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STUDY OF THE PROCESS OF HEAT AND MASS TRANSFER IN A PYROLYSIS PLANT FOR HEATING LIVESTOCK PREMISES

Agricultural production is one of the most energy-intensive sectors of national economy. One of the unsolved problems of modern livestock breeding in Ukraine remains the creation of standardized conditions for keeping animals in livestock buildings. High concentration of livestock per unit area leads to deterioration of air composition, which is polluted with ammonia, hydrogen sulfide, carbon dioxide and dust. As a result, slaughter increases, weight gain and safety of animals decrease.

The standardized air exchange of livestock buildings is provided by the system of mechanical forced supply and exhaust ventilation. The main part of energy in animal husbandry, about 50%, is spent on maintaining the required microclimate parameters. During the heating period, which lasts 6-9 months in 80% of Ukraine, it is necessary to heat air blown into livestock buildings. For this purpose, from 60 % to 80 % of total heat energy consumed is used. At the same time, to ensure the required microclimate parameters inside the livestock house, ventilation air is removed to the atmosphere and, along with harmful substances, a significant amount of heat is removed (90% of total heat loss of buildings).

For Ukraine, which has a developed agriculture that produces a significant amount of organic waste, biomass could become a priority source of renewable energy resources. Currently, one of the directions of energy utilization of biomass is production of fuel gas obtained by its thermal decomposition. The study of a large number of pyrolysis plants of various designs cited in scientific literature allows us to conclude that many technologies cannot be sufficiently efficient due to a number of drawbacks: improvement of technological modes is not considered in functional connection with heat and mass transfer and hydrodynamic processes in pyrolysis chambers during thermal decomposition of organic raw materials; no measures are provided for prompt response to current changes in physical and mechanical properties in the feedstock flow and correction of pyrolysis process parameters in order to achieve the required optimal results, which does not allow predicting the composition of resulting gas. Therefore, research aimed at the development of technology for effective heating of livestock buildings is relevant.

Keywords: *mathematical model, microclimate, pyrolysis, heating, ventilation, air, heat and mass transfer, discharge, heat transfer, livestock building.*

Introduction. Pyrolysis of raw material is carried out by heating it to a temperature of 300-400ºC. In the process of heating and interaction of the material with air flow, intensive heat and mass transfer processes occur in layer, among which we will distinguish three main types of heat energy and mass transfer. In first case, the heat and matter transfer inside the bed should be considered. As it was noted earlier, the fluidized bed has a high volumetric heat capacity, so transfer processes are fully determined by mixing of the solid phase. In this case, the effective diffusivity (*a*) will be identical to the diffusion coefficient (*D*) [1, 2, 3, 4].

The second type of energy transfer is

transfer from air to particles. Differences of heat and mass transfer are caused by different heating rates of particles. That is, in this case it is necessary to consider problem of heat conduction of particle and temperature distribution inside the particle in time.

The third type of energy transfer is caused by the interaction of particle layer with the walls of pyrolysis chamber. In our case, the walls are isolated, so we will not consider heat exchange with the walls.

The main obstacle to heat propagation is air gaps, so the effective thermal conductivity decreases with increasing porosity characteristic of upper part of the material layer.

But because of heat transfer by moving particles λ_{ef} is practically constant. Therefore, the diffusivity (*a*) of the layer coincides with the diffusion coefficient of mixing of solid particles [3, 4].

Volumetric heat capacity of particles:

$$(1-\varepsilon)\cdot C_s\cdot\rho \approx 1300 \text{ kJ/m}^3\text{K} \qquad (1)$$

Then the effective thermal conductivity of layer:

$$\lambda = a(1-\varepsilon)\, C_s\cdot\rho \approx 860 \text{ W/mK}, \qquad (2)$$

is quite high, even compared to metals.

Analysis of the latest research and publications. In agriculture, livestock breeding is a unique branch, because the peculiarities of keeping one kind of animals can differ strikingly from another. The most energy-intensive process (up to 40% of the total energy consumption) in animal husbandry is the process of formation of the required microclimate.

Indoor microclimate is a climate of a limited space, which includes a set of environmental factors: temperature, humidity, air velocity and cooling capacity, atmospheric pressure, noise level, content of airborne dust particles, microorganisms, gas composition of air and illumination [5, 6, 7, 8].

The interaction of a set of these parameters directly affects the vital activity of organisms in the room. The main parameters of indoor microclimate affecting animal health are temperature and humidity parameters.

The microclimate of livestock housing has been considered by many researchers around the world [7, 8, 9, 10]. Interesting are the results of domestic scientists, each of whom developed a method of microclimate research, or used an already known one, but taking into account the task set by their research [11, 12, 13].

Creation and maintenance of rational temperature and humidity parameters of microclimate in livestock buildings requires solving engineering and technical problems [9, 10, 14].

Rational indicators of temperature and humidity parameters in livestock buildings contribute to a more complete realization of the genetic potential of animals, disease prevention, increasing natural resistance, as well as lengthening the service life of buildings and equipment installed in them. Provision of rational parameters of temperature and humidity in premises is achieved by observing scientifically-based values of the forming factors of the environment (temperature, humidity, air velocity, etc.), which are generalized and given for each type of animal in relevant norms of technological design of livestock enterprises [6, 7].

The aim and objectives of the research. The aim of the study is to determine the main parameters of the heat and mass transfer process in the pyrolysis chamber for stable and efficient heating of livestock premises.

