# Effect of Tempering After Drying on Cooling Shelled Corn

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A recent advance in grain drying methods, called dryeration and consisting of three stages, was developed to reduce the brittleness and improve the quality of dried grain. The three stages are (a) rapid drying with heated air to a moisture level two to three percentage points higher than the desired final moisture level, (b) tempering with no air flow for a prescribed length of time, and (c) cooling the grain slowly with low air flow rates to remove the final two to three percentage points of moisture by utilizing the heat in the grain.

A field study by Thompson and Foster (1967) on dryeration of shelled corn showed that the amount of moisture removed during cooling increased as the tempering time increased. Under one heated air drying condition (187 F drying air temperature and 45 cfm per bu air flow rate), they found that the amount of moisture removed incident to cooling was higher after eight hours of tempering than after 2-hr and 4-hr tempering periods. It was also higher than the amount of moisture removed after 12 hr of tempering. Thus, there appears to be an optimum length of time for tempering.

The purpose of this study was to determine the effect of tempering time on the cooling rate and on the moisture removal during the cooling of shelled corn.

## TESTS, PROCEDURE AND EQUIPMENT

A series of tests was conducted in the laboratory. The test procedure involved three stages. First, the corn was dried. Then it was tempered before cooling. Finally it was cooled with air. A factorial experimental design was used involving five levels of tempering time (0, 1, 2, 4 hr, and complete), and three levels of cooling air flow rate (5, 20, and 75 cfm per bu). Sixty percent of the tests were replicated.

The equipment used in each test included a dryer, a cooler and a tempering cabinet. A special test section was used to contain the grain.

The test section was a cylinder made of fiberglass insulating material. Bare and shielded copper-constantan thermocouples were installed on the center line at different distances from the bottom of the column, so that each location had one shielded thermocouple to indicate air temperature and a bare thermocouple to indicate an intermediate temperature considered to be halfway between that of the air and that of the grain.

Air used for cooling the corn was maintained at near constant condition by an Aminco air conditioner and forced through the grain in the test section. Cooling air flow rate was measured by a rotameter and controlled by a combination of a throttling valve and a relief valve.

Corn initially at about 23.5 percent moisture was dried to 17 ± 0.2 percent, wet basis. Sample size was either 0.2 or 0.4 bu. In all except the complete tempering tests, the corn was dried in the 8-in. diameter test section using heated air at 165 ± 5 F. Immediate cooling was considered as 0-hour-tempering. For the 1-, 2-, and 4-hr tempering, the test section with the grain was removed from the dryer, almost sealed with Styrofoam lids at the top and bottom, weighed, and put in the tempering cabinet. Temperature in the cabinet was adjusted and controlled at 145 ± 2 F, the average temperature of the corn after drying was completed. After tempering, the test section was taken out of the cabinet, weighed and the lids removed to start cooling.

The complete tempering was accomplished by drying the corn slowly with unheated air to 17 ± 0.2 percent. After several hours, the corn was packed in almost-sealed metal cans, heated in an oven to 145 ± 2 F, emptied in the test section, and cooling was started.

The temperatures of the air and grain were recorded throughout each test. The sample was weighed at 15-min intervals.

## TEST RESULTS, ANALYSIS

### Cooling

A temperature ratio for the grain defined as

$$TR_i = \frac{T_{gi}-T_a}{T_{goi}-T_a} \quad \ldots\ldots\ldots\ldots [1]$$

was used in the analysis, where $TR_i$ is the temperature ratio at the ith location in the grain bed, $T_{gi}$ is the grain temperature, $T_{goi}$ is the original grain temperature at the ith location, and $T_a$ is the cooling air temperature at the inlet. A dimensionless average temperature ratio for the whole bed of grain was calculated as follows:

$$TR_{av} = \frac{1}{2d} \left[(TR_0+TR_1)X_i + (TR_1+TR_2)X_2 + \text{---} + (TR_n+TR_e)X_n\right] \quad \ldots\ldots [2]$$

in which d is the total depth of the bed and $TR_O$ and $TR_e$ are the temperature ratios at the entrance and the exit, respectively. $X_i$ (i = 1, 2, ---n) is the distance between (i-1) and the ith location in the bed. Plots of $TR_{av}$ versus time of cooling are shown in Figs. 1, 2 and 3 for the five levels of tempering and at the three levels of air flow rate.

