JUSTIFICATION OF VACUUM PARAMETERS FOR DRYING WET SEED

Viktor Shvydia, Serhii Stepanenko, Alvian Kuzmych, Ihor Popadiuk
Institute of Mechanics and Automatics of Agroindustrial Production
of the National Academy of Agrarian Sciences of Ukraine, Ukraine
stepanenko_s@ukr.net

Abstract. The article deals with theoretical and experimental substantiation of the value of vacuum inside the drying chamber for drying wet seeds. The differential diffusion equation for a model with an absorbing screen in partial derivatives with given initial and boundary conditions is used. On the basis of solving the partial differential equation of diffusion with an absorbing screen and the dependence of moisture evaporation from the free surface under conditions of constant air pumping out from the drying chamber, the condition of the critical vacuum value inside the drying chamber at which moisture evaporates from the outer surface of the seed without the formation of cracks is found. The value of the critical vacuum inside the drying chamber does not depend on the properties of the seeds and must be no less than the pressure of saturated water vapor at a given seed heating temperature. To confirm the critical value of the vacuum inside the drying chamber, experimental studies were conducted on the example of wet soybean seeds. It was found that at vacuum values from 2 to 10 kPa, cracks were observed on the outer surface of the seeds. At vacuum values close to critical, the number of seeds with cracks is more than 60%, which confirms the condition of a critical vacuum value inside the drying chamber. It was also found that when drying wet seeds, the vacuum at the beginning of drying should be kept at a level nearly to the critical one. Then the vacuum should be gradually increased to the values determined by the conditions of gentle drying without cracks when moisture evaporates to equilibrium humidity.

Keywords: moisture diffusion, drying chamber, vacuum, wet seeds, drying.

Introduction

Wet seeds are seeds whose surface is covered with a thin film of water. Such seeds include melons, vegetables and most fruit crops that are delivered for drying covered with a film of water. Such seeds are placed inside the pulp of the fruit and are covered with a layer of mucilage, which is then soaked with water. In addition, seeds of other crops may be delivered for drying wet due to particularly long wet harvest periods [1].

Traditional hot air drying in a moving, stationary or fluidized state leads to a deterioration in the sowing and technological properties of seeds [2-5] due to the negative impact of the seed heating temperature, which is 35-50 °C for convection dryers. Excessive heating of seeds also leads to the oxidation of polyunsaturated fatty acids [3], the destruction of proteins and other biologically active substances, which changes the quantitative composition of seeds and requires additional sorting after drying [6]. In addition, when a thick layer of seeds is loaded into the drying chamber, overdrying of nearby layers and underdrying of distant layers is observed.

One of the promising areas for improving the properties of seeds after drying, as a gentle technology, is the use of vacuum inside the drying chamber. The use of vacuum and simultaneous heating of seeds with microwave or infrared radiation [7-11] can reduce the effective drying temperature and reduce the negative impact of the dryer on the seeds, as well as improve the uniformity of drying. The use of pulsating drying modes can reduce energy consumption and more effectively remove moisture from the internal parts of the seed [11].

When drying seeds in a vacuum, in addition to moisture evaporation, moisture diffusion from the internal parts simultaneously occurs [12-13]. Different drying rates of the surface and internal parts of the seed lead to drying stresses, which contributes to the appearance of cracks on the seed surface and shrinkage of its individual parts.

The above studies considered evaporation only in a confined space, which in most cases is not true, since most vacuum dryers operate with constant air suction from the vacuum chamber. In addition, works [12-13] consider the evaporation of moisture from the surface of capillaries, but do not take into account the moisture that wets the outer surface of the seed. With the constant pumping of air from the drying chamber, as well as from the inter-seed space, the equilibrium humidity is close to zero, which changes the conditions of vacuum drying.

This requires additional justification of the value of vacuum under these drying conditions, which makes this study relevant. Justifying the value of vacuum inside the drying chamber will make it possible to safely dry seeds with a wet surface without cracking.

The purpose of the research is to ensure that wet seeds are dried in a vacuum without cracking.

Materials and methods

For the theoretical justification of the vacuum in the drying chamber, we used the partial differential equation of diffusion for the model with an absorbing screen [13], in which the seed was considered as an equilibrium ball:

$$\frac{\partial u}{\partial \tau} = \beta \cdot \frac{\partial^2 u}{\partial r^2}, \tag{1}$$

where u – seed moisture content, %;
τ – drying time, s;
β – diffusion coefficient, $m^2 \cdot s^{-1}$;
r – distance from the absorbing screen, m.

With the initial condition:

$$u(r, 0) = u_0, \tag{2}$$

where u_0 – initial seed moisture content, %.

