AIR FLOW AND THERMAL STATE IN LARGE AERATED GRAIN STORAGE

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Abstract. *A mathematical model, algorithm and software were developed for simulation of airflow and heat transfer in an aerated soya bean storage under non-uniform conditions of the seed mass. The problems of airflow in an aerated soya bean store and speed of cooling front moving through grain bulks were solved consecutively. To simulate the cooling dynamics of soya bean mass three models offered were analyzed and compared with experimental data. The first method is based on the solution of system of partial differential equations, describing the heat and mass transfer and conservation of energy. In second method the deep-bed is hypothetically divided into limited number of thin layers ("homogeneous reactors"), in which temperature of a grain and air is considered identical. Experimental equipment was developed to study soybean cooling dynamics for different airflow velocities in deep-bed of uniform and variable cross-section. Using homochronous number as argument, the dimensionless temperature data in deep-bed of uniform cross-section in different sections at various speeds were satisfactorily described by generalizing empirical dependence. The third method of simulation of cooling dynamics of soya bean mass, based on use of this dependence, has given the best results in comparison with other considered methods. This method was adapted for variable section deep-bed, tested on experimental data and used for modeling thermal state of silos.*

Keywords*: Aeration, deep-bed model, heat and mass transfer, simulation, soya bean cooling dynamics*

1. Introduction

The aeration is widely used with the purpose of cooling and equalizing temperature throughout the grain bulk, eliminating biological heating in moist grain, introducing fumigant gases, removing odors and fumigant residues. Preservation of slightly damp grain by aeration in this region possible due to the large difference in temperature at the night and day, so the ambient night temperatures enable removal of metabolic heat that develops during storage. In spite of considerable amount of the recommendations about management of aerated storages, grain storage systems designers and commercial grain facility operators meet with difficulties on design and operation of the grain aeration systems. To optimize of planning and operating grain aeration systems is necessary to develop software for predicting the distribution dynamics of the parameters in grain bulk, first of all static pressure, airflow velocity and temperature.

Many authors tried to describe temperature dynamics of a grain bulk. Some authors, for example, Schumann (1929), Furnas (1930), Bakker-Arkema and Bickert (1966), Foster (1967) assumed that mass (moisture) transfer is negligible. Others, for example, Boyce (1966), Burrel and Laundon (1967), Henderson and Henderson (1968), Sutherland *et al*. (1971), Bakker-Arkema *et al*. (1974), Brooker *et al*. (1974), Ingram (1979), Hunter (1988), Sanderson *et al*. (1988), White (1988), Sun and Woods (1997), Montross and Maier (2000), Lamrani *et al*. (2001), Ranalli *et al*. (2002), Kurpaska *et al*. (2004) consider heat and mass transfer in the grain bulk. In spite of the fact that the models of these last authors are sometimes united by the term "Aeration models" (Navarro and Noyes, 2002), the term "Drying models" seems more pertinent.

The principal objectives of the present work are:

a) to create a mathematical model, an algorithm and software for the calculation of temperature dynamics in non-homogeneous conditions of air stream in aerated grain store;
b) to obtain an experimental data on soybean cooling dynamics at different airflow velocities;
c) to develop a mathematical model which describes soybean cooling dynamics; and
d) to accomplish numerical simulations of grain stores with aeration to detect the operational risk areas.

2. Mathematical Model

The simulation object represents a capillary - porous body. The heat transfer to/from grain at heating/cooling is carried out by means of gaseous agent. It is obvious, that the grain thermal treatment is typical non-stationary process.

The layer disperse (damp) material consisting of the spherical form particles of radius R is considered. The heat-carrier by temperature T_{a0} is blown with constant velocity w through a layer of thickness H in a direction y. The system of the transfer equations for this problem has represented in works Lykov and Mikhailov (1963) and Lykov (1966).

This system consists from the energy and moisture transfer differential equations for an individual grain located in a layer, the heat and mass transfer differential equations written for a surface of a grain, where there is a contact of air and grain, the equation of conservation of energy of the fluid (air). It is possible to obtain various similarity parameters from this system of the equations, for example, homochronous number *Ho*, which characterize scale transformation of time t (inverse to criterion Strouhal):

$$Ho = \frac{w \cdot t}{R}; \quad Ho = \frac{w \cdot t}{H}, \tag{1}$$

and also widely known Biot number (*Bi*) and Fourier number (*Fo*).

