The influence of convective drying on the change of Kirpichev mass-exchange criterion

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Abstract. The results of experimental studies of changes in the Kirpichev mass-exchange criterion during drying of grain related to leguminous crops, which are susceptible to cracking and deterioration in quality during drying, are presented. Based on the results of experimental studies of the moisture content of the center and the surface of the caryopsis, regression equations have been obtained to determine the maximum allowable values of the Kirpichev criterion for different grain drying modes, which have been verified by determining the germination energy of the grain.

1. Introduction
The heat and mass-exchange criteria of Kirpichev, Kossovich and Rebinder [1] are among of the main criteria, determining the drying efficiency and maintaining the quality of the dried material. The Kirpichev criterion is the main criterion for moisture transfer during drying. In the drying process, many materials, due to the violation of the drying regimes, can lose their quality: wood, leather, building materials, agricultural materials, as well as grain of various crops. The quality deterioration of grains susceptible to cracking - rice, corn, soybeans, legumes - can be noted in the process of drying. In the Instruction for Drying, for some shaft grain dryers, the limits of the temperature of the drying and heating of the grain are provided, which ensures its quality. However, there are new types of grain dryers and methods of grain drying of leguminous crops, for example, which require some refinement of these parameters. So, the Instructions for drying in direct-flow mine grain dryers for drying, for example, soybeans, allow the temperature of the drying agent depending on the initial humidity from 50 to 800°C. Recommendations indicate that the level of cracking of shells of soybeans is 50-90%, and the level of cracking of soybeans themselves is 20-70%, even at a temperature of the drying agent of 55°C. Although, such an important parameter as the maximum permissible temperature for heating them is not mentioned. In accordance with, the drying agent should not exceed a temperature of 40°C, with a soybean seed moisture of 16-19%, and with a seed moisture of 25-30% - 30°C. The formation of cracks in the grains during drying occurs due to a significant unevenness in the moisture content of the central and surface parts of the grains caused by the low value of the moisture diffusion coefficient. The Kirpichev mass-exchange criterion, which is also called the technological criterion, is the value characterizing the process of crack formation. It determines the intensity ratio of moisture evaporation from the surface of the grains to the of moisture content gradient, which determines the supply of
moisture from the center to the surface. For the parabolic distribution of moisture content in the caryopsis, the Kirpichev mass-exchange criterion can be determined by the dependence [1,2]:

$$K_{1m} = q_m R_v a_n u_o u_n = \frac{2(u_n - u_{\text{mon}})}{u_m}$$  \hspace{1cm} (1)

where \(q_m\) is the moisture evaporation intensity from the surface of the grain, kg / (m\(^2\)h); \(R_v\) - determining caryopsis size, m; \(a_n\) - moisture diffusion coefficient, m\(^2\) / h; \(p_0\) - density of dry matter of the grain, kg / m\(^3\); \(u_o\) - initial moisture content of the grain, kg H2O / kg dry...; \(u_n\) and \(u_{\text{mon}}\) - moisture content in the center and on the surface of the sample, kg. H2O / kg dry...

During a period of constant drying speed, the Kirpichev mass-exchange criterion depends on the temperature, relative humidity and speed of the drying agent. It does not depend on the duration of this period. In the period of the decreasing drying rate, the Kirpichev criterion changes in time, since the flow of removed moisture, as well as the diffusion coefficient of moisture, change during the drying process and the value of this function will be determined by the ratio of these flows. Moreover, the Kirpichev criterion is directly proportional to the drying intensity and inversely proportional to the moisture diffusion coefficient.

As for the individual caryopsis, due to its small size and relatively insignificant humidity, the period of constant drying speed is practically absent and the change in the Kirpichev criterion will be determined by the change in moisture content between the center and the surface of the caryopsis.

In the Instruction for drying for grain of various crops, the temperature limits of the agent for drying and heating grain of various initial humidity are established, ensuring the preservation of its quality. However, they are not tied to the maximum allowable value of the Kirpichev criterion and are intended only for certain types of grain dryers. The study of the dependence of the Kirpichev criterion on the initial moisture content of the grain, its heating temperature, the temperature of the drying agent and the rate of its filtration will improve the drying conditions of grain and the design of grain dryers.

The aim of the study is to study the dependence of the Kirpichev criterion on the initial moisture and grain temperature, the temperature and the filtration rate of the drying agent in relation to the drying of leguminous crops, as well as the grain of other grain crops subject to cracking during drying, to ensure and maintain their quality and reduce energy consumption during drying.

