# COOLING AND HEATING OF THE FLUID IN THE CYLINDRICAL VOLUME

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*Article history: Received 2 October 2021, Received in revised form 16 November 2021, Accepted 25 November 2021, Available online 28 November 2021*

## Abstract

Experimental studies of the non-stationary heat exchange in the system «environment I – body II» have been carried out. It is established that in the body II, which consists of the fluid and thin-walled metal envelope, the characteristic features of the regular thermal mode occur, i.e., cooling (heating) rate of the body II- $m = \text{const}$; heat transfer coefficient between the water (environment I) and body II is practically stable $\alpha_1 = \text{const}$; uneven temperatures distribution coefficient in the body II $\psi = \text{const}$.

This new notion of the heat transfer regularities in the body II is planned to apply for further development of the experimental-calculation method for the forecasting of the heat exchange intensity in the compound fluid media with limited information regarding thermophysical and rheological properties.

## Keywords

non-stationary heat exchange; regular thermal mode; cooling (heating) rate; heat transfer coefficient; uneven temperatures distribution coefficient.

## Introduction

For the sustainable development of the economy with minimal pollution of the environment it is expedient to construct a chain of enterprises according to the requirements (recommendations) of the UNO. Waste of the first enterprise may be used as the input materials for the second enterprise, waste of the second – input for the third, etc. It is known that the organization of the technological processes is possible only on the conditions of corresponding thermal stabilization of these processes. In general case, operating media in the reactor of the biogas units (BGU) are liquid, heterogeneous mixtures of the organic waste of different processing plants, crop farming, livestock farming, in certain cases they may represent three phrases coarsely dispersed colloid systems on the aqueous base, i.e., compound fluid mixtures (CFM). The existing testing facilities for the experimental studies of the heat exchange in the technological equipment are cumbersome, expensive

https://doi.org/10.32933/ActaInnovations.42.2 • ISSN 2300-5599 • © 2021 RIC Pro-Akademia – CC BY

and require much time for carrying out multivariate studies [1–3]. The research, dealing with the study of heat exchange intensity in liquid organic mixtures for BUR, aimed at final practical result [4–8], for instance, heat exchange intensification, are known. More profound study and understanding of heat exchange processes is not only of practical importance but it has great impact on the selection of the research process direction, search of general regularities of research, broadening knowledge regarding heat exchange liquid organic waste. Taking into consideration, mentioned above new method of the heat exchange intensity forecast is suggested [9–14], where such notions as «model», «partially-model», «virtually model», «calibrating» fluid (further in the text «auxiliary fluids») and basic experimental testing facility are used [10,11]. Below in the text this method is called «experimentally–calculation method of the compound fluid mixtures (ECM)».

In the elements of the experimental testing facility ECM the intensity of the heat exchange in the compound media of the real technological processes is determined. Calibration is carried out on the fluids with known thermal physical properties (TPP), such as water, sugar solution of different concentration, glycerin, sunflower oil, etc., further in the text – «auxiliary fluids». Criterial equations of the heat exchange regularities in the elements of the basic experimental bench are specified, using «auxiliary fluids»[10,11]. Further improvement of the methods of the results analysis in the conditions of the «auxiliary fluids» application is required.

In the studies of the non-stationary thermal mode on the conditions of the conjugate problem [15] regular thermal mode (RTM) is established and analyzed in the bodies: metal ball, placed in thermal insulation envelope; solid ball of the simplest form, placed in the thin envelope of the uniform thickness; ball, made of thermal insulation material, placed in metal; ball, cylinder, disk, made of thermal insulation material, placed in metal envelope; ball, made of metal, placed in thermal insulation material; two-part plates of the symmetric structure; two-part balls of the symmetrical structure; infinitely long two-part cylinder with the metal core and envelope, made of thermal insulation material; ball metal core, placed in thermal-insulation envelope; metal plates, coated with thermal insulation material, three-part body, made of two metals, separated by thermal insulation material. Main connections, existing between the cooling (heating) rate of the solid body m, on one hand, and physical properties of the body, its form, dimensions and cooling conditions – on the other hand, are determined [15]. This enabled to develop methods of the approximate calculation of non-stationary temperature fields, methods of modeling of non-stationary processes in complex objects, evaluate the non-uniformities of the temperature fields at different conditions. On the base of the theory of the regular mode [15–18] new methods of determination of thermophysical properties, gained wide spread occurrence: thermal conductivity coefficient, conductivity, heat capacity coefficient, heat transfer coefficient. Advantages of these methods are simple experimental procedures, high accuracy of the obtained results and short duration of the experiment.

Developed methodical support, for the processing and analysis of the experiment with compound fluid medium and “auxiliary fluids” requires a great number of the experimental results [12,13]. In the given research the method of non-stationary heat exchange process was taken for study on the basis of the following reason [17]: processes are fast flowing, they do not require much time for the preliminary holding at the pre-set temperature; measurements of thermal parameters of the fluid media occur at minor temperature changes, this improves the reliability of the results; the given method enables to carry out measurements in the conditions of the constant changes of the temperature to certain value; non-stationary methods provide wider possibilities, regarding the choice of heat (cold) source than the stationary methods.

Our preliminary experimental results [19,20] partially showed the possibility of the existence of the regular thermal mode in the system «environment I – fluid environment in thin metal cylinder enveloped (body II)». Comparison of the studied objects with literature data is presented in Table. 1. The conclusion can be made that our results are original and are referred to practically unexplored field. Authors can refer only to their studies of the regular thermal mode in the body II [19,20] which, unlike other bodies represents fluid environment in thin metal cylinder envelope.

