Influence of water temperature and moisture increase on wheat temperature during moistening

Yevgen Kharchenko, Valentyn Chorny, Andriy Sharan

National University of Food Technologies, Kyiv, Ukraine

Abstract

Keywords:

Wheat
Temperature
Moisture

Article history:

Received 01.03.2020
Received in revised
form 29.05.2020
Accepted 30.06.2020

Corresponding author:

Yevgen Kharchenko
E-mail:
a-537@ukr.net

DOI: 10.24263/2310-
1008-2020-8-1-7

Introduction. The purpose of this work is to develop a simplified dependence for determining the grain temperature of wheat during moistening, taking into account the heat capacity coefficients, which relates the grain temperature of the wheat after moistening with its initial temperature, water temperature and the amount of water to moisten the grain.

Materials and methods. The studies were performed on the basis of mathematical modeling using the law of thermal conductivity of grain and water. The experimental data were processed using the least squares method. Checking adequacy obtained depending performed using Fisher's F-test.

Results and discussion. When moistening of wheat grain, the temperature of which increases from -10 °C to 50 °C with water, the temperature of which increases from 5 °C to 60 °C leads to an increase in grain temperature in a linear relationship. This made it possible to develop a linear dependence of the wheat grain temperature after moistening, which takes into account the initial grain temperature and the initial water temperature with a constant amount of water added to the grain.

The dependence of the change in wheat grain temperature on its initial temperature and different amount of added water was investigated. The water temperature was 20 °C. The analysis of the results showed that the wheat grain temperature increases linearly with increasing its temperature and increasing the amount of water added to the grain mass. It is established that linear straight change the angle of inclination relative to the point equal to temperature 10 °C. This made it possible to introduce in a linear relationship an indicator that takes into account the amount of water added to the grain mass.

Checking the adequacy of the obtained linear dependence showed that the equation is adequate. Analysis of the obtained data showed that the deviation of the grain temperature calculated by the linear equation and the physical model varies within 1.0 °C in absolute value.

Conclusion. After conducting a study of the change in the grain temperature during moistening with heated water, we obtained a generalized dependence, which takes into account the thermal conductivity coefficients. The obtained dependence can be recommended for the analysis of the wheat grain temperature in the process of its moistening.

Introduction

Grain temperature in flour milling technology is a factor that determines the conduct of hydrothermal treatment processes [1, 2, 4] and grinding [3, 5, 9].

In winter and in the transition period of the year, when grain with reduced or even negative temperature flows from storage systems to flour mills, the yield of high-grade flour decreases and also its quality. When the grain temperature drops below 15 °C, its technological properties deteriorate significantly, especially at temperatures below 0 °C [4]. In works [4, 8] showed changes in grain temperature in the cold season during grain preparation for grinding.

The mechanical properties of wheat grain are significantly affected by temperature [3, 4]. Cold grain is more brittle [3] than room temperature or high temperature grain, so its strength decreases [4] and microhardness numbers increase [4]. When grinding such a grain, the endosperm is deformed into large particles, and the bran into smaller particles, resulting in the yield of large particles increasing, and the specific energy consumption for grinding 1 kg of grain is reduced [4]. Due to the increased brittleness of the bran they are easily crushed and getting into the flour impairs its color [4]. At the same time, the detaching adhering endosperm particles from the bran deteriorates [4]. When milling grain with a low temperature, its ash content increases by 0.02–0.06% compared to the flour obtained by milling grain in the summer [4]. When grinding cooled grain, both moist and dry, its strength decreases [4]. When milling the bran and endosperm are crushed almost equally, which is contrary to the principles [4] grinding grain during processing it into high-grade flour. In this regard, the processing of grain with low or negative temperature into flour significantly deteriorates the performance of flour mills and reduces their profitability [4]. The energy consumption per unit of the formed surface decreases with decreasing temperature [4].

In conditions of temperate continental climate, moistening of wheat grain in flour milling plants is carried out by heated water [3]. Practical determination of grain temperature in a stream after the addition of heated water to it is a difficult task [3], but it can be solved on the basis of grain thermal conductivity laws.