2. Materials and methods

These studies are a continuation of earlier studies of the moisture content fields on the model body of chickpea caryopsis, in order to increase the domain of determination and to obtain new calculated dependences. Additional studies were carried out in an experimental setup to determine the moisture content fields on the model body of chickpea kernels using the direct method. The installation consists of an experimental cell with a diameter of 100 mm and a height of 200 mm, on the mesh bottom of which there is a one grain layer caryopsis with the given initial moisture content; a wind tunnel on which an experimental cell is installed using an electromagnet; a fan sucking air through an electric air heater with an adjustable number of sections, and after heating, supplying it through a control valve and a diaphragm to the wind tunnel.

Air flow rate is measured using a micromanometer, the temperature inside the caryopsis and the drying agent is measured by chromel-kapel thermocouples with an automatic potentiometer. The temperature and relative humidity of the atmospheric air is measured by a psychrometer. A thermostat is used to prepare caryopsis for experiments. Caryopsis cutting with the release of the spherical segment is carried out by a special device with parallel knives, and the selection of the components of the spherical segment - by a punch with cylindrical knives. Weighing the components of the grain is carried out on a torsion scales VT. The selected samples are dried in special foil cuvettes - in drying cabinet SESh-3M. The moisture content of the components of the grains was determined by mass wastage according to standard method GOST 13586.5-93. Three caryopsides are used for one sample. In this case, the moisture content of the central, middle and surface parts of the caryopsides is determined during the selection of prototypes during the drying process, and the average moisture content of the caryopsides is determined as a control. The studies were conducted on chickpea caryopsis with an initial...
grain moisture content of Wn = 18.9 - 40.7%, and a temperature of the drying agent t.c. = 35, 50 and 700C, its filtration rate Vf = 0.3 -1.0 m / s, the drying time ranged from 90 to 240 minutes depending on the parameters of the grain and the drying agent.

3. Results and discussion
It was found that the filtration rate of the drying agent for a high-moisture caryopsis, does not play a significant role (figure 1).

![Figure 1. Change of the mass-exchange criterion of Kirpichev during the drying process at different filtration rates of the drying agent: 1 - filtration rate Vph = 0.3 m / s, initial humidity W = 38.7%; 2 - V = 1.0 m / s, Wn = 40.7%. Drying agent temperature t=a.s. is 350C.](image1)

As can be seen from the figure, at approximately the same initial grain moisture, the values of the Kirpichev mass-exchange criterion for the same drying time are close to each other. Moreover, with an increase in the drying time and a decrease in the grain moisture, the value of the Kirpichev mass-exchange criterion initially increases due to a decrease in the moisture diffusion coefficient, and then decreases due to a decrease in the total flow of evaporated moisture and a decrease in the moisture content difference between the center and the surface of the caryopsis. It was found that with an increase in initial humidity to Wn = 38.7 - 40.7%, the time to reach the maximum value of the Kirpichev criterion is 70 -90 minutes with a value of KIm(max) = 0.65 - 0.7, which indicates an increase in the moisture content difference between the center and the surface of the caryopsis and the greatest risk of of the grain cracking.

The moisture content of the grain significantly affects the value of the mass-exchange criterion of Kirpichev and the time of its onset (figure 2).

![Figure 2. The change in the Kirpichev mass-exchange criterion in the drying process at different initial grain moisture: 1 - initial humidity Wn = 18.9%; 2 - 22.3; 3-30.8; 4 - 36.2. Drying agent temperature t.a.s. is 500C, its filtration rate Vf = 0.5 m / s.](image2)
At a filtration rate of the drying agent of 0.5 m / s, its temperature of 50 ° C and initial grain moisture from 18.9 to 36.2%, the maximum value of the Kirpichev mass-exchange criterion changes from 0.25 to 0.7, respectively, and its onset time decreases from 105 up to 70 minutes, so, the shift to the beginning of the drying process occurs.

The temperature of the drying agent, which determines the grain heating temperature, also affects the time of the onset of the maximum value of the Kirpichev mass-exchange criterion, and with increasing temperature of the drying agent this value decreases significantly (figure 3). That is, with an increase of the temperature of the drying agent at the maximum value of the Kirpichev criterion, the danger of cracking and deterioration of grain quality comes faster.