For a comprehensive analysis that involved tempering time and air flow rate as independent factors, the data were arranged so that the time required to accomplish a certain percentage of cooling was used as the dependent variable. A detailed explanation of the technique used in the analysis, as well as the results of the analysis, are given by Sabbah (1971).

As tempering time was increased, the rate of cooling increased, and the cooling time decreased at all levels of air flow rate. Similar results were obtained when the air flow rate was increased. The statistical analysis applied to the data indicated that the effect of both tempering and air flow rate on cooling time was highly significant (0.01 level).

The effect of tempering on cooling rate (and on cooling time) was more pronounced in the early stages of cool-

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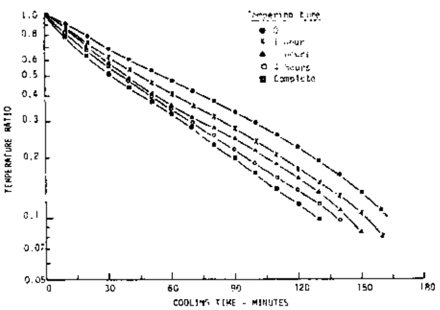

**FIG. 1 Effect of tempering on the rate of cooling corn with 5 cfm per bu air flow rate.**

ing and decreased as the cooling progressed. The effect of tempering on cooling time was more pronounced at low air flow rates and less effective at higher air flow rates. These relationships were statistically significant.

## MOISTURE REMOVAL

The effect of tempering on moisture removal incident to cooling was presented in terms of moisture ratio, $MR_c$, defined as follows:

$$MR_c = \frac{M - M_c}{M_f - M_c} \quad \ldots\ldots\ldots [3]$$

in which M is the average moisture content of the corn at any time during cooling, $M_f$ is the average moisture content of the corn after high temperature drying and $M_c$ is the final corn moisture content when no further moisture is removed incident to cooling. $M_c$ is believed to be more appropriate for the drying incident to cooling than the equilibrium moisture content used in conventional drying calculations. $M_c$ can be calculated as follows:

$$M_c = M_f - M_{max} \quad \ldots\ldots\ldots\ldots [4]$$

in which $M_{max}$ is the maximum percentage of moisture that can be removed by the usable residual heat in the grain assuming that the exhaust air comes out at temperature and moisture equilibrium with the initial grain temperature and moisture content. It was calculated by applying a heat balance between the cooling air and the grain.

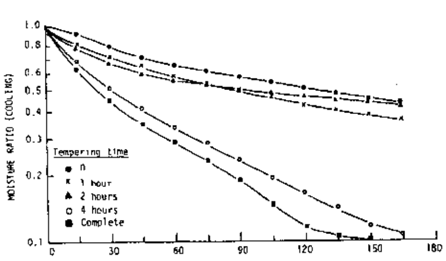

**FIG. 4 Effect of tempering time on the amount of moisture removed during cooling of corn with 5 cfm per bu air flow rate**

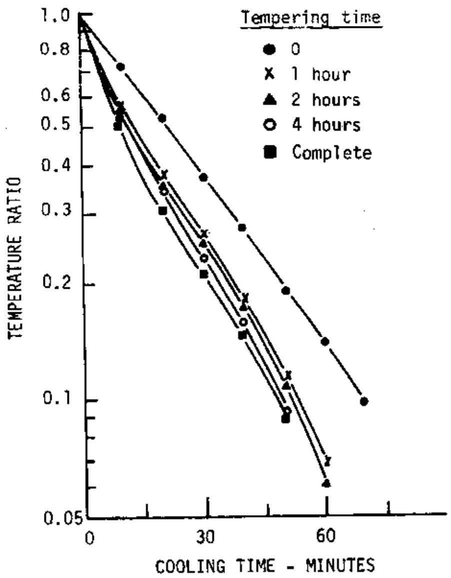


**FIG. 2 Effect of tempering on the rate of cooling corn with 20 cfm per bu air flow rate.**

Figs. 4, 5 and 6 present plots of $MR_c$ versus time of cooling for the three air flow rates.

The amount of moisture removed incident to cooling decreased as air flow rate increased at all levels of tempering. For example, following complete tempering and when cooling at air flow rates of 5 cfm per bu, about 90 percent of $M_{max}$ was removed when 90 percent of the cooling was accomplished. At air flow rates of 20 cfm per bu, and complete tempering, about 68 percent of $M_{max}$ was removed. At 75 cfm per bu, about 47 percent of $M_{max}$ was removed. Thus, at lower air flow rates, more of the residual heat in the corn was used in evaporating moisture.