To determine the grain temperature Egorov G.A. cites dependence, which is based on thermophysical properties of grain [3]. The practical application of this formula is complicated by the fact that it is necessary to take into account the water heat capacity, which varies depending on the water temperature and the grain heat capacity, which changes with the change of moisture and grain temperature. One of the disadvantages of this formula is the need to take into account the mass of grain and water. This complicates the practical use of this dependency. These disadvantages give rise to a simplified dependency that takes into account the above parameters.

Materials and methods

Determination of grain temperature after moistening

The grain temperature after moistening t_g , °C was determined by the formula [3]:

$$t_g = \frac{M_g t_0 c_g + m_w t_w c_w}{(M_g + m_w) \cdot c_{mg}} \quad (1)$$

where M_g – mass of grain, kg; M_w – mass of water, kg; t_0 – grain temperature before moistening (cold grain), °C; t_w – water temperature, °C; c_g – specific heat capacity of grain,

J/kg·K; c_w – specific heat capacity of water, J/kg·K; c_{mg} – specific heat capacity of moistened grain, J/kg·K; M_g – mass of grain, which is equal to $M_g = 1.0$ kg; m_w – mass of water added to the grain for its moistening is calculated by the formula 5, kg.

Determination of specific heat capacity of grain

The specific heat capacity of dry grain, c_g , J/kg·K was calculated by the formula [12]:

$$c_g = (891.7 + 87.49W - 1.545W^2 + 0.01149W^3) \times [1 + 0.287 \cdot 10^{-3} (25 - W)(t_0 - 28)] \quad (2)$$

where W – grain moisture by total weight, %; t_0 – grain temperature, °C.

Given that the grain temperature after moistening is unknown and is the subject of research, the formula 2 was not used to calculate the specific heat capacity of the moistened grain.. Specific heat capacity of grain, c_{mg} , J/kg·K after moistening was determined by the formula [11, 12]:

$$c_{mg} = \frac{W}{100} c_w + \frac{100 - W}{100} c_{ds} \quad (3)$$

where W – moisture grain, %; c_w – specific heat capacity of water, calculated by the formula 4, J/kg·K; c_{ds} – specific heat capacity of wheat dry matter, which is equal $c_{cp} = 1550$ J/kg·K.

Determination of water specific heat capacity

The specific heat capacity of water, c_w , J/kg·K was calculated by the formula proposed by Osborne, Stimson and Ginningson [7]:

$$c_w = c_w(15^\circ \text{C}) \cdot \left[0.99618 + 0.0002874 \left(\frac{t_w + 100}{100} \right)^{5.26} + 0.011160 \cdot 10^{-0.036t_w} \right] \quad (4)$$

where $c_w(15^\circ \text{C})$ – specific heat capacity of water at 15 °C, $c_w(15^\circ \text{C}) = 4185.5$ J/kg·K; t_w – water temperature, °C.

Determining the amount of water to grain moistening

The mass of water, m_w , kg was determined by the following formula:

$$m_w = \frac{W_1 - W_0}{100} \quad (5)$$

where W_1 – final predetermined moisture content of the total grain weight, %; W_0 – initially set grain moisture to total weight, %.

Mathematical processing of research results

The dependencies were processed based on the least squares method [6, 10].

The adequacy of the obtained mathematical model was verified by Fisher criterion by comparing the calculated F_c and tabulated F_t values of the criterion. Subject to inequality $F_c \leq F_t$, it was concluded that the obtained equation was adequate [6, 10].

Results and discussion

Temperature dependence of wheat grain after its moistening with different water temperature

Figure 1 shows the results of calculating the grain temperature during moistening with different water temperatures and a fixed value of the increase in moisture of 4 %. Water temperature was taken from +5 to +50 °C.

Figure 1. Temperature dependence of moistened wheat on the water temperature and the initial grain temperature (shown only three straight):

1 – water temperature +5 °C; 2 – water temperature +20 °C; 3 – water temperature +50 °C.