Boundary condition (absorbing screen):

$$u(0, \tau) = u(d_e, \tau) = u_0 - k \cdot \tau, \tag{3}$$

where d_e – equivalent seed diameter, m;
k – evaporation rate of the free surface of water, calculated using the Hertz-Knudsen formula [14], $\% \cdot s^{-1}$:

$$k = \frac{\alpha}{\rho} \cdot \frac{P_H(\theta) - P}{\sqrt{\frac{M}{2\pi R \cdot T}}}, \tag{4}$$

where α – mass transfer coefficient, $kg \cdot m^{-4} \cdot Pa^{-1}$;
ρ – water density, 1000 $kg \cdot m^{-3}$;
$P_H(\theta)$ – pressure of saturated water vapor at seed temperature θ, Pa;
P – vacuum inside the drying chamber, Pa;
M – molar mass of water, $18 \cdot 10^{-3}$ $kg \cdot mol^{-1}$;
R – universal gas constant, 8.314 $J \cdot mol^{-1} \cdot K^{-1}$;
T – seed temperature, K.

Equations (2) and (3) define the boundary and initial conditions for the diffusion equation (1), the solution of which is obtained as a function of two variables: the seed moisture content as a function of the radial distance from the seed surface r and the drying time t. Equation (2) specifies the initial moisture content of the seed at $t = 0$, while equation (3) defines the moisture content at the seed surface for $r = 0$ and d_e. Therefore, it cannot be substituted with the temperature variable θ [15].

To experimentally substantiate the amount of vacuum inside the drying chamber, an experimental device consisting of a drying drum, a vacuum pump, and a control unit was constructed (Fig. 1).

A 10-kg sample of wet soybean seeds with an initial moisture content of 28% was loaded into a drying drum with a heater 1. During the drying process, the temperature of the soybean seeds was maintained at 30 °C, while the vacuum in the drying drum was varied from 2 kPa to 40 kPa. The dried seeds were visually inspected for cracks. The ratio of the number of seeds with cracks to the total number of seeds in the sample was determined as the seed damage index.

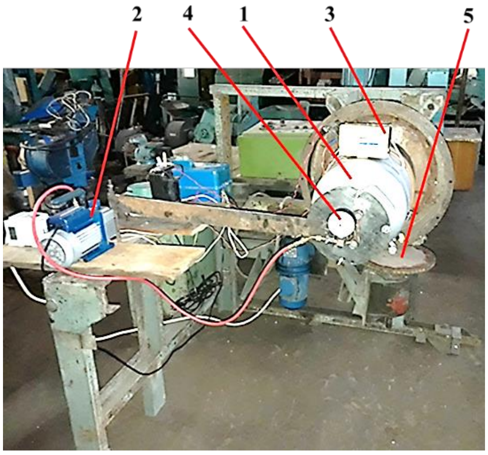

Fig. 1. **Experimental device for testing the effect of vacuum on the appearance of cracks on the surface of wet seeds:** 1 – drying drum with a heater; 2 – vacuum pump; 3 – seed temperature control unit; 4 – vacuum gauge; 5 – drive for rotation of the drying drum

Results and discussion

The partial differential diffusion equation (1) with initial condition (2) and boundary conditions (3) was solved by the Fourier method (separation of variables) [16; 17]. The solution is presented in the form of a functional series:

$$u(r,\tau) = u_0 - \frac{k}{2\beta}\cdot(r^2 - d_e\cdot r) - k \cdot\tau + \sum_{n=1}^{\infty}\frac{k\cdot {d_e}^2}{\beta\cdot(\pi\cdot n)^3}\left[-1^n - 1\right]\cdot\sin\left(\frac{\pi\cdot n\cdot r}{d_e}\right)\cdot \mathrm{e}^{-\beta\frac{\pi^2\cdot n^2}{{d_e}^2}\cdot\tau}. \tag{5}$$

The condition for drying without cracking on the seed surface is that the drying rate on the surface does not exceed the drying rate inside the seed [13]. Taking the partial derivative of τ from expression (5) and the derivative of τ from the boundary conditions (3), and equating them with each other, we obtain the algebraic equation:

$$-k = -k - k\sum_{n=1}^{\infty}\frac{-1^n - 1}{\pi\cdot n}\cdot\sin\left(\frac{\pi\cdot n\cdot r}{d_e}\right)\cdot \mathrm{e}^{-\beta\frac{\pi^2\cdot n^2}{{d_e}^2}\cdot\tau}. \tag{6}$$

Equality (6) is satisfied when $k = 0$. Expanding k by formula (4), we can write the following equality:

$$\frac{\alpha}{\rho}\cdot\frac{P_H(\theta) - P}{\sqrt{\frac{M}{2\pi R\cdot T}}} = 0. \tag{7}$$

It follows that for crack-free drying of wet seeds, it is necessary that the vacuum value inside the drying chamber is greater than the value of saturated water vapor pressure at a certain seed temperature θ:

$$P_{cr} \geq P_H(\theta). \tag{8}$$

From the condition of gentle vacuum drying for wet seeds (8), it follows that the vacuum value inside the drying chamber does not depend on the properties of the seeds, but it depends only on the saturated vapor pressure at a given seed temp erature θ. Therefore, the gentle drying regimes for any wet seed (drying chamber vacuum and seed heating temperature) can be described by the dependence of P_{cr} on θ (Fig. 2), similar to the dependence of saturated vapor pressure on temperature [18-19].