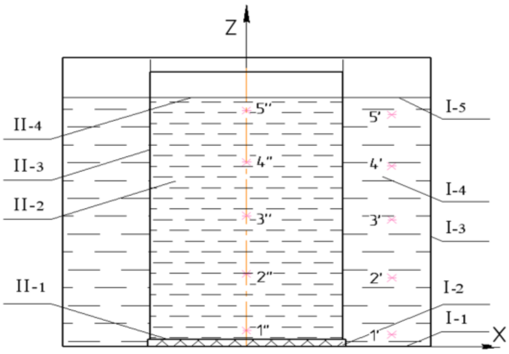
Table 1. Comparison of the objects of the study.

| **Research, performed by G. M. Kondratiev [15]** | **Research, performed by the authors** |
|---|---|
| 1. Regular thermal mode | |
| 1.1 Studied bodies | |
| Body – solid body, complex of the solid bodies.<br>System: environment (E) I – body | Body II – fluid medium in the cylindrical metal envelope.<br>System: environment (E) I – body II |
| 1.2 Conjugate problem (E – body) | |
| Newton – Richmann law – Fourier’s law | Newton – Richmann law – Fourier’s law - Newton – Richmann law |

Aim of the research: determine the possibility of existing regular thermal mode in the body II on conditions of non-stationary heat exchange in the system “environment (E) I – body II».

**Methods**

Experimental results are obtained on the test bench, which is the component of the ECM [10]. Figure 1 presents the systems “environment (E) 1 – body II». Water I-$_4$. at the temperature $T_1$ is poured into the external vessel I-$_3$. Studied substance II-$_2$ at the temperature $T_2$ is poured into the internal cylindrical vessel II-$_3$. Recording of the temperatures in the process of the experiment is performed in ten points, using thermal sensors 1 and 2.



a)

| № | X | Z |
|---|---|---|
| thermal sensor 1 | | |
| 1’ | 70 | 2 |
| 2’ | 70 | 27 |
| 3’ | 70 | 44 |
| 4’ | 70 | 64 |
| 5’ | 70 | 90 |
| thermal sensor 2 | | |
| 1’’ | 0 | 2 |
| 2’’ | 0 | 11 |
| 3’’ | 0 | 33 |
| 4’’ | 0 | 52 |
| 5’’ | 0 | 72 |

b)

Figure 1. Basic experimental bench: a) Environment I (I-$_1$, I-$_2$, I-$_3$, I-$_4$, I-$_5$); body II (II-$_1$, II-$_2$, II-$_3$, II-$_4$); b) location of the thermocouples on the sensor 1 (1’- 5’) and sensor 2 (1”-5”) relatively the axes x, z, mm

In Figure 1 the environment 1: I-$_1$ – metal bottom; I-$_2$ – thermal insulation support; I-$_3$ – external cylinder with thermal insulation surface; I-$_4$ – water; I-$_5$ – free water surface. Body II: II-$_1$ – metal bottom of the body II, 0.5 mm of the thickness; II-$_2$ studied fluid medium; II-$_3$ – thin-walled metal cylinder, diameter is 100/99 mm; II$_4$ – free surface of the studied fluid medium.

Body II consists of the following elements: thin-walled cylinder II-$_3$ of the diameter 100/99mm of the finite height which is measured from the metal bottom II-$_1$ to the free surface of the studied fluid II-$_4$; metal bottom II-$_1$ of 0.5 mm of thickness; studied fluid medium II-$_2$. Free surfaces of the studied fluid II-$_4$ and water I-$_5$ are located at the same level during the experiment.

Heat exchange of the body II with water I-$_4$, i.e., with the environment, through the lateral external surface II-$_3$, is studied. Minor flows of the heat between the surfaces II-$_4$ and I-$_5$, outflows of the heat through the metal bottom II-$_1$ are considered in the process of errors determination.

For the processing of the experimental results characteristic curves of averaged temperatures change are presented in Figure 2(a) and 2(b). Averaged temperatures are determined as the arithmetic mean by the results of temperature measurements by the thermocouples, installed at the vertical thermal sensors 1 and 2 (Figure 1) at a certain moment of time.

Heat transfer coefficients $\overline{\alpha_1}$ between the water I-$_4$ (Figure 1) and external surface of the thin-walled metal cylinder II-$_3$ (Figure 1) and uneven temperature distribution coefficients $\psi$ in the body II according to [15] on conditions of cooling (heating) of sugar solution of b=50%, sunflower oil are calculated, using the experimental data. For this purpose, the processes of cooling, heating of the body II in RTM range are shown schematically in Figure 2(a), 2(b). This range is in time $\tau_1$-$\tau_n$ ($\tau_1$ start of RTM, $\tau_n$ – end of the experimental study within the limits of RTM). In the given range of cooling (heating) the average value $\overline{\alpha_1}$, and $\overline{\psi}$ is determined, besides, $\overline{\alpha_1}$ and $\overline{\psi}$ in the limited ranges of time $\tau_{1i} - \tau_{1(n+i)}$ is determined.

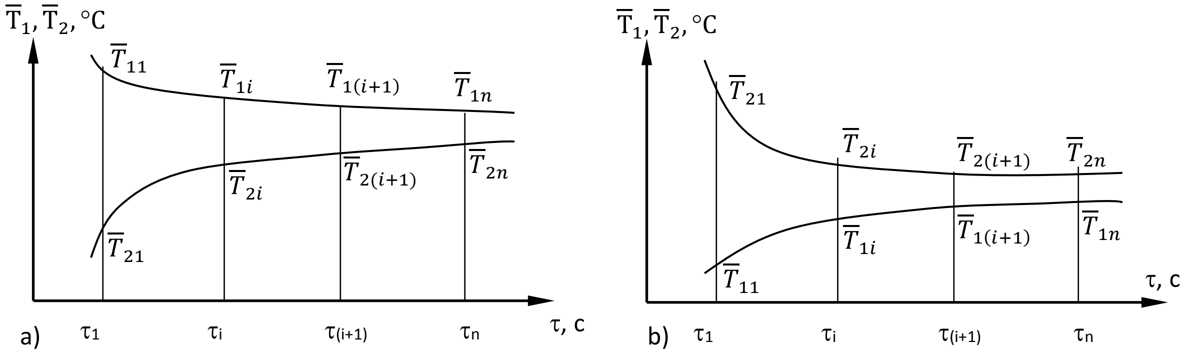


Figure 2. Processes of heating (a) and cooling (b) of the body II in RTM range for the processing of the experimental data of the studied fluid (see Table 3)

Cooling, heating of the sugar solution of the concentration c=50% and refined sunflower oil is studied experimentally. Results of the primary processing of the experimental data are presented in Figure 3.