As tempering time increased, both total amount and rate of moisture removal incident to cooling increased at all levels of air flow rates. As a result, the time required to complete cooling

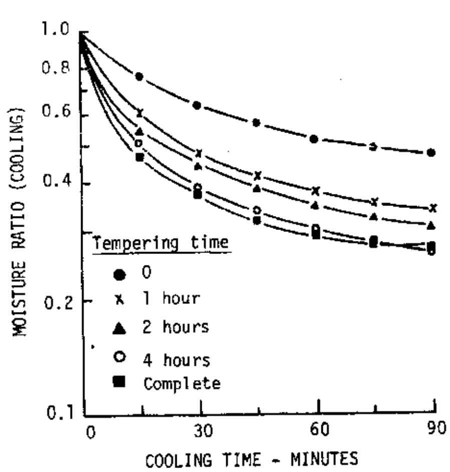


**FIG. 5 Effect of tempering time on the amount of moisture removed during cooling of corn with 20 cfm per bu air flow rate**

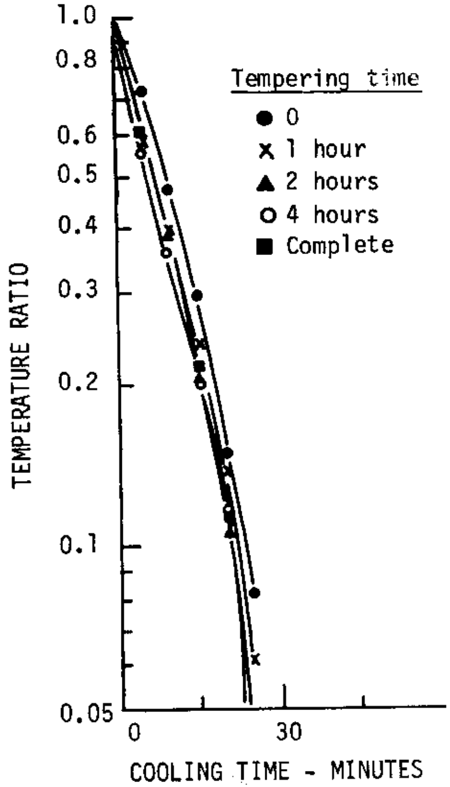


**FIG. 3 Effect of tempering on the rate of cooling corn with 75 cfm per bu air flow rate**

of the grain decreased. For example, at 20 cfm per bu air flow rate, it took 66 min to accomplish 90 percent of the cooling and remove 0.47 $M_{max}$ following no tempering. After complete tempering, and with the same air flow rate, it took 45.5 min to accomplish 90 percent cooling and to remove 0.68 $M_{max}$. The effect of tempering on cooling time was more pronounced at low air flow rates (5 and 20 cfm per

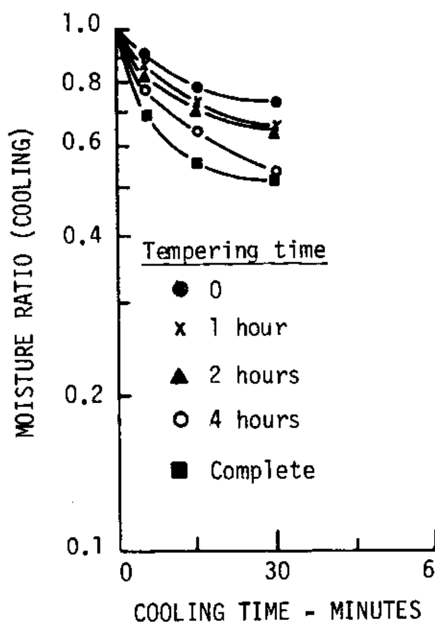


**FIG. 6 Effect of tempering time on the amount of moisture removed during cooling of corn with 75 cfm per bu air flow rate**

bu), where large amounts of moisture were removed, than it was at high air flow rates (75 cfm per bu) where relatively small amounts of moisture were removed.

There is no explanation for the low moisture removal indicated for two-hr tempering in cooling tests at the five cfm cooling air flow rate (Fig. 4). Apparently, the data from this test are in error, since similar results did not occur in tests at 20 and 75 cfm per bu air flow rates (Figs. 5 and 6).

The statistical analysis showed that the effect of air flow rate and tempering on the moisture removal was significant at the 0.01 level. It showed also that the interaction between tempering and air flow rate was significant.