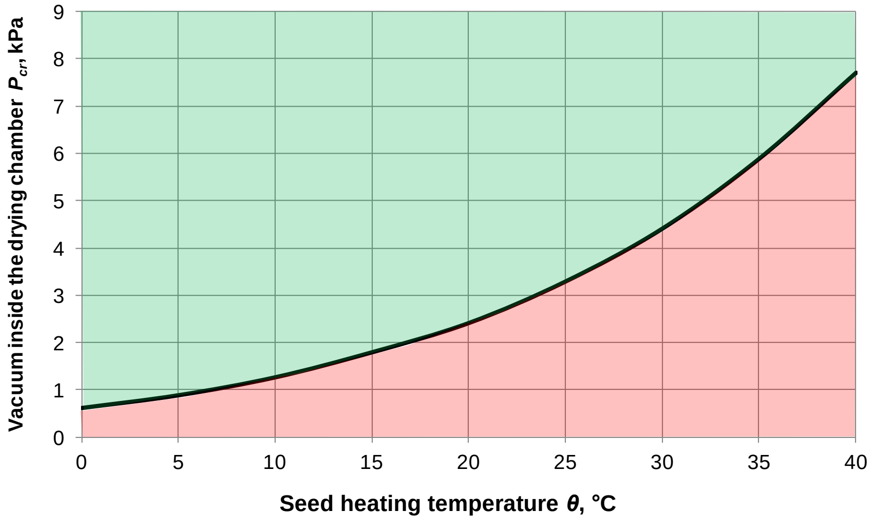

Fig. 2. **Dependence of the critical vacuum value inside the drying chamber P_{cr} on the seed temperature θ**

From the dependence shown in Fig. 2, it is possible to determine the critical vacuum value inside the drying chamber P_{cr}, knowing the seed heating temperature θ.

Fig. 3 shows the dependence of the damage coefficient K_S of wet soybean seeds on the value of the vacuum in the drying chamber P.

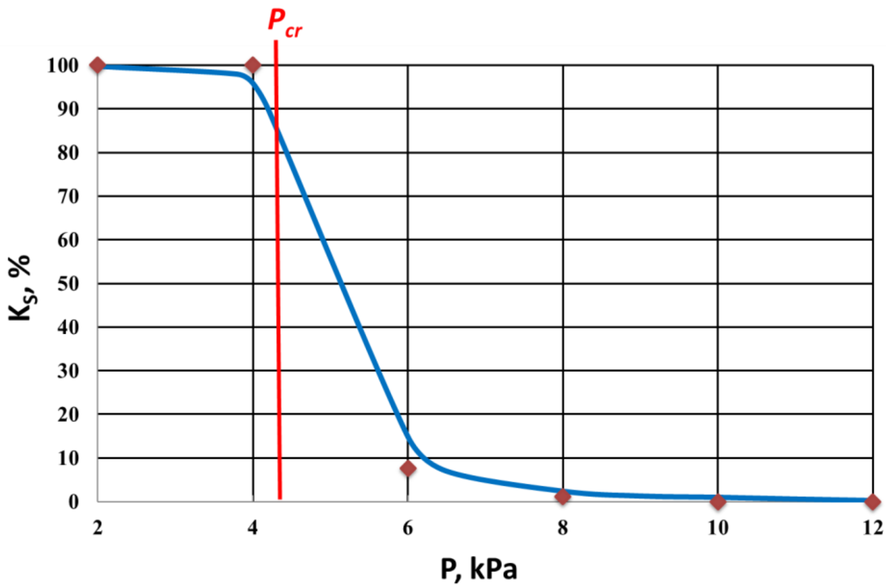

Fig. 3. **Dependence of the damage coefficient K_S of wet soybean seeds on the value of rarefaction in the drying chamber P at heating temperature of 30 °C**

The dependence in Fig. 3 shows that as the vacuum value approaches the critical value, the number of damaged seeds approaches 100%. When the pressure is increased above 10-12 kPa, no seed damage is observed. Damaged seeds are observed even at a vacuum greater than the critical P_{cr} up to 10 kPa, which is explained by the different heating temperature of the seeds θ.

