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NEW ASPECTS OF SIMILARITY THEORY APPLICATION IN THERMALENGINEERING COMPUTATIONS OF BIOCONVERSION SYSTEMS

Practical experimental calculation technique intended for evaluation of heat transfer factors from solid wall to complex non stable in time organic mixture sin condition of free and forced convection at different geometric execution of heat exchange surfaces is suggested.

***Key words**: bioconversion, heat exchange in organic mixtures, forced convection, free convection, heat exchange modes, criterial equations.*

1. Problems set – up

Thermostabilization subsystems of bioconversion systems are characterized by uncertainty of initial conditions, due to variety of operation environments, changes of their thermal physical properties in time and influence of numerous factors, which cannot always be taken into account. As a rule three-phase colloid-dispersive systems are operation environments. Their basic components are solid and liquid phases, as well as gas, formed as a result of biochemical processes, taking place in operation environments in the process of storage [1]. As a result, thermal physical properties of the substrates undergo changes depending on conditions and duration of storage prior to charging into biogas installation (BGI). Uncertainty of initial conditions requires elaboration of original techniques of calculation and specific methods of mathematical models composition for thermostabilization processes in equipment of biogas installation.

We suggest in [2, 3] available experimental-calculation technique (ECT) intended for determination of convective heat transfer coefficients from solid wall to complex instable in time organic mixtures in conditions of natural convection at various geometry of heat exchange surface. The given paper is the continuation of already carried out research [2, 3], its goal is to improve ECT, that provides more profound theoretical and experimental substantiation of the method, simplification of experimental part and technique of results processing, improvement of reliability, more exact determination of the spheres of ECT application.

In order to evaluate heat exchange modes, being realized or to be realized in heat exchanging units of biogas installations, and for conditions, in which the possibilities of ECT applications are to be analyzed, the evaluation is performed and boundaries of substrates parameters, applied in biogas installations are determined: hen's excrement, substrate of pigs, cattle, their mixtures, mixtures of vegetable origin at the temperature of t_c = 15...55°C with mass concentration of dry substances b=4...14%. The following variable range of thermal physical parameters corresponds to this class of mixtures: density ρ = 910…1035 kg/m^3; dynamic viscosity μ = 0,029…2,4 Pa·s; thermal conductivity λ = 0,46…0,6 Wt/(m·K); heat-capacity C_p = 3860…4090 kJ/(kg·K). Sources of thermal physical properties (TPP) of vegetable origin mixtures, substrate mixtures of various origin are not known. Reference liquids, TPP of which can be used for mathematical models within the limits of ECT algorithms are selected: sugar solution, malt-residue, soapstock, hen's excrement, cattle substrate. Range of TPP change for this class of liquids is: ρ = 900…1380 kg/m^3; μ = 0,024…16,2 Pa·c; $\nu = 2\cdot10^{-5}\ldots1{,}18\cdot10^{-2}$ m^2/s; λ = 0,3…0,64 Wt/(m·K); C_p = 2200…4182 kj/(kg·K); temperature change – t = 20…60°C.

2. Theoretical and experimental substantiation of ECT

We assume the basic heat exchange mode to be the following: natural convection of liquid (mixture) is performed near vertical wall, mode of flow in thermal boundary layer is laminar, volume of liquid is such that free motion, occurring near other bodies, located within this volume,

does not influence the flow being considered.

Criterial equation

$$Nu = C \cdot Ra^{0,25} \cdot \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w} \right)^{0,25} \tag{1}$$

of selected basic mode is substantiated both analytically and by the methods of similarity theory [4 – 6]. In (1): C – is constant, which is selected depending on the mode of heat exchange; Nu = $(\alpha \cdot \iota^*)/\lambda$– Nusselt number; L^* – determining size, m; α – convective heat transfer factor, $Wt/(m^2 \cdot K)$; λ – thermal conductivity, Wt/(m·K); Ra = Gr·Pr –Relay criterion; Gr = $(g \cdot \beta \cdot \Delta t \cdot L^{*3})/\nu^2$ – Grashof number; β – coefficient of thermal expansion, K^{-1}; g – free fall acceleration, m/s^2; ν – kinematic viscosity of liquid, m^2/s; $(Pr_l/Pr_w)^{0,25}$ – correction for heat exchange direction; $Pr_l = \nu/a$ – Prandte number at liquid temperature; Pr_w – Prandle number at temperature of the wall; a – thermal diffusivity factor, m^2/s.

We reduce the equation (1) to the following form

$$\alpha_b = C_b \cdot CPP^b \cdot f\left(\overline{\Delta t}_b\right) \cdot f\left(H_b\right) \cdot \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w} \right)_b^{0,25}, \tag{2}$$

i. e.

$$\alpha_Б = CPP^b \left\{ \left(C \cdot g^{0,25} \right) \cdot \overline{\Delta t}_b^{0,25} \cdot H_b^{-0,25} \right\} \cdot \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}\, w} \right)_Б^{0,25}, \tag{3}$$

where CPP_b – complex of physical properties of liquid, mixture in basic heat exchange mode

$$CPP_b = \left(\frac{\lambda^{0,75} \cdot \beta^{0,25}}{\nu^{0.25}} \right) \cdot \left(C_p \cdot \rho \right)^{0,25}, \tag{4}$$

where $C_b = C \cdot g^{0,25}$; ρ – density of the mixture, kg/m^3; C_p – heat capacity of the mixture, kj/(kg·K).