Materials and methods of research. In the considered technology of heating of livestock buildings, periodic feeding of layer by cold particles with frequency $\Delta\tau$ is assumed.

$$G_l\frac{C\rho_l}{S}\frac{dT}{dR}=\lambda_{ef}\frac{d^2T}{dR^2}-\alpha(T_R-T_0), \qquad (3)$$

where G_l - flow characteristic of the layer (m^3/s); S - cross-sectional area of the apparatus; ρ_l - fluidized bed density; R - radius of the apparatus; T_0 - temperature of the layer in center (on the axis of apparatus); T_R - temperature of the layer at wall of the apparatus; α - effective heat transfer coefficient.

Boundary conditions

$$\lambda_{ef}\frac{dT}{dR}\Big|_R = G_lC\rho_l(T_0-T_R), \qquad (4)$$

$$\lambda_{ef}\frac{dT}{dR}\Big|_0 =0. \qquad (5)$$

Time of layer temperature equalization along the apparatus diameter

$$\tau_e=\frac{C\rho_lR^2}{\lambda_{ef}} \qquad (6)$$

For our case according to the given dependence τ_e≈0.5 s, comparable to the layer pulsation interval.

Solving the equation, we obtain dependence that allows us to estimate the temperature difference at material loading during its interaction with the air and the layer during the time period τ_e≈0.5 s:

$$\Delta T=T_0-T_R=\frac{(T_B-T_R)(C\rho_lG_l+\alpha RS)}{C\rho_lG_l}. \qquad (7)$$

ΔT in first 0.5 s is approximately 10ºC.

Results of the research. The air temperature in front of gas distribution grille differs significantly from the layer temperature. Consider the heating rates of layer and thus determine at what height of the layer the particle temperature will be equal to air temperature. Measurements made in industrial apparatuses of various sizes show that this height does not exceed 10 diameters of dispersed phase particles. If we assume that heat and mass transfer process can be quantitatively characterized by the specific volumetric heat transfer coefficient α_V (W/m^{3}K), then the temperature difference between air and raw particles should decrease exponentially in the direction of air movement and will tend to zero at the exit from the layer. At high thermal conductivity of particles, it is possible to consider their heating as a rather fast-flowing process. Measurement of the temperature field inside particle is practically a difficult task. Therefore, let us consider below theoretically problem of thermal conductivity of a particle. But first, let us evaluate heat transfer processes for each of phases. For this purpose, let us write down the heat transfer equation for air:

$$d\varepsilon C_A\rho_A\frac{dT_A}{d\tau}=G(1-\varepsilon)\alpha'(T_M-T_A) \quad (8)$$

for the layer

$$\alpha(1-\varepsilon)C_M\rho_M\frac{dT_M}{d\tau}=G(1-\varepsilon)\alpha'(T_A-T_M). \quad (9)$$

Let us introduce characteristic parameters of gas heating time T^*_A at T_M=const and T_M* at T_A=const:

$$\tau^*_A=\frac{\varepsilon}{1-\varepsilon}\frac{C_g\rho_g d}{G\alpha'}, \quad (10)$$

$$\tau^*_M=\frac{C_M\rho_M d}{G\alpha'}. \quad (11)$$

Interfacial heat transfer equations:

$$\begin{cases}\tau^*_A\frac{d\,T_A}{d\tau}=T_M-T_A\\ \tau^*_M\frac{d\,T_M}{d\tau}=T_G-T_A\end{cases} \quad (12)$$

Solving these equations, we obtain:

$$\tau^*_A T_{A_0}+\tau^*_M T_{M_0}=(\tau^*_A+\tau^*_M)T_f, \quad (13)$$

where T_f - the final temperature of the phases (equilibrium temperature), T_A and T_M are the initial temperatures of the phases.

The final solution of the equations is of the form:

$$\begin{cases}T_M-T_f=\frac{T_{A_0}-T_f}{e^{\frac{\tau}{\tau_0}}}\\ T_A-T_f=\frac{T_A-T_f}{e^{\frac{\tau}{\tau_0}}},\end{cases} \quad (14)$$

where τ_0 - characteristic time of heat exchange

$$\tau_0=\frac{\tau^*_A\tau^*_M}{\tau^*_A+\tau^*_M}\approx\tau^*_A \quad (15)$$

The characteristic time of heat exchange determines the layer height h_0, at which the condition $T_M = T_A$ is fulfilled

$$h_0=\frac{\varepsilon^2}{G(1-\varepsilon)}P_r 100d\ \approx 10d$$

It is theoretically proved that the layer height h_0≈10d. The time of particle heating is determined from the equations:

$$\frac{\partial T(r,\tau)}{\partial\tau}=a\left(\frac{\partial^2 T(r,\tau)}{\partial r^2}+\frac{2}{r}\cdot\frac{\partial T(r,\tau)}{\partial r}\right) \quad (16)$$

Initial condition:

$$T(r,0)=T_1 \qquad 0\le r\le R_1 \quad (17)$$

Boundary condition:

$$\lambda\frac{\partial T(R_1,\tau)}{\partial r}=\alpha(T_0-T_H)+L\cdot D\cdot\frac{\partial C(R_1,\tau)}{\partial r}=\mu(\tau) \quad (18)$$

Let us represent the solution of the problem (16)-(18) in the form:

$$T(r,\tau)=\overline{T}(r,\tau)+U(r,\tau) \quad (19)$$

We select the function so that the boundary condition (18) is satisfied, that is:

$$U(r,\tau)=\frac{r}{\lambda}\cdot\mu(\tau) \quad (20)$$

We differentiate (19) and substitute into (18), then:

$$\lambda\frac{\partial T(R_1,\tau)}{\partial r}=\lambda\left(\frac{\partial\overline{T}(R_1,\tau)}{\partial r}+\frac{1}{\lambda}\cdot\mu(\tau)\right)=$$
$$=\alpha(T_1-T_H)+L\cdot D\cdot\frac{\partial C(R_1,\tau)}{\partial r}=\lambda\frac{\partial\overline{T}(R_1,\tau)}{\partial r}+\mu(\tau) \quad (21)$$