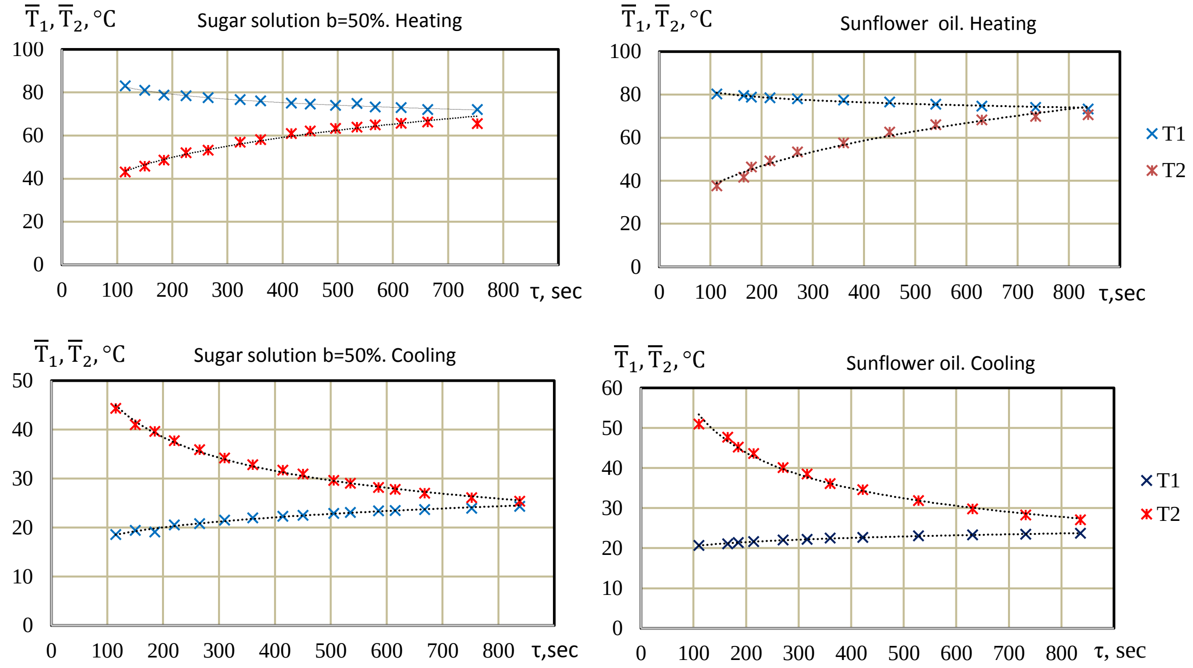


Figure 3. Change of the environment temperature and studied fluid medium in time: $\overline{T_1}$ – volume averaged temperature of the environment (water); $\overline{T_2}$ – volume averaged temperature of the body II.

Real noted range of thermal physical properties change of the studied fluid media is presented in the Table 2.

Table 2. Thermal physical properties of the studied fluid media.

| **№** | **Studied fluid** | **Heat exchange direction** | **Range of changes of temperature $\overline{T_2}$ °C** | **Coefficient of heat conductivity, $\lambda_2$, W/(m·K)** | **Coefficient of kinematic viscosity, $\nu_2$, m²/c** | **Density, $\rho_2$, kg/m³** | **Specific heat capacity, $Cp_2$, J/(kg·K)** |
|---|---|---|---|---|---|---|---|
| 1 | sugar solution b=50% | heating | 48-65 | 0.417-0.434 | $(4.8\text{-}7.4) \cdot 10^{-6}$ | 990-982 | 4174-4175 |
| 2 | sugar solution b=50% | cooling | 27-25 | 0.435-0.418 | $(9.3\text{-}5.1) \cdot 10^{-6}$ | 995-999 | 4173-4174 |
| 3 | sunflower oil | heating | 46-70 | 0.165-0.163 | $(2.82\text{-}1.37) \cdot 10^{-5}$ | 901-892 | 2304-2338 |
| 4 | sunflower oil | cooling | 41-30 | 0.166-0.167 | $(3.46\text{-}6.13) \cdot 10^{-5}$ | 901-911 | 2351-2219 |

Cooling (heating) rate m of the body II is determined from the equation, $c^{-1}$ [15]

(1) $$m = \frac{\ln \vartheta_1 - \ln \vartheta_2}{\tau_1 - \tau_2},$$

where $\vartheta_1$, $\vartheta_2$ – is excessive volume-averaged temperature of the studied fluid medium in the cylindrical vessel on the side of the water, °C

(2) $$\vartheta = \left| \overline{T}_1 - \overline{T}_2^{II} \right| .$$

Excessive temperature is modulus of difference between volume-averaged temperature $T_1$ of the water ($I_{-4}$) in the environment I and volume-averaged temperature $T_2$ of the body II:

(3) $$\overline{T}_1 = \left( T_1^{I} + T_1^{II} + T_1^{III} + T_1^{IV} + T_1^{V} \right) / 5;$$

(4) $$T_2^{II} = \overline{T}_2 \pm (0.01 \div 0.03).$$

Values 0.01-0.03 are obtained because of the calculation of the divergences between volume-averaged temperature of the studied fluid environment in the body II and volume – averaged temperature of the body II overall.
Volume-averaged temperature of the studied fluid medium in the cylinder $\overline{T}_2$:

(5) $$\overline{T}_2 = \left( T_2^{I} + T_2^{II} + T_2^{III} + T_2^{IV} + T_2^{V} \right) / 5,$$

where $T'_1 \ldots T^V_1$ – are local temperatures, measured by thermocouples, installed in the thermal sensor 1 (1'-5') on the height in the external cylinder $I_{-ex}$ (Figure 1) with water $I_{-4}$ (Figure 1); $T'_2 \ldots T^V_2$ – are local temperatures, measured by the thermocouples, installed in the thermal sensor 2 (1''-5'') in the cylinder $II_{-ex}$ (Figure 1) with the studied fluid medium $II_{-2}$ (Figure 1).
Methods of mean integral values of temperatures $\overline{\overline{T}}_1$, $\overline{\overline{T}}_2$ determination, in the time range of $\tau_{i1} - \tau_{1\,(n+i)}$ are used by means of the dependences, presented in Table 3. It is taken into consideration that the time range takes new value $\tau_{i1} - \tau_{1\,(n+i)}$.