The regression equation has been obtained to calculate the maximum value of the Kirpichev mass-exchange criterion during drying:

\[
K_{\text{im}}^{(\text{max})} = 0.012 W_n + 0.011 t_{\text{c,a}} + 0.65 V_\phi - 0.83, \quad R^2 = 0.9661
\]  

where \( W_n = 21.7 - 30.8\% \), t.a.s. = 35 - 70 ° C, \( V_\phi = 0.3 - 1.0 \) m / s - the initial grain moisture, temperature and filtration rate of the drying agent respectively. In this case, the grain heating temperature is taken equal to the temperature of the drying agent.

An increase in the maximum value of the Kirpichev criterion with the growth of the grain moisture, the temperature, and the filtration rate of the drying agent is associated with an increase in the rate of the moisture evaporation and the gradient of moisture content between the center and the surface of the caryopsis.

The equation has been also obtained to calculate the time to reach the maximum value of the Kirpichev mass-exchange criterion in the drying process,

\[
\tau_{\text{max}} = 239.8 - 1.98 W_n - 1.51 t_{\text{c,a}} - 44.0 V_\phi, \quad \text{мин}, \quad R^2 = 0.9155
\]  

where \( W_n = 18.9 - 40.7\% \), t.a.s. = 35 - 70 ° C, \( V_\phi = 0.3 - 1.0 \) m / s - the initial grain moisture, the temperature and the filtration rate of the drying agent respectively. As can be seen from this equation, the time to reach the maximum value of the Kirpichev mass-exchange criterion decreases both with an increase of the initial moisture content of the grain, and with an increase of the temperature and the filtration rate of the drying agent, i.e. the danger of cracking during drying with an increase of these parameters comes earlier. The significant effect of the speed of the drying agent on reaching the maximum value of the Kirpichev criterion should be noted.

To prevent this negative phenomenon, “for each product, the range of acceptable gradients is established experimentally; the area of such operating parameters, at which drying of products with moisture gradients not higher than permissible is guaranteed” [2]. Such an area is also defined for drying leguminous crops, providing, for example, the maximum heating temperature of 40° C for mine direct-
flow grain dryers with grain moisture up to 20%. Using the above equations (2) and (3), and assuming the temperature of the drying agent to be equal to the grain heating temperature, at a filtration rate of the drying agent in the grain layer equal to 0.5 m/s, typical for shaft grain dryers, the maximum value of the Kirpichev criterion will be 0.175, and its time of occurrence is 118 minutes.

To determine the maximum allowable value of the Kirpichev criterion in accordance with [3], an assessment of the influence of regime parameters of drying on the viability and germination of chickpea seeds has been made. For viability “V” and germination “G”, the following calculation equations have been obtained:

\[ V = 70.4 + 8.1 \, W_k - 0.53 \, W_n - 2.3 \, \Theta, \quad R^2 = 0.8594, \] (4)

\[ G = 76.2 + 7.9 \, W_k - 0.52 \, W_n - 2.35 \, \Theta, \quad R^2 = 0.8589, \] (5)

where \( W_k \) and \( W_n \) - grain moisture before and after drying, %, \( \Theta \) - grain heating temperature equal to the temperature of the drying agent, °C.

According to the obtained equations, it is possible to calculate the heating temperature of the legume crops grain to provide 100% of viability and germination. For example, when drying grain of legumes with an initial humidity of 20 to 14% and ensuring 100% germination, the temperature of heating of the grain calculated by equation (5) should not exceed 32.50 °C. In this case, the maximum allowable value of the Kirpichev criterion calculated by equation (2) should not exceed the values \( K_{im} \) (ext) = 0.093. This exceeds the calculated maximum value of this criterion \( K_{im(\max)} = 0.175 \), and involves drying under seed mode, with a decrease of the grain heating temperature.

To intensify the drying process of such grain and increase the maximum allowable value of the Kirpichev mass-exchange criterion, it is advisable to use ramped drying modes, combine drying with tearing and active ventilation, use the grain “dry aeration” technology to reduce the moisture content gradient in the caryopsis and utilize the heat that was previously used to heat the grain, as well as electrophysical and other methods that contribute to the intensification of the process of moving moisture in the grain [4].

4. Conclusions

The experimental study of the change in the Kirpichev mass-exchange criterion during drying of grain subject to cracking has been made. Its dependence on the initial moisture content of the grain, the temperature, and the filtering rate of the drying agent has been determined. Equations have been obtained to determine its maximum value, as well as the time to reach this value during the drying process. According to the indicators of viability and germination on the example of chickpea grain, the maximum allowable value of the Kirpichev criterion depending on the drying conditions has been established.

References

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