The mathematical modeling of changes in grain moisture and heat loss on adsorption drying from parameters of grain dryer

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Abstract. The literary review has established that to reduce the heat loss of a dryer, the heat insulation of the dryer design, heat recovery and suction air flow are used. However, the use of prospective suction airflow is not fully disclosed. In the article, based on the equations of mass transfer, thermal and material balance, the dependences of grain moisture and heat consumption on drying from the regime parameters of the dryer, grain properties, and air flow used during drying are found. Analytical dependencies are illustrated by the corresponding schedules. Analysis of the analytical and graphical dependences of grain moisture and heat consumption on the corn grain sample has established that reducing the heat consumption when drying the grain, possibly reducing the pressure in the dryer, while simultaneously draining the air stream before it is fed to the drying chamber.

1. Introduction

Drying is at the same time one of the largest energy-consuming processing operations in post-harvest grain processing \cite{1}.

Due to the fact that in recent years the energy resources have risen significantly (natural gas – 2.5-4 times, electricity – 1.5-3.5 times, diesel fuel – 2-3 times) and tend to further increase in value, the problem of reducing the cost of heat energy for drying the grain became a topical issue. In most cases, the drying of grain is used for industrial drying of grain, which is realized in mine and modular dryers, which have a low thermal coefficient of efficiency \cite{2}.

The main reason for the low coefficient of utility of these dryers is the imperfection of drying technology and their design \cite{3}. Therefore, the actual scientific and technical problem is the search for methods that will enable to increase the thermal efficiency of the mine and modular grain dryers \cite{4}.

Most of the grain dryers that are used in the world operate under a straight-line scheme, where drying occurs when the heat is continuously calibrated throughout the entire process \cite{5}. In this case, the heating period of the grain takes a large part of the process, and the evaporation of moisture passes at a temperature of the grain, much lower than the edge, which greatly reduces the efficiency of drying and increases the cost of energy \cite{6}. If drying is applied to grain of high humidity, the repeated transmission of grain in the dryer is used, which leads to over-consumption of fuel and electricity, decrease of productivity. Adsorption-contact heat and mass exchange \cite{7} grains can be used to further increase the moisture removal and reduce the energy intensity of the process.
World practice already knows a lot of ways adsorption-contact drying of grain with the help of artificial (aluminum silica gel) [8] or natural adsorbents. But in the conditions of farms, it is possible to use without restriction at least one natural adsorbent – dry grain [9].

The use of dry grain as an adsorbent was the basis of the recirculation methods of grain drying, which are based on the alternation of grain heating and its cooling by repeatedly recirculation a part of the dry grain [10]. Significant energy savings can be achieved using this method when drying grain of high humidity of 28-32% [11]. Such methods allow drying at elevated temperatures of the coolant and a slight exposure (5...40 s), and fuel consumption is reduced by 25...40% [12].

So, when drying sunflower wet seeds 18...24%, the specific fuel consumption was 4.6...3.7 MJ/kg [13]. But this method requires additional re-equipment of the dryer and economically expedient when drying grain of high humidity. The regeneration of the drying agent and the thermal insulation of the dryer designs are the main methods for improving the energy efficiency of drying. To further improve the thermal efficiency, use of suction air flow can be used [14].

The promise of this method is that without changing the design of the dryer, only by changing the mode of air flow passage, it is possible to reduce the energy costs of drying the grain [15].

However, the authors in a simplified form analyze the influence of air pressure on the speed of drying and does not take into account the dependence of the partial pressure of water vapor from the moisture content of the drying agent, which makes research in this direction relevant.