Values $\overline{\alpha}_1$ and $\overline{\psi}$ are obtained during processing of the experimental data in the following way. Specific thermal flux from the water $I_{-4}$ to the body II is determined: $q_1 = q_2 = \frac{M_2 \cdot C_{p2} \cdot \Delta\overline{\overline{T}}_2}{F \cdot \Delta\tau}$, W/m², where $M_2$ – is the mass of the body II, kg; $C_{p2}$ – is the averaged specific heat capacity of the body II, J/(kg·K); F – is the area of the external surface of the thin metal cylinder $II_{-3}$, m²; $\Delta\tau$ - is time interval, where studies are carried out, sec; difference of mean interval temperatures $\Delta\overline{\overline{T}}_2 = \overline{\overline{T}}_{21} - \overline{\overline{T}}_{2n}$ (see Table 3).

Table 3. Methods of mean-integral values of temperatures $\overline{\overline{T_1}}, \overline{\overline{T_2}}$ determination in the time range $\tau_1 - \tau_n$.

| № | Studied fluid | Heat exchange direction | Dependence for the determination of temperatures in the environment, °C | Dependence for the determination of temperatures in the studied fluid medium, °C |
|---|---|---|---|---|
| 1 | sugar solution b=50% | heating | $\overline{\overline{T}}_1=\frac{\int_{\tau_1}^{\tau_n} 116.62\cdot x^{-0.073} d\tau}{\tau_1-\tau_n}$ | $\overline{\overline{T}}_2=\frac{\int_{\tau_1}^{\tau_n} 13.573\cdot x^{0.2456} d\tau}{\tau_1-\tau_n}$ |
| 2 | sugar solution b=50% | cooling | $\overline{\overline{T}}_1=\frac{\int_{\tau_1}^{\tau_n} 9.5206\cdot x^{0.1405} d\tau}{\tau_1-\tau_n}$ | $\overline{\overline{T}}_2=\frac{\int_{\tau_1}^{\tau_n} 173.5\cdot x^{-0.284} d\tau}{\tau_1-\tau_n}$ |
| 3 | sunflower oil | heating | $\overline{\overline{T}}_1=\frac{\int_{\tau_1}^{\tau_n} 99{,}919\cdot x^{-0.045} d\tau}{\tau_1-\tau_n}$ | $\overline{\overline{T}}_2=\frac{\int_{\tau_1}^{\tau_n} 8.4629\cdot x^{0.323} d\tau}{\tau_1-\tau_n}$ |
| 4 | sunflower oil | cooling | $\overline{\overline{T}}_1=\frac{\int_{\tau_1}^{\tau_n} 14.922\cdot x^{0.0691} d\tau}{\tau_1-\tau_n}$ | $\overline{\overline{T}}_2=\frac{\int_{\tau_1}^{\tau_n} 250.21\cdot x^{-0.329} d\tau}{\tau_1-\tau_n}$ |

Heat transfer coefficient $\overline{\alpha_1}=\frac{\overline{Nu_1}\cdot\lambda_1}{H}$ is determined on the condition of free convection, applying the iteration method for the time intervals $\tau_1 - \tau_n$ and $\tau_1 - \tau_{(i+1)}$. For the determination of $\overline{Nu}_1$ , the formula, recommended for the vertical surfaces (pipe) on the condition of the laminar mode ($10^3<(Ra_1)<10^9$) in the non-limited space [21] is used

$$\overline{Nu}_1 = 0{,}76 Ra_1^{0{,}25}\left(\frac{Pr_1}{Pr_w}\right)^{0{,}25} \tag{6}$$

where $Ra_1 = Gr_1\cdot Pr_1$ – is Rayleigh criterion; $Gr_1 = (g\cdot\beta_1\cdot\overline{\overline{\Delta T}}\cdot H^3)/\nu_1^2$ – is Grashof criterion; g – is free fall acceleration, m/s$^2$; H – is characteristic length (distance on vertical from the surface of the metal bottom II-$_1$ to the level of the studied fluid II-$_4$ in the vessel), m; $\Delta\overline{\overline{T}} = \left|\overline{\overline{T}}_1 - \overline{T}_w\right|$ – is temperature drop; $\overline{T}_w$ – is external average temperature of the wall of the thin-metal cylinder II-$_3$ , washed by the water, °C; $\beta_1$ – is coefficient of thermal expansion of water, °C$^{-1}$; $\nu_1$ – is the coefficient of kinematic viscosity of water, m$^2$/sec; $Pr_1$ – is Prandtl criterion – by mean-integral temperature of water within the limits of $\tau_1 - \tau_n$ ; $Pr_w$ – is Prandtl criterion for the water of the temperature $\overline{T}_w$ of the wall in the process of iteration; $\lambda_1$ – is coefficient of heat conductivity of water, W/(m·K).

On the base of mean-integral value of water temperature $\overline{\overline{T}}_1$ (Table 3) within the time range of $\tau_1 - \tau_n$ thermal physical properties (TPP) of water are determined, namely, coefficient of thermal expansion $\beta_1$, kinematic viscosity $\upsilon_1$ , coefficient of heat conductivity $\lambda_1$.

