FIRE HASARD OF VEGETABLE RAW MATERIALS

1. Mathematical model of self-heating of vegetable raw materials in bulk

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ABSTRACT

Mathematical model of self-heating of vegetable raw materials in the form of sphere and slice are proposed. The fact that the models fit the full-scale and laboratory test results adequately permits to use them to tackle a number of applied problems, namely, to calculate the thermal detector sensivity radius, fire hasardous rate of temperature rise, fire safe storage life of vegetable raw materials, to access the efficiency of thermal control system.

INTRODUCTION

Bulk of vegetable raw materials is a dispersal medium with low coefficients of heat and temperature conductivity [1]. That is why with activization of microbiological processes in any part of the bulk, the heat educed is kept in the bulk, and a centre of high heat-activity appears. Heat spreading in a dispersed bulk is carried out by heat transfer, mainly by heat conductivity. To define temperature field in vegetable raw material, we need using equations of heat- and moisture-transfer that are solved combined [3]. However, in the considered interval of temperatures (under 100°C) steam transfer is low [4], and seeming heat conductivity does not depend on moisture content [5]. It may also be assumed that thermal characteristics of the material are constant and equal in all directions [4] because of dispersed mass isotropic properties. Thus, difinition of temperature field in the bulk comes to solution of equation of heat conductivity with constant coefficients with inner source of heat educing.

While forms of self-heating cources are vari-ous, two main forms may be chosen: flat heat source formed as a layer with thickness $2R$ and spherical source formed as a sphere with radius R .

Flat source

The task of heat-spreading in the bulk by means of heat conductivity in the case of a flat source may be formulated in the following way: in unlimited medium with initial temperature T_0 in the moment of time $t = 0$ flat source of heat educing begins to act; its specific intensity is continuous function of coordinate $q = q(x)$. In papers [6, 7], the task on definition of temperature fields in a dispersed bulk of mixed fodder raw material is given. It is solved numerally and analitically for various values of variables, characterizing the object of investigation: density ρ , specific

heat c , coefficient of heat conductivity λ , initial temperature T_0 , size of the source R , its specific capacity in the centre q_0 and in periphery q_ϕ . The theory of similarity allows to derive a common solution of the task. Using the theory of generalized variables, let us pass to dimensionless values [8]: Fourier's number T_0 dimensionless temperature T_* , relative distance x_*

$$F_0 = \frac{\lambda t}{\rho c R^2}; \quad T_* = \frac{(T - T_0)\lambda}{q_0 R^2}; \quad x_* = \frac{x}{R}. \quad (1)$$

Then mathematical formulation of the task will look like this

$$\frac{\partial T_*}{\partial F_0} = \frac{\partial^2 T_*}{\partial x_*^2} + \frac{q(x_*)}{q_0}; \quad (2)$$

$$T_*(x_*; 0) = 0; \quad (3)$$

$$\frac{\partial T_*(0; F_0)}{\partial x_*} = \frac{\partial T_*(\infty; F_0)}{\partial x_*} = 0. \quad (4)$$

Using Fourier cosine-transformation, we shall get differential equation

$$\frac{dT_{c*}(p, F_0)}{dF_0} + p^2 T_{c*}(p, F_0) = \frac{q_c(p)}{q_0}, \quad (5)$$

where

$$q_c(p) = \int_0^\infty q(x_*) \cos px_* dx_*. \quad (6)$$

The following expression is the solution of equation (5) under condition (3)

$$T_{c*}(p, F_0) = \frac{q_c(p)}{q_0 p^2} (1 - e^{-p^2 F_0}), \quad (7)$$

its original looks like

$$T_*(x_*, F_0) = \frac{2}{\pi q_0} \int_0^\infty \frac{q_c(p)}{p^2} \times (1 - e^{-p^2 F_0}) \cos px_* dp. \quad (8)$$

In the bulk of mixed fodder microflora distribution is casual [9], and specific intensity of heat educing may be written in the following way

$$q(x_*) = q_0 f(x_*). \quad (9)$$

Then the solution (8) will look like this

$$T_* = \frac{2}{\pi} \int_0^\infty \frac{f_c(p)}{p^2} (1 - e^{-p^2 F_0}) \cos px_* dp, \quad (10)$$

where

$$f_c(p) = \int_0^\infty f(x_*) \cos px_* dx_*.$$

Factorizing the exponent, we shall get

$$T_* = F_0 \theta(x_*, F_0), \quad (11)$$

where

$$\theta(x_*, F_0) = \frac{2}{\pi} \int_0^\infty f_c(p) \times \sum_{m=0}^\infty (-1)^m \frac{F_0^m p^{2m}}{(m+1)!} \cos px_* dp. \quad (12)$$

