HEATING THE GRAIN BY HOT WATER "PART OF A TWO-STAGE RECIRCULATING COUNTERFLOW DRYER"

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ABSTRACT

HEATING THE GRAIN BY HOT WATER
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By

Shehab Sokhansanj

Conventional grain drying is a major energy consumer in production agriculture. Considerable investigation is being done to improve the energy utilization of grain dryers. One of the designs proposed for less energy requirement to dry corn and other grains is a two-stage recirculating counterflow dryer. The dryer consists of a heater utilizing water as a heating medium and a cooler and dryer which uses air for moisture evaporation. Air and water will be thermally coupled in a heat exchanger and after transferring their energy, are recirculated within the system.

In this study, a yellow shelled seed corn was investigated for water absorption and heat transfer characteristics as a single particle and as a moving bed. After the completion of the heating process, a measure of corn quality was made with respect to germination, damage and stress cracks and chemical losses.

It was found that a maximum of 90 seconds is sufficient for corn to reach the equilibrium temperature with water at constant temperatures of 180, 160 or 140°F. A maximum of 5-6 percent increase in moisture content is predicted when the initial moisture content is the lowest (15.5 percent wet basis). Germination increases slightly at 140°F and drops rapidly at higher temperatures. Chemical losses amount to low and negligible quantities. For example, starch losses are below .005 percent, protein .1 percent and ash .02 percent.

A computer program for simulating the heater was developed in order to adjust water and grain flows within the time required to heat the grain.

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LIST OF SYMBOLS

A	Surface area, ft^2
a	Specific surface area, ft^{-1}
C	Heat capacity, BTU/lbmin-^oF
c	Concentration, lb/ft^3
D	Diffusion coefficient, ft^2/sec
d	Diameter, ft
G	Mass velocity, lbm/ft^2-hr
G_e	Apparent mass velocity, lbm/ft^2-hr
h	Convective heat transfer coefficient, BTU/hr-ft^2-^oF
j	Mass diffusion, lbm/ft^2-hr
k	Thermal conductivity, BTU/hr-ft-^oF
L	Length, ft
$\overline{M}$	Average moisture ratio
m	Moisture content
q	Rate of heat transfer, BTU/ft^2-hr
T	Temperature (water), ^oF
t	Time, hours
V	Volume, ft^3
v	Velocity, ft/sec
V_e	Apparent velocity, ft/sec

x Characteristic dimension

ρ Density, lbm/ft^3

μ Viscosity, lbm/ft-hr

ψ Shape factor

θ Grain temperature, ^{o}F

α Thermal diffusivity

Dimensionless Groups

BIOT	$= h\left(\frac{V}{A}\right)/k$	BIOT Number
N_u	$= hx/k$	Nusselt Number
Pr	$= C\mu/k$	Prandtle Number
R_e	$= \frac{\rho V d}{\mu}$	Reynolds Number

Subscripts

P Grain

W Water

o Initial

∞ Surroundings

s Effective

x x-axis direction

in Initial

f Final

Abbreviations

MC	Moisture content
DB	Dry basis
WB	Wet basis
ml	Mililitre
gr	Gram
lb	Pound
mv	Millivolt

I. INTRODUCTION

Future projections of increased costs and reduced availability of fuels in food production necessitate the reassessment of agricultural operations and related processes. An inventory of energy expenditure through the whole course of crop production is a basic requirement in order to eliminate unnecessary operations or improve the efficiency of the essential processes.

Grains and the grain products are the major source of food and feed, and also have numerous industrial applications in the world. Because of large amounts of grain produced (Table A-1) and the short time available, harvesting of the grain starts from the time when the grain moisture content is high. Mechanized harvesting of the grain requires rather high moisture (20-22 percent for corn) in order to minimize the losses. Harvested high-moisture grain is not suitable to be stored for extended time periods. The moisture contained in the grain has to be reduced to a safe level. Artificial drying is a basic practice, in order to reduce the moisture content and preserve the grain safely. About 70 percent of the energy required to produce corn (Table A-2) is used for artificial drying. This energy is required to remove the moisture contained within the grain kernel and to energize other accessories required in a dryer. Many designs have been devised to expose the grain to the hot air. Stationary drying columns and continuous flow beds are examples of dryers that are commercially available.

Theoretically, 960 BTUs are required for one pound of water at 212^{O}F to evaporate at atmospheric pressure (latent heat of vaporization). To the above energy, some additional amount has to be added as sensible heat for increasing water temperature to 212^{O}F. The energy for blowing air and moving the grain and the energy which will be lost, due to the inefficiency of the system, also have to be considered. Available dryers consume from 1500 to 3500 BTU per pound of water to evaporate from the grain. Table A-4 shows energy requirements of different types of dryers.

There have been many recent efforts to investigate the drying process in order to find new ways to reduce the energy requirements of grain dryers. Because of low thermal and drying efficiency, which is about 50 percent, some new designs and modifications have been proposed to improve efficiency. Foster et al. (1973), Anderson (1972), Converse (1972), Lerew et al. (1972) and Bakker-Arkema et al. (1974) experimented or simulated modifications which improved somewhat the overall efficiency. Roth *et al*. (1973) simulated a dryer that showed very low energy requirements. The dryer is a recirculating counterflow device (Fig. 1) with a completely closed air circulation system. A heat exchanger/condenser is used to condense the water evaporated from the grain in order to reclaim the energy of vaporization. Since the moisture leaves the system as a liquid, the theoretical energy requirement for drying is low. Roth *et al*. (1973) reported that about 350-500 BTU is needed to evaporate one pound of water from corn. This means that about a four- to sixfold decrease in energy requirement is obtained compared to conventional drying systems.

There have been some potential problems in the counter-flow drying system. Because of its higher sensitivity to varying environmental conditions, air is considered a limiting factor. Thermal properties of the air are relatively low and impose questions such as its pumping costs and heat exchanger size. Therefore, based on the original design concept and the problems with air as a pure heating medium, it was suggested by Roth *et al*. (1973) that water or perhaps other liquids be used in the above system.

The present work is a preliminary study to evaluate the problems involved in using water in the proposed process as a heating medium.