In equation (19) - is the solution of the boundary value problem with initial condition:

$$T(r,0)=T_1=\overline{T}(r,0)+U(r,0)$$

from where:

$$\overline{T}(r,0)=T_1-U(r,0)=T_1-\frac{r}{\lambda}\mu(0) \quad (22)$$

Boundary conditions for:

$$\lambda\left(\frac{\partial\overline{T}(r,\tau)}{\partial r}+\frac{\partial U(r,\tau)}{\partial r}\right)\Bigg|_{r=R_1}=$$
$$=\alpha(T_0-T_H)+L\cdot D\cdot\frac{\partial C(R_1,\tau)}{\partial r}=\mu(\tau) \quad (23)$$

Let us substitute into (23) the expression for from (20):

$$\lambda\frac{\partial\overline{T}(R_1,\tau)}{\partial r}+\mu(\tau)=\mu(\tau)$$

$$\lambda\frac{\partial\overline{T}(R_1,\tau)}{\partial r}=0 \quad (24)$$

Equality (24) is the zero boundary condition.

Let us substitute (19) into (16), having previously differentiated the expression

$$\frac{\partial\overline{T}(r,\tau)}{\partial\tau}+\frac{\partial U}{\partial\tau}=a\left(\frac{\partial^2\overline{T}(r,\tau)}{\partial r^2}+\frac{2}{r}\cdot\frac{\partial\overline{T}(r,\tau)}{\partial r}\right)+$$
$$+a\left(\frac{\partial^2 U}{\partial r^2}+\frac{2}{r}\cdot\frac{\partial U}{\partial r}\right)$$

Let us differentiate the expression for from (20), then:

$$\frac{\partial\overline{T}(r,\tau)}{\partial\tau}-a\left(\frac{\partial^2\overline{T}(r,\tau)}{\partial r^2}+\frac{2}{r}\cdot\frac{\partial\overline{T}(r,\tau)}{\partial r}\right)=$$
$$=-\frac{r}{\lambda}\mu'(\tau)+\frac{2a}{r\lambda}\cdot\mu(\tau) \quad (25)$$

Let's assume that

$$-\frac{r}{\lambda}\mu'(\tau)+\frac{2a}{r\lambda}\cdot\mu(\tau)=\Phi(r,\tau) \quad (26)$$

The solution of the boundary value problem (24) with initial condition (22) for the differential equation (25) is represented in the form:

$$\overline{T}(r,\tau)=\overline{T_1}(r,\tau)+\overline{T_2}(r,\tau) \quad (27)$$

where $\overline{T_1}(r,\tau)$ there is a solution to the problem

$$\overline{T_1}(r,0) = T_1 - \frac{r}{\lambda}\cdot\mu(0) \qquad (28)$$

$$\lambda\frac{\partial\overline{T_1}(r,\tau)}{\partial r} = 0 \qquad (29)$$

$$\frac{\partial\overline{T_1}(r,\tau)}{\partial\tau} = a\left(\frac{\partial^2\overline{T_1}(r,\tau)}{\partial r^2} + \frac{2}{r}\cdot\frac{\partial\overline{T_1}(r,\tau)}{\partial r}\right) \qquad (30)$$

and $\overline{T_1}(r,\tau)$ there's a solution to the problem

$$\overline{T_2}(r,0) = 0 \qquad (31)$$

$$\lambda\frac{\partial\overline{T_2}(r,\tau)}{\partial r} = 0 \qquad (32)$$

$$\frac{\partial\overline{T_2}(r,\tau)}{\partial\tau} - a\left(\frac{\partial^2\overline{T_2}(r,\tau)}{\partial r^2} + \frac{2}{r}\cdot\frac{\partial\overline{T_2}(r,\tau)}{\partial r}\right) \qquad (33)$$

Let us solve the problem (28)-(30), it is necessary that the homogeneous boundary condition (29) is satisfied. The solution is represented in the form:

$$\overline{T_1}(r,\tau) = \sum_{m=1}^{\infty} T_m^{(1)}\cdot\frac{\sin\gamma_m\frac{r}{R_1}}{r}\cdot e^{-a\frac{\gamma_m^2}{R_1^2}\tau} \qquad (34)$$

where γ_m - the positive roots of the transcendental equation $tg\gamma_m = \gamma_m$.

Substituting (34) into the initial condition (28), we obtain:

$$\sum_{m=1}^{\infty} T_m^{(1)}\cdot\frac{\sin\gamma_m\frac{r}{R_1}}{r} = T_1 - \frac{r}{\lambda}\cdot\mu(0) = z(r) \qquad (35)$$

Let us decompose the right part of equality (35) into a Dini series:

$$z(r) = \sum_{m=1}^{\infty} z_m\frac{\sin\gamma_m\frac{r}{R_1}}{r} \qquad (36)$$

$$z_m = \frac{1}{\left\|\frac{\sin\gamma_m\frac{r}{R_1}}{r}\right\|^2}\int_0^{R_1} z(r)\sin\frac{\gamma_m\frac{r}{R_1}}{r}r^2dr = $$

$$= \frac{1}{\left\|\frac{\sin\gamma_m\frac{r}{R_1}}{r}\right\|^2}\int_0^{R_1} z(r)\sin\gamma_m\frac{r}{R_1}rdr \qquad (37)$$