Fig. 4 shows the results of the experimental verification of the gentle vacuum drying condition for wet seeds (8) using wet soybean seeds as an example.

At a vacuum less than the critical value at a given temperature (4.4 kPa), cracks were observed on the surface of soybean seeds due to the formation of drying stresses, which corresponds to condition (8) (Fig. 4).

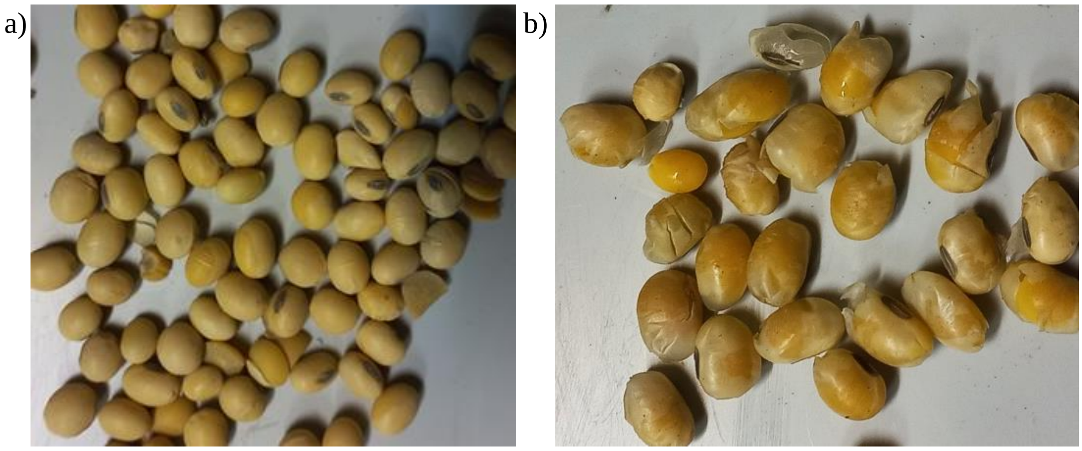

Fig. 4. **Appearance of soybean seeds after drying at vacuum value more than critical (a) and less than critical (b) at temperature 30 °C**

It should be noted that condition (8) is valid only for the drying period when the water film covering the outer surface of the seed evaporates. Since during this period only the free surface of the water covering the outer surface of the seed evaporates, the critical value of the vacuum inside the drying chamber P_{cr} does not depend on the properties of the seed. Subsequently, the drying process takes place according to the dependencies described in [13], which is characterized by a higher value of the critical vacuum P_{cr}. Therefore, for drying wet seeds, at the beginning of drying, the vacuum can be maintained at a level nearly to the value according to condition (8). Then the vacuum can be gradually increased to the values determined by the conditions of gentle drying. When evaporating moisture from the inner walls of the capillaries, it is necessary to take into account the equilibrium humidity (air from the seed capillaries is almost not sucked out).

Conclusions

According to the results of the conducted researches it is established that the critical value of vacuum inside the drying chamber for drying of wet seeds should be not less than the pressure of saturated water vapor at the given temperature of heating seeds, so at the range of heating temperatures 20-40 °C when drying seeds, the critical value of vacuum is 2.4-7.7 kPa. The critical value of vacuum in the drying chamber does not depend on the properties of seeds.

The results of these studies take into account not only water evaporation from the seed surface, but also diffusion processes in the middle of the seed. However, the obtained results refer to the drying period, when evaporation of liquid film from the seed surface and diffusion of moisture from the center of the seed occur simultaneously. When describing the following drying steps, the equilibrium moisture content must be taken into account. Therefore, for drying moist seeds, the vacuum at the beginning of drying should be maintained at a level close to the critical vacuum. Then the vacuum can be gradually increased to values determined by the conditions of gentle drying without cracking when moisture evaporates to equilibrium moisture.

The obtained results can be used in calculations of vacuum dryers for seeds of vegetable and fruit crops, the seeds of which come to drying covered with a film of liquid. This will reduce the loss of biological properties of seeds during drying.

Acknowledgements

The research was carried out within the framework of the project under grant 2023.04/0040, funded by the National Research Foundation of Ukraine.

Author contributions

Conceptualization, V.S.; methodology, V.S.; validation, V.S. and S.S; formal analysis, V.S. and A.K.; investigation, V.S. and S.S.; data curation,, V.S. and I.P.; writing – original draft preparation, V.S.; writing – review and editing, V.S. and A.K.; visualization, V.S. and I.P.; project administration, S.S.; funding acquisition, V.S. All authors have read and agreed to the published version of the manuscript.

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