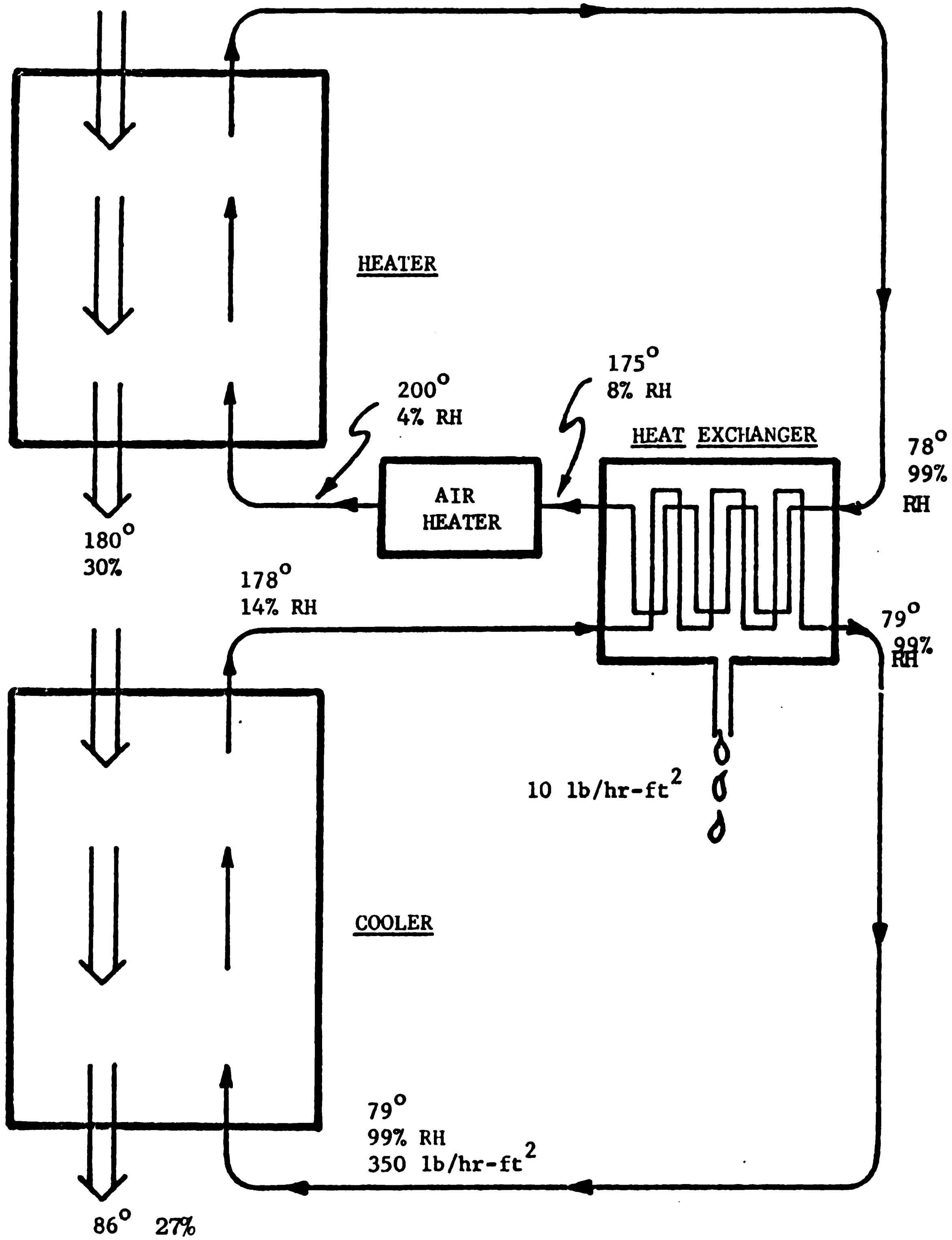

Figure 1. Simulation test of the two-stage recirculating counterflow (from Roth *et al.*, 1973).

II. BACKGROUND AND REVIEW OF LITERATURE

As far as the author knows, there are no investigations available on the use of hot water to heat grain for a short period of time. However, much research has been done in the grain processing industry to clarify the relationships between water and grain for some processes. Wet milling, malting and dry milling are examples of the processes in which the grain is exposed directly to water.

Wet Milling

The process of extraction of starch, oil, sugar and other substances from corn or other starchy grains is called wet milling. The term "wet milling" is used because the corn is wet when it is ground and water is used as the suspension medium during most of the other operations.

According to Matz (1959), in the wet milling process, shelled corn is first transferred to steeping tanks. The purpose of the steeping operation is to soften the kernels so that subsequent milling operations and separation can be carried out efficiently. Warm water containing a small amount of sulfur dioxide is circulated through the steeping tank. The steeping water, containing six to ten percent solid material, will be withdrawn, concentrated and used for such purposes as manufacturing penicillin or animal feeds, and as an ingredient in the food industry. The corn, after steeping in successive operations, will be degerminated and the hulls and fiber will be separated from the starch and gluten.

Malting

In this process, a steeping operation is also involved. Barley kernels are steeped in warm water (68^{o}F) for a certain period of time (30-72 hours) until their moisture content reaches 42 to 44 percent. The steeped barley is then placed in special compartments for germination. The water, after steeping, is not of great importance because there are no extracted materials in it. During the process, water does not penetrate through the semi-permeable membranes of the barley (Matz, 1959).

Dry Milling

The process of making flour from grain is called dry milling or simply milling. The operation consists of five main parts: reception and storage, cleaning, tempering or conditioning, milling grain to flour, and storage of the flour. Water is used in part of the cleaning process and in the operation of tempering and conditioning. After removing light impurities and undesirable seeds from wheat, a water wash is employed as the final cleaning step. The water dissolves the dirt and permits stones and bits of metal to sink. In some cases, it appears to reduce microbiological contamination of the wheat (Matz, 1959). In all cases, the washer tends to add about one percent to the original moisture content of the wheat.

Tempering refers to addition of water to the grain to raise the moisture content from 15 to 19 percent for wheat and from 17 to 22 percent for corn in a period of 18 to 72 hours. Conditioning, in contrast to tempering, always involves the use of heat (100-140^{o}F) since quick diffusion of water into the endosperm, as well as the bran, is desired.

Water Absorption

One of the major problems in bringing grain and water in direct contact is the possibility of penetration of water into the corn kernels. Campel and Jones (1955, 1957) have done considerable work on water penetration into wheat kernels. All of their study, and those of others, are for extended time periods, which is normally required in wet and dry milling processes.

Fan et al. (1963 and 1965) reported a linear relationship between moisture absorption and the square root of time for steeping up to 45 minutes. Chung et al. (1971) reported an increase in the rate of moisture absorption when the initial moisture content of the grain was lowered. They concluded that at lower moisture contents there exists a greater potential difference for moisture absorption. Fan et al. (1962) studied the volume increases in corn and sorghum and concluded that volume and weight increases are closely related.

Wolf et al. (1952) analyzed extensively the structure of a corn kernel and the significance of each part in the process of moisture absorption. They indicated that two layers must be considered in relation to the entrance of moisture into the kernel; first, the pericarp and tip cap and second, the seed coat and hilar layer (Figure 2). The aleurone layer forms a third covering which may be of some importance in controlling water movements into and out of the kernel. The outer layer of the pericarp is cutinized, which makes it an impervious layer to water. Within the first few seconds of absorption process, the entrance of water into the corn is largely through the end of the torn cap or at the basal portion of the kernel. Once the water enters the kernel, it moves rapidly through the spongy structure of the tip cap and the cells under the pericarp. Capillary forces are primarily responsible for this movement of water (Wolf et al., 1952). Absorption of water by the outer pericarp cells is a diffusion process. In this case, water diffuses across the membrance, therefore, water movement is very slow.