If physical properties of the liquid, in which heat exchange processes are studied, are unknown, then according to ECT, we recommend to determine experimental values of the complex of physical properties

$$CPP_b = \frac{\alpha_Б}{\left\{ \left(C \cdot g^{0,25} \cdot \overline{\Delta t}_b^{0,25} \cdot H_b^{-0,25} \right) \cdot \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w} \right)_b^{0,25} \right\}}, \tag{5}$$

where $\left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w} \right)^{0,25} = f\left(t, \overline{\Delta t}\right)$, for evaluative calculations we assume $\left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w} \right)^{0,25} = f\left(\overline{\Delta t}\right)$.

Correction for heat transfer direction in substrates we determine, using thermal physical properties of reference liquids in the form of relation (Fig. 1)

$$\left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w} \right)^{0,25} = 0,76 \cdot \overline{\Delta t}^{0,152}. \tag{6}$$

Thus, the expression of CPP_b is defined more exactly, so that CPP_b corresponding to the complex of physical properties of heat exchange mode to be found, CPP_F can be determined experimentally, maintaining identical only one parameter – determining substrate temperature for basic mode and

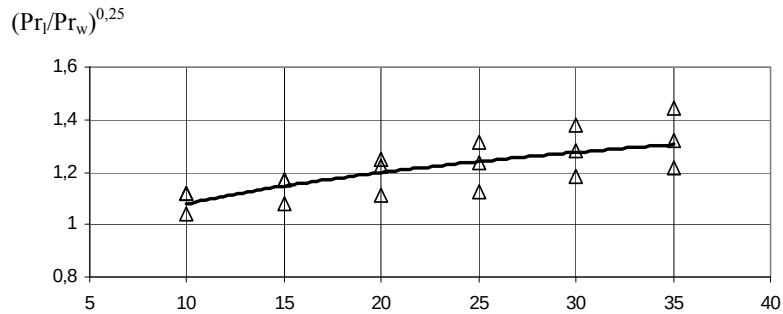

Fig. 1. Dependence of correction (Pr_l/Pr_w) on temperature head between the wall and the liquid $\overline{\Delta t}$ by physical properties of malt-residue t=20….55^{0}C, $\overline{\Delta t}$ =10,….35^{0}C

mode to be found. We suggest to take into account the direction of heat exchange on the intensity of heat exchange using the known method, but for evaluation of relation $(Pr/Pr_w)^{0,25}$ value we suggest to apply TFP of model liquids, mixtures.

Restructurization of criterial equations for modes to be found we perform as: natural convection (n. c.).

$$\alpha_{f.i}^{n.c} = C_{f.i}^{n.c} \cdot \left\{ \Pi_{f.i(b)}^{n.c.} \cdot CPP_b \right\} \cdot f_{f.i}\left(\overline{\Delta t}_{fi}\right) \cdot f_{f.i}\left(\ell_{f.i}\right) \cdot \left(\frac{\mathrm{Pr}_l}{Pr_w} \right)_{f.i}^{0,25}, \tag{7}$$

where $\overline{\Delta t}_{f.i}$, $\ell_{f.i}$ – temperature head and determining geometric size in the mode to be found correspondingly $CPP_{f.i} = P_{f.i(b)}^{n.c} \cdot CPP_b$; $P_{f..i(Б)}^{n.c} = f\left(TFP_{f.i}\right)$; TFP_F – is the set of parameters in i-th mode to be found (λ; β; ρ; ν, C_p); i = 1, 2,… – heat exchange mode in condition of natural convection (f. c.);

forced convection

$$\alpha_{f.j}^{f.c} = C_{f.j}^{f.c} \left\{ P_{f.j(b)}^{f.c.} \cdot CPP_b \right\} \cdot f_{f.j}\left(\overline{\Delta t}_{f.j}\right) \cdot f_{f.j}\left(\ell_{f.j}\right) \cdot f\left(w_{f.j}\right) \cdot \left(\frac{\mathrm{Pr}_l}{Pr_w} \right)_{f.j}^{0,25}, \tag{8}$$

where $w_{f.j}$ – flow rate in the mode to be found; $CPP_{f.j} = P_{f.j(b)}^{f.c} \cdot CPP_b$; $P_{f.j(b)}^{f.c} = f\left(TFP_{f.j}\right)$; j = 1, 2,… – heat exchange mode in conditions of forced convection.

As it follows from the above mentioned, CPP_B, obtained experimentally in basic mode of heat exchange, allows to define CFP_F in the mode to be found. Recalculation CFP_B into CFP_F for substrates and mixtures of substrates is carried out by means of introducing correction $P_{F(Б)}$ = CFP_F/CFP_B = f(TFP), which is determined as $P_{F(B)}$ = f[CFP_B]. Fig. 2 shows the example of dependence $\Pi_{F(B)}$ = f[CFP_B] construction. For this purpose model liquids with know thermal physical properties were used.

Thus, determination of CFP_F by means of CPP_b is recommended to perform by means of dependences, in which for engineering practice it is sufficient to use thermal physical properties of model liquids, mixtures.

