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Influence of vacuum on diffusion of moisture inside seeds of cereals

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The article solves the problem of thermal injury of seeds of grain crops during drying, which are capillary-porous bodies. It is hypothesized that the use of a vacuum in the drying chamber reduces the risk of thermal stress. In this regard, the article studies the effect of a vacuum inside the drying chamber on the diffusion of moisture inside the seeds. Seeds are complex materials in which moisture has different bonds with dry matter. During the working process, the drying speed in the surface layers and inside the seeds occurs at different speeds. As a result, drying stresses occur, which cause cracks on the surface of the seeds. Based on the solution to the differential diffusion equation with an absorbing screen as a boundary condition, the condition for drying without thermal stresses is found. Experimental verification of theoretical studies is carried out on a specially made experimental setup on the example of corn seeds. The effect of thermal stress on seed viability is determined by laboratory germination. Experimental studies confirm the adequacy of theoretical statements. Thus, when drying the seeds of grain crops, which are capillary-porous bodies, there is a limit value of rarefaction, above which cracks appear on the surface of the seeds due to different drying rates on the surface and inside. For drying seeds of grain crops without thermal stresses, it is necessary to consider not only the heating temperature but also the rarefaction in the drying chamber, which should be close to the limit value.

Keywords: seeds, dilution, vacuum, drying, laboratory germination, exposure.

Introduction

One of the components of the success of obtaining a high yield of cereals is the use of quality seed. Quality sowing material is determined not only by varietal characteristics, but also by homogeneity, content of weed seeds, debris, injured seeds, and moisture.

When drying the seeds, the main attention is paid to the level of injury to the seeds by dryers, and fuel consumption becomes a secondary issue.

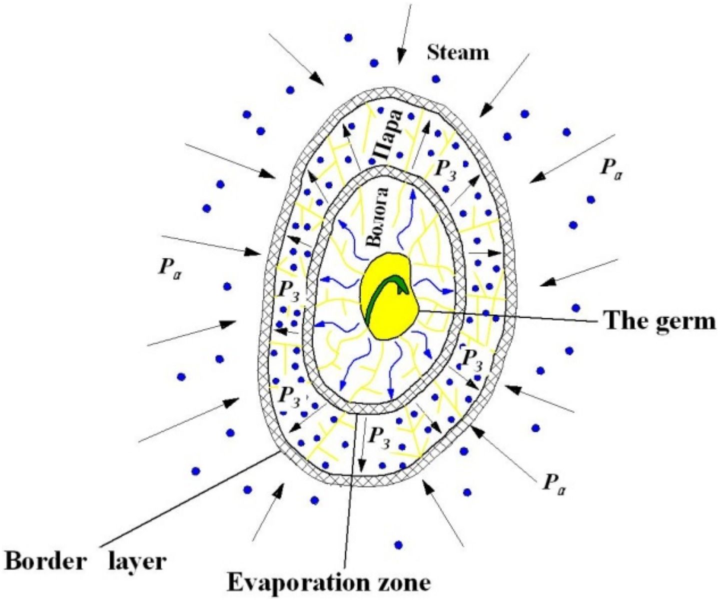
In seed production and selection for drying seeds with high humidity, convective drying in a stationary, sedentary and fluidized bed is usually used, which is realized in chamber, conveyor, bunker and mine dryers.

To intensify the moisture transfer in the seeds heating is used, which is provided by air flow with a temperature not exceeding 65 °C. The upper value of the temperature is due to the fact that at a given temperature level there is an intensive removal of moisture, but not yet denatured protein structures of the seed. Mild temperatures have been developed for different crops [1–4], which must be maintained when drying the seeds in different convective dryers to reduce the risk of thermal injury. Since convective drying uses mainly hot air or a mixture of air with combustion products, and the seeds are dried in a layer with a given thickness, when using adapted thermal regimes with minimal mechanical impact, areas of undried seeds are possible. In addition, depending on the type of heat generator used, it is necessary to constantly maintain the required mode during the drying process, which is not always possible to withstand during the working season due to the human factor. All this is especially important for selecting seed dryers, where each seed counts.