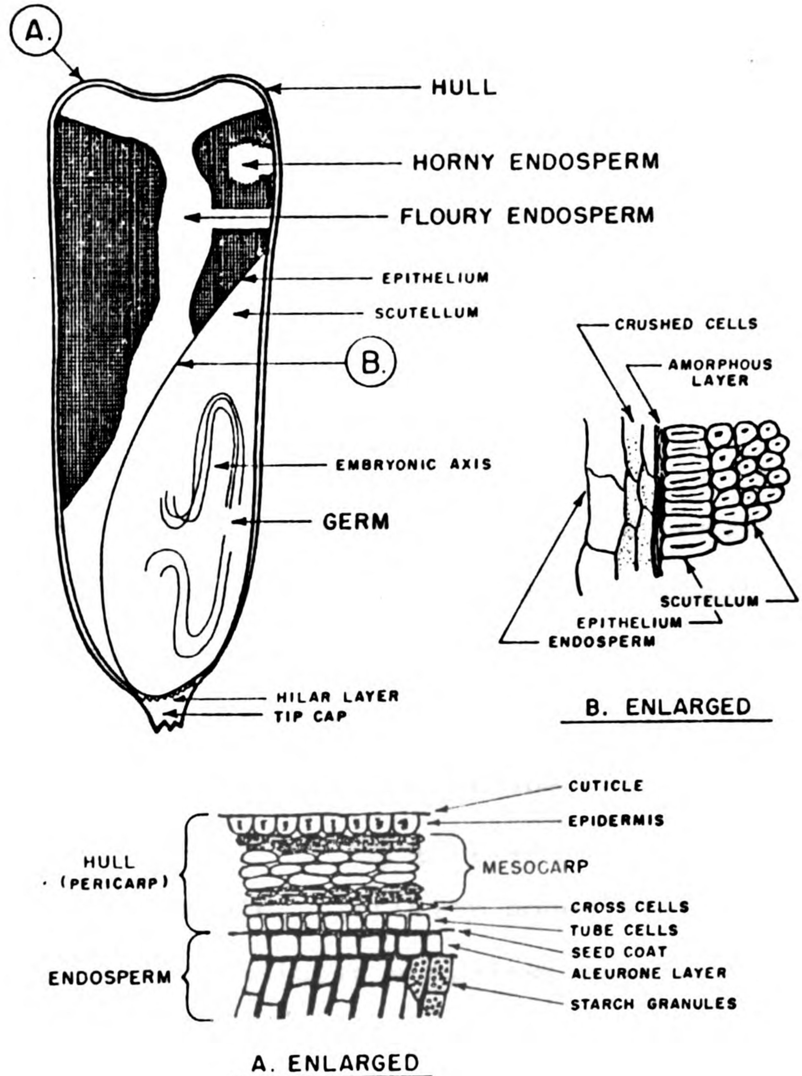

Figure 2. Structural elements of the corn kernel (Mohsenin, 1970).

From the above discussion, it can be concluded that water uptake by corn kernels proceeds in two stages: a rapid absorption followed by a slow diffusion process. The first stage of water uptake is due to capillary forces. Fan et al. (1963) have shown that the time required for completing the first stage of water absorption in corn kernels is about five seconds. In this stage, the rate of water uptake is constant for a water temperature of from 32^o to 212^oF.

The different layers of a corn kernel are considered semi-permeable for penetration of different liquids. The absorption is a selective process depending on the size of molecules of the diffusing species. For example, SO_2 solutions have a retarding effect on water absorption in the initial steps of steeping (Fan et al., 1965). It has been concluded that SO_2 molecules partially cover the outer micropores and create a resistance against moisture penetration.

About 70 percent of a corn kernel consists of endosperm. The outermost layer of the endosperm is called aleurone layer. The aleurone is under the seed coat and separates germ and endosperm in the kernel. It varies in thickness from about seven to seventy μ (microns). It is thinnest over the germ and thickest over the back and sides of the kernel (Wolf et al., 1952). The thick aleurone cell walls (4-6.5 μ) constitute an added semi-permeable envelope which encloses the germ and starchy endosperm. The aleurone layer controls the entrance of water and other solutes into the endosperm and germ. Actually, the aleurone layer is the first endosperm tissue that the water encounters after the seed coat has been penetrated. Since this layer has no intercellular spaces, it constitutes a continuous coverage. Water, therefore, must diffuse through the thick aleurone cell walls before reaching the starchy endosperm cells. But, once the water penetrates through the aleurone layer, it spreads rapidly through endosperm structures.

Wolf (1952) and many other investigators have indicated that starch granules in the endosperm are held in a proteinacious matrix within the individual cells. Both cell walls and matrix must be broken down in order to release the starch. The cell walls of the horny endosperm are thinner than those of the floury endosperm. Despite the difference in wall thickness, water penetration and starch release are much easier in the case of floury endosperm than horny endosperm.

In the germ, flow of water cannot occur through the ambryonic vascular bundles. This is because of the dormancy of these cells. Therefore, the water has to diffuse instead of moving by capillary flow. Water absorbed by the embryo is held as free water in the intercellular spaces and is more or less firmly bound to the cell walls and to the protoplasm. The protoplast holds most of the water absorbed as a result of the hydration of cell components. The water-holding capacity of the embryo is much greater than that of the endosperm. Consequently, the germ is capable of absorbing water from the endosperm until equilibrium is established.

Kumar (1973) in a study of moisture absorption by parts of corn kernels concluded that the diffusion path of water is shorter when it enters through the germ. Thus, the germ absorbs more water than the endosperm. This difference appears distinctly after 10-15 minutes of steeping.

III. EFFECTS OF WATER ON GRAIN PROPERTIES

There are many reports on the effects of cold or hot water on the structure, chemical substances and physical properties of the grain. As was mentioned earlier, most of the investigations have been carried out with water in dry and wet milling, malting and related areas.

Importance of Grain Quality

The whole purpose of grain drying is to facilitate its handling and preserving quality for an extended period of time. During the drying, any mechanical, physical or chemical damage to the grain should be avoided. These damages increase susceptibility of the grain to deterioration during storage. The desired qualities of the grain as listed by Bakker-Arkema (1973) are as follows:

1) Appropriate low and uniform moisture content
2) Low percentage of stress-cracked, broken and damaged kernels and of foreign substances
3) Low susceptibility to breakage
4) High test weight
5) High starch yield (millability)
6) High oil recovery
7) High protein quality

8) High viability

9) Low mold count

10) High nutritive value

Each specific use of the grain determines which items of the mentioned properties are important. For example, for seed purposes, item 8; wet milling items 5, 6 and 7; cattle feeding, items 9 and 10 and the grain dealer is interested in items 1, 2, 3 and 4. These properties have to be evaluated after completion of the drying process. In this study, the effects of hot water on some physical, chemical and mechanical properties of the grain will be investigated.