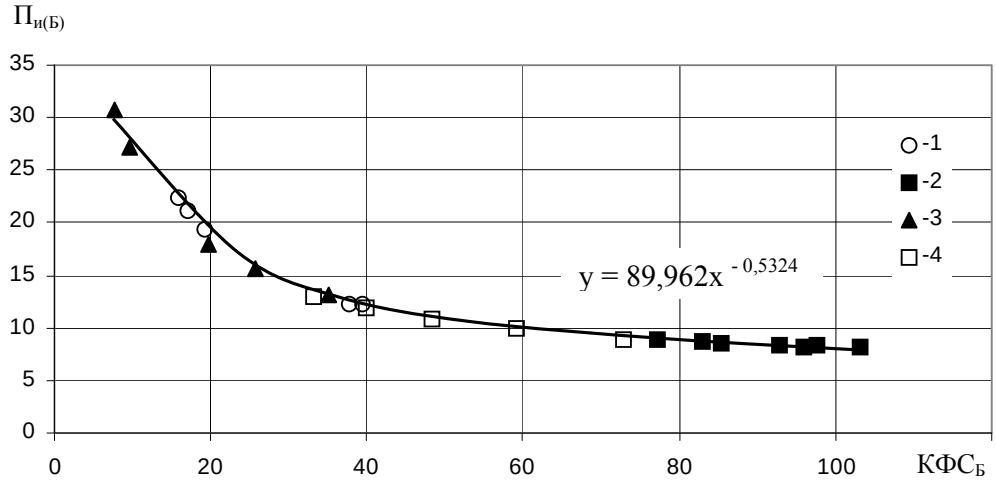

Fig.2. Dependence of correction on thermal physical properties on CPP_b for conditions of forced convection ,laminar current, viscous-gravitational mode of heat exchange:1-soapstock;2 hen excrement ;3—malt –residue; 4-sugar solution

Substrates of different nature in tubes and circular channels, in conditions, interesting for practice of heat-exchanging installations constructions move in laminar mode [Table 1]. That is why in Table 2, where the results of criterial equations restructurization are given, forced convection is presented only by laminar flow.

Table 1

Range of measurement of heat-exchange parameters and modes in conditions of forced convection

Substrate	d, m	Ranges of parameters change			Re[1]	Note
		b, %	t_c, °C	w, m/s		
hens	0,05…0,088	4 – 14	20 – 50	0,2…0,6	203…1770	laminar mode
pigs	0,05…0,088	4 – 14	20 – 55	0,2…0,6	16…1589	laminar mode
cattle	0,05…0,088	4 – 14	20 – 55	0,2…0,6	4…1547	laminar mode

[1]Re = (w·d)/ν – Reynolds number; w – liquid velocity, m/s.

ECT has two components: calculated and experimental. The substantiation of basic experimental stand which is of very simple construction, has small dimensions, possibility to realize the chosen basic mode of heat exchange within the whole range of thermodysicul properties of substrates and heat exchange mode parameters changes and which enables to provide correspondence of ECT results accuracy, as well as accuracy of single-valnedhess process formation. The stand and technique of research execution are described in [2, 3].

Fig. 3 shows main element of basic experimental stand, hypothetic characteristic distribution of the temperature in the heated water (further-water) and heated substrate is shown.

Table 2

Restructurization of criteria equations

Conditions of heat exchange	Mode of heat exchange process	Criterial equations	**Restructurized criteria equations**	$CPP_F = f\ TFP$	$P_{f(b)}^* = (CPP)_f/(CPP)_b$ / $P_{f(b)}^{**} = f[(CPP)_b]$
1	2	3	4		5
1. Free convection near vertical wall	laminated [5]	$Nu = 0{,}76 \cdot (Gr_l \cdot \mathrm{Pr}_l)^{0{,}25} \cdot \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$\alpha_f = P_{f(b)} \cdot CPP_b \times$ $\times \left[(0{,}76 \cdot g^{0{,}25}) \cdot \{\overline{\Delta t}^{0{,}25} \cdot H_b^{-0{,}25}\}\right]$ $\times \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$CPP_f = CPP_b$	$P_{f(b)} = 1$ / $P_{f(b)} = 1$
	turbulent [5]	$Nu = 0{,}15 \cdot (Gr_l \cdot \mathrm{Pr}_l)^{0{,}33} \cdot \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$\alpha_f = P_{f(b)} \cdot CPP_b \times$ $\times \left[(0{,}15 \cdot g^{0{,}33}) \cdot \{\overline{\Delta t}^{0{,}33} \cdot H^{-0{,}01}\}\right]$ $\times \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$CPP_f = \frac{\lambda_l^{0{,}67} \cdot \beta_l^{0{,}33}}{\nu_l^{0{,}33}} \cdot (C_l \cdot \rho_l)^{0{,}33}$	$P_{f((b)} = \left[\frac{(\beta_l \cdot C_l \cdot \rho_l)^{0{,}08}}{(\lambda_l \cdot \nu_l)^{0{,}08}} \cdot\right]$ / $P_{f(b)} = 1{,}705 \cdot [(CPP)_b]^{0{,}2519}$
2. Free convection near horizontal tubes	laminated [4]	$Nu = 0{,}54 \cdot (Gr_l \cdot \mathrm{Pr}_l)^{0{,}25} \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$\alpha_f = P_{f(b)} \cdot CPP_b \times$ $\times \left[(0{,}54 \cdot g^{0{,}25}) \cdot \{\overline{\Delta t}^{0{,}25} \cdot d^{-0{,}25}\}\right]$ $\times \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$CPP_f = CPP_b$	$P_{f(b)} = 1$ / $P_{f(b)} = 1$
3. Forced convection in tubes and circular channels	Laminated Viscous gravitational [6]	$Nu = 0{,}15 \cdot \mathrm{Re}^{0{,}33} \cdot \mathrm{Pr}_l^{0{,}33} \cdot (Gr_l \cdot \mathrm{Pr}_l)^{0{,}1} \cdot \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$\alpha_f = P_{f(b)} \cdot CPP_b \times$ $\times \left[(0{,}15 \cdot w^{0{,}33} \cdot d^{-0{,}37} \cdot \overline{\Delta t}^{0{,}1})\right] \times \left(\frac{\mathrm{Pr}_l}{\mathrm{Pr}_w}\right)^{0{,}25}$	$CPP_f = \frac{\lambda_l^{0{,}57} \cdot \beta_l^{0{,}1}}{\nu_l^{0{,}1}} \cdot (C_l \cdot \rho_l)^{0{,}43}$	$P_{f(b)} = \frac{\nu_l^{0{,}15} \cdot \beta_l^{-0{,}15}}{\lambda_l^{0{,}18}} \cdot (C_l \cdot \rho_l)^{0{,}18}$ / $P_{f(b)} = 89{,}962 \cdot [(CPP)_b]^{-0{,}5324}$