Analysis of the data Figure 1 shows that the nature of the change in the moistened grain temperature can be approximated by linear dependencies for all parameters of grain moistening. The slight deviation from the linear form of the obtained points can be explained by the fact that the calculated formula 1 takes into account the nonlinear dependence of the water heat capacity coefficient, which introduces an error in the calculation of the final grain temperature.

The linear dependences of the grain temperature after moistening, which are shown in Figure 1 are approximated by linear equations:

– for water temperature +5 °C:

$$t_{mg} = 0.885 \cdot t_0 + 0.3857 \quad (6)$$

– for water temperature +10 °C:

$$t_{mg} = 0.886 \cdot t_0 + 0.7928 \quad (7)$$

– for water temperature +20 °C:

$$t_{mg} = 0.886 \cdot t_0 + 1.6357 \quad (8)$$

– for water temperature +30 °C:

$$t_{mg} = 0.886 \cdot t_0 + 2.45 \quad (9)$$

– for water temperature +40 °C:

$$t_{mg} = 0.886 \cdot t_0 + 3.2785 \quad (10)$$

– for water temperature +50 °C:

$$t_{mg} = 0.886 \cdot t_0 + 4.0785 \quad (11)$$

– for water temperature +60 °C:

$$t_{mg} = 0.886 \cdot t_0 + 4.8928 \quad (12)$$

where t_{mg} – temperature of moistened wheat grain, °C; t_0 – initial grain temperature, °C.

The analysis of the obtained equations shows that the free coefficient b increases with increasing water temperature, which gives grounds to approximate the value of this coefficient from the change in water temperature and to obtain the corresponding dependence. The coefficient a , does not change and is 0.886.

In Figure 2 shows the dependence of the coefficient b of the linear equations 6–12 on the water temperature during moistening of wheat grain. As can be seen from Figure 2 his dependence is described by a linear equation:

$$b = 0.082 \cdot t_w - 0.016 \quad (13)$$

where t_w – water temperature, which is added to grain, °C.

Figure 2. The dependence of the coefficient b on the water temperature during moistening of wheat grain

Taking into account equation 9–13, we can write the general equation for calculating the grain temperature of wheat, taking into account its initial temperature and the water temperature at which it is moistened:

$$t_{mg} = 0.886 \cdot t_0 + 0.082 \cdot t_w \quad (14)$$

where t_0 – initial grain temperature, °C; t_w – initial water temperature, °C.

It can be seen from equations 6–12 that at a constant value of moistening but at different temperatures the free term of equations b , changes, and the coefficient a remains unchanged.

This gives rise to conjecture that coefficient a may change with the amount of water added to the grain during moistening. On this basis, it is sufficient to study the change in grain temperature depending on the initial grain temperature and different increase in moisture, but the water temperature must be constant for all parameters. This will allow to analyze the change in the grain heating process for one variant and the results can be transferred to any other conditions, but if the nature of the process is also linear.

Dependence of wheat grain temperature on the amount of water added

Modeling of temperature change at constant temperature, but the different amount of water needed to increase the grain moisture content to 16.0 % indicates that an increase in the amount of water that must be added to the grain during moistening leads to an increase in the grain temperature. That is, with increasing water temperature, the grain temperature also increases. The results of the studies are shown in Figure 3.

Figure 3. Change in grain temperature when moistened with constant temperature water +20 °C and changes in the initial grain temperature and increase in moisture: 1 – $\Delta W = 1.0$ %; 2 – $\Delta W = 2.0$ %; 3 – $\Delta W = 3.0$ %; 4 – $\Delta W = 4.0$ %; 5 – $\Delta W = 5.0$ %; 6 – $\Delta W = 6.0$ %.

The nature of the temperature change of the moistened grain can be approximated by linear dependences for all moistening parameters.