Zotova et al. (1960) experimented with cold and hot water conditioning of grain (wheat) and investigated the effects of temperature on protein, starch and ash. They concluded that although the treatment facilitates separation of bran from endosperm, it also improves certain physiochemical qualities of the grain. At low moisture contents, the germ of the grain (corn) is friable, and when too dry, it will break into small flour-sized pieces during the milling process. If enough water is added, not only the bran toughens, but also the germ. According to Matz (1959), the moisture content of corn is raised to 21 percent in the case of corn and about 17 percent in the case of wheat. The addition of water is done in conveyors and whizzers.

Starch

According to Leach (1958), starch granules exhibit a limited capacity for absorbing cold water and for swelling. Thus, the intermicellar network of a starch molecule possesses a limited degree of elasticity. If an aqueous suspension of starch is heated, the granules do not change in appearance until a certain critical temperature is reached. At this point, some of the granules start swelling and simultaneously lose their polarization properties. This change in starch granules is called gelatinization. Different varieties of corn starch show essentially the same gelatinization temperature (about $140^{\circ}F$). In the process of gelatinization, the micellar network within the granule is weakened due to the influence of heat or some chemicals. The gelatinization point of high amylose corn starch is at a higher temperature due to the straight micellar structure of the amylose and the highly associated granules. The amount of water available is a limiting factor for granule swelling. As the granules swell, starch molecules that have become fully hydrated separate from the intricate micellar network and diffuse into the surrounding aqueous medium. The higher ratio of amylose to amylopectine and the presence of non-carbohydrate impurities and fatty acids in the starch solution inhibit the gelatinization process.

Watson _et al_. (1961) immersed starch molecules, which were only held by the protein matrix, into a 52°F distilled water. The solutions were shaken for six to twenty-four hours. No starch was observed in the solution. It was concluded that the thick protein matrix causes difficulty in starch extraction. The same investigators also reported that temperatures above 180°F cause the starch granules to be locked irreversibly into the protein matrix.

Protein

Crain et al. (1958) determined the types of proteins extracted by water from a sample of ground corn. Kernels were ground, and the samples were mixed with distilled water for 24 hours. The water contained .4 mg of nitrogen and .5 mg of phosphorus per milliliter. These quantities are equivalent to 16 percent of the nitrogen and 95 percent of the phosphorus of the whole corn meal. The final result showed that about 37 percent of the nitrogen was non-protein nitrogen. McGuire et al. (1958) in a study of possible existence of protein in wet milling steeping water, found 12.2 percent nitrogen. In these experiments, 400 gram corn was immersed into 1700 ml of water.

Minerals

Minerals are distributed unevenly throughout the different parts of a grain kernel (Myasnikova, 1965). The highest amount of minerals is found in the embryo, the aleurone, seed coat and pericarp. Endosperm contains the lowest quantity of minerals. Most of the minerals are in combined forms with organic substances (starch, proteins or fats).

Germination

As far as the author knows, there is no data available in the literature describing the effect of cold or hot water on germination.

IV. EXPERIMENTAL

The objective of the experiments was to study heating rate, moisture absorption, germination, appearance and chemicals leaking from the kernel when immersed in distilled water.

Material

Single cross garno (WIOXM5206 N/2F/1971, Kellog.) seed corn was used in the experiments. The corn was donated by the Michigan Crop Improvement Association.

Sample Preparation

Shelled corn at 25 percent moisture content was mixed with distilled water and put in a 40°F box for different periods of time to obtain higher moisture kernels. To obtain moisture contents below 25 percent, the corn was put in an 80°F box with a relative humidity of 75 percent. A moisture content check of each group of the samples was made periodically with a Steinlite moisture meter. After obtaining the desired moisture content, the samples were put in zip-lock plastic bags and stored in a 40°F box.

Equipment

The following equipment was used for heat treatment of corn kernels in the water:

1) A constant temperature bath with a capacity of one gallon
2) Beakers, 80 ml
3) A wire mesh cylindrical basket with a capacity of about 50 grams shelled corn
4) Two channel temperature recorders for copper constantan thermocouples
5) A mechanical stirrer
6) Blotting paper and absorbing filter-type material
7) A scale with accuracy of ±.001 gram

General Procedure

An 80-ml beaker was filled with distilled water and put in the constant-temperature bath, which was filled with about one-half gallon of distilled water. The water had been heated to the desired temperature before a sample of about 25 grams corn kernels was immersed into the beaker. The mechanical stirrer was used in the bath to ensure a uniform temperature distribution throughout the bath. The temperatures of the water in the bath and in the beaker were monitored by the thermocouples attached to the recorder. Cold water was added, in case the temperature was higher than desired and hot water if the temperature was lower. In all cases, the temperature of the water in the beaker was kept at a constant level (±2^{O}F). The length of the heating period was measured with a stop watch.

Heating Time

In order to obtain the temperature history of corn kernels during the heating process, the following method was used:

A hole with a diameter of .039 inch was drilled into a kernel from the hull end (Crown) along the longitudinal axis. A copper-constantan thermocouple was inserted into the kernel, and the entrance was sealed with a waterproof sealant. The wired kernel and about 25 grams of corn were immersed into the hot water in the beaker. The temperature history of the corn kernel, along with the temperature of the water in the beaker, was recorded. In order to maintain a constant temperature in the beaker, the temperature of the main bath was raised 10^{O}F above the desired temperature. Table 1 indicates the grain temperature while being heated at different temperatures for various times.

Moisture Absorption

Corn kernels were heated in water at different temperatures for certain periods of time. The kernels were removed from the water and were spread on a large,

	15% MC			19% MC			25% MC			35% MC		
Sec	140°F	160°F	180°F	140	160	180	140	160	180	140	160	180
0	78	78	78	78	78	78	78	78	78	78	78	78
10	122	131	164	118	142	145	116	134	145	110	127	145
20	131	142	172	126	150	164	125	145	157	122	139	163
30	134	147	174	130	153	170	129	150	164	128	146	169
40	136	150	174	132	154	174	131	153	168	130	148	171
50	137	152	175	134	155	175	134	154	170	132	150	172
60	138	153	175	135	156	176	135	156	172	134	152	173
90	140	156	176	138	158	178	138	158	174	138	155	174

Table 1. Heating time and corn kernel temperature as measured by thermocouple after being placed in hot water of different temperatures.

Water-to-grain ratio: 3-to-1 on a weigh basis.

thick, absorbent cloth (Becker, 1959; Fan et al., 1963 and 1965; Kumar, 1973). The corn kernels were blotted in order to remove the surface moisture and then weighed and placed in a 212^{O}F oven for 72 hours to determine their moisture content (Hall, 1967). Table 2 indicates the change of weight and moisture content for a 22-percent MC corn sample being heated in 180^{O}F water for various periods of time. Table 3 shows the change of weight and moisture content for various initial moisture contents, time and temperatures.