Despite the measures developed to reduce thermal injury to seeds during drying, dried seeds have lower germination, growth strength, and germination friendliness compared to undried seeds. This is explained by the difference in the properties of individual seeds and the nonlinear nature of the thermal conductivity of the seed layer, which leads to overheating or underdrying of individual seeds. To improve the sowing properties of seeds after drying, it is necessary to reduce their thermal injury by limiting or eliminating the influence of the temperature field, as well as increasing the uniformity of drying of seeds. In [5–9], the positive effect of vacuum on the drying process is shown. However, the effect of vacuum on the drying process of crop seeds has been insufficiently explored, which makes this study relevant.

1. Theoretical part

The main parameters that affect the quality of dried seeds are the temperature of the seeds θ and the vacuum in the vacuum drying chamber P. To understand their effects, one needs to know the process of drying seeds. Since we did not consider the diffusion of moisture during drying, but only the evaporation of moisture from the surface layers of the seed, then it is not possible to identify the causes of cracks in the seeds. Therefore, seeds should be considered a heterogeneous material. Any seed consists of an embryo, endosperm, or cotyledon and shell. For most crop seeds, the movement of moisture during drying is as follows (Fig. 1).



P_Z – partial pressure of water vapor inside the seed; P_α – partial pressure of water vapor inside the drying chamber.

Figure 1. The scheme of removal of moisture during drying of seeds

During vacuum drying, the substance of the seed is heated and part of the moisture located near its shell evaporates. At the same time, a moisture gradient is created, due to which, under the action of diffusion, moisture continuously moves from the inner parts of the seed, where the embryo is located, to the surface on which it evaporates. Water vapor molecules diffuse through the boundary layer and saturate the volume of the vacuum drying chamber. A necessary condition for evaporation is $P_Z > P_\alpha$ (Figure 1). It should be noted that the evaporation of moisture does not occur from the surface, but from the evaporation zone, located in the peripheral part of the seed (Fig. 1). As the moisture evaporates, this area moves deep into the seed.

The heterogeneity of the seed structure is the reason that moisture is removed from different parts in different ways: from the outside - through evaporation, from the inside - due to diffusion. Because of different methods of moisture removal, different parts of the seed are dried at different speeds, which means that the drying of the seeds is uneven. This can be represented by the following scheme (Fig. 2).

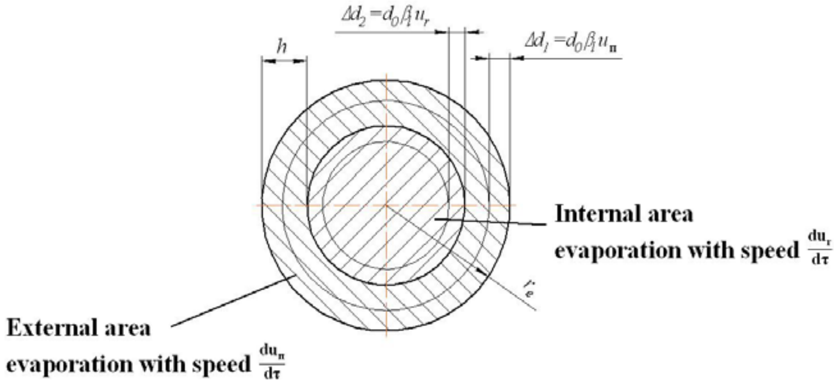


Figure 2. Scheme for determining the drying stresses in the seed

It is divided into two zones: a zone of external evaporation with a thickness of h and a zone of internal evaporation with a thickness of r_e-h. Drying stresses in the seed occur when the difference in deformation of the seed areas $\Delta d_1 - \Delta d_2 > 0$. It is equal to the following value according to Fig. 2:

$$\Delta d_1 - \Delta d_2 = d_0 \cdot \beta_l \cdot (u_\text{п} - u_r), \tag{1}$$

where Δd_1, Δd_2– deformations in the outer and inner zone of seed evaporation, respectively, m;

d_0 – the equivalent diameter of a completely dry seed, m;

β_l – coefficient of linear drying;

$u_\text{п}$, u_r – humidity in the outer and inner zone of seed evaporation [10–12], respectively, %.