Note: In equations, corresponding to the conditions of heat exchange 1,2, determining temperature is the temperature of boundary layer, and determining dimension – the height of vertical wall and external diameter of the tube, correspondingly. In 3 the determining is average temperature of the liquid in the tube, determining dimension is internal diameter of the tube, equivalent diameter of circular channel.

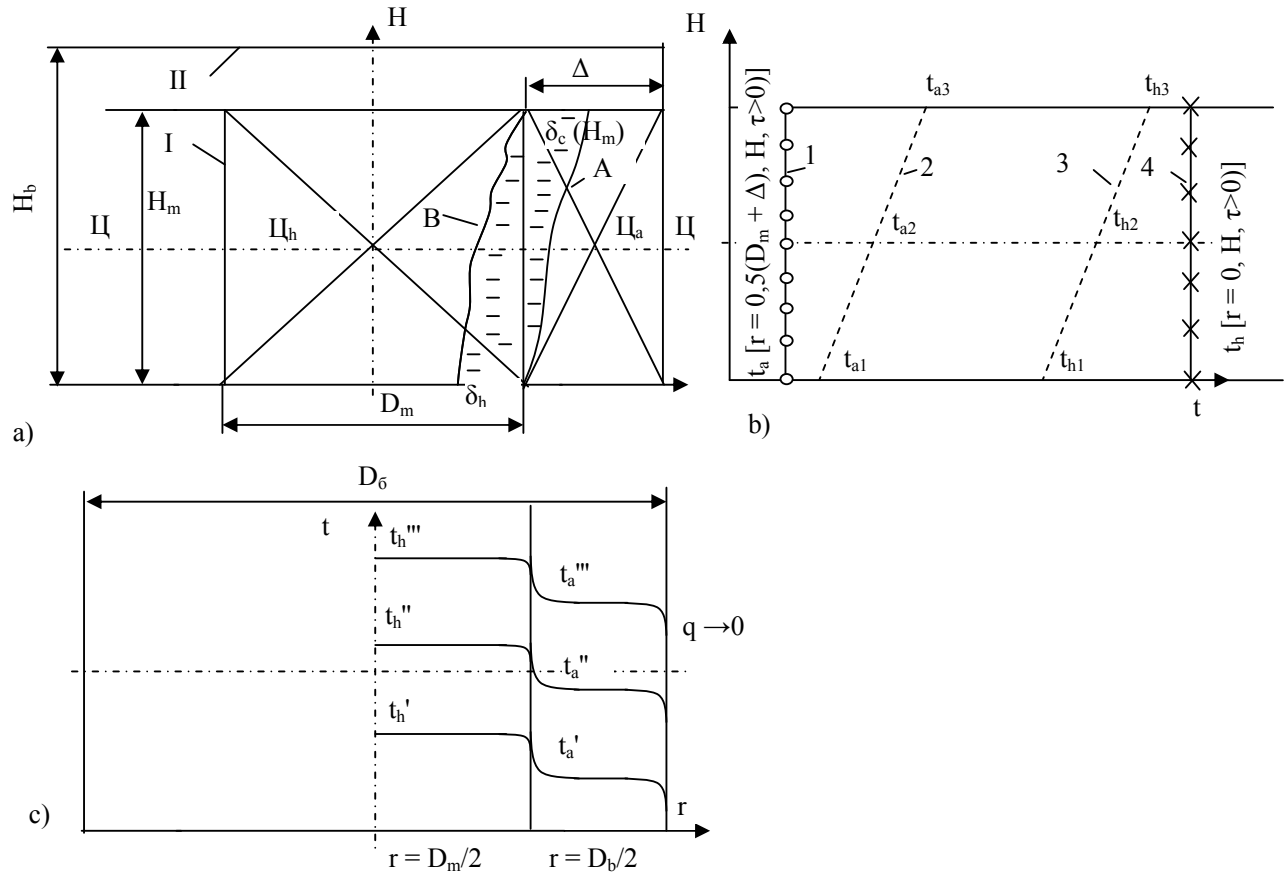

Fig. 3. Principle element of basic experimental stand with representation of hypothetic characteristic distribution of temperature

Fig 3a shows two vessels I and II. Geometrical dimensions are: vessel I – D_m = 72 mm; H_m = 88 mm; δ_w = 1 mm; II – $D_б$ = 200 mm; $H_б$ = 120 mm; Δ = 64 mm.