## DISCUSSION

Drying grain with heated air establishes a temperature and a moisture gradient in each kernel. However, several workers have neglected the temperature gradient, and have assumed a uniform temperature in both drying and cooling analyses.

Ideally, tempering takes place in an airtight and well-insulated container so that no moisture escapes and no heat is conducted out of the grain. Under these conditions the change in the average temperature and moisture content of the grain due to tempering is negligible. The only change during tempering is in the moisture distribution in the kernels.

As cooling starts and cooling air passes through hot grain, heat is transferred from grain to air in two forms, sensible and latent. The rate of sensible and latent heat transfer are governed by both internal and external resistances. External resistances are dependent on air velocity. The internal resistance to sensible heat transfer is very low and can be neglected, thus sensible heat transfer depends mainly on air velocity. Internal resistance to moisture transfer is dependent on mass diffusivity which is a function of grain temperature and moisture content. Thus, rate of moisture removal and, accordingly, rate of cooling attributed to moisture removal depends more on temperature and moisture content of the grain and less on air velocity.

The amount of heat that can be removed during cooling is limited. Thus, as air flow rate increases, cooling attributed to sensible heat transfer increases, and cooling attributed to moisture removal decreases. The air flow rate can reach a level where the amount of moisture removed becomes insignificant, and therefore, all cooling is due to sensible heat transfer. At this level of air flow rate, tempering has no effect on moisture removal or on cooling rate.

## TEMPERING AND MOISTURE DIFFUSION THEORY

A rather detailed theoretical analysis was performed to provide a basis for predictions of the effect of tempering on moisture removal and cooling of grain. The following discussion presents briefly the approach used and defines a proposed tempering index. Sabbah (1971) has more details.

The following assumptions were made in the analysis:

1 Internal moisture diffusion was the only significant process occurring during the tempering period. It was assumed to be isothermal and one-dimensional because the single kernel was assumed to be a sphere.

2 The moisture diffusing from the kernel surface to the interstitial space during the tempering process (no air flow) was neglected, and calculations showed that this actual amount of moisture was insignificant.

3 All the moisture in the kernel at the beginning of the tempering process was assumed to be concentrated at a point in the center of the kernel.

The time to complete the tempering process, $t_{max}$, was defined as the time required for the moisture concentration at the surface to reach a maximum, determined as

$$t_{max} = R_k^2/6D \quad \text{. . . . . . . . . . [5]}$$

where $R_k$ equals the radius (ft) and D is the mass diffusivity of the kernel in sq ft per hr. Since the moisture at the beginning of tempering cannot all be concentrated at one point, as stated in assumption 3, and its distribution was unknown, the actual time for complete tempering, $t_c$, was estimated by

$$t_c = 0.8\, t_{max} \quad \text{. . . . . . . . . . . . . [6]}$$

This definition of $t_c$ is based on the research data reported herein.

Mass diffusivity, D, is a function of grain temperature and moisture content. Data obtained by Chittenden and Hustrulid (1966) and Baughman (1967) were used to obtain the following expression for mass diffusivity as a function of M, moisture content (dry basis, decimal equivalent) and $T_g$, grain temperature (degrees F).

$$D = 0.057\, M \exp \frac{-4812}{T + 460} \quad \text{. . [7]}$$

Using these equations for corn initially at 19 percent moisture content and 140 F, $t_c$ was found to be 9.7 hours. Under the same conditions in the field, Thompson and Foster (1967) reported that in tempering trials of two, four, six, eight, and 12 hours duration, the eight-hr period gave essentially complete tempering (no greater moisture removal during cooling was obtained with any of the other tempering periods).

A tempering index was formulated to predict the effect of partial tempering on rate of moisture removal during cooling. The above assumptions were used, and the tempering index, I, is a function of the actual tempering time, t, the diffusivity, D, and the equivalent radius of the spherical kernel, $R_k$.

$$I = \frac{1.0}{(6tD/R_k^2 + 0.2)^{3/2}}$$

$$\exp 3/2 \left(1.0 - \frac{1.0}{6tD/R_k^2 + 0.2}\right) \quad \text{. . . [8]}$$

In order to estimate the moisture removed during the cooling process, a drying equation is necessary which applies during the process of cooling grain that has been completely tempered. Development of such an equation was beyond the scope of this research. However, using data from this research, drying curves were plotted based on complete tempering and several levels of partial tempering. The tempering index, applied graphically, gave a reasonable prediction of the actual drying curve for partially tempered grain.


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