We assume that the deformation occurs in the elastic region, then using the value of deformation (1), the formula for the deformation of spherical shells and the Laplace equation for the sphere [13] we obtain the expression for calculating the drying stresses in the seed:

$$\sigma = \frac{d_0 \cdot \beta_l \cdot E}{r_e \cdot (1-\mu)} \cdot (u_\text{п} - u_r), \tag{2}$$

where E – modulus of linear deformation, H/m^2;

μ – Poisson's ratio.

When a certain value of σ exceeds the surface of the seed, cracks appear. Expression (2) shows that the main factor influencing the appearance of cracks is the humidity gradient $(u_\text{п} - u_r)$. Therefore, for safe drying it is necessary that the drying rate on the surface was less than or equal to the diffusion rate:

$$\frac{du_\text{п}}{d\tau} \le \frac{du_r}{d\tau}. \tag{3}$$

$\frac{du_\text{п}}{d\tau}$ according to [14] is:

$$\frac{du_\text{п}}{d\tau} = \frac{A1}{P} \cdot (u_p - u_0) \cdot e^{-\frac{A1}{P} \cdot \tau}, \tag{4}$$

where $A1$ — regime coefficient characterizing the thermophysical properties of seeds, Pa$^{1/2}$/s;

u_p, u_0 — equilibrium and initial seed moisture, respectively,%;

P —vacuum in the drying chamber, Pa.

Drying speed inside the seed $\frac{du_r}{d\tau}$, on the other hand, is described by the differential diffusion equation with an absorbing screen, assuming that moisture is absorbed on the surface of the seed according to the law (4), the diffusion flow is parallel to the equivalent seed radius, and that the rate of moisture diffusion from the center of the equivalent seed ball in all directions and depends only on the distance r) [15–18] (Fig. 3):

$$\frac{\partial u_r}{\partial \tau} = \beta_m \frac{\partial^2 u_r}{\partial r^2}, \tag{5}$$

where β_m – moisture diffusion coefficient, m^2/s;

r – distance from the absorption screen, m.

The center of the equivalent seed ball retains moisture for the longest time ($r = \frac{d_e}{2}$), therefore, comparing the humidity at this point and on the surface of the equivalent sphere, we observe the largest gradient($u_{\text{п}} - u_r$).

To find the gradient ($u_{\text{п}} - u_r$) it is necessary to know the dynamics of humidity change inside the seed u_r. To do this, solve the differential equation (5) under the following boundary conditions:

$$u_r(0,\tau) = u_r(d_e,\tau) = \left(u_0 - u_p\right) \cdot e^{-\frac{A1}{P}\cdot\tau} + u_p \qquad (6).$$

Initial conditions:

$$u_r(r,0) = u_0 \,. \qquad (7)$$

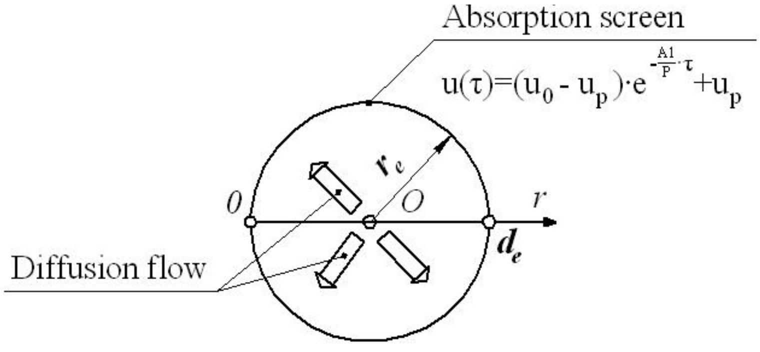


Figure 3. Scheme for determining the differential equation of diffusion inside the seed.

Final condition:

$$u_r(r,\infty) = u_p \,. \qquad (8)$$

The differential equation in partial derivatives (5) is a differential equation in partial derivatives of the second order of the parabolic type. They are solved by the Fourier method by introducing an additional function. Then the drying rate inside the seed $\frac{du_r}{d\tau}$ is equal to:

$$\frac{\partial u_r}{\partial\tau} = \frac{A1}{P}\cdot\left(u_p - u_0\right)\cdot e^{-\frac{A1}{P}\cdot\tau} + \left(u_0 - u_p\right)\cdot \mathrm{A1}\cdot\sum_{n=1}^{\infty}\frac{2}{\pi\cdot n}\cdot\left[1 - cos(\pi\cdot n)\right]\cdot\sin(\lambda_n\cdot r)\times,$$

$$\times\frac{\beta_m\cdot\lambda_n^2\cdot e^{-\beta_m\cdot\lambda_n^2\cdot\tau} - \frac{A1}{P}\cdot e^{-\frac{A1}{P}\cdot\tau}}{\beta_m\cdot\lambda_n^2\cdot P - A1}, \qquad (9)$$

where $\lambda_n = \frac{\pi\cdot n}{d_e}$ — own functions of the boundary value problem.