Verification of the set external temperature of the wall II-$_3$ in the time range of $\overline{T_w}=\overline{\overline{T}}_1-\frac{q_2}{\alpha_1}$ is performed. If the obtained temperature of the wall differs from the previously accepted by less than 3%, calculation is over and $\overline{\psi}$ is determined. Coefficient of the uneven temperature distribution in the system "E I – body II" is found from the dependence $\overline{\psi} = \vartheta_f/\vartheta_v$, where $\vartheta_v$ – is the excessive temperature of the body II relatively the temperature E I, $\vartheta_v = |\overline{\overline{T}}_1 - \overline{\overline{T}}_2|$, °C; $\vartheta_f$ – is the excessive temperature of the wall relatively the temperature $\overline{\overline{T}}_1$ , $\vartheta_f = |\overline{\overline{T}}_1 - \overline{T_w}|$.

## Results and discussion

According to Figure 4 and Table 4 dependence $\ln(\vartheta) = f(\tau)$ is of linear character, that proves the presence of regular thermal mode in the body II.

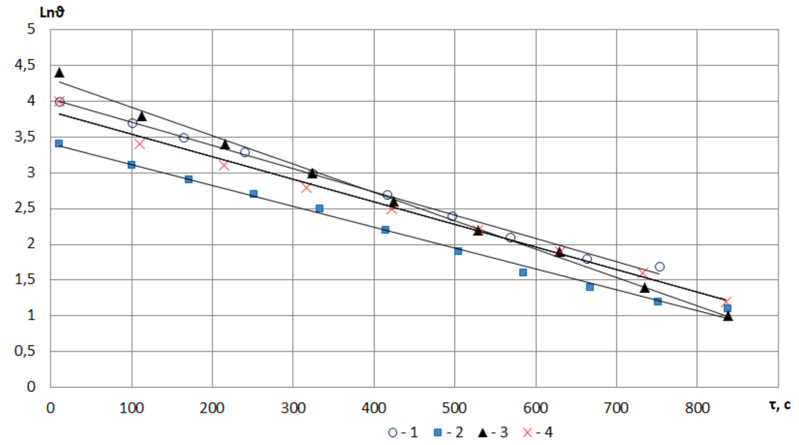


Figure 4. Distribution of the excessive temperature in time: 1 – sugar solution b=50% at heating; 2 – sugar solution b=50% at cooling; 3 – sunflower oil at heating; 4 – sunflower oil at cooling.

Table 4. Cooling (heating) rate of the studied fluid medium.

| № | Studied fluid | Direction of heat exchange | Function of the form $\ln\vartheta = m\cdot\tau + C$ | Determination factor $R^2$ |
|---|---|---|---|---|
| 1 | sugar solution b=50% | heating | $\ln\vartheta = -0.0033\cdot\tau + 4.0355$ | 0.9931 |
| 2 | sugar solution b=50% | cooling | $\ln\vartheta = -0.003\cdot\tau + 3.4342$ | 0.9964 |
| 3 | sunflower oil | heating | $\ln\vartheta = -0.0038\cdot\tau + 4.2334$ | 0.9990 |
| 4 | sunflower oil | cooling | $\ln\vartheta = -0.003\cdot\tau + 3.7605$ | 0.9989 |

Analytical substantiation of the validity of linear dependence $\mathrm{Ln}\vartheta = f(\tau)$ regularity is presented [18]. In the given case differential heat-transfer equation in solid bodies on condition of the missing internal sources of heat is the output equation.

Experimentally obtained linear regularities $\mathrm{Ln}\vartheta = f(\tau)$ for fluid environment, limited by thin-walled cylindrical envelope also can be explained, using differential thermal conductivity equation [18], if the notion of the equivalent thermal conductivity coefficient $\lambda_{eq}$ and convection coefficient $\varepsilon_c = \lambda_{eq}/\lambda$, which characterizes the impact of convection is introduced. Convection coefficient characterizes impact of convection or condition of heat transfer from heat-releasing surface to heat-receiving surface throughout the fluid. According to [21] compound process of the convective heat exchange is considered as the elementary phenomenon of thermal conductivity.

In the solid bodies on condition of the regular thermal mode due to the temperature change λ does not change greatly. In our experiment $\lambda_{eq}$ and $\varepsilon_c$ also does not change greatly, within the limits of ±6%.

Figure 5 and Tables 5 – 10 contain experimental results for the comparison of the local in time heat transfer coefficients $\bar{\alpha}_1$ and local in time coefficients of uneven temperature distribution $\bar{\psi}$ for sugar solution b=50% and sunflower oil. Processing was performed, applying the method of stationary heat exchange, when the whole-time interval was studied, taking different steps Δ and changing time interval $\Delta\tau$; in the first case $\Delta$=50 sec and $\Delta\tau$=100 sec; in the second case $\Delta$ = 90 sec and $\Delta\tau$ = 180 sec. Study of the experimental fluids is carried out in the identical temperature range.

The following designations of the local in time heat transfer coefficients are introduced:

- $\bar{\alpha}_{1(100)}$ – is local in time heat transfer coefficient between the water (I-$_4$) and external surface of thin-walled metal cylinder II-$_{ex}$ in the time range $[\tau_{i+1} - \tau_i]$ = 100 sec, W/(m$^2$·K);
- $\bar{\alpha}_{1(180)}$ – is local in time heat transfer coefficient between the water (I-$_4$) and external surface of thin-walled metal cylinder II-$_{ex}$ in the time range $[\tau_{i+1} - \tau_i]$ = 180 sec, W/(m$^2$·K).

The following designations of the local in time coefficients of uneven temperatures distribution in the body II are introduced:

- $\bar{\psi}_{(100)}$ – is local in time coefficient of uneven temperatures distribution in the body II in the time range $[\tau_{i+1} - \tau_i]$ = 100 sec;
- $\bar{\psi}_{(180)}$ – is local in time coefficient of uneven temperatures distribution in the body II in the time range $[\tau_{i+1} - \tau_i]$ = 180 sec.