Temperature of heating water t_h in the vessel I was measured in $Ц_h$ (r = 0; H = H_m/2), temperature of heated substrate t_s in the vessel II – in $Ц_m$(r = 0,5·(D_m + Δ) + δ_w; H = H_m/2) (Fig. 3b). That is, according to our hypothesis, for calculation of K $\bar{t}_a \equiv t_{a2} = \frac{t_{a1}+t_{a2}+t_{a3}}{3}$, $\bar{t}_h \equiv t_{h2} = \frac{t_{h1}+t_{h2}+t_{h3}}{3}$, was assumed t_a, t_h, temperature head $\overline{\Delta t} = \bar{t}_h - \bar{t}_a$ changed in time $\bar{t}_a, \bar{t}_h, \overline{\Delta t} = f(\tau)$. Thermal flux from water to substrate also changed $Q = f(\tau)$. Thus, average during final period of time heat transfer factor from the water is determined by the dependence

$$\overline{K} = \frac{\overline{Q}}{F \cdot \frac{1}{\tau}\int_0^{\tau} \overline{\Delta t} d\tau}. \qquad (9)$$

Integration was performed by graphic method, using experimental curves. Convective heat exchange coefficients from heating wall to substrates and mixture of substrate were defined by experimentally determined K, applying known calculation methods. Fig 3a, 3c shows thermal layers from the side of water (B) and substrate (A) and temperature distribution in vessels, correspondingly. Near the external isolated wall (r = 0,5·D_m + δ_w + Δ), if thermal flow across it obtains small values q → 0, the thickness of thermal layer tends to zero $\delta_a^3 \to 0$.

Evaluation of boundary thermal layer thickness values was performed using the methods of heat

exchange stationary mode for large volume in conditions of heat exchange on cylindric surface of the vessel I (inside and outside).

Fig 3b shows: vertical straight lines 1 and 4 show invariance of the temperature of the substrate itself $r = 0{,}5\cdot(D_m + \Delta) + \delta_w$ and water $r = 0$ при $\tau = 0$ curves 2 and 3 give qualitative characteristic of temperature value of substrate ($r = 0{,}5\cdot(D_m + \Delta) + \delta_w$) and water ($r = 0$) by height $\tau > 0$ correspondingly.

Fig 3c shows water temperature change (t_h', t_h'', t_h''') and substrate (t_a', t_a'', t_a''') in horizontal planes (by radius r) at three heights ($H = 0$; $H = H_m/2$; $H = H_м$) at $\tau > 0$ from the start of the process.

Temperature in the volume of water and volume of substrate in the in the course of experiment changed in time and space [1]

$$t_h = f_1\,(x, y, z, \tau), \tag{10}$$

$$t_h = f_2\,(x, y, z, \tau). \tag{11}$$

Non – stationary conditions of heat exchange were characterized by such indices; water temperature changed in the course of experiment with the rate in time $\frac{dt_h}{d\tau} \approx 1{,}67\cdot10^{-3}\ldots0{,}17\,\frac{^0\mathrm{C}}{\mathrm{c}}$, temperature of heated water and substrate $\frac{dt_a}{d\tau} \approx 8{,}33\cdot10^{-4}\ldots0{,}083\,\frac{^0\mathrm{C}}{\mathrm{c}}$.

Evaluation of boundary thermal layer was carried out, applying known dependence [5]

$$`\delta = 4{,}23\cdot\sqrt[4]{\frac{\mu\cdot\lambda\cdot H_m}{C_p\cdot\beta\cdot\rho_0\cdot g\cdot\vartheta_c}}, \tag{12}$$

where $\vartheta_a = t_a - t_0$ - difference of temperature, °C; t_w – temperature of the wall, °C; t_0 – temperature of the liquid far from the wall, °C; β – coefficient of thermal expansion, K^{-1}; μ – dynamic viscosity of the liquid, Pa·s; ρ_0 – density of the liquid at t_0, kg/m^3.

Fig 4 presents evaluation calculated magnitudes of relative values of thermal boundary layer for water and substrate in given conditions ($H = H_m$) of experimental stand. The greatest thickness of boundary thermal layer near the wall in substrate δ_s does not exceed 0,25...0,3 annulus thickness between vessels I and II; near the wall in the water – $\delta_w/(D_m/2) \le 0{,}12\ldots0{,}15$.

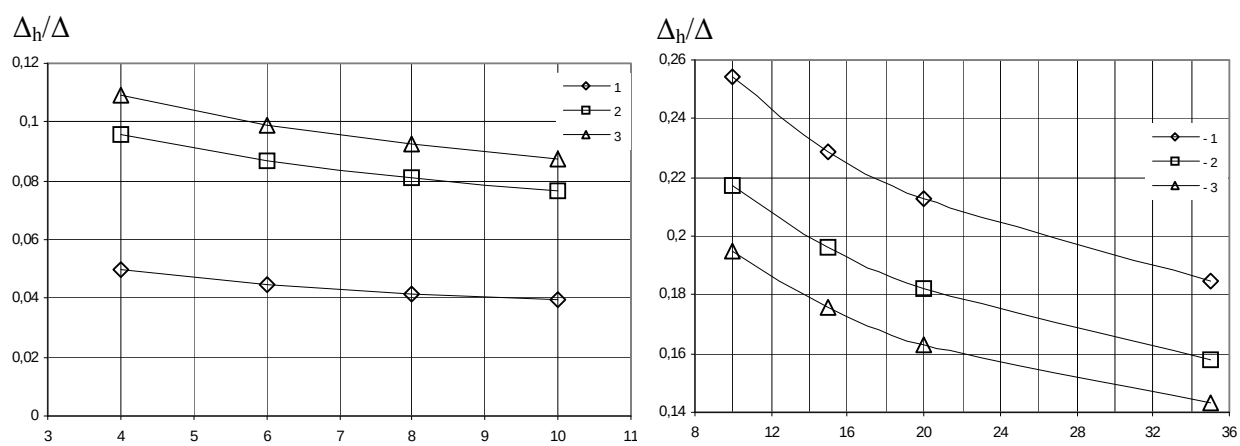

Fig. 4. Dependence of boundary thermal layer thickness virsus the width of annulus on temperature head. $\overline{\Delta t} = [t_c - t_p(t_в, t_c)]$: a) heating water : 1 – t = 90 °C; 2 – t = 45 °C; 3 – t = 25 °C;
b) cattle substrate: W = 12%: 1 – t = 20 °C; 2 – t = 30 °C; 3 – t = 40 °C