Equating $\frac{du_{\text{п}}}{d\tau}$ to $\frac{du_r}{d\tau}$ and solving the algebraic equation with respect to *P* we obtain:

$$P = \frac{A1\cdot d_e^2}{\beta_m\cdot\pi^2}. \qquad (10)$$

The moisture diffusion coefficient β_m depends on the heating temperature of the seeds θ and slightly on the humidity u according to the formula [14]:

$$\beta_m = \beta_m^0\cdot\left(\frac{\theta}{273+\theta_0}\right)^k, \qquad (11)$$

where β_m^0 – moisture diffusion coefficient at seed heating temperature θ_0, m^2/s;

k – empirical coefficient depending on humidity.

Substituting the value (11) in the formula (10) we obtain the minimum value of pressure *P* for gentle drying of seeds of cereals:

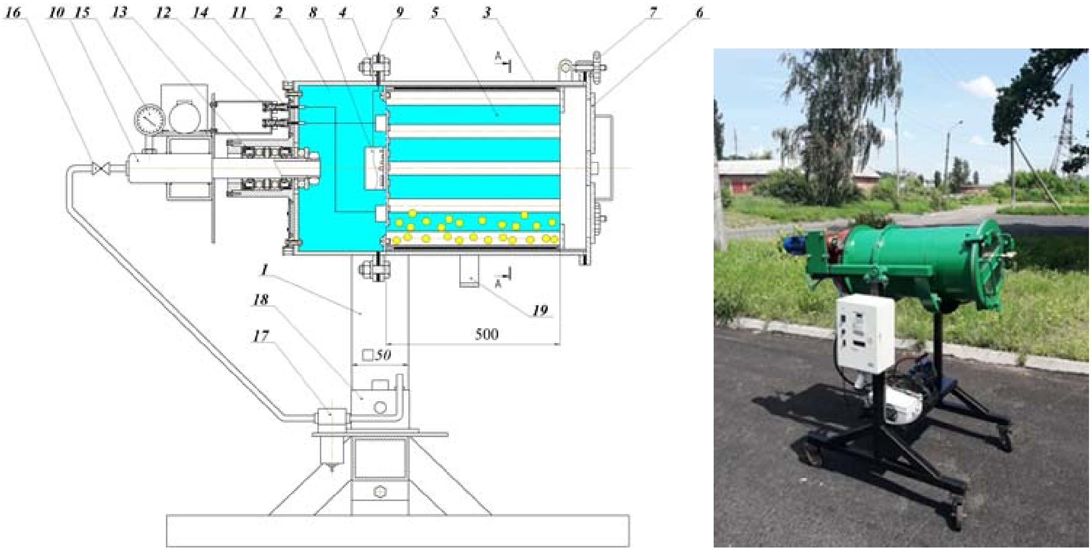
$$P \geq A1\cdot\frac{d_e^2}{\beta_m^0\cdot\left(\frac{\theta}{273+\theta_0}\right)^k\cdot\pi^2}. \qquad (12)$$

Dependence (12) shows that the value of the pressure inside the drying chamber *P* is directly proportional to the mode coefficient A1 and inversely proportional to the seed temperature θ. Dependence (12) also shows that for gentle drying of seeds in the drying chamber the value of pressure must not decrease less than the value of *P*. With a large value of dilution, damage to the seeds is possible. To verify the validity of this statement, it is necessary to conduct experimental research.