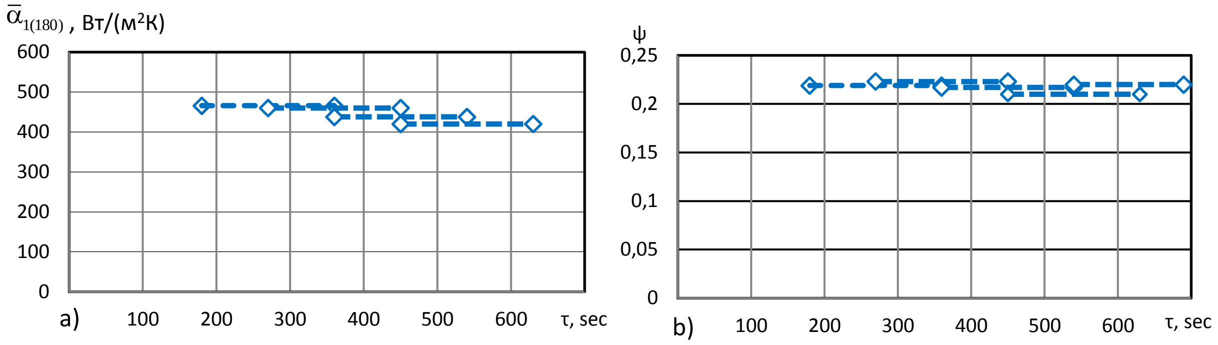


Figure 5. Heat transfer coefficients $\overline{\alpha}_{1(180)}$ between the water I-$_4$ and external surface of the thin-walled metal cylinder II-$_{ex}$ (a) and coefficients of uneven temperature distribution $\overline{\psi}_{(180)}$ in the body II in time while cooling sunflower oil.

In Tables 5 – 10 $\overline{\overline{T}}_{1TR}$ – is mean-integral temperature of water in the time range $[\tau_{i+1} - \tau_i]$ = 100 sec. or $[\tau_{i+1} - \tau_i]$ = 180 sec., °C; $\overline{\overline{T}}_{2TR}$ – is mean-integral temperature of the studied fluid medium in the time range $[\tau_{i+1} - \tau_i]$ = 100 sec. or $[\tau_{i+1} - \tau_i]$ = 180 sec, °C.

Table 5. Results of studying sugar solution b = 50% heating, $[\tau_{i+1} - \tau_i]$ = 100 sec.

| № | Time interval Δτ, sec. | $\overline{\overline{T}}_{1TR}$, °C | $\overline{\overline{T}}_{2TR}$, °C | $\overline{T}_w$, °C | m, c$^{-1}$ | q, kW/m$^2$ | $\overline{\psi}_{(100)}$ | $\overline{\alpha}_{1(100)}$, W/(m$^2$·K) |
|---|---|---|---|---|---|---|---|---|
| 1 | 200-300 | 78.2 | 52.1 | 67.4 | 0.0032 | 5.6 | 0.22 | 777 |
| 2 | 250-350 | 77 | 55 | 68 | | 4.6 | 0.23 | 741 |
| 3 | 300-400 | 76.1 | 57.1 | 69.2 | | 4.1 | 0.26 | 732 |
| 4 | 350-450 | 75.3 | 59.1 | 69.9 | | 3.7 | 0.27 | 700 |
| 5 | 400-500 | 74.7 | 60.8 | 69.8 | | 3.4 | 0.28 | 676 |
| 6 | 450-550 | 74.1 | 62.4 | 69.8 | | 3.2 | 0.29 | 645 |
| 7 | 500-600 | 73.6 | 63.9 | 70 | | 3.0 | 0.31 | 618 |

Table 6. Results of studying sugar solution b = 50% heating, $[\tau_{i+1} - \tau_i]$ = 180 sec.

| № | Time interval Δτ, sec. | $\overline{\overline{T}}_{1TR}$, °C | $\overline{\overline{T}}_{2TR}$, °C | $\overline{T}_w$, °C | m, c$^{-1}$ | q, kW/m$^2$ | $\overline{\psi}_{(180)}$ | $\overline{\alpha}_{1(180)}$, W/(m$^2$·K) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100-270 | 76.1 | 53.2 | 69.2 | 0.0032 | 4.8 | 0.26 | 804 |
| 2 | 180-360 | 75.4 | 57 | 69.9 | | 3.8 | 0.27 | 746 |
| 3 | 270-450 | 74.9 | 60 | 69.8 | | 3.1 | 0.28 | 702 |
| 4 | 360-540 | 74.4 | 62.6 | 69.8 | | 2.7 | 0.31 | 665 |
| 5 | 450-630 | 74.1 | 64.9 | 69.8 | | 2.4 | 0.34 | 638 |

Table 7. Results of studying sunflower oil heating, $[\tau_{i+1} - \tau_i]$ = 100 sec.

| № | Time interval Δτ, sec. | $\overline{\overline{T}}_{1TR}$, °C | $\overline{\overline{T}}_{2TR}$, °C | $\overline{T}_w$, °C | m, c$^{-1}$ | q, kW/m$^2$ | $\overline{\psi}_{(100)}$ | $\overline{\alpha}_{1(100)}$, W/(m$^2$·K) |
|---|---|---|---|---|---|---|---|---|
| 1 | 200-300 | 78.1 | 49.7 | 73.3 | 0.004 | 3.5 | 0.17 | 743 |
| 2 | 250-350 | 77.3 | 53.3 | 73.2 | | 3.0 | 0.17 | 704 |
| 3 | 300-400 | 76.8 | 56.1 | 73.1 | | 2.7 | 0.18 | 673 |
| 4 | 350-450 | 76.3 | 58.5 | 73 | | 2.4 | 0.19 | 664 |
| 5 | 400-500 | 75.9 | 60.8 | 72.8 | | 2.3 | 0.21 | 639 |
| 6 | 450-550 | 75.6 | 62.9 | 72.7 | | 2.1 | 0.22 | 625 |
| 7 | 500-600 | 75.2 | 64.9 | 72.5 | | 2.0 | 0.23 | 604 |
| 8 | 550-650 | 74.9 | 66.8 | 72.5 | | 1.9 | 0.23 | 579 |