The linear dependencies (Figure 3) are described by the following equations:

– with increasing moisture $\Delta W = 1.0$ %:

$$t_{mg} = 0.985 \cdot \Delta W + 0.3857 \quad (15)$$

– with increasing moisture $\Delta W = 2.0$ %:

$$t_{mg} = 0.951 \cdot \Delta W + 0.8357 \quad (16)$$

– with increasing moisture $\Delta W = 3.0$ %:

$$t_{mg} = 0.918 \cdot \Delta W + 1.2357 \quad (17)$$

– with increasing moisture $\Delta W = 4.0$ %:

$$t_{mg} = 0.886 \cdot \Delta W + 1.6357 \quad (18)$$

– with increasing moisture $\Delta W = 5.0$ %:

$$t_{mg} = 0.852 \cdot \Delta W + 2.0142 \quad (19)$$

– with increasing moisture $\Delta W = 6.0$ %:

$$t_{mg} = 0.816 \cdot \Delta W + 2.4071 \quad (20)$$

where ΔW – the amount of moisture that is added to the grain in the moistening process, %.

An analysis of equations 15–20 shows that the coefficient a in the equations decreases with an increase in the amount of moisture that is added to grain for its moistening.

To enter the moisture increase parameter in equation 14 conduct analysis of coefficient change a from the moisture increase. In Figure 4 shows the dependence of the coefficient a the equations 15–20 on the increase of moisture in grain.

Figure 4. Dependence of the coefficient a on increase in moisture ΔW

The linear dependence shown in Figs. 4 is approximated by a linear equation:

$$a = -0.033449 \cdot \Delta W + 1.0189 \quad (21)$$

where ΔW – increase in moisture, $\Delta W = (W_1 - W_0)$ %; W_1 – final (predetermined) grain moisture, %; W_0 – initial grain moisture content, %.

Given the equation 21, equation 14 will take the following form:

$$t_{mg} = (-0.033449 \cdot \Delta W + 1.0189) \cdot t_0 + 0.082 \cdot t_w \quad (22)$$

Equation 22 makes it possible to determine the grain temperature of wheat after its moistening and takes into account the initial grain temperature, the water temperature during moistening, and the increase in moisture. This greatly simplifies the calculations of grain temperature after moistening, since it takes into account the coefficients of grain and water heat capacity. Dependency 22 is recommended for approximate practical application to analyze grain temperature.

Equation 25 is valid only for determining the temperature of the wheat grain during its moistening. For other types of grain, it is necessary to enter other parameters of the grain thermal conductivity.

Checking the adequacy of the obtained mathematical dependence

Let us check the adequacy of the regression equation for Fisher criterion. Calculate the value of the grain temperature after moistening at the initial water temperature $t_w = 55^\circ\text{C}$ and moisture increase $\Delta W = (16.0 - 12.5) = 3.5\%$ by formulas 1 and 25. The initial grain temperature is changed from -10 to 50°C in 10°C increments. The results of the calculation are given in Table 1.

Table 1
Results of the calculation of the grain temperature after moistening for each variant of the initial grain temperature with a constant moisture increase of 3.5%, and the initial water temperature 55°C .

Initial grain temperature	Moisturized grain temperature, $^\circ\text{C}$	
	by physical model 1, x_{1i}	by the equation 22, x_{2i}
-10	-3.5	-4.5
0	3.9	4.5
10	12	13.5
20	20.8	22.5
30	30.1	31.5
40	40.1	40.6
50	50.7	49.6
Average value, $\bar{x}$	22.0	22.5

The results of the dispersion calculation are given in table. 2.

Table 2
Intermediate dispersion calculations

$\text{№ } p / n$	$x_{1i} - \bar{x}_1$	$x_{2i} - \bar{x}_2$	$\left(x_{1i} - \bar{x}_1\right)^2$	$\left(x_{2i} - \bar{x}_2\right)^2$
1	-25.5	-27.0	651,0	730,5
2	-18.1	-18.0	328,1	325,0
3	-10.0	-9.0	100,3	81,5
4	-1.2	0.0	1.5	0.0
5	8.1	9.0	65.4	80.5
6	18.1	18.1	327.1	326.6
7	28.7	27.1	822.9	732.9
Σ			2296.2	2277.0

Calculate the dispersion of the values obtained by the physical equation 1:

$$S_1^2 = \frac{\sum_{i=1}^n \left(x_{1i} - \bar{x}_1\right)^2}{n-1} = \frac{2296.2}{7-1} = 382.7$$

Calculate the dispersion of the values obtained by the equation 22:

$$S_2^2 = \frac{\sum_{i=1}^n (x_{2i} - \bar{x}_2)^2}{n-1} = \frac{2277.0}{7-1} = 379.5$$

Calculate the estimated value of Fisher criterion [10]:

$$F_e = \frac{S_1^2}{S_2^2} = \frac{382.7}{379.5} = 1.0084$$

Table value of F-Fisher criterion for the degree of freedom of the numerator and denominator is 4.3.