2. Experimental part

2.1 Methods of experiments

To conduct experiment, we use a drum dryer, inside the drying chamber of which it is possible to create a vacuum of up to 2 kPa (Fig. 4).



a

b

Figure 4. Structural scheme of the drum dryer (a) and its general view (b):

1 – rack; 2 – technological chamber; 3 – drying chamber; 4 – flanges; 5 – heating cylinder with blades; 6 – cover; 7 – clamping mechanism; 8 – transmitter of signals from sensors; 9 – Bluetooth antenna; 10 – hollow axis; 11 – chain crown; 12 – sliding contacts; 13 – drive flange; 14 – cap; 15 – vacuum gauge; 16 – valve of the vacuum pump; 17 – capacitor; 18 – vacuum pump; 19 – arc with support rollers

The vacuum inside the drying chamber (3) is created by the vacuum pump (18). When the required vacuum is reached, the readings are removed from the vacuum gauge (15), close the valve 16 and turn off the vacuum pump (18). The seeds are loaded into the drying chamber (3) by opening the cover (6). A capacitive humidity sensor and a digital temperature sensor DS18b20 are connected to the walls of the heating cylinder with blades (5). During the drying process, the drying chamber (3) rotates around a hollow axis (10). Seed heating in the drying chamber (3) took place through the cylindrical surface of the heating cylinder with blades (5), on the outer cylindrical surface of which through the insulator is wound nichrome wire. The temperature seeds were adjusted by changing the electric power supplied to the heater of the heating cylinder with blades (5). When the humidity reaches the heater is turned off, then open the vacuum valve on the cover (6), after reaching atmospheric pressure in the drying chamber (3) by means of a clamping mechanism (7) open the cover (6) and pour dried seeds (3).

To verify the validity of condition (12), a sample of corn weighing 715 g with an equivalent diameter of 7 mm, with an initial humidity of 24% and a temperature of 15 ºC was used. The drying exposure was determined as the time during which the corn seeds reach a moisture content of 13%. In the experiments, the temperature was changed from 25 ºC to 37 ºC in steps of 3 ºC. For each step, the drying exposure and the change in laboratory germination after drying at a dilution of 45 kPa, 60 kPa, and 75 kPa were determined. Owing to laboratory germination the level of seed injury after drying was identified.

The change in laboratory germination after drying was defined as the difference between the laboratory germination of the sample before drying and the laboratory germination after drying. Laboratory germination of maize samples was determined according to DSTU 4138-2002 [19]. Based on the calculations of the dependence (12) for the sample of corn, the limit value of the vacuum in the drying chamber is 52.4 kPa. This dependence was tested by a series of experiments at a dilution of 45 kPa and 60 kPa. At the same time, a visual inspection of corn seeds for cracks was performed with a magnifying glass. Also, the vacuum in the drying chamber changed from 42 kPa to 60 kPa in increments of 2 kPa, while calculating the percentage of seeds with cracks to the total number of seeds received for drying.

3. Results and Discussion

Figure 5 demonstates the result of visual inspection of corn seeds after vacuum drying at a vacuum of 45 kPa and 60 kPa at a temperature of 30 ºC.

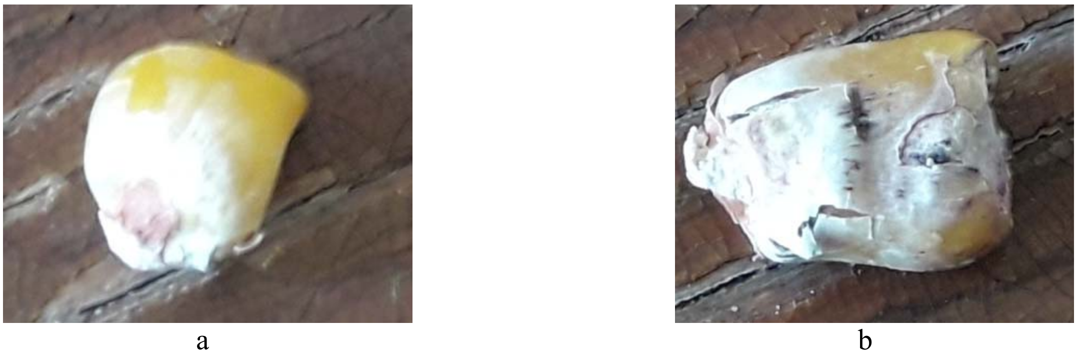

a
b

Figure 5. Appearance of maize seed at a vacuum of 60 kPa (a) and a vacuum of 45 kPa (b)

This review confirmed the validity of condition (12). Due to the significant difference in the drying rate inside the seed and in the surface layers, drying stresses occur, which result in cracks on the surface of the seed, which reduces the sowing quality. Therefore, when choosing the mode of drying the seeds must take into account condition (12).