Table 8. Results of studying sunflower oil heating, $[\tau_{i+1} - \tau_i] = 180$ sec.

| № | Time interval Δτ, sec. | $\overline{\overline{T}}_{1TR}$, °C | $\overline{\overline{T}}_{2TR}$, °C | $\overline{T_w}$, °C | m, $c^{-1}$ | q, kW/$m^2$ | $\overline{\psi}_{(180)}$ | $\overline{\alpha_1}_{(180)}$, W/($m^2$·K) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100-270 | 77.4 | 51.6 | 73.7 | 0.004 | 2.7 | 0.18 | 730 |
| 2 | 180-360 | 76.6 | 56 | 73.6 | | 2.2 | 0.18 | 678 |
| 3 | 270-450 | 76.1 | 59.5 | 73.6 | | 1.8 | 0.20 | 663 |
| 4 | 360-540 | 75.6 | 62.5 | 73.4 | | 1.6 | 0.22 | 625 |
| 5 | 450-630 | 75.3 | 65.1 | 73.4 | | 1.4 | 0.19 | 545 |

Table 9. Results of studying sugar solution b = 50% cooling, $[\tau_{i+1} - \tau_i] = 180$ sec.

| № | Time interval Δτ, sec. | $\overline{\overline{T}}_{1TR}$, °C | $\overline{\overline{T}}_{2TR}$, °C | $\overline{T_w}$, °C | m, $c^{-1}$ | q, kW/$m^2$ | $\overline{\psi}_{(180)}$ | $\overline{\alpha_1}_{(180)}$, W/($m^2$·K) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100-270 | 20.2 | 38.2 | 27.6 | 0.0029 | 4.5 | 0.41 | 654 |
| 2 | 180-360 | 21.1 | 34.7 | 26.4 | | 2.7 | 0.39 | 567 |
| 3 | 270-450 | 21.8 | 32.6 | 25.8 | | 2.0 | 0.37 | 508 |
| 4 | 360-540 | 22.2 | 31.1 | 25.8 | | 1.5 | 0.4 | 484 |
| 5 | 450-630 | 22.7 | 30 | 25.8 | | 1.2 | 0.42 | 453 |
| 6 | 540-720 | 23 | 29,1 | 25.7 | | 0.9 | 0.44 | 420 |

Table 10. Results of studying sunflower oil cooling, $[\tau_{i+1} - \tau_i] = 180$ sec.

| № | Time interval Δτ, sec. | $\overline{\overline{T}}_{1TR}$, °C | $\overline{T}_{2TR}$, °C | $\overline{T_w}$, °C | m, $c^{-1}$ | q, kW/$m^2$ | $\overline{\psi}_{(180)}$ | $\overline{\alpha_1}_{(180)}$, W/($m^2$·K) |
|---|---|---|---|---|---|---|---|---|
| 1 | 100-270 | 21.4 | 40.9 | 25.2 | 0.0032 | 2.5 | 0.19 | 507 |
| 2 | 180-360 | 22 | 37.2 | 25.2 | | 1.5 | 0.21 | 486 |
| 3 | 270-450 | 22.3 | 35 | 25.1 | | 1.0 | 0.22 | 466 |
| 4 | 360-540 | 22.6 | 33.4 | 25.3 | | 0.8 | 0.22 | 460 |
| 5 | 450-630 | 22.8 | 32.2 | 24.9 | | 0.6 | 0.22 | 438 |
| 6 | 540-720 | 23 | 31.2 | 24.8 | | 0.5 | 0.22 | 420 |

It was established experimentally, that the features of the RTM take place in the studied system, i.e., heating rate of the studied fluid in the cylinder vessel m=const; heat transfer coefficient is practically stable in the process of RTM $\bar{\alpha}_1$=const; coefficient of uneven temperatures distribution $\bar{\psi}$=const. Characteristic features of the RTM are presented in Table 11.

The existence of dependencies of $\psi$=const and $\alpha_1$=const for solid bodies can be expended as a result of the realization of linear dependence $Ln\vartheta=f(\tau)$, i.e., m=const [15,21]. The same substantiation of $\psi$=const and $\alpha_1$=const can be made for the volume of the fluid in thin-walled metal cylinder envelope, if it is taken into account that the compound process of heat exchange is considered as the elementary phenomenon of thermal conductivity [21].

The existence of dependencies $\psi$=const and $\alpha_1$=const for solid bodies can be expended as a result of the linear dependence $Ln\vartheta=f(\tau)$, i.e., m=const [15,21]. The same substantiation of $\psi$=const and $\alpha_1$=const can be made for the volume of the fluid in thin-walled metal cylinder envelope, if it is taken into account that the compound process of heat exchange is considered as the elementary phenomenon of thermal conductivity [21].

In the body II, components of which are fluid and metal on conditions of cooling (heating) RTM, characteristic for solid bodies, set of solid bodies, is realized.

Based on experimental studies, presented and analyzed above, for the fluid in thin-walled metal cylindrical envelope, for the whole range of the regular thermal mode of cooling (heating) it is established that $\psi$ = const, $\alpha_1$ = const, m = const.