The inequality $F_c < F_t$ holds because $1.0084 < 4.3$. On this basis, we can conclude on the adequacy of $f = (7-1) = 6$ for the obtained regression equation 25 to the physical model of process 1, which describes the change in grain temperature after its moistening.

The results are given in table. 1 indicates that the calculation temperature deviation ranges 1.0 °C. Such changes can be explained by the fact that the water heat capacity coefficient has a nonlinear relationship.

Conclusion

1. Therefore, by mathematical modeling of the change in grain temperature during its moistening with heated water, we obtain a generalized dependence:

$$t_{mg} = (-0.033449 \cdot \Delta W + 1.0189) \cdot t_0 + 0.082 \cdot t_w$$

2. The advantages of this dependency are its simplified form, which allows to determine the temperature of wheat grain in moistening with warmed water, taking into account the amount of water added to the grain and the initial temperature of the wheat grain. This does not require consideration of the thermal conductivity coefficients of water and grain, since these coefficients are taken into account when calculating the temperature of grain and water at their different values. The dependence can be used to calculate water temperature more than 60 °C.
3. The calculation error at -10 to 50 °C ranges between 1.0 °C in absolute value.
4. The obtained dependence can be recommended for the analysis of the grain temperature of wheat in its the moistening process.

References

1. Dexter, J.E., Sarkar, A.K. (2003), Flour: Roller milling operations. Encyclopedia of Food Sciences and Nutrition, Second Edition, *Academic Press*, pp. 2535–2543.
2. Dubat, A., Bock, J. (2019), Impact of the wheat tempering procedure on the grain behavior during milling and on the flour quality at the laboratory. Part 1: Effect of final tempering moisture content, *Chopin Technologies*, 1, pp. 1–15
3. Egorov, G.O. (1968), *Hydrothermal grain processing*, Kolos, pp. 96.
4. Egorov, G.O., Moksyakova, A.A., Ulchenko, R.A. (1981), *Features of the preparation and grinding of frozen grain of wheat*, CNTII, pp. 56.

5. Fang, C., Campbell, G.M. (2003), On predicting roller milling performance V: Effect of moisture content on the particle size distribution from first break milling of wheat, *Journal of Cereal Science*, 37, pp. 31-41.
6. Granato, D., Ares, G. (2014), *Mathematical and Statistical Methods in Food Science and Technology*, John Wiley and Sons, pp. 514.
7. Kaye, G.W., Laby, T.H. (1970), *Tables of physical and chemical constants*, Longmans, Green & Co, London, New York, Toronto.
8. Kharchenko, Y.I., Shapovalenko, O.I., Ilchuk, V.B., Pertsev, S.M. (2010), The study of the temperature of the grain in its preparation for milling, *Grain Storage and Processing*, 3, pp. 45.
9. Lupu, M.I., Padureanu, V., Canja, C.M., Mazarel, A. (2016), The effect of moisture content on grinding process of wheat and maize single kernel, *IOP Conf. Series: Materials Science and Engineering*, 145, pp. 1-7.
10. Lychkovskiy, Y.I., Sverdau, P.L. (2012), Higher mathematics. Theory of Scientific Research in Pharmacy and Medicine, *Znannia*, pp. 476.
11. Stankevych, G.M., Strakhova, T.V., Atanazyevich, V.I. (1997), Grain drying, *Lybid*, pp. 352.
12. Zhydko, V.I., Riezchikov, V.A., Ukolov, V.S. (1982), *Grain drying and grain dryers*, Kolos, pp. 239.