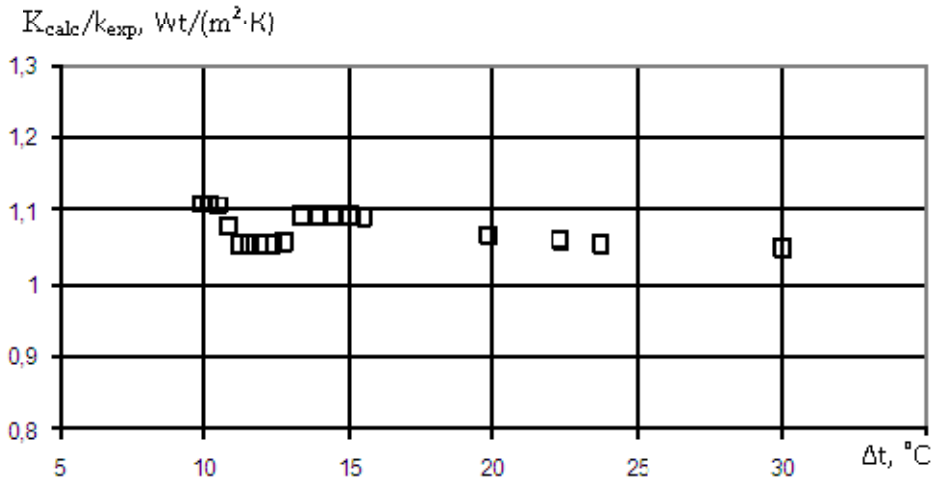

Fig. 5. Dependence of calculated and experimental coefficients relation of heat transfer to water in conditions of free convection near vertical cylindrical wall on head temperature: t = 20 – 40°C; $\overline{\Delta t}$ = 10 – 30 °C

Approximate estimation of relative values of boundary thermal layer thickness δ/Δ allows, to predict the assumption of measuring temperature of water and substrate in points $Ц_h$ and $Ц_m$ correspondingly for definition of heat transfer coefficient between water and substrate. Secondly, there exists the possibility to calculate convective heat transfer coefficients from the water to metallic wall, and from metallic wall to substrate by criteria dependencies for greater volume in conditions of natural circulation.

Analysis of possible models of heat exchange to substrates of various origin in parameters range of practical interest is performed on basic stand. The existence in conditions of free convection of laminar current in boundary thermal layer is clearly seen on basic stand, since 103 < Gr·Pr < 109 (Table 3).

Table 3

Range of parameters and heat exchange modes change in conditions of free convection

Substrate	$H_м$, м	Range of parameters change				Note
		b, %	t_c, °C	$\overline{\Delta t}$, °C	Gr·Pr	
hens	0,088	6 – 14	20 – 40	10 – 30	$1{,}4\cdot10^6\ldots6{,}6\cdot10^6$	laminar mode
pigs	0,088	6 – 14	20 – 40	14 – 30	$3{,}0\cdot10^3\ldots3{,}4\cdot10^6$	laminar mode
cattle	0,088	4 – 12	20 – 40	18 – 35	$1{,}0\cdot10^5\ldots7{,}0\cdot10^6$	laminar mode

Experiments on determination of heat transfer and convective heat coefficients correspondingly from water (in vessel 1) to water and substrates in vessel II (Fig. 5, 6) were performed at experimental stand (Fig. 3).

Fig 5 gives the comparison of experimental and calculated by known dependences values of heat transfer coefficient K on water in the vessel I to water in the vessel II. Technique of experimental results processing, suggested in [2, 3, 7] was used.

Analysis of the comparison of experimental and calculated values of heat transfer coefficients K on the, which we assume to be basic one, showed the following:

- heat transfer coefficients, obtained experimentally in non – stationary conditions of heat exchange, i. e. ECT 20% experiments have discordance within the limits of 20% with calculated values of coefficients, obtained by known criteria dependences and in similar, but quasi stationary conditions of heat exchange ;

- it is expedient to apply known criterial equations for determination and in conditions of natural convection;

- it is expedient to apply our suggested technique for determination heat exchange intensity in non – stationary thermal and hydrodynamic conditions.

Hence, the construction and dimensions of basic experimental stand is substantiated. Experimental and numerical research revealed:

- in vertical cylindrical vessel of $D_м$ = 72 mm and height $H_м$ = 88 mm convective heat exchange in conditions of free convection from water to metal wall is governed by the laws of heat exchange in large volume;

- circular channel with slot width Δ = 64 mm and height $H_м$ = 88 mm convective heat exchange from heating wall of cylindrical vessel to water and substrates of different origin is governed by the laws of convective heat exchange in large volume in conditions of natural convection;

- relative values of thermal layer thickness from one another side of the wall of internal cylindrical vessel do not exceed $\delta/\Delta < 0{,}3\ldots0{,}35$;

-according to evaluative calculations, taking into account range of changes of substracts thermophysical properties, which is of practical interests and temperature head which is of practical interest and temperature head between the wall and substrate only one mode of heat exchange is realized, in this mode, laminar current in boundary thermal layer in conditions of natural convection occurs;

- evaluative calculations of boundary thermal layer thickness, as well as measurements of temperatures field in vessels of basic experimental stand allow to suggest technique of measurements, according to which it is sufficient to measure determining temperatures only in two characteristic points: one – in heating water $Ц_h$, the second – in the mixture $Ц_m$ (Fig. 3), being heated, that is very important in experiments with rapid processes

3. Analysis of experimental research of compared with ECT.

Comparison of convective heat exchange experimental coefficients from heating wall to substrates of different origin in conditions of free and forced convection with values of coefficients, defined at the same conditions by means of ECT.