Let's calculate the norm:

$$\left\|\frac{\sin\gamma_m\frac{r}{R_1}}{r}\right\|^2 = \int_0^{R_1}\frac{\sin^2\gamma_m\frac{r}{R_1}}{r^2}\cdot r^2dr = \int_0^{R_1}\frac{\cos 2\gamma_m\frac{r}{R_1}}{2}dr =$$

$$= \frac{1}{2}\left(r - \frac{R_1\sin 2\gamma_m\frac{r}{R_1}}{2\gamma_m}\right)\Bigg|_0^{R_1} = -\frac{1}{2}\left(-R_1 + \frac{R_1\sin 2\gamma_m}{2\gamma_m}\right) = \qquad (38)$$

$$= -\frac{1}{2}R_1(\cos^2\gamma_m - 1) = \frac{1}{2}R_1\sin^2\gamma_m$$

Then, taking into account formulas (35) and (38), expression (37) will take the form:

$$z_m = \frac{2}{R_1\sin^2\gamma_m}\int_0^{R_1}\left[T_1 - \frac{r}{\lambda}\mu(0)\right]r\cdot sim\gamma_m\cdot\frac{r}{R_1}dr \qquad (39)$$

Let $T_1 = const$, then:

$$z_m = \frac{2}{R_1\sin^2\gamma_m}\cdot\left[T_1\int_0^{R_1} r\sin\gamma_m\frac{r}{R_1}dr - \frac{\mu(0)}{\lambda}\int_0^{R_1} r^2\sin\gamma_m\frac{r}{R_1}dr\right] \qquad (40)$$

Let's calculate the integral $\int_0^{R_1} r\sin\gamma_m\frac{r}{R_1}dr$ applying the formula for integration by parts:

$$\int_0^{R_1} r\sin\gamma_m\frac{r}{R_1}dr = \left\{\begin{array}{l} u = r; dv = \sin\gamma_m\frac{r}{R_1}dr \\ du = dr; v = -\frac{R_1}{\gamma_m}\cos\gamma_m\frac{r}{R_1}\end{array}\right\} = -\frac{r\cdot R_1}{\gamma_m}\cdot\cos\gamma_m\frac{r}{R_1}\Bigg|_0^{R_1} + \int_0^{R_1}\frac{R_1}{\gamma_m}\cdot\cos\gamma_m\frac{r}{R_1}dr =$$

$$= -\frac{R_1^2}{\gamma_m}\cos\gamma_m + \frac{R_1^2}{\gamma_m^2}\sin\gamma_m\frac{r}{R_1}\Bigg|_0^{R_1} = -\frac{R_1^2}{\gamma_m}\cos\gamma_m + \frac{R_1^2}{\gamma_m^2}\sin\gamma_m = \qquad (41)$$

$$= -\frac{R_1^2}{\sin\gamma_m}\cos^2\gamma_m + \frac{R_1^2}{\sin^2\gamma_m}\cos^2\gamma_m\sin\gamma_m = \frac{R_1^2}{\sin\gamma_m}(-\cos^2\gamma_m + \cos^2\gamma_m) = 0$$

Let's calculate the integral $\int_0^{R_1} r^2 \sin\gamma_m \frac{r}{R_1}dr$ using the same method:

$$\int_0^{R_1} r^2 \sin\gamma_m \frac{r}{R_1}dr = \left\{\begin{matrix} u=r^2; dv=\sin\gamma_m\frac{r}{R_1}dr \\ du=2rdr; v=-\frac{R_1}{\gamma_m}\cos\gamma_m\frac{r}{R_1}\end{matrix}\right\} = -r^2\frac{R_1}{\gamma_m}\cos\gamma_m\frac{r}{R_1}\Big|_0^{R_1} +$$

$$+\frac{2R_1}{\gamma_m}\int_0^{R_1} r\cos\gamma_m\frac{r}{R_1}dr = -\frac{R_1^3}{\gamma_m}\cos\gamma_m + \frac{2R_1}{\gamma_m}\int_0^{R_1} r\cos\gamma_m \frac{r}{R_1}dr =$$

$$=\left\{\begin{matrix} u=r; dv=\cos\gamma_m\frac{r}{R_1}dr\\ du=dr; v=\frac{R_1}{\gamma_m}\sin\gamma_m\frac{r}{R_1}\end{matrix}\right\} = -\frac{R_1^3}{\gamma_m}\cos\gamma_m + \frac{2R_1}{\gamma_m}\times(\frac{rR_1}{\gamma_m}\sin\gamma_m\frac{r}{R_1}\Big|_0^{R_1} -$$

$$-\int_0^{R_1}\frac{R_1}{\gamma_m}\sin\gamma_m\frac{r}{R_1}dr) = -\frac{R_1^3}{\gamma_m}\cos\gamma_m + \frac{2R_1}{\gamma_m}\times(\frac{R_1^2}{\gamma_m}\sin\gamma_m + \qquad (42)$$

$$+\frac{R_1^2}{\gamma_m^2}\cos\gamma_m\frac{r}{R_1}\Big|_0^{R_1}) = -\frac{R_1^3}{\gamma_m}\cos\gamma_m + \frac{2R_1^3}{\gamma_m^2}\sin\gamma_m + \frac{2R_1^3}{\gamma_m^3}\cos\gamma_m - \frac{2R_1^3}{\gamma_m^3} =$$

$$= -\frac{R_1^3}{\sin\gamma_m}\cos^2\gamma_m + \frac{2R_1^3}{\gamma_m^2}\sin\gamma_m + \frac{2R_1^3}{\gamma_m^3}\cos\gamma_m - \frac{2R_1^3}{\gamma_m^3} =$$

$$= -\frac{R_1^3}{\sin\gamma_m}\cos^2\gamma_m + \frac{2R_1^3}{\sin^2\gamma_m}\cos^2\gamma_m\sin\gamma_m + \frac{2R_1^3}{\sin^3\gamma_m}\cos^4\gamma_m -$$

$$-\frac{2R_1^3}{\sin^3\gamma_m}\cos^3\gamma_m = \frac{R_1^3}{\sin\gamma_m}\cos^2\gamma_m + 2R_1^3\frac{1}{\gamma_m^3}(\cos\gamma_m - 1)$$