If numerical values of generalized variable *Bi* is very great ($Bi > 100$), the intensity of grain heating/cooling is determined by grain thermophysical properties and depends on intensity of heat transfer inside a grain (internal problem). In case of small values *Bi* ($Bi < 0.2$) it is possible to consider uniform distribution of grain temperature pattern for everyone grain and to reduce a problem to definition of a grain surface temperature only.

The heating rate of a grain in this case is determined by heat transfer rate from air to a surface of a grain (external problem). In case of $0.2 < Bi < 100$ it is necessary to take into account both processes (boundary problem).

The numerical analysis executed in this work has shown that the conditions appropriate for an external problem are realized during aeration. In these conditions there is no necessity to include in system the equation of energy for an individual grain. Besides it is possible to exclude also moisture transfer differential equation for an individual grain out of system, if to have experimental data on drying in thin layer for all range of realizable conditions in process. In this case the system contains a known function of the main parameters of drying/aeration process (temperature and grain humidity content, temperature and humidity of the air, the equilibrium moisture content, porosity degree, the airflow velocity, and so on) to calculate the mass flux. The model of drying/aeration, presented in work Khatchatourian *et al.* (2003), can be used to simulate soya bean mass heating/cooling and drying dynamics. This model is based on the model developed by Courtois *et al.* (1991) for maize drying and transformed by Khatchatourian *et al.* (2003) to simulate soya bean mass drying dynamics and presents the system of four quasi-linear partial differential equations. Usually temperatures and moisture content conditions during aeration correspond to domain next to soybeans equilibrium moisture content curves, that allows to neglect additional drying during of aeration. Therefore the thermal state of aerated soya bean store can be written by system:

$$\frac{\partial T_g}{\partial t} + w_g \frac{\partial T_g}{\partial y} = \frac{-a\,(\Phi_m H_v + \Phi_h)}{\rho_g (C_g + C_w X)} \tag{2}$$

$$\frac{\partial T_a}{\partial t} + w_a \frac{\partial T_a}{\partial y} = \frac{a(1-\varepsilon)}{\rho_a\,\varepsilon} \cdot \frac{\Phi_m C_{pv}(T_g - T_a) + \Phi_h}{C_{pa} + C_{pv} Y} \tag{3}$$

Where the T is temperature in °C; the a is ratio of grain surface area A_g to grain volume V_g in m^{-1}; the C is specific heat at constant pressure in J $kg^{-1}K^{-1}$; the ρ is specific density in kg m^{-3}; the ε is porosity factor, dimensionless; the H_v is latent heat of water vaporization in J kg^{-1}; X is grain moisture content, kg water/kg dry grain; Y is air absolute humidity in dryer, kg water/kg dry air; inferior indices: *a* - air; *g* - grain; *h* – heat; *m* – mass; *v* – vapor; *w* – water.

For aerated grain storage problem (w_g=0), the following initial and boundary conditions were considered:

$$T_a(0, y) = T_{g0}\ ;\ \forall y \in (0, H];\ T_g\,(0, y) = T_{g0};\ \forall y \in [0, H];\ T_a(t, 0) = T_{a0};\ \forall t \in [0, \infty), \tag{4}$$

To fulfil the numerical simulation using the system of Eqs. (2) and (3), it is necessary to know the dependence of the mass flux Φ_m and of the heat flux Φ_h on the main parameters of drying process (grain temperature and grain humidity content, temperature and humidity of the air, the equilibrium moisture content, porosity factor, the airflow velocity , and so on). In this work the dependences of the heat flow density Φ_h from airflow velocity and temperature was obtained experimentally for soya bean seed. The method of calculus of the mass flow density Φ_m for soya bean seed was presented in work of Khatchatourian *et al.* (2003).

3. Identification of the mathematical model

The realization of experiments in this work has as objectives: 1) to obtain dependences of the heat flow density from airflow velocity and temperature (in thin layer); 2) to obtain experimental data on soybean cooling dynamics for different airflow velocities in deep-bed of uniform and variable cross-section.