We investigated natural convection at the stand, similar to the stand in Fig 3, but geometrical parameters of heat exchange surface were different: H_m = 116 mm; $H_б$ = 120 mm; $D_м$ = 96 mm; $D_б$ = 200 mm and Δ = 52 mm. Internal vessel the volume of water $V = 3{,}6\cdot10^{-4}$ m^3 was poured at the t_h= 70°C. In external vessel $V = 3{,}5\cdot10^{-3}$ m^3 substrate of pigs, hens, cattle, mixture and pig substrates was poured at t_c = 15°C.

Technique of the experiment is described in [2, 3, 7]. Results of research are presented in Fig 6. Deviation of experimental α_{exp} and experimentally – calculated values α_{ECT} was within the limits of ±35%. It can be explained by the following: experiments in basic variant of experimental stand and non – basic one were carried out in conditions of non – stationary thermal and hydraulic processes : intake and preparation of mixtures for experimental conditions and ECT conditions was shifted in time difference of substrates humidity for these two types of experiments is evaluated $\Delta W/W$=0,0208...0,0232.

Fig 7 presents the comparison of experimental coefficients of convective heat exchange, obtained by empirical formula [8] and coefficients obtained by ECT for conditions of forced convection in annular channel.

Discrepancy of experimental coefficients of convective heat exchange and α, defined by ECT, is within the limits of ±35%. Such discrepancy can be explained by the fact that properties of substrate depend on the kind and age of the animal, nutrition, degree of substrate dilution by water and natural condition of the area [9].

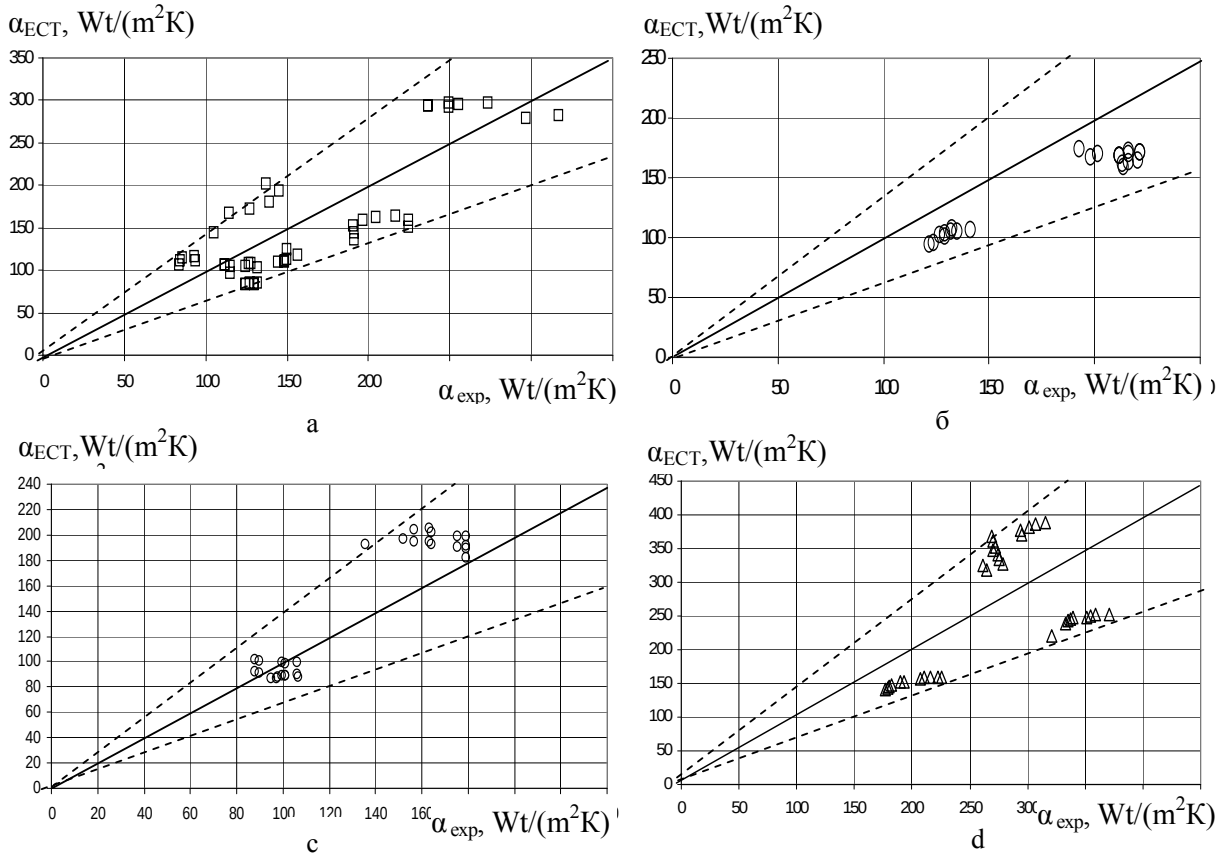

Fig.6. Comparison of experimental convective heat exchange coefficients and coefficients obtained by ECT with substrates in conditions of free convection near vertical cylindrical wall : a) pigs W = = 6, 10, 14%; t = 20…40°C; $\overline{\Delta t}_{bas}$ = 14…28°C; Δt_f = 14…30°C; b) mixture of cattle + pig substrates (1:1) W = 6, 10, 14%; t = 20…40°C; $\overline{\Delta t}_{bas}$ = 10…31°C; Δt_f = 10…31°C; c) cattle = 4, 8, 12%; t = 20…40°C; Δt_{bas} = 18…35°C; $\overline{\Delta t}_f$ = 23…29°C; d) hens W = 6, 10, 14%; t = 20…40°C; Δt_{bas} = 10…28°C; $\overline{\Delta t}_f$ = 11…28°C