Figure 6 shows a number of seeds with cracks as a percentage of the vacuum inside the drying chamber.

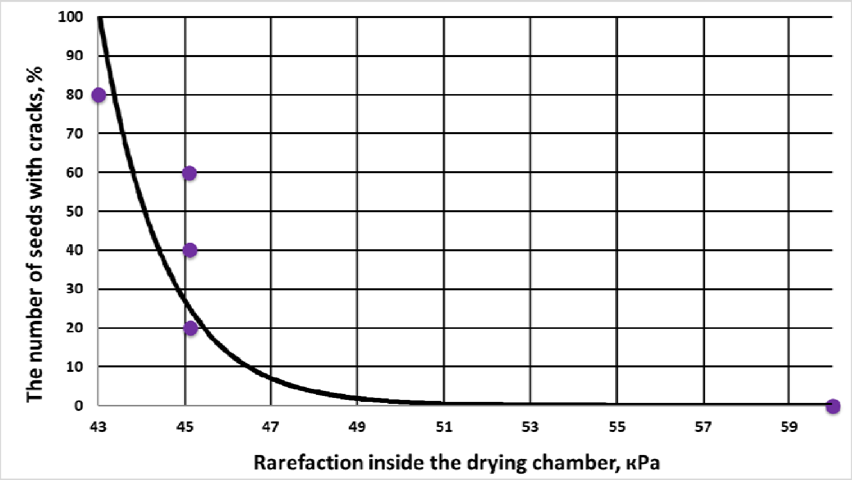


Figure 6. A number of seeds with cracks

It can be seen from Figure 6 that the percentage of cracks increases exponentially when the vacuum decreases above 45 kPa.The fact that cracked seeds begin to appear at different values of vacuum inside the drying chamber (43-51 kPa) is explained by the scattering of the values of the coefficient of diffusion of moisture inside the seeds of corn.

The effect of seed temperature and dilution inside the drying chamber on the change in laboratory germination of corn seeds is presented in Figure 7.

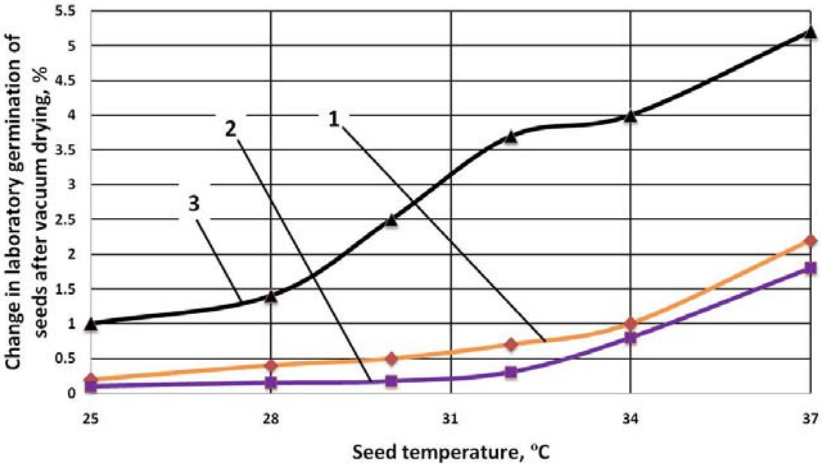


Fig. 7. Graphs of changes in laboratory germination of corn seeds
from its heating temperature: 1 - 75 kPa; 2 - 60 kPa; 3 - 45 kPa

According to Figure 7, it is seen that increasing the temperature of the seeds during drying reduces the laboratory germination of seeds. When the value of the vacuum in the drying chamber exceeds the value calculated under condition (12) - graph 3, the laboratory germination decreases sharply. When the vacuum in the drying chamber is reduced to the limit value, the change in the laboratory germination of seeds decreases, this is due to the fact that at a lower value of the vacuum, the part of heat that is spent directly on moisture evaporation increases.