3.1. Equipment description

The equipment, schematically shown in Fig. 1, is composed by an electric motor of ¾ of hp (552 W), with control system of rotational frequency, that sets in motion two centrifugal fans in series, creating a canalized airflow; an orifice plate to measure the airflow rate; a heat booster to heat the air, composed by 8 electric resistors, each one with a nominal potency of 400 W; and a drying/cooling/heating box.

The air temperature was measured by six thermocouples, calibrated in an interval from 0°C up to 100°C. One of them was put in the beginning of the drying box and the others in its centre. To measure the grain temperature, a thermocouple sensor has been carefully introduced into the grain, which was duly put at the centre of the corresponding section.

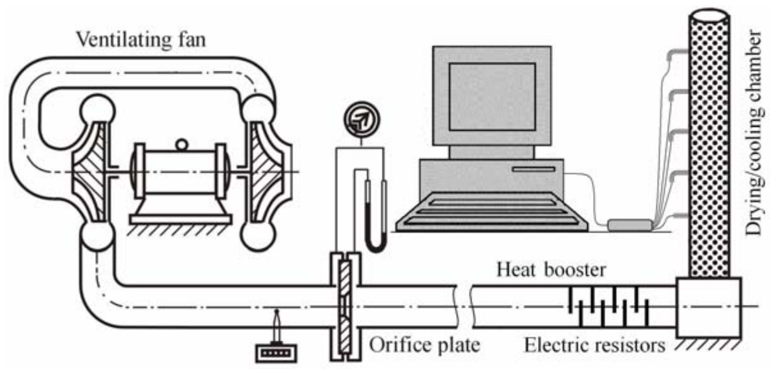

Figure 1. Sketch of the experimental equipment

3.2. Determination of heat-transfer coefficients

The method of a regular thermal regime (Lykov and Mikhailov, 1963) was used to determinate of heat-transfer coefficients. The experimental data on soybean heating in a thin layer were obtained for an interval of velocity airflow from 0.5 up to 3 m/s and temperatures of air 80, 110 and 120°C. The measurement of grain temperature was realized by the thermocouple, whose thermocouple sensor was located at the centre of a grain.

In all experiences initial temperature of a grain was 4°C and humidity 13% w.b. The temporal variation of the logarithm of dimensionless grain temperature for different velocities and temperatures of air was represented by linear function, using least-squares method (Fig. 2).

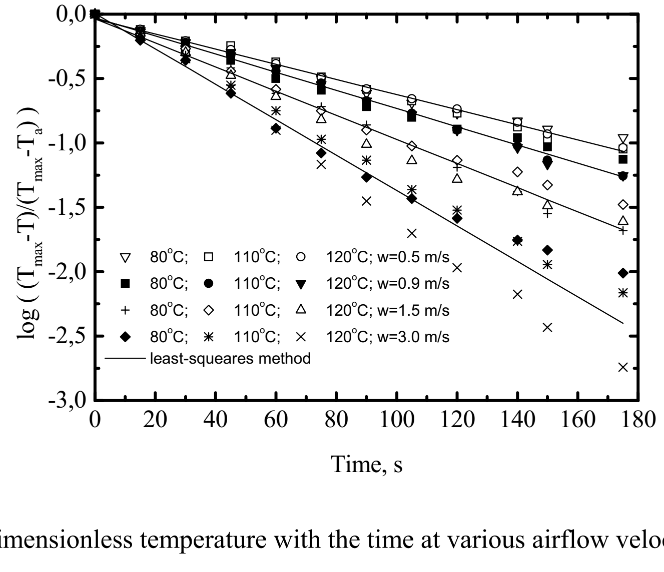

Figure 2. Variation of dimensionless temperature with the time at various airflow velocities and temperatures

The angular coefficients k of these functions named as rate of cooling (heating), at small numbers Biot are related to heat-transfer coefficient by dependence (Lykov and Mikhailov, 1963):

$$\alpha = k \frac{\rho_g \, C_g V_g}{A_g} \tag{5}$$

It was found that the variation of temperature in considered range (80-120°C) does not influence essentially on heat-transfer coefficient α. The influence of velocity can be expressed by dependence (line in Fig. 3):

$$\alpha = 16.62 \cdot w^{0,5} \tag{6}$$

This dependence was used in the accounts based on the obtained analytical solution of heating problem for homogeneous sphere, on which surface there is a heat transfer with an environment. By means of average-out of the theoretical spatial distribution of grain temperature, it was obtained average grain temperature at each moment of time, which satisfactorily describes grain heating dynamics for the investigated conditions.