2. Materials and methods
In general, the process of drying the grain is described by the differential equation of heat and moisture transfer, provided that all heat is brought to the surface of the moist material, spent on its heating and evaporation of water:

\[
\frac{dQ}{d\tau} = rM_M \frac{du}{d\tau} + M_M c_G \frac{d\theta}{d\tau} + \frac{df(Q, \tau)}{d\tau},
\]

where \(u\), \(\theta\) – moisture content and temperature of the heating of the grain, \%, °C; \(f(Q, \tau)\) – function of heat loss of a dryer, J/s; \(M_M\) – mass of wet grain, kg; \(c_G\) – specific heat of grain, J/kg °C; \(r\) – specific heat of steam reduction, J/kg; \(\tau\) – hour, s.

Figure 1. Scheme of evaporation of moisture from grains in the near-grain air environment.

As mentioned earlier [16] to increase the thermal efficiency of the dryer must reduce heat loss as \(f(Q, \tau)\), which is achieved using the insulation design and use of warm heated grain \((M_M c_G \frac{\partial \theta}{\partial \tau})\) through recovery drying agent.

To further increase the thermal efficiency, it is necessary to analyze the member of the differential equation \(rM_M \frac{du}{d\tau}\), which represents the rate of wet discharge.

That is, to further increase the thermal efficiency of the dryer, it is necessary to intensify the process of moist waste without increasing the thermal energy \(Q\).
For this we consider the process of evaporation of moisture from the grain. To simplify the simulation of the evaporation of moisture from the grain, we neglect the diffusion processes of moisture transfer inside the grains.

We consider the process of drying grain as thermodynamic process of transferring moisture from the surface of the liquid in the surrounding air space (figure 1). On the elementary section of the grains surface with the area of \( dS \) the molecules of water, moving at arbitrary speeds at an arbitrary angle, create a pressure \( P_G \) (figure 1).

Meanwhile, the outside of the grains surface presses the partial pressure of water vapor in the air \( P_\alpha \), due to which part of the water molecules again enters the grains surface, as well as other molecules entering the air creating a general pressure \( P \). From figure 1 it follows that for to ensure that there is evaporation, it is necessary that the number of molecules that left the grains surface exceeds the number of molecules that returned to it.

That is: \( P_G > P_\alpha \). This means that the velocity of evaporation of moisture from the grain is directly proportional to the surface area of the evaporation \( S \), the difference \( P_\alpha \) and \( P_G \), and also inversely proportional to the general pressure \( P \). In view of this, we can write the equation of mass transfer:

\[
\frac{du}{d\tau} = -V_G \cdot f \cdot \beta_0 (P_\alpha - P_G) \frac{P_0}{\rho},
\]

where \( P_0 \) – atmospheric pressure, \( P_0 = 101325 \) Pa; \( \beta_0 \) – mass transfer coefficient at atmospheric pressure \( P_0 \), kg/Pa·s·m; \( f \) – specific grain surface, m\(^2\)/m\(^3\); \( V_G \) – volume of dried grain, m\(^3\).

The partial pressure \( P_G \) of water vapor inside the grains and \( P_\alpha \) in the drying agent depends on its heating temperature \( \theta \) and the moisture content of the drying agent \( D \) are described by empirical dependencies [9]:

\[
P_G = a \cdot \theta + c, \quad P_\alpha = b \cdot D
\]

where \( a, b, c \) – empirical coefficients: \( a=2.15, b = 1.14, c=25 \).

During drying, the moisture content of the drying agent \( D \) and the temperature of the heating of the grain \( \theta \) are constantly changing.

Expressing the moisture content of the drying agent as an unknown function from time to time \( D(\tau) \), and changing the temperature of the heating of the grain \( \frac{d\theta}{d\tau} \), rewrite the formula for determining partial pressure of water vapor in drying agent \( P_\alpha \) and inside the grains \( P_G \):

\[
\frac{dP_\alpha}{d\tau} = a \cdot \frac{d\theta}{d\tau} + c, \quad P_\alpha = b \cdot D(\tau).
\]

3. Results and discussion

Substituting the meaning \( \frac{dP_G}{d\tau} \) and \( P_\alpha \) instead of \( P_G \) and \( P_\alpha \) in the differential equation (2), we obtain:

\[
\frac{du}{d\tau} = -V_G \cdot f \cdot \beta_0 \left( b \cdot D(\tau) - a \cdot \frac{d\theta}{d\tau} - c \right) \frac{P_0}{\rho}.
\]