Germination

After removing a grain sample from the hot water, the grain was blotted, as explained earlier. The blotted sample was wrapped in germination paper, using the so-called "rag doll" method and placed in a closed top can in an 80^{O}F box for seven days (Mayer et al., 1963; Diaz, 1973).

For each category of moisture content, two untreated samples were tested for germination, as Control. Table 4 indicates the percentage of germination of the treated samples with respect to those of controls.

Stress Crack and Damage Test

In order to detect stress cracks (fissures or fault lines) or any change in the appearance of corn kernels, a sample was obtained from two moisture contents. All

Time Sec	Gram Wt_f	% MC_f	% WT Change	% MC Change	Time Sec	Gram Wt_f	% MC_f	% WT Change	% MC Change
15	50.8	23.2	1.6	1.2	90	51.6	51.6	3.2	2.7
20	51.0	23.5	2.0	1.5	120	52.4	25.6	4.8	3.6
25	51.0	23.5	2.0	1.5	150	52.3	25.7	4.6	3.7
30	50.9	23.4	1.8	1.4	180	52.3	25.7	4.6	3.7
35	51.0	23.5	2.0	1.5	240	53.1	26.5	6.2	4.5
40	50.9	23.4	1.8	1.4	300	53.4	27.0	6.8	5.0
50	51.4	24.1	2.8	2.1	360	54	27.7	8.0	5.7
60	51.6	24.4	3.2	2.4					

Table 2. Weight and moisture content change for 22-percent moisture content corn at 78°F being immersed in hot water at 180°F for different time periods.

Grain-to-water ratio, 1:2 on a weight basis.

SAMPLE	% MC_{in}	Gram WT_{in}	% MC_f	Gram WT_f	SAMPLE	% MC_{in}	Gram WT_{in}	% MC_f	Gram WT_f
A1	15.66	25.25	17.70	25.73	D1	27.38	24.81	27.83	24.83
A2	15.66	24.80	17.90	25.20	D2	24.38	24.97	27.94	25.14
A3	15.66	25.00	17.90	25.67	D3	27.38	25.02	27.93	25.03
A4	15.66	24.92	18.40	25.65	D4	27.38	24.96	27.88	25.00
B1	20.48	25.22	21.40	25.50	E1	29.76	25.26	29.72	24.62
B2	20.48	24.98	22.00	25.42	E2	29.76	24.97	29.93	24.86
B3	20.48	24.94	20.90	25.07	E3	29.76	25.11	29.11	24.76
B4	20.48	25.00	22.70	25.42	E4	29.76	24.80	29.49	24.11
C1	25.00	25.25	25.60	25.48	F1	34.47	25.04	33.33	24.78
C2	25.00	25.00	25.70	25.31	F2	34.47	24.90	33.90	24.57
C3	25.00	25.02	25.10	25.27	F3	34.47	24.80	33.47	24.32
C4	25.00	24.63	25.60	24.88	F4	34.47	25.06	32.81	24.63

Table 3. Weight and moisture content for various corn moisture contents before and after being immersed in hot water. For conditions of test for each sample, see Appendix B-1.

MC in %	TEMP oF	GERMINATION %			
		40 Sec	60 Sec	90 Sec	Control
16	140	107	100	100	94
	160	107	92		
	180	91	95	2	
19	140	95	93	96	86
	160	93	80	69	
	180	0	0	0	
20	140	110	101	110	86
	160	85	93	80	
	180	0	0	0	
24	140	100	92	92	49
	160	4	1	5	
	180	0	0	0	
27	140	---	125	---	62
	160	---	25	---	
	180	---	0	---	
30	140	---	13	---	46
	160	---	0	---	
	180	---	0	---	

Table 4. Corn germination at different moisture contents after immersion for varying times in different water bath temperatures. Percent germinations in the table are the ratio of experimental to the control germinations.

foreign materials; all broken, cracked or physically damaged kernels, and kernels with chalky or otherwise impaired endosperm were removed from the sample. The sample of 80 sound kernels was treated with hot water as previously was explained. The kernels were then examined individually over a 150-watt incandescent lamp with a small square glass-covered opening. The damaged kernels were categorized as single crack, multiple cracks, checked and broken. The percentage in each category was computed. Single and multiple cracks are in one direction, checked, in two directions (Gygax et al., 1973) and tears are any damage to the skin (pericarp, seed coat) or hull parts. Table 5 indicates the results of the test for 15- and 25-percent moisture content and various times and temperatures.

Chemical Tests

Three tests were selected for determining possible losses in organic matter by the corn kernels during the water immersion process. After each treatment, the solution in the beaker was saved in a plastic bottle and stored in a refrigerator with a temperature above the freezing point. This solution was then used for subsequent chemical tests.

MC in %	Temp Sec	Time Sec	Single % crack	Multiple % Crack	Checked %	Broken %
15%	140	50	--	4	--	--
		90	--	6	--	--
	180	50	2	2	--	4
		90	4	--	--	4
25%	140	50	4	--	--	2
		90	4	--	--	--
	180	40	--	--	--	1
		50	--	2	--	2
		60	--	--	--	2
		90	--	--	--	2
		120	--	--	--	3
		300	1	--	--	5

Table 5. Damage test for sound kernels after being placed in hot water. The corn kernels were examined by the candling method.

Starch

The Blue Index method was used for estimating the amount of starch present in the solution (Cording et al., 1959). A solution consisting of 2 ml of the sample, 24 ml of distilled water and 1 ml of iodine solution (.02 N) was obtained. The Beckman spectrophotometer model 2400 was used to measure absorbency (Ewing, 1959). The instrument was standardized to 100-percent transmittancy with a blank solution (water and iodine) at 660 nm. Each sample was checked against the blank and the percentage of transmittancy was recorded. In order to obtain a relationship between transmittancy and starch concentration, a standard solution with corn starch was prepared and its transmittancy was measured. See Table 6.

Protein

A combination of the standard micro-kjeldahl method and direct measurement of free nitrogen was carried out. For sample digestion, 5 ml of the solution with 5 ml concentrated sulfuric acid was mixed. Potassium sulfate and mercury oxide were used as catalysts. For measuring free nitrogen, an Orion ammonia electrode (which is a gas-detecting electrode), along with a Leads and Northrup 7407 pH meter, was used. The digested sample was diluted 400 times, and after adding 2 ml of 10 M basic solution, the mv reading was recorded. Ammonium chloride (.01 M)

Sample	Absorb-ency	% Trans-mittancy	Sample	Absorb-ency	% Trans-mittancy
A1	.0066	98.5	D1	.0039	99.1
A2	.0044	99.0	D2	.0022	99.5
A3	.015	96.6	D3	.0101	97.7
A4	.0168	96.2	D4	.0052	98.8
B1	0	100	E1	.0044	99.0
B2	.0048	98.9	E2	.0052	98.8
B3	.0088	98.0	E3	.0106	97.6
B4	.0083	98.1	E4	.0123	97.2
C1	.0039	99.1	F1	.0066	98.5
C2	.0083	98.1	F2	.0088	98.0
C3	.0227	94.9	F3	.0218	95.0
C4	.0088	98.0	F4	.0177	96.0

Table 6. Results of Blue Index method for starch losses from corn after immersion in distilled water. For conditions of tests (MC, temperature and time) see Table B-1.