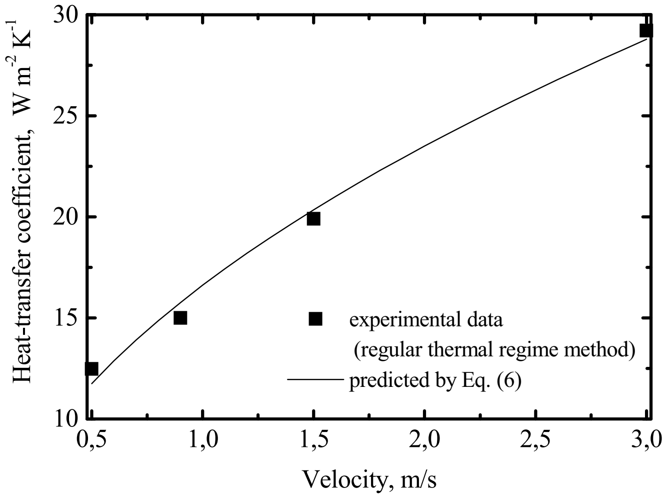

Figure 3. Influence of the airflow velocity on the convection heat-transfer air/soybean seed coefficient α

3.3. Experimental soybean cooling study

The experimental data on cooling dynamics of soya bean mass were received in small "silo" composed of a heat-insulated polyvinyl chloride tube (diameter of 0.15 m and height of 1 m). Soya bean mass was heated up in thermostat to temperature 45°C during time, sufficient for obtaining of a uniform temperature distribution in an individual grain, and then was located in the chamber. The total soya bean layer depth in experiments constituted 0.60 m. The cooling of heated grain was realized by ventilation with ambient air, the airflow velocity was maintained constant. Grain temperature was measured by thermocouples established in sections y=0 m, y=0.15 m, y=0.27 m, y=0.40 m and y=0.54 m. Comparison of cooling dynamics of properly grains (thermocouple sensor was located at the centre of an individual grain) with dynamics of air temperature variation (thermocouple sensor was established in space between grains and isolated from contact to a grain by punched plastic tubule) in section y=0.15 m has shown that the difference of temperatures of air and grain is very small (< 0.5°C). In spite of the fact that in real conditions the excess of temperature inside silos above temperature of cooling air (ambient temperature) rarely exceeds 10°C, in experiments on cooling soya bean mass this difference amounted to 20-25°C to increase sensitivity of measurements and to reduce their relative mistake. The experimental points in Fig. 4 show the grain temperature variation with time on different depths of deep bed for initial grain temperature 45°C, entrance temperature of cooling air 25°C and velocity 0.68 m/s. For each examined section it is possible to note three characteristic intervals of time in cooling dynamics, which differ by cooling rate. The cooling rate during the first temporal interval, which begins from the moment of a beginning of cooling, is relatively not great. The extension of this interval is increased for sections more removed from entrance section. In the second interval the cooling rate is considerably increased. The basic part of cooling process of a grain, located in this section, is realized here. In the third interval the cooling rate sharply decreases again. As experiments indicate (points in Fig. 5), the cooling dynamics is strongly velocity dependent.

4. Simulation results and discussion

To choose mathematical model of cooling dynamics of soya bean mass, appropriate for creation software, in the present work three methods are compared. The first method (Khatchatourian *et al.*, 2003) is based on the solution of system of partial differential equations (PDE) taking into account dependences of the mass flux Φ_m and of the heat flux Φ_h on the main parameters of cooling/drying process. In overwhelming majority of cases, typical for Brazil, the stored soybean humidity does not exceed 13 % w.b. As have shown calculations, variation of soybean humidity with time during storage is so small, that does not exert any influence on thermophysical and thermotecnical parameters determining cooling/heating process. It allows to use for simulation of a thermal state of grain storage only equations

(2) and (3) with boundary conditions (4), assuming Φ_M=0; w_g=0. The results of simulation by this model are submitted on a Fig. (4) by dot lines.