To find \( D(\tau) \), we use the equation of the material balance for the drying process in the shaft and modular dryer:

\[
U_G = U_{air} \quad \Rightarrow \quad \rho_G \cdot v_G \cdot \frac{du}{d\tau} = \rho_{air} \cdot v_{air} \cdot \left( \frac{\varepsilon}{1-\varepsilon} \right)^2 \cdot V_3 \cdot \frac{dD}{d\tau},
\]

where \( U_G, U_{air} \) – the moisture from the grain and moisture absorbed by the drying agent is removed, respectively, kg; \( \rho_3, \rho_{air} \) – grain density and drying agent, respectively, kg/m\(^3\); \( v_3, v_{air} \) – the speed of the grain movement and the drying agent in the drying chamber, respectively, m/s; \( \varepsilon \) – is the porosity of the grain layer in the drying chamber.

Dividing the equation (6) into \( d\tau \) and integrating the initial conditions \( \tau = 0, u(\tau) = u_0, D(\tau) = D_0 \), we obtain the moisture content of the drying agent \( D \) at the gravimetric grain humidity \( u \):


\[ D = \frac{\rho_G v_G}{\rho_{air} v_{air} \left( \frac{\xi}{1-\xi} \right)^2 V_G} \cdot (u - u_0) + D_0. \]  \hfill (7)

Since the moisture content of the grain varies over time with some dependence \( u(\tau) \), then the moisture content of the drying agent changes over time:

\[ D(\tau) = \frac{\rho_G v_G}{\rho_{air} v_{air} \left( \frac{\xi}{1-\xi} \right)^2 V_G} \cdot [u(\tau) - u_0] + D_0. \] \hfill (8)

Substituting the value \( D(\tau) \) from differential equation (8) into the mass transfer equation (5) we obtain:

\[ \frac{du}{d\tau} = -V_G \cdot f \cdot \beta_0 \cdot \frac{p_0}{p} \left( \frac{\rho_G v_G b}{\rho_{air} v_{air} \left( \frac{\xi}{1-\xi} \right)^2 V_G} \cdot [u(\tau) - u_0] + b \cdot D_0 - a \cdot \frac{d\theta}{d\tau} - c \right). \] \hfill (9)

To simplify the differential equation (9), we use the Rebinder criterion [16]: \( R_b = \frac{c_G d\theta}{r \frac{du}{d\tau}} \). Substituting the expression \( \frac{r \frac{du}{d\tau} R_b}{c_G} \) instead of \( d\theta \) in the differential equation (9) after transformations, we obtain a homogeneous differential equation with the right-hand side of the first order:

\[ A \cdot u(\tau) + B \cdot \frac{du}{d\tau} = C, \] \hfill (10)

where

\[ A = \frac{f \beta_0 \rho_G v_G b p_0}{\rho_{air} v_{air} \left( \frac{\xi}{1-\xi} \right)^2 p}, \quad B = 1 - \frac{r \cdot a \cdot R_b p_0}{c_G \cdot p}, \quad C = u_0 A - V_G \cdot f \cdot \beta_0 \cdot \frac{p_0}{p} \cdot [b \cdot D_0 - c]. \]

Solutions of differential equation (10) under initial conditions: \( \tau = 0, \ u(0) = u_0 \).

\[ u(\tau) = u_0 \cdot e^{-A/B} \cdot \left[ 1 - e^{-A/B} \right]. \] \hfill (11)

Modification coefficients \( A, B, C \) influence the intensification of wet discharge. The coefficients \( A, B, C \) depends on the pressure of the near-terrestrial airspace (Figure 1). The coefficient \( C \) also depends on the moisture content of the drying agent \( D_0 \) at the drying inlet.