NOTE: Transmittancy of 89% is equivalent to 50 PPM of pure corn starch in the solution.

was added using "known addition method" (Orion Res., 1972; LeBlanc, 1973). The difference between two readings was converted to PPM of nitrogen in the solution. This quantity times 6.25 gives the protein content of the sample. Table 7 gives nitrogen in solution, in grain and respective conversions to protein.

Ash

The standard oven method was employed to determine the ash content of the solution. The sample solution was dried at 217°F for 24 hours and then was placed into a 1112° oven for 45 minutes. The initial weight of the porcelain cap, the solution after drying and, finally, the weight of the ash were recorded and the ash content calculated. Table 8 is the result of this experiment.

Sample	N (1) % Sol	Prot(2) % corn Prot.	Sample	N % Sol.	Prot% corn prot.
A1	.0319	.0679	D1	.0212	.0435
A2	.0319	.0629	D2	0	0
A3	.0263	.0510	D3	.0123	.0243
A4	.0375	.0679	D4	.0560	.1065
B1	.0627	.1320	E1	.0509	.0986
B2	.0039	.0070	E2	.0212	.0444
B3	.0319	.0639	E3	.0375	.0746
B4	.0784	.1404	E4	.0375	.0713
C1	.0627	.1344	F1	.0168	.0372
C2	.0212	.0429	F2	.0560	.0386
C3	.0319	.0575	F3	0	0
C4	.0168	.0335	F4	.0212	.0457

Table 7. Results of the protein test for corn at different moisture contents.

For conditions of test, see Table B-1.

1) Gram N per 100 ml solution
2) Gram protein per 100 gram of corn protein (Based on 9.91 percent protein content of corn kernels).

Sample	% Solids	% Ash	Sample	% Solids	% Ash
A1	.0311	.0016	D1	.0130	0
A2	.0334	.0016	D2	.0093	0
A3	.0304	.0058	D3	.0286	.0121
A4	.0280	0	D4	.0175	0
B1	.0055	0	E1	.0118	0
B2	.0212	0	E2	.0094	0
B3	.0230	0	E3	.0141	0
B4	0	0	E4	.1463	.0093
C1	.0133	0	F1	.0538	.0214
C2	.0448	.0169	F2	.0359	0
C3	.0231	0	F3	.0296	0
C4	.0395	.0097	F4	.1009	.0238

Table 8. Results of solid and ash content for samples of different moisture content.

For conditions of test, see Table B-1.

V. RESULTS AND DISCUSSION

In this part, the experimental results are discussed, and, whenever possible, a comparison will be made between the experimental and theoretical results.

Heating

Experimental Results: The rate of heating of corn kernels of different moisture contents at different temperatures in an excess of water (ratio of water to corn, 3:1 on a weight basis) has been plotted in Figure 3. It can be concluded that:

a) At all levels of moisture contents and temperatures, 60 to 90 seconds is sufficient time for the kernels to reach the equilibrium temperature. This result is in agreement with the findings of Karazian *et al*. (1965). They concluded in evaluating the thermal properties of corn that 40 seconds is enough for temperature to reach equilibrium.

b) At a constant moisture content, higher water temperatures cause steeper corn heating rates. This is due to a higher temperature driving

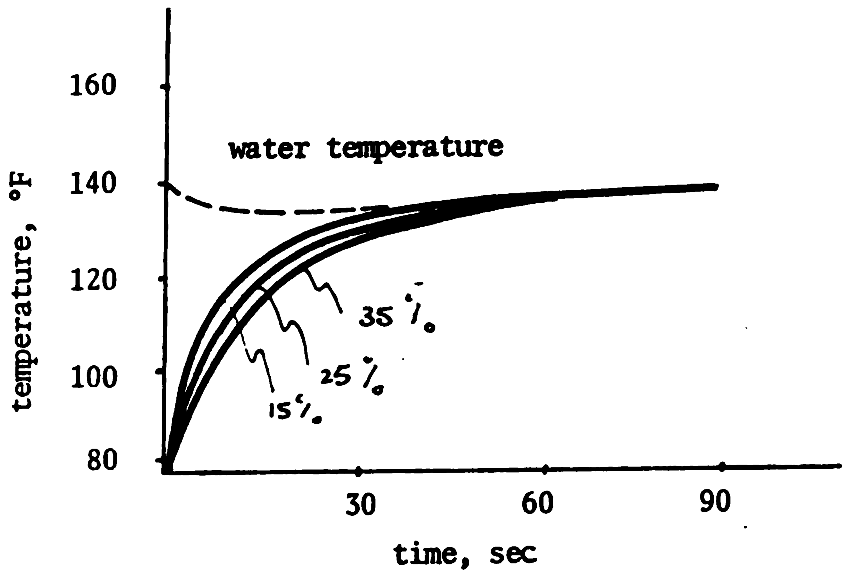

Figure 3a. Heating rate for corn with different moisture contents in the water at 140°F.

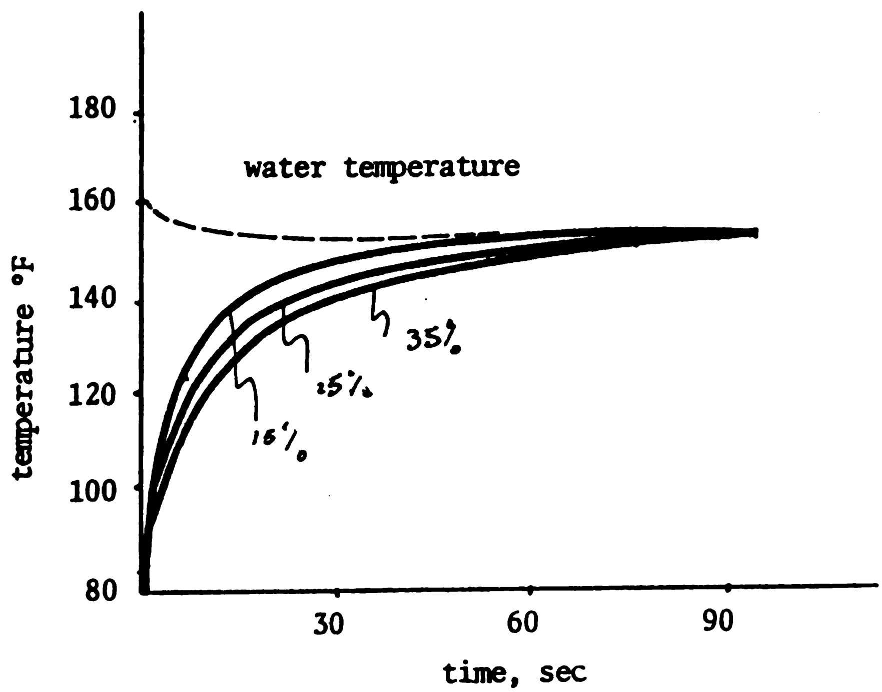

Figure 3b. Heating rate for corn with different moisture content in the water at 160°F.