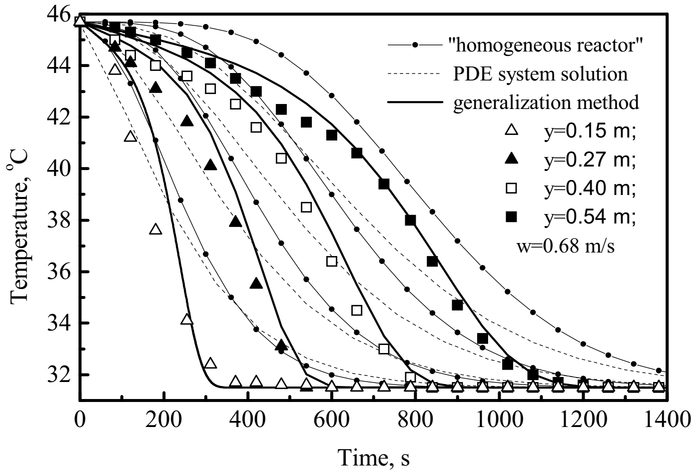

Figure 4. Experimental and calculated cooling dynamics of soya bean mass at various chamber sections

As a whole, the curves satisfactorily describe the cooling dynamics, though in some sections and at some velocities the deviation from experimental data can be significant. Disadvantage of a method is the difficulty of adaptation of system of the equations to the real outline of silos, when the area of cross section is not constant.

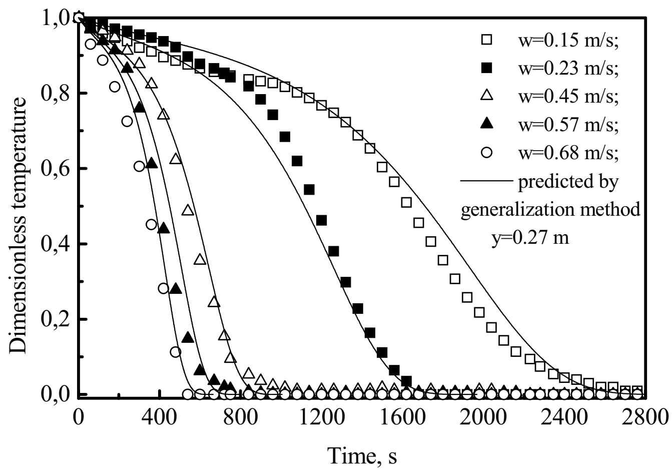

Figure 5. Influence of the airflow velocity (w) in m/s on the cooling dynamics

The continuous lines with marker in Fig. 4 represent results of simulation by the second method named conditionally as the method of "homogeneous reactor". In this method all deep-bed is hypothetically divided into limited number of thin layers ("homogeneous reactors"), in which temperature of a grain and air is considered identical. This temperature is calculated for each temporal step by the equation of thermal balance consistently from initial section up to last. The quantity of spatial steps was chosen such that the results of accounts did not vary with the subsequent reduction of thickness of a layer. This method qualitatively correctly describes cooling process, but with increase of air velocity and for last sections of the chamber gives the too large deviation from experimental data.

The best results were received for the third method, in which the homochronous number *Ho* was used as an argument to obtain generalized curve for dimensionless temperature θ. A Figure (6) shows the generalized experimental data on cooling dynamics in all studied sections obtained for velocities w=0.15 m/s; 0.23 m/s; 0.45 m/s; 0.57 m/s and 0.68 m/s. The ordinate represents dimensionless temperature (ratio of a difference between current grain temperature and entrance air temperature to a difference between initial grain temperature and entrance air temperature), on an abscissa axis is put local homochronous number, which characterize scale transformation of time for each of section y:

$$Ho = \frac{w \cdot t}{y}, \tag{7}$$

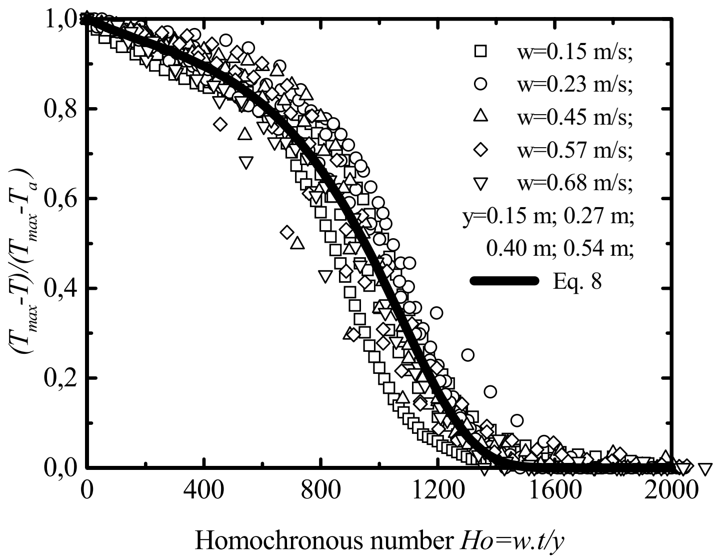

Figure 6. Generalization of experimental data for various chamber sections *y* in m and airflow velocities in dimensionless coordinates

The expression for a generalizing curve (continuous line) was chosen as function:

$$\theta = e^{-(Ho/a)^{(c+Ho/b)}} \tag{8}$$

The use of the generalized curve has allowed satisfactorily describing the cooling dynamics of soya bean mass at all researched air velocity in all sections of the chamber (continuous lines in Figs. 4 and 5).

As was already mentioned, real silos frequently has no the constant cross-section area and the variation of airflow velocity in different sections can be very essential. The special experiments on cooling soya bean mass in the chamber of variable cross-section area were executed to estimate influence of this variation and related to this variation of airflow velocity on chamber height. The experiments were realized in the two-dimensional expanding channel of height H=1 m of rectangular cross-section, executed from a wood with wall thickness of 2 cm. The inlet area was chosen of the equal inlet area to the experimental cylindrical chamber, the expansion ratio q (relation of the discharge area to inlet area) was equal to 2, i.e. q=2.

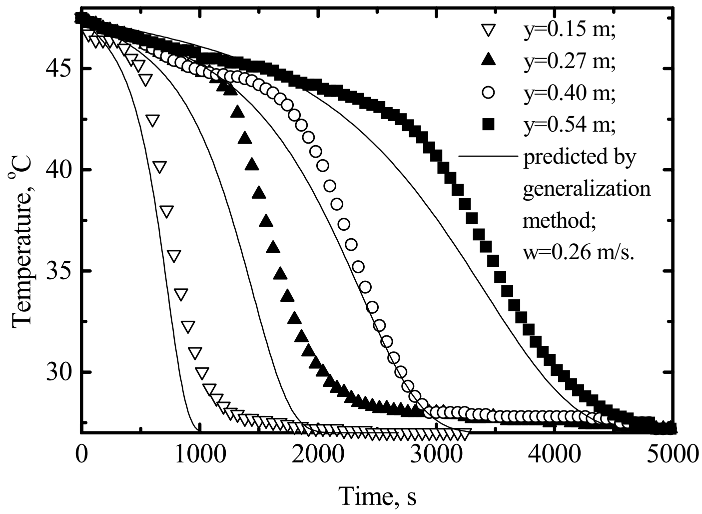

Figure 7. Cooling dynamics of soya bean mass in variable cross-section chamber

The results on cooling dynamics of soya bean mass in the variable section channel are shown in Fig. 7. As expected, at identical initial airflow velocities the cooling in the chamber with expansion occurs more slowly in comparison with cooling in the constant cross-section chamber. As the cross-section area increased the cooling rate becomes less and less what related to reduction of cooling airflow density. To use a generalizing curve for a case of a flow with the variable area of section, the dependence of increment of time Δt_i on a small displacement Δy_i was obtained:

$$\Delta t_i = \frac{Ho_i \cdot \Delta y_i}{w_0 A_0} \cdot \left[1 + \frac{(q-1)}{H}\left(2y_i + \Delta y_i\right)\right]. \tag{9}$$

Continuous lines in Fig. 7 represent output computations with use of this formula. The satisfactory concordance between the experimental and calculated data has allowed using this empirical model for thermal state simulation of real silos.