Discreapency of experimental coefficients of convective heat exchange coefficients obtained ±35% (Fig. 8). We do not known themophysical properties of vegetable mixture. Visually in the course of time more intensive separation of mixture components was observed than in substrates of

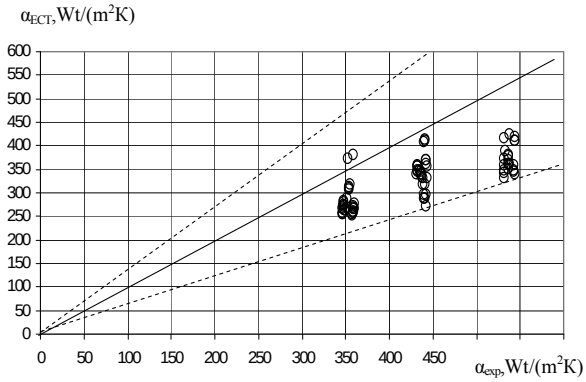

Fig.7 Comparison of experimental coefficients of convective heat exchange(data taken from the literature[8]) with coefficients,obtained applying ECM in case of laminar flow of cattle substrate in annular channel. Mode of heat exchange is viscous-gravitational. W=4,8,12 %; t=20…40 ºC; $\overline{\Delta t}_b$=10…35ºC; $\overline{\Delta t}_f$=10…35ºC

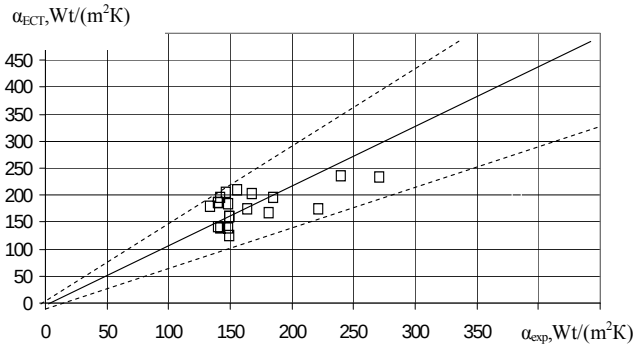

Fig.8 Comparison of experimental and obtainedby ECMcoefficients of cor heat exchange to vegetable mixture in condition of free convection near ho tube. W= 6, 14 %; t=20…40 ºC; $\overline{\Delta t}_b$=14…28ºC; $\overline{\Delta t}_f$=14…30ºC

cattle, pigs and hens.

Thus, analysis of comparison of experimental coefficients and convective heat exchange coefficients to substates, obtained by ECT: pigs, mixture, of cattle + pigs substrates, cattle, hens excrement in the range of humidity W=6...14%, temeprature t = 20…40°C – in conditions of free convection near vertical cylindrical wall; cattle – W = 4...12%, t = 20…40°C in conditions of forced laminar current in annular channel d_{eq} = 50…88 mm; vegetable mixture W = 6, 14%, t = 20…40°C. In conditions of free convection near horizontal tube d = 12mm – showed the validity, of hypothesis, assumptions, evaluations, ECT is based on.

4. Conclusions

Further substantiation of theoretical and experimental components of experimental calculation method intended for determination of heat exchange intensity between metal wall and substrate, the information regarding thermal physical properties of which is rather limited, has been performed

1. Basic mode of heat exchange is substantiated and proposed; in this mode laminar flow along vertical surface in boundary thermal layer is realized in conditions of natural convection.

2. Experimental definition of CFP_B, methods of CFP_F using modeling liquids, mixtures is simplified.

3. Construction and dimensions of basic experimental stand with limited overall dimensions, in which convective heat exchange in non – stationary thermal hydrodynamic conditions is governed by the laws of heat exchange in large volume is substantiated.

The expression CFP_B is redetermined so that CFP_B corresponding to CFP_F experimentally can be determined maintaining identical only one parameters – substrate determining temperature for basic mode and mode to be determined.

4. It is suggested to take into account the influence of heat exchange direction on heat exchange intensity by the known method, using relation (Pr_l/Pr_w), but for evaluation of the value of latter it is suggested to use TFP of model liquids, mixtures.

5. Definition of CFP_f by means of CFP_B is recommended to perform with the help dependences, in which for engineering practice it is sufficient to use thermophysical properties of model liquids, mixtures, which are determined as a result of calculated and experimental research.

6. Analysis of comparison of heat exchange experimental results in substrates of various origin (large volume, forced convection) with α values obtained by means of ECT, showed the validity of the hypothesis, assumptions, evaluations, ECT is based on, restructurization of criteria equations and operation according to ECT algorithm within the limits of one heat exchange mode does not led to the loss of valuable qualities of similarity theory, for instance, account of uniform parameters influence on heat exchange process, which is considered in conditions of simultaneous influence of other dimensional parameters on this process.

7. New aspects of similarity theory application in engineering thermal technical calculations are very promising

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