Table 11. Characteristic features of the RTM.

| **Studies of G.M. Kondratiev [15]** | **Authors studies** |
|---|---|
| 1. Features of the regular thermal mode | |
| Body | Body II |
| 1.1. Cooling (heating) rate of the body - m | |
| m = const | m = const |
| 1.2. Heat transfer coefficient on the boundary E – body | |
| Remains stable $\alpha_1$ = const | Slightly changes $\alpha_1 \approx$ const;<br>$\frac{\overline{\alpha_1}-\alpha_{1m}}{\alpha_{1m}} \cdot 100\% = \pm 13...16\%$ - heating; $\alpha_{1m}$- arithmetic mean value<br>$\frac{\overline{\alpha_1}-\alpha_{1m}}{\alpha_{1m}} \cdot 100\% = \pm 14...25\%$ - cooling. |
| 1.3. Coefficient of non-uneven temperatures distribution in the body $\psi$ | |
| Remains stable $\psi$ = const | Slightly changes $\psi \approx$ const;<br>$\frac{\overline{\psi}-\psi_m}{\psi_m} \cdot 100\% = \pm 10...17\%$ - heating; $\psi_m$ - arithmetic mean value<br>$\frac{\overline{\psi}-\psi_m}{\psi_m} \cdot 100\% = \pm 10...18\%$- cooling. |
| 2. Temperature of the environment in the process of cooling (heating) | |
| Remains stable $\overline{T}_1$=const | Changes by 3…6°C, $\overline{T}_1 \neq$ const |

Heat transfer coefficient $\overline{\alpha_2}$ between the internal surface of the thin-walled metal cylinder II – 3 and studied by RTM method fluid environment (Figure 1) is determined by the expression

$$\overline{\alpha_2} = \left( \frac{F \cdot \overline{\Delta T}}{Q} - \frac{F \cdot \overline{\psi}}{m \cdot C_1} \right)^{-1} \tag{7}$$

where Q – is heat flux, taken by the studied fluid environment locally in time, W; $\bar{\Delta}T$ – is mean overall temperature drop, °C; F – is the area of the thin-walled metal cylinder, $m^2$ ; $C_1$ – is specific heat capacity of the environment (water), J/(kg·K); $\frac{F \cdot \overline{\psi}}{m \cdot C_1}$ – is thermal resistance of the heat exchange between the environment (water) and wall [15], $(m^2 \cdot K)/W$.

Heat transfer coefficient $\overline{\alpha_2}$ also can be determined by the known dependence

$$\overline{\alpha_2'} = \left( R_{ov} - R_1 - R_w \right)^{-1}, \tag{8}$$

where $R_{ov}$ – is thermal resistance of the heat exchange between the environment (water) and studied fluid environment, $(m^2 \cdot K)/W$; $R_1$ – is thermal resistance of environment (water) and thin metal wall, $(m^2 \cdot K)/W$; $R_w = \delta_w/\lambda_w$ – is thermal resistance of thermal conductivity across thin metal wall is 1 % of the total and in the given case is not taken into account, $(m^2 \cdot K)/W$; $\delta_w$ – is the thickness of the wall of the thin metal cylinder, m; $\lambda_w$ – is thermal conductivity of the wall of the thin metal cylinder, W/(m·K).

Heat transfer coefficient $\overline{\alpha_2''}$ can be determined applying the known criterial equation for large volume [16,17]. Difference between $\overline{\alpha_2}$ and $\overline{\alpha_2'}$ is up to 10 %. Difference between $\overline{\alpha_2}$ and $\overline{\alpha_2''}$ is up to 40 % [22]. That is why, determination of $\overline{\alpha_2}$ , applying criterial dependences for large volume does not enable to predict the intensity of heat exchange with the sufficient accuracy. Thus, the method of regular thermal mode allows to describe the regularities of heat exchange between the fluid environment and metal cylindrical wall in the vessel of limited dimensions. Thus, experimentally calculation method of the heat exchange intensity prediction in compound fluid mixtures has been improved.

## Impact

Biogas – it is a gas, obtained by means of hydrogen or methane fermentation of the biomass. Biogas units are used for obtaining biofuel of the first generation. Their advantage is the possibility of useful disposal of the organic waste of the cattle breeding, crop growing, domestic waste, sewage water, etc., with positive energy, ecological, social and economic effect [3,23,24].

Performance and material-output ratio of the biogas unit and correspondently investments in its construction greatly depend on the efficiency of thermal technological processes in the bioreactor.

To provide high efficiency of biogas technologies at modern scientific level it is necessary to coordinate thermal technological and biotechnological processes. Nowadays for the solution of this problem the study of the regularities of heat and mass exchange in the compound fluid environments used in biogas units is not sufficient nowadays [3,10,24,25].

Authors suggested experimentally-calculation method for the forecast of the intensity of heat exchange intensity in the compound fluid environments with limited information regarding thermal physical properties [9,10,14]. This method enables to determine more accurately the needed area of the surfaces of heat exchange equipment of biogas units, and this will reduce specific amount of metal per structure.

ECM provides for large amount of the experiments with the compound fluid environments and «auxiliary fluids» with known thermal physical properties and rheological behavior at the basic experimental bench [12,13]. In the given research the existence of regular thermal mode in fluid environment in the thin metal cylindrical envelope was determined experimentally. The advantage of RTM as the method of studying heat exchange intensity is the simple technique of experiments, high accuracy of the obtained results and low time consumption for carrying out the experiment. All these characteristics improve experimental-calculation method.

Therefore, the suggested methods enable to reduce metal consumption of biogas units, investments in their construction and technogenic pressure on the environment during the life cycle at the expense of more accurate determination of heat-exchange intensity in the compound fluid environments.

## Conclusions

Problem of heat exchange forecast in the compound fluid environments with limited data regarding TPP and rheological behavior in real technological processes exists in theoretical and applied aspects.

It was established experimentally, that in the studied system «environment I – fluid environment in thin metal cylinder envelope (body II) the features at regular thermal mode take place i.e., heating (cooling) rate of the studied fluid in the cylinder vessel m=const; heat transfer coefficient is practically stable $\overline{\alpha}_1$ =const; non- uniformity factor of temperatures distribution $\overline{\psi}$ =const. Studies have been carried out for c=50% sugar solution end sunflower oil.

Thus, the method of regular thermal mode allows with a reasonable degree of accuracy to describe the regularities of heat exchange between the fluid environment and metal cylindrical wall in the vessel of limited dimensions.

ECM is improved because of more profound study of heat exchange regularities by means of experimental methods, in "auxiliary fluids" with the known TPP and rheological behavior at the basic experimental bench.

The obtained scientific result is the base for further study of ECM, aimed at the forecast of heat exchange intensity in thermal technological equipment of biogas technologies.

## Conflict of interest

There are no conflicts to declare.

## Acknowledgments

This research has not been supported by any external funding.

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