It should be noticed that solution (11) coincides with solution of the task with cooling of a warming plate in unlimited medium from paper [8] if heat-physical characteristics and initial temperature of the plate are the same as those of the medium. Putting (1) into (11), we derive the solution in case of absence of background heat educing ($q_\phi = 0$)

$$T - T_0 = \frac{q_0 t}{\rho c} \theta(x_*, F_0). \quad (13)$$

In a stationary case of presence of uniform background warming-up with specific capacity q_ϕ the following correlation is true

$$\frac{\partial T_\phi}{\partial t} = \frac{q_\phi}{\rho c}. \quad (14)$$

Using the principle of superposition of heat fields, we derive an approximate formula allowing to calculate temperature distribution in a dispersed bulk with presence of background heat educing

$$T - T_0 = \frac{(q_0 - q_\phi)t}{\rho c} \cdot \theta(x_*, F_0) + T_\phi, \quad (15)$$

where $T = q_\phi t / \rho c$ according to (14). Let us notice that formula (15) coincides in its form with formula for engineering calculations from paper [10]. However in paper [10] piece-constant function of sources capacity distribution is considered, and it is idealized. In this very paper continuous function $q(x)$ is used that was derived from probabilistic suppositions, taking into account casual character of particles distribution with higher heat activity.

Calculation of dimensionless relative temperature $Q = Q(x_*, F_0)$ was carried out on the computer EC-1045 by numerical integrating of equation (2) with initial condition (4) for values of Fourier's number $F_0 \in [0, 05; 8]$ and relative distance $x_* \in [0; 15]$ that is where values of parameters have practical interest. Values $Q(x_*, F_0)$ were calculated according to (11) for case $q_\phi = 0$ that does not change community of results obtained. Nomogramma $Q = Q(x_*, F_0)$ shown in figure 1 was built as a result of calculations.

Figure 1: Nomogramma of dimensionless relative temperature for a flat source (F_0 - Fourier's number)

The nomogramma allows to define temperature field in a dispersed bulk of raw mixed fodder by using correlation (15). In figure 2, calculation curves of temper-

ature distribution in a bulk of grass powder (obtained according to formula (15) with various parameters of the source) are shown. In figure 3, nomogramma of temperature change in the centre of the source up to fire hazardous value ($\sim 100^\circ\text{C}$) in dependence on time for various intensity of heat educing is shown.

Spherical source

Experiments showed that the task of finding of temperature fields comes to solution of symmetrical task that if generalized looks like:

$$\frac{\partial T_*}{\partial F_0} = \frac{\partial^2 T_*}{\partial r_*^2} + \frac{2}{r_*} \cdot \frac{\partial T_*}{\partial r_*} + \frac{q(r_*)}{q_0}; \quad (16)$$

$$T_*(r_*, 0) = 0; \quad (17)$$

$$\frac{\partial T_*(0, F_0)}{\partial r_*} = \frac{\partial T_*(\infty, F_0)}{\partial r_*} = 0, \quad (18)$$

where relative coordinate $r_* = r/R$.

The task was solved numerally combined with the equation

$$\theta(r_*, F_0) = \frac{T_*(r_*, F_0)}{F_0} \quad (19)$$

and, as a result, nomogramma $Q = Q(r_*, F_0)$ was built for practically important values of parameters. It allows to define temperature distribution using formula (15) (figure 4).

Figure 2: Temperature curves with various parameters of the source for grass powder (material description: $q_\phi = 5 \text{ wt} \cdot \text{m}^{-3}$, $\lambda = 0.09 \text{ wt} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, $\rho c = 8.5 \cdot 10^5 \text{ J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$):

$R = 0.1 \text{ m}$; $q = 80 \text{ wt} \cdot \text{m}^{-3}$; $t = 59 \text{ days}$;

$R = 0.3 \text{ m}$; $q = 60 \text{ wt} \cdot \text{m}^{-3}$; $t = 30 \text{ days}$;

$R = 0.5 \text{ m}$; $q = 80 \text{ wt} \cdot \text{m}^{-3}$; $t = 15 \text{ days}$.

Figure 3: Growth of temperature in the centre of a flat source ($R = 0.3 \text{ m}$) with various intensity of heat-emission (solvent cake, oilcakes)

The mathematical self-heating model supposed above coordinates satisfactorily with the experiment [7]. So, calculation curves and experimental temperature values obtained in the large-scale experiment on a fragment of silage with size $3 \times 3 \times 4,8$ m are shown in figure 5. Some asymmetry of temperature fields with respect to flatness $x = 0$ corresponding to the centre of the source, is explained by convection of warmed air and water steam into the upper part of the bulk.

The fact that the model corresponds to the experiment allows to use it for solving applied tasks [11]: calculation of the sensitivity radius of the temperature detector, estimation of temperature control systems efficiency, calculation of fire hazardous rate of temperature rise and fire safe periods of raw materials storage.

Figure 4: Nomogram of dimensionless relative temperature for a spherical source (F_0 - Fourier's number)

Figure 5: Temperature fields of flat self-heating of grass powder (large-scale experiment):

$$\rho = 470 \text{ kg} \cdot \text{m}^{-3}; \quad R = 0.25 \text{ m}; \quad q_0 = 74 \text{ wt} \cdot \text{m}^{-3}.$$

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