![Figure 2](attachment:image1.png)

**Figure 2.** Graphic dependences of the kinetics of corn grain drying under different: a – pressures of the terrestrial airspace \( P \); b – initial moisture content of drying agent \( D_0 \) (in brackets the value of relative humidity is indicated at 120 °C).

To demonstrate the influence of pressure on the terrestrial air space \( P \) and the initial moisture content of the drying agent \( D_0 \) on the moisture output intensity, construct the graphical dependences of the...
kinetics of drying at atmospheric pressure and pressure of 70 kPa, which can be achieved by a centrifugal high pressure fan for corn \((R_0 = 0.025; \varepsilon = 0.45; c_3 = 23000 \text{ J/kg C}; f = 3.484 \text{ m}^2/\text{m}^3; \beta_0 = 0.0004 \text{ kg/Pa-s-m}^2; \rho_f = 1350 \text{ kg/m}^3)\) at the speed of the grain \(v_3 = 0.0028 \text{ m/s}\) and drying agent \(v_{a0} = 4.2 \text{ m/s}\). Calculations were made for corn grain weighing 1 t with initial grain moisture \(u_0 = 28\%\) and initial absolute humidity of the drying agent \(D_0 = 0.411 \text{ kg/m}^3\). The graphical dependences of the kinetics of drying under different pressures of the near-ground airspace are presented in figure 2a. This figure 2b shows that reducing the pressure of the near-ground air stream leads to an increase in the speed of drying the grain.

After some time, which is called \(\tau_{expo}\) exposure drying, the grain moisture content does not change over time and approaches to some minimum possible moisture \(u_p\) value, which is called equilibrium humidity. At equilibrium humidity \(u_p\), the moisture that evaporates in the near-grain air is equal to the moisture that returns to the grain. To find its value, we find the boundary for \(\tau = \infty\):

\[
u_p = \lim_{\tau \to \infty} u(\tau) = \frac{\varepsilon}{A} = u_0 - \frac{v_3[b-D_0-c_1\rho_{air}v_{air}(\frac{\varepsilon}{\tau_x})^2]}{\rho_3 v_3 b}.
\] (12)

As can be seen from equation (12), equilibrium humidity depends on grain properties \((\rho_3, \varepsilon)\), regime drying parameters \((v_3, u_{air})\) and the initial moisture content of the drying agent \(D_0\). Since humidity is infinitely close to the equilibrium moisture \(u_p\), but never equals it, to find the time of exposure \(\tau_{expo}\) we introduce the minimum possible drying rate \(\Delta u_{min}\), which can be measured on the basis of practical considerations. Then the drying rate \(\frac{du}{d\tau}\) is equal to:

\[
\frac{du}{d\tau} = \frac{A}{B} \cdot e^{-\frac{A}{B} \tau} \cdot \left[ \frac{C}{A} - u_0 \right].
\] (13)

Equivalent to \(\frac{du}{d\tau}\) to \(\Delta u_{min}\) we solve the algebraic equation:

\[
\frac{A}{B} \cdot e^{-\frac{A}{B} \tau_{expo}} \cdot \left[ \frac{C}{A} - u_0 \right] = \Delta u_{min}.
\] (14)

By solving the equation relative to the \(u_p\) and using the formula (12) of equilibrium humidity \(u_p\), we find the required exposure time \(\tau_{expo}\):

\[
\tau_{expo} = -\frac{B}{A} \cdot \ln \left[ \frac{\Delta u_{min} B}{A (\frac{C}{A} - u_0)} \right].
\] (15)