According to (35) and (36) we will have:

$$\sum_{m=1}^{\infty} T_m^{(1)} \frac{\sin\gamma_m \frac{r}{R_1}}{r} = \sum_{m=1}^{\infty} z_m \frac{\sin\gamma_m \frac{r}{R_1}}{r} \qquad (43)$$

then it can be stated that: $T_m^{(1)} = z_m$

Substitute into (34) to find (43).

Let us find $\overline{T_2}(r,\tau)$ as the solution of problem (31)-(33). Let us represent $\overline{T_2}(r,\tau)$ as:

$$\overline{T_2}(r,\tau) = \sum_{m=1}^{\infty} T_m^{(2)} \frac{\sin\gamma_m \frac{r}{R_1}}{r}\cdot e^{-a\frac{\gamma_m^2}{R_1^2}(\tau-\tau')} \qquad (44)$$

$$\overline{T_2}(r,\tau) = \int_0^{\tau}\int_0^{R_1} G(r,\rho,\tau-\tau')\Phi(\rho,\tau')\cdot\rho^2 d\rho d\tau' \qquad (45)$$

where is $G(r,\rho,\tau-\tau')$ - the Green's function of problem (31)-(33), calculated by the formula

$$G(r,\rho,\tau-\tau') = \frac{2}{R_1}\sum_{m=1}^{\infty}\frac{1}{\sin^2\gamma_m}\times\frac{\sin\gamma_m\frac{r}{R_1}\cdot\sin\gamma_m\frac{\rho}{R_1}}{r\cdot\rho}\times$$

$$\times e^{-a\frac{\gamma_m^2}{R_1^2}(\tau-\tau')} \qquad (46)$$

$$\Phi(\rho,\tau') = -\frac{\rho}{\lambda}\mu'(\tau') + \frac{2a}{\lambda\rho}\mu(\tau')$$

Features of mass transfer in the pyrolysis chamber. The features of interfacial heat transfer presented above are also true for interfacial mass transfer processes. Since active pyrolysis occurs in layer region $h_0 \approx 10d$, the pyrolysis gas concentration in upper layers does not differ practically from that in equilibrium with the dispersed phase. In layer with height $h0 \approx 10d$, the concentration of volatile components of raw mixture significantly differs from the equilibrium one. To estimate the intensity of mass transfer in the literature [6, 7] the dependence is proposed

$$\mathrm{Sh} = \beta\frac{\mathrm{d}}{\mathrm{D_{ef}}}, \tag{47}$$

where β - the heat transfer coefficient; D_{ef} - diffusion coefficient.

For this layer, the mass transfer rate constant must be calculated for specific conditions. Practically, the effective mass transfer coefficient β* is usually used. If size h_0 is estimated, i.e. the effective mass transfer coefficient is actually determined by correlation

$$\mathrm{Sh} = 0{,}025\mathrm{ReSc}^{0{,}33} \tag{48}$$

The equation of the balance of the concentration of volatile components in the particle and air is represented by the equation

$$\frac{\partial C(r,\tau)}{\partial\tau} - D\left[\frac{\partial^2 C(r,\tau)}{\partial r^2} + \frac{2}{r}\cdot\frac{\partial C(r,\tau)}{\partial r}\right] = \Phi(r,\tau) \tag{49}$$

$r\in[R_1,R_2]$ boundary conditions:

$$C(R_1,\tau) = C_n(\tau) \tag{50}$$

$$C(R_2,\tau) = \overline{C_n}(\tau) \tag{51}$$

Initial conditions

$$C(r,\tau)\big|_{\tau=0} = \psi_2(\tau) = const \tag{52}$$

The right-hand side of equation (49) represents the heat source and is a delta function:

$$\Phi(r,\tau) = 0 \tag{53}$$

We solve the problem (49)-(52) in parts using the method of superpositions. Let us represent the function $C(r,\tau)$ as a sum of unknowns; choose a solution in such a form that it satisfies the boundary conditions (50) and (51).

$$C(r,\tau) = \overline{C}(r,\tau) + \overline{U}(r,\tau) \tag{54}$$

where r - the current radius of particle.

The summand takes into account the inhomogeneity of equation (49) and initial condition (52); the summand takes into account the boundary conditions (50) and (51) for equation (49).

$$\overline{U}(r,\tau) = \frac{r-R_2}{R_1-R_2}C_n(\tau) + \frac{r-R_1}{R_2-R_1}\overline{C_n}(\tau) \tag{55}$$

Let's find $\overline{U}(r,\tau)$ at the initial moment of time:

$$\overline{U}(r,0) = \frac{r-R_2}{R_1-R_2}C_n(0) + \frac{r-R_1}{R_2-R_1}\overline{C_n}(0) \tag{56}$$