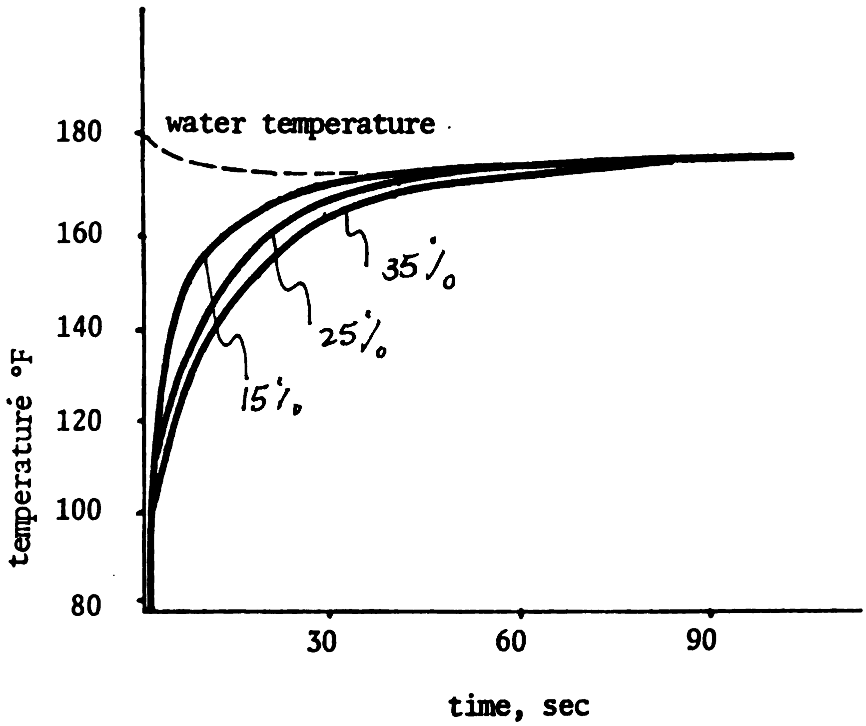

Figure 3c. Heating rate for corn with different moisture content in the water at 180°F.

force.

c) At any temperature, low-moisture corn reaches the equilibrium temperature faster than higher-moisture-content corn. It may be concluded that when the moisture content of the grain is low, the water absorption is high (this will be shown in the water absorption section). Therefore, water diffusion into the corn kernels will carry additional heat (thermal diffusion).

d) At lower temperatures, equilibrium will be reached faster than at higher temperatures.

Theoretical Analysis

In order to study analytically the heating rate of the kernel immersed into the hot water, the following assumptions will be made:

1) The temperature of the water will be constant.
2) Thermal mass diffusion will be neglected.
3) The corn structure is homogenous, so a single value of thermal conductivity, heat capacity are applicable.
4) There is no volume increase; therefore, the values of density and average dimensions and other properties are constant.
5) The properties of the fluid (water) are constant within the temperature range from $78^{o}F$ to $180^{o}F$.

There are two possible methods for determining the center temperature of the body:

Lumped-Heat-Capacity System

If there is a uniform temperature distribution in a body during heating or cooling, resistance to heat transfer by conduction is small compared with the convective resistance. The most effective temperature gradient will be at the surface through the fluid film. The convective heat transfer from the water to the corn kernel will increase the internal energy of the particle. In this case, the following heat balance can be written:

$$q = hA\,(T - T_\infty) = -C\rho V \frac{dT}{dt} \qquad (5\text{-}1)$$

Applying the initial and boundary conditions and integrating:

$T = T_O$ at $t = 0$

$T = T_\infty$ at $t = \infty$

$$\frac{T-T_\infty}{T_o-T_\infty} = e^{-\left(\frac{hA}{\rho CV}\right)t} \qquad (5\text{-}2)$$

The applicability of the above equation is restricted to the following criterion:

$$\frac{h\,X}{k} < 0.1 \qquad (5\text{-}3)$$

The dimensionless value of hX/k is called the Biot Number. The above ratio evaluates the validity of the assumption that the surface-convective resistance is large compared to the internal-conduction resistance.

In order to obtain a numerical value of Biot Number for the test condition, the values of h - the convective heat transfer coefficient, X - the characteristic dimension and k - the thermal conductivity, have to be determined for corn kernels.

For h, the semi-empirical equation of Ranz and Marshal (Bird et al., 1960) can be used:

$$Nu = \frac{h\,d}{k} = 2.0 + .6\,(Re)^{\frac{1}{2}}\,(Pr)^{1/3} \qquad (5\text{-}4)$$

When the fluid is motionless Re, the Reynolds Number, is negligible. Therefore, Nu, the Nusselt number, can be written as:

$$Nu = \frac{h\,d}{k} = 2.0 \qquad (5\text{-}5)$$

The characteristic diameter d can be estimated from the geometric mean of the kernel dimensions (See Appendix C). Thus:

$$\frac{h(.0221)}{.384} = 2.0$$

$$h = 34.75 \text{ BTU/hr-ft}^2\ {}^{\circ}\text{F}$$

Evaluating the Biot number:

$$\text{Biot} = \frac{h\ X}{k} = \frac{(34.75)(.0221)}{1.2} = .6399$$

Thus, the Biot number is not significantly greater than 0.1. Therefore, as a first try, the Lumped-Heat-Capacity System will be employed. The time required for the kernel initial temperature (78°F) to reach 178°F from eqn. (5-2) is:

$$\frac{h\ A}{\rho CV} = \frac{(34.75)(180)}{(80.7)(.567)} = 136.7 \text{ hr}^{-1}$$

$$\frac{178 - 180}{78 - 180} = e^{-136.7t}$$

$$.0196 = e^{-136.7t}$$

$$t = .028 \text{ hr or } 1.7 \text{ min}$$

The time value obtained by the lumped parameter method is slightly higher than the experimental value (60-90 seconds).