Conclusions

These results show that the thermal stresses in capillary porous bodies, which include in particular the seeds of cereals, significantly depend on the value of the vacuum in the drying chamber. If the critical value of the vacuum is exceeded, cracks appear on the surface of the seeds due to different drying rates on the surface and inside. Therefore, to drying cereal seeds without thermal stresses, it is necessary to consider not only the heating temperature, but also the vacuum in the drying chamber, which must be close to the limit value.

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В.А. Швидя, С.П. Степаненко, Б.И. Котов, А.В. Спирин, В.Ю. Кучерук

Вакуумның тұқым ішіндегі ылғалдың таралуына әсері

Мақалада капиллярлы-кеуекті денелер болып табылатын дәнді дақылдар тұқымдарын кептіру кезіндегі термиялық зақымдану мәселесі шешілген. Кептіру камерасында вакуумды қолдану термиялық кернеу қаупін азайтады деген болжам бар. Осыған байланысты авторлар кептіру камерасының ішіндегі вакуумның тұқым ішіндегі ылғалдың таралуына әсерін зерттеуді қарастырған. Тұқымдар — бұл ылғалдың құрғақ затпен әртүрлі байланыстары бар күрделі материал. Жұмыс процесін орындау кезінде беткі қабаттардағы және тұқымдардың ішіндегі кептіру жылдамдығы әртүрлі жылдамдықта болады. Нәтижесінде кептіру кернеулері пайда болады, бұл тұқымдардың бетінде жарықтар тудырады. Шектік шарт ретінде жұту экраны бар диффузиялық диффузия теңдеуінің шешімі негізінде термиялық кернеулерсіз кептіру шарты табылады. Теориялық зерттеулерді тәжірибелік тексеру жүгері тұқымының мысалында арнайы жасалған тәжірибелік қондырғыда жүргізілді. Тұқымның өміршеңдігіне термиялық кернеудің әсері зертханалық өну арқылы анықталды. Эксперименттік зерттеулер теориялық тұжырымдардың сәйкестігін растады. Сонымен, капиллярлы-кеуекті дене болып табылатын дәнді дақылдардың тұқымдарын кептіру кезінде сиретудің шекті мәні бар, ол асып кеткен кезде тұқым бетінде және ішінде әр түрлі кептіру жылдамдығына байланысты жарықтар пайда болады. Дәнді дақылдардың тұқымын термиялық кернеусіз кептіру үшін қыздыру температурасын ғана емес, сонымен қатар кептіру камерасындағы сиретуді де ескеру керек, ол шекті мәнге жақын болуы керек.

Кілт сөздер: тұқымдардың термиялық зақымдануы, астық дақылдары, жылу температурасы, капиллярлы-кеуекті денелер.

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Влияние вакуума на диффузию влаги внутри семян

В статье решена проблема термического травмирования семян зерновых культур при сушке, которые являются капиллярно-пористыми телами. Была выдвинута гипотеза о том, что применение вакуума в сушильной камере позволяет снизить риск термических напряжений. В этой связи авторами рассмотрено исследование влияния вакуума внутри сушильной камеры на диффузию влаги внутри семян. Семена являются сложным по структуре материалом, в котором влага имеет разные связи с сухим веществом. При выполнении рабочего процесса скорость сушки в поверхностных слоях и внутри семян происходит с разной скоростью. В результате чего возникают сушильные напряжения, которые вызывают трещины на поверхности семян. На основе решения дифференциального уравнения диффузии с поглотительным экраном в качестве граничного условия найдено условие для сушки без термических напряжений. Экспериментальная проверка теоретических исследований проводилась на специально изготовленной экспериментальной установке на примере семян кукурузы. Воздействие термических напряжений на жизнеспособность семян определяли из-за лабораторной всхожести. Экспериментальные исследования подтвердили адекватность теоретических утверждений. Таким образом, при сушке семян зерновых культур, являющихся капиллярно-пористым телом, существует предельное значение разрежения, при превышении которого на поверхности семян появляются трещины из-за разной скорости сушки на поверхности и внутри. Для сушки семян зерновых культур без термических напряжений следует учитывать не только температуру нагрева, а также разрежение в сушильной камере, которое должно быть близко к предельному значению.

Ключевые слова: термическое травмирование семян, зерновые культуры, температура нагрева, капиллярно-пористое тело.

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