Let us find the function $\overline{C}(r,\tau)$, which will satisfy equation (56) when redefining C in $\overline{C}$:

$$\frac{\partial\overline{C}(r,\tau)}{\partial\tau} - D\left[\frac{\partial^2\overline{C}(r,\tau)}{\partial r^2} + \frac{2}{r}\cdot\frac{\partial\overline{C}(r,\tau)}{\partial r}\right] = \Phi_1(r,\tau) \tag{57}$$

and the initial condition

$$\overline{C}(r,0) = \psi_2(r) - \frac{r-R_2}{R_2-R_1}\cdot C_n(0) - \frac{r-R_1}{R_2-R_1}\cdot\overline{C_n}(0) = \overline{C}(r) \tag{58}$$

and boundary conditions

$$\begin{cases}\overline{C}(R_1,\tau) = 0\\ \overline{C}(R_2,\tau) = 0\end{cases} \tag{59}$$

The function $\overline{C}(r,\tau)$ will be:

$$\overline{C}(r,\tau) = C(r,\tau) - \overline{U}(r,\tau) \tag{60}$$

We differentiate (59) by first substituting (55) into (59):

$$\overline{C}(r,\tau) = C(r,\tau) - \frac{r-R_2}{R_1-R_2}\cdot C_n(\tau) - \frac{r-R_1}{R_2-R_1}\cdot\overline{C}_n(\tau) \tag{61}$$

by τ:

$$\frac{\partial\overline{C}(r,\tau)}{\partial\tau} = \frac{\partial C(r,\tau)}{\partial\tau} - \frac{r-R_2}{R_1-R_2}\cdot C_n'(\tau) - \frac{r-R_1}{R_2-R_1}\cdot\overline{C_n'}(\tau) \tag{62}$$

by r:

$$\frac{\partial\overline{C}(r,\tau)}{\partial r} = \frac{\partial C(r,\tau)}{\partial r} - \frac{1}{R_1-R_2}\cdot C_n'(\tau) - \frac{1}{R_2-R_1}\cdot\overline{C_n}(\tau) \tag{63}$$

$$\frac{\partial^2\overline{C}(r,\tau)}{\partial r^2} = \frac{\partial^2 C(r,\tau)}{\partial r^2} \tag{64}$$

Let us substitute (61)-(63) into (56):

$$\frac{\partial\overline{C}(r,\tau)}{\partial\tau} - D\left[\frac{\partial^2\overline{C}(r,\tau)}{\partial r^2} + \frac{2}{r}\cdot\frac{\partial\overline{C}(r,\tau)}{\partial r}\right] =$$

$$= \Phi(r,\tau) - \frac{r-R_2}{R_1-R_2}\cdot C_n'(\tau) - \frac{r-R_1}{R_2-R_1}\cdot C_n'(\tau) +$$

$$+ D\left[\frac{2}{r}\cdot\frac{1}{R_1-R_2}\left(C_n(\tau) - \overline{C_n}(\tau)\right)\right]$$

The right-hand side of (56) is of the form:

$$\Phi_1(r,\tau) = \Phi(r,\tau) + \frac{r-R_2}{R_1-R_2}\cdot\frac{\partial C_n(\tau)}{\partial\tau} +$$
$$+ \frac{r-R_1}{R_2-R_1}\cdot\frac{\partial\overline{C_n}(\tau)}{\partial\tau} - D\cdot\frac{2}{r}\cdot\frac{1}{R_1-R_2}\cdot\left[C_n(\tau) - \overline{C_n}(\tau)\right] \tag{65}$$

Let us use the superposition principle (superposition principle) to solve (64):

$$\overline{C}(r,\tau) = A(r,\tau) + B(r,\tau) \tag{66}$$

where $A(r,\tau)$ - is the solution of the boundary value problem

$$A(r,0) = \overline{C_n}(r,0) \tag{67}$$

$$A(R_1,\tau) = 0 \tag{68}$$

$$A(R_2,\tau) = 0 \tag{69}$$

for the equation:

$$\frac{\partial A(r,\tau)}{\partial\tau} - D\left[\frac{\partial^2 A(r,\tau)}{\partial r^2} + \frac{2}{r}\cdot\frac{\partial A(r,\tau)}{\partial r}\right] = 0 \tag{70}$$

where $B(r,\tau)$ - the solution of the boundary value problem

$$B(r,0)=0 \tag{71}$$

$$B(R_1,\tau)=0 \tag{72}$$

$$B(R_2,\tau)=0 \tag{73}$$

for the equation:

$$\frac{\partial B(r,\tau)}{\partial\tau}-D\left[\frac{\partial^2 B(r,\tau)}{\partial r^2}+\frac{2}{r}\cdot\frac{\partial B(r,\tau)}{\partial r}\right]=\Phi_1(r,\tau) \tag{74}$$

Let us take the solution of (68) in the form:

$$A(r,\tau)=\sum_{m=1}^{\infty}A_m\cdot\frac{\sin\frac{m\pi(r-R_1)}{R_2-R_1}}{r}\cdot e^{-D\left[\frac{m\pi}{R_2-R_1}\right]^2\tau} \tag{75}$$

$$A(r,0)=\sum_{m=1}^{\infty}A_m\cdot\frac{\frac{\sin m\pi(r-R_1)}{R_2-R_1}}{r}=\overline{C_n}(r)= \tag{76}$$

$$=\sum_{m=1}^{\infty}C_{n(m)}\frac{\frac{\sin m\pi(r-R_1)}{R_2-R_1}}{r}$$

Let's change the variable of integration:

$$C_{n(m)}=\frac{2}{R_2-R_1}\cdot\int_{R_1}^{R_2}\overline{C_n}(\rho)\cdot\frac{\frac{\sin m\pi(\rho-R_1)}{R_2-R_1}}{\rho}\cdot\rho^2 d\rho \tag{77}$$