The exposure time depends on the equilibrium humidity \(u_p\) (or the humidity to which it is necessary to dry), as well as on the thermophysical properties of the grain \((\rho_3, R_0, c_3)\). Since the equilibrium humidity \(u_p\) depends on the initial moisture content \(D_0\), we will construct the kinematic curves of drying at different initial moisture content of the drying agent \(D_0\). Graphic dependencies on figure 2b shows that a decrease in the initial moisture content of the drying agent \(D_0\) contributes to an increase in the drying rate and a decrease in the equilibrium moisture \(u_p\), which also confirms formula (12). Therefore, the pre-drying of the drying agent prior to being fed into the dryer can additionally be used together with the suction air stream as a method for increasing the drying rate and its energy efficiency. To estimate the heat energy consumption using a suction airflow, as well as a pre-dried drying agent, use the differential equation (1). To simplify the estimation of energy consumption during drying using the above methods, it will be assumed that the technological drying process takes place in the “theoretical” dryer, that is \(f(Q, \tau) = 0\). We use the Reclinder \(R_b\) criterion to exclude \(d\theta\) from equation (1). Taking into account this assumption and the Reclinder \(R_b\) criterion, the differential equation (1) takes the form:

\[
\frac{dQ}{d\tau} = r \cdot M_b (R_b + 1) \cdot \frac{du}{d\tau}.
\] (16)
pressure), that affect the drying rate without consuming the thermal energy of the drying agent. To take into account, it is necessary from the drying rate \( \frac{du}{d\tau} \) to take away the growth rate of drying due to parameters that do not use the thermal energy of the drying agent \( dQ \). The growth rate of drying due to parameters that do not use the thermal energy of the drying agent \( dQ \) can be expressed as the difference between the drying rate at a pressure lower than atmospheric and the drying rate at atmospheric pressure. Then the differential equation (16) can be written:

\[
\frac{dQ}{d\tau} = r \cdot M_M (R_b + 1) \cdot \frac{du}{d\tau} - r \cdot M_M (R_b + 1) \cdot \left( \frac{du_p^*}{d\tau} - \frac{du}{d\tau} \right),
\]

(17)

where \( \frac{du_p^*}{d\tau} \) – drying rate at a pressure lower than atmospheric, kg/s.

Substituting expression (11) with corresponding coefficients instead of \( \frac{du}{d\tau} \) and \( \frac{du_p^*}{d\tau} \) and integrating with \( d\tau \) under initial conditions: \( \tau = 0, Q(0) = 0 \), we obtain the dependence of heat consumption on the regime parameters of the dryer and grain properties:

\[
Q(\tau) = 2 \cdot \frac{E}{A_0} \cdot (u_0A_0 - C_0) \left[ 1 - e^{-\frac{A_0}{B_0} \cdot \tau} \right] - \frac{E}{A} \cdot (u_0A - C) \left[ 1 - e^{-\frac{A}{B} \cdot \tau} \right],
\]

(18)

where \( A_0 = f \cdot \beta_0 \cdot \frac{\rho_0 \cdot \rho_u \cdot \beta_0 \cdot b}{\rho_\text{air} \cdot \rho_\text{air} \cdot \left( \frac{\beta_0}{1 - \beta_0} \right)} \), \( B_0 = 1 - \frac{r \cdot a \cdot R_b}{c_G} \), \( C_0 = u_0A - V_G \cdot f \cdot \beta_0 \cdot [b \cdot D_0 - c] \).

On the basis of dependence (18) graphic dependences of heat expenditures on corn grain drying \( (u_0 = 28\%) \) from time under atmospheric pressure and pressure, which is less than atmospheric, as well as with different initial moisture content of the drying agent \( D_0 \) (figure 3).

![Figure 3. Graphic dependences of heat losses during the drying of corn grain \( (u_0 = 28\%) \) at different pressures of near-grain airspace \( P \) (a) and different initial moisture content of the drying agent \( D_0 \) (b).](image)

4. Conclusions

The use of pre-drained prior to supplying the suction air stream to the dryer (to a relative humidity of 10-20%), which creates a pressure in the dryer at a level of 70-80 kPa, makes it possible to reduce the heating costs for drying by 10-20% in comparison with a traditional drying method by increasing the drying speed. Therefore, the use of dryers with the use of suction air flow and its preliminary drainage before delivery to the drying chamber absorber is promising.

5. References

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