Cooling air density in real conditions of aeration practically does not vary, because both an absolute interval of temperature variation (less than 10°C) and rate of change of temperature on time are very small. Therefore the problems of airflow in an aerated soya bean store and speed of cooling front moving through grain bulks can be solved consecutively. In this work for simulation of airflow in silos the model developed by Khatchatourian and Savicki (2004) for isothermal flows was used. Using the finite element method with an iterative process for the solution of partial difference equations for the pressure and the stream function, the streamlines were calculated for a V-form floor silo with soya bean layer depth 22 m. These lines separate domains of flow with the identical discharge, but the velocity varies along streamline. The method developed for the channel of variable section was applied to simulate of cooling dynamics of grain mass. The isotherms corresponding to distribution of temperatures after 36 hours of cooling are shown on Fig. 8.

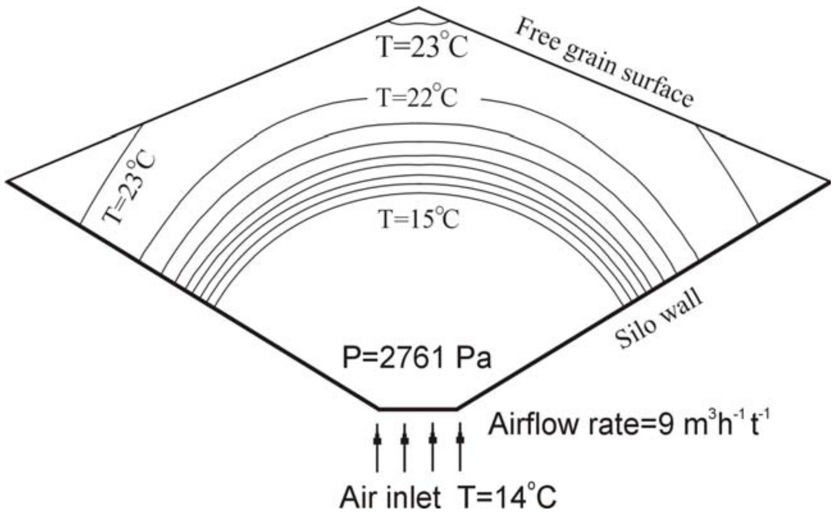

Figure 8. Isothermal lines for a V-form floor silo; initial seeds temperature T_{g0}=24°C; cooling time t=36 h

It is possible to note, that for studied soya beans storage, the top areas, adjacent to walls or concentrated near to an axis of symmetry, require more time for achievement of required temperature. It is a consequence that these areas are located on the greater distance from the cooling air entrance, air passes the greater way up to an output and cools large grain mass. Identification of mathematical model now is made, using the data for temperature fields in real soya beans storage.

5. Conclusions

1. A mathematical model, algorithm and software were developed for simulation of airflow and heat transfer in an aerated soya bean storage under non-uniform conditions of the seed mass.
2. Experimental data on soybean cooling dynamics for different airflow velocities in deep-bed of uniform and variable cross-section were obtained. Using homochronous number as argument, the dimensionless temperature data in deep-bed of uniform cross-section in different sections at various speeds were satisfactorily described by generalizing empirical dependence.
3. Experiments were conducted to obtain dependences of the heat flow density from airflow velocity and temperature (in thin layer).
4. To simulate the cooling dynamics of soya bean mass three models offered were analyzed and compared with experimental data. The first method is based on the solution of system of partial differential equations, describing the heat and mass transfer and conservation of energy. In second method the deep-bed is hypothetically divided into limited number of thin layers ("homogeneous reactors"). The method, based on use of empirical dependence, has given the best results in comparison with other considered methods.
5. The cooling dynamics of soya bean mass in real seed storage was simulated using software elaborated.

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7. Responsibility notice

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