It follows from (75) that $A_m=C_{n(m)}$, then given the initial conditions:

$$A(r,\tau)=\sum_{m=1}^{\infty}C_{n(m)}\cdot\frac{\frac{\sin m\pi(r-R_1)}{R_2-R_1}}{r}\cdot e^{-D\left[\frac{m\pi}{R_2-R_1}\right]^2\tau}=$$

$$=\int_{R_1}^{R_2}\left[\frac{2}{R_2-R_1}\cdot\sum_{m=1}^{\infty}\frac{\sin\frac{m\pi(\rho-R_1)}{R_2-R_1}}{\rho}\cdot\frac{\frac{\sin m\pi(r-R_1)}{R_2-R_1}}{r}\cdot\overline{C_n}(\rho)\right]\cdot\rho^2 d\rho \tag{78}$$

Let us take the solution (72) in the form:

$$B(r,\tau)=\sum_{m=1}^{\infty}B_m\frac{\sin\frac{m\pi(r-R_1)}{R_2-R_1}}{r}\cdot e^{-\frac{m^2\pi^2 D\tau}{(R_2-R_1)^2}} \tag{79}$$

We will consider the right-hand side of equation (72) as:

$$\Phi_1(r,\tau)=N(r)\cdot P(\tau) \tag{80}$$

Let's do $N(r)$ a Dini series:

$$N_r=\sum_{m=1}^{\infty}N_m\frac{\sin\frac{m\pi(r-R_1)}{R_2-R_1}}{r} \tag{81}$$

where N_m - Fourier coefficient:

$$N_m=\frac{2}{R_2-R_1}\int_{R_1}^{R_2}N(\rho)\frac{\sin\frac{m\pi(\rho-R_1)}{R_2-R_1}}{\rho}\cdot\rho^2 d\rho \tag{82}$$

Substituting (77) into (72) and differentiating, we obtain:

$$\sum_{m=1}^{\infty}B_m\left[-D\left(\frac{m\pi}{R_2-R_1}\right)^2-D\left(-\frac{m\pi}{R_2-R_1}\right)^2\right]\sin\frac{m\pi}{R_2-R_1}(r-R_1)\cdot e^{-D\frac{m\pi}{(R_2-R_1)^2}\tau}=\sum_{m=1}^{\infty}N_m\cdot\sin\frac{m\pi(r-R_1)}{R_2-R_1}\cdot P(\tau) \tag{83}$$

From the condition of generalized functions $B_m=N_m$

From (81) taking into account (72):

$$\frac{\partial B}{\partial\tau}+D\left(\frac{m\pi}{R_2-R_1}\right)^2 B=P(\tau) \tag{84}$$

$$B(r,\tau)=\overline{B}(r)\cdot\overline{\overline{B}}(\tau) \tag{85}$$

$$\overline{\overline{B}}(\tau)=e^{-\left(\frac{m\pi}{R_2-R_1}\right)D\tau} \tag{86}$$

$$B(r,\tau)=\sum_{m=1}^{\infty}N_m\frac{\sin\frac{m\pi}{R_2-R_1}(r-R_1)}{r}\cdot\int_0^{\tau}e^{-D\left(\frac{m\pi}{R_2-R_1}\right)^2(\tau-t)}P(t)dt=$$

$$=\int_0^{\tau}\frac{2}{R_2-R_1}\int_{R_1}^{R_2}\sum_{m=1}^{\infty}\frac{\sin\frac{m\pi}{R_2-R_1}(\rho-R_1)}{\rho}\cdot\frac{\sin\frac{m\pi}{R_2-R_1}(r-R_1)}{r}\times$$

$$\times e^{-D\left(\frac{m\pi}{R_2-R_1}\right)^2(\tau-t)}\cdot\Phi_1(\rho,t)\cdot\rho^2 d\rho= \tag{87}$$

$$=\int_0^{\tau}dt\int_{R_1}^{R_2}\frac{2}{R_2-R_1}\cdot\sum_{m=1}^{\infty}\frac{\sin\frac{m\pi}{R_2-R_1}(\rho-R_1)}{\rho}\cdot\frac{\sin\frac{m\pi}{R_2-R_1}(r-R_1)}{r}\times$$

$$\times e^{-D\left(\frac{m\pi}{R_2-R_1}\right)^2(\tau-t)}\Phi_1(\rho,t)\cdot\rho^2 d\rho.$$

The resulting equations were solved in Mathcad 2001 (Fig. 1).

