin Oleg, Hrushko Oleksandr, and etc. System of three-dimensional human face images formation for plastic and reconstructive medicine // Teaching and subjects on bio-medical engineering Approaches and experiences from the BIOART-project Peter Arras and David Luengo (Eds.), 2021, Corresponding authors, Peter Arras and David Luengo. Printed by Acco cv, Leuven (Belgium). - 22 P. ISBN: 978-94-641-4245-7.

[17] Kukharchuk, Vasyl V., Sergii V. Pavlov, Volodymyr S. Holodiuk, Valery E. Kryvonosov, Krzysztof Skorupski, Assel Mussabekova, and Gaini Karnakova. 2022. "Information Conversion in Measuring Channels with Optoelectronic Sensors" *Sensors* 22, no. 1: 271. https://doi.org/10.3390/s22010271

[18] Avrunin, O.G.; Nosova, Y.V.; Pavlov, S.V.; Shushliapina, N.O.; and etc. Research Active Posterior Rhinomanometry Tomography Method for Nasal Breathing Determining Violations. *Sensors* **2021**, *21*, 8508. doi: 10.3390/s21248508, https://www.mdpi.com/1424-8220/21/24/8508.

[19] Avrunin, O.G.; Nosova, Y.V.; Pavlov, S.V.; and etc. Possibilities of Automated Diagnostics of Odontogenic Sinusitis According to the Computer Tomography Data. Sensors 2021, 21, 1198. https://doi.org/10.3390/ s21041198.

[20] Vasyl V. Kukharchuk, Sergii V. Pavlov, Samoil Sh. Katsyv, and etc. "Transient analysis in 1st order electrical circuits in violation of commutation laws", PRZEGLĄD ELEKTROTECHNICZNY, ISSN 0033-2097, R. 97 NR 9/2021, p. 26-29, doi:10.15199/48.2021.09.05.

[21] Sensors of electric magnetic radiation for bioengineering research / G. S. Tymchyk; V. I. Skytsiuk, M. A. Waintraub, T. R. Klochko. – K. : S.E. Lesia, 2004. – 64 p.

[22] Osadchuk O. V Microelectronic frequency converters on the base of the transistor structures with negative resistance / O. V. Osadchuk. – Vinnytsia: UNIVERSUM- Vinnytsia, 2000. – 303 p.

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РОЗРОБКА МАТЕМАТИЧНОЇ МОДЕЛІ ТЕПЛОВОГО ПОЛЯ ІНТЕГРАЛЬНОЇ СТРУКТУРИ ПРИ РЕАЛІЗАЦІЇ СЕНСОРІВ ДЛЯ БІОМЕДИЧНИХ ДОСЛІДЖЕНЬ

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