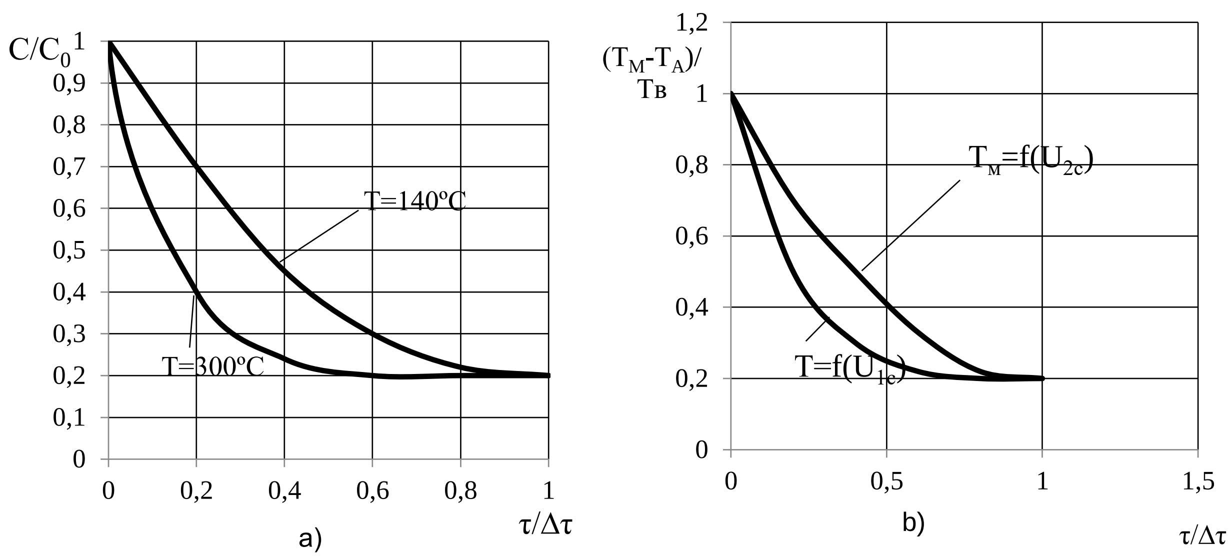

Fig. 1 Heat and mass transfer characteristics of the particle: a) dependence of relative concentration of volatile components on heat treatment time; b) temperature change in time.

Assuming that concentration distribution in layer by analogy with the temperature distribution has an exponential law:

$$C - C_H = \frac{C_M - C_H}{e^{H/h_0}} \quad (88)$$

where $h_0 = U/\beta^* S_{H_0}$, we obtain the equation for calculating the effective mass transfer coefficient:

$$\frac{\beta^*}{\beta} = \frac{U\left(U^2 - 4\beta S_H\right)^{0,5} - U^2}{\beta S_{H_0} D_{ef}} \quad (89)$$

Passing to the layer as a whole for the stationary regime we write:

$$D_{ef}\frac{d^2C}{dH} - U\big|_{U\in\{U_{1c};U_{2c}\}}\frac{dC}{dH} = \beta^* S_{H_0}(C - C_H), \quad (90)$$

where S_{H_0} - the mass transfer area; C_H - the saturation concentration.

Conclusions.

1. Effective reduction of energy costs in systems of providing heating of livestock buildings can be achieved by using pyrolysis plants.

2. In the pyrolysis unit, two types of unsteadiness of the temperature and concentration fields are identified, which are related to the feeding of the bed with cold feed particles. Due to the fact that inside the layer there is intensive circulation mixing of material, all thermophysical characteristics across the cross-section of the layer are equalized. At the same time due to mechanical transfer of thermal energy concentrated in the particles thermal conductivity of the layer can exceed the thermal conductivity of metals.

3. It was found that the equalization of temperature and concentration differences due to the above effects occurs within 0.5-1s, i.e. in the time interval comparable to the period of layer pulsations.

4. To evaluate the heat and mass transfer characteristics in the layer, effective heat transfers and mass transfer coefficients are introduced. In this case for their calculations.

5. It was found by calculation that the equalization of concentration and temperature values of the layer material and air occurs at a height of 10d of the particle.

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ДОСЛІДЖЕННЯ ПРОЦЕСУ ТЕПЛОМАСООБМІНУ В ПІРОЛІЗНІЙ УСТАНОВЦІ ДЛЯ ЗАБЕЗПЕЧЕННЯ ОПАЛЕННЯ ТВАРИННИЦЬКИХ ПРИМІЩЕНЬ

Сільськогосподарське виробництво є однією з найбільш енергоємних галузей народного господарства. Однією з невирішених проблем сучасного тваринництва в Україні залишається створення нормованих умов утримання тварин у тваринницьких приміщеннях. За високої концентрації поголів'я на одиницю площі, відбувається погіршення складу повітря, яке забруднюється аміаком, сірководнем, вуглекислим газом і пилом. Унаслідок цього збільшується падіж, знижуються приріст маси та збереженість тварин.

Нормований повітрообмін тваринницьких приміщень забезпечується системою механічної примусової припливно-витяжної вентиляції. Основна частина енергії у тваринництві, близько 50 %, витрачається на підтримання необхідних параметрів мікроклімату. Під час опалювального періоду, який на 80% території України триває 6-9 місяців, необхідно підігрівати повітря, що нагнітається у тваринницькі приміщення. З цією метою використовується від 60 % до 80 % усієї витраченої теплової енергії. Водночас для забезпечення необхідних параметрів мікроклімату всередині *тваринницького приміщення вентиляційне повітря видаляється в атмосферу і, поряд зі шкідливими речовинами, видаляється значна кількість теплоти (90 % від загальних тепловтрат будівель).*

Для України, яка має розвинене сільське господарство, що продукує значну кількість органічних відходів, біомаса може стати пріоритетним джерелом відновлюваних енергоресурсів. Нині одним із напрямів енергетичного використання біомаси є виробництво паливного газу, отриманого шляхом її термічного розкладання. Дослідження великої кількості піролізних установок різної конструкції, наведених у науковій літературі, дає змогу дійти висновку про те, що багато технологій не можуть бути достатньо ефективними через низку недоліків: удосконалення технологічних режимів не розглядають у функціональному зв'язку з тепломасообмінними та гідродинамічними процесами в камерах піролізу під час термічного розкладання органічної сировини; не передбачено заходів оперативного реагування на поточну зміну фізико-механічних властивостей у потоці сировини та кореляції з нею; не передбачено заходів оперативного реагування на поточну зміну фізико-механічних властивостей у потоці сировини та кореляції параметрів технологічного процесу піролізу з метою досягнення необхідних оптимальних результатів, що не дає змоги прогнозувати склад отриманого газу. Тому дослідження, спрямовані на розробку технології ефективного опалення тваринницьких приміщень є актуальними.

Ключові слова: *математична модель, мікроклімат, піроліз, опалення, вентиляція, повітря, тепломасообмін, нагнітання, теплопередача, тваринницьке приміщення.*

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