<u>Convection Boundary Condition</u>: In this solution, the corn kernel is assumed to be a rectangular body (made up of three infinite plates). The center temperature of each plate will be determined with the help of the so-called Heisler charts (Holman, 1972). The final solution for a single kernel will be the product of the three individual solutions. The desired dimensionless temperature to be arrived at with a trial-and-error technique is .0198. The results of calculations are given in Table 9.

t (sec)	S (a)	S (b)	S (c)	S (a) S (b) S (c)
60	.56	.40	.17	.038
70	.5	.37	.14	.026
80	.45	.27	.10	.012
90	.40	.25	.08	.008

Table 9. Solution for dimensionless temperature of corn kernel by Heisler charts.

Therefore, 70 to 80 seconds is sufficient for the temperature of the corn kernels to reach equilibrium. With the assumption of constant properties of the corn, the times indicated above will be identical for the conditions where the bath temperature is 160°F or 140°F. Although there are many assumptions in this analysis, the experimental and theoretical values agree well.

Moisture Absorption

Experimental Results: Tables 10 and 11 indicate the change in the moisture content and in the weight of the corn kernels during the immersion process. The moisture content differences between the initial and final ones are added cumulatively for each moisture content, and the resulting curves are plotted in Figure 4. The following conclusions can be drawn:

a) The moisture content increases rapidly at low initial moisture contents and levels off at about 27-30 percent moisture content (WB).

b) As the moisture content increases, there is less potential for absorption. Absorption reaches zero at about 27-30 percent moisture content (WB). At higher moisture contents, it starts to decrease. As was noted in the section on corn kernel structure, moisture normally penetrates into the kernel from the basal end. This water, which may be classified as free water, stays under the pericarp layer until it either diffuses into the internal structure of the corn or evaporates from the kernel. High-moisture corn has a low potential to absorb additional water.

Temp	Time Sec	Change In % Moisture Content					
		15.7%	20.5%	25.0%	27.06%	29.0%	34.0%
140	50	2.04	.92	.60	.45	-.04	-1.14
140	90	2.24	1.52	.70	.58	.17	- .57
180	50	2.24	.42	.10	.55	-.65	-1.00
180	90	2.74	2.22	.60	.50	-.27	- .34

Table 10. Percent change in moisture content after the corn being immersed in hot water (concluded from Table 3).

Temp	Time Sec	Change in % Weight					
		15.7%	20.5%	25.0%	27.06%	29.0%	34.0%
140	50	.48	.28	.23	.02	-.63	-.26
140	90	.40	.44	.31	.17	-.11	-.33
180	50	.67	.13	.25	.01	-.35	-.48
180	90	.73	.42	.25	.04	-.69	-.43

Table 11. Percent change in weight after the corn being immersed in hot water (concluded from Table 3).

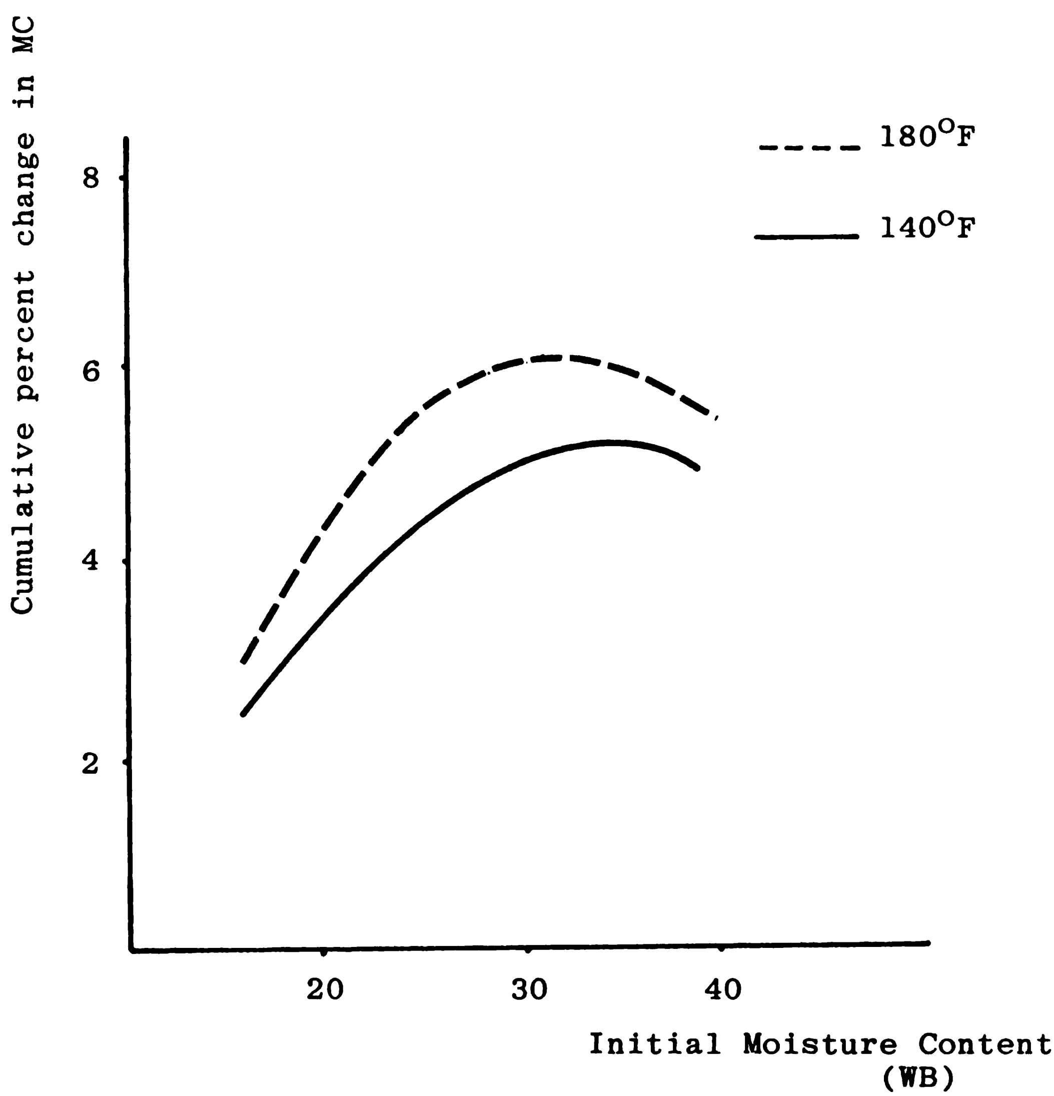

Figure 4. Initial moisture content vs. cumulative percent change in moisture content for corn immersed in hot water at two different temperatures for a period of 90 seconds.

Therefore, the corn kernels not only do not absorb moisture, but lose some during the transfer of heated samples to the blotter (Becker, 1960).

c) Figure 4 also indicates that moisture absorption increases as the initial temperature of water and the duration of heating increase.

Theoretical Analysis: Although several investigators have worked on the moisture absorption of grain, Becker (1959) was the first to use analytical equations to describe the process. He used Fick's first law of diffusion:

$$J_X = -D \frac{\partial c}{\partial X} \qquad (5\text{-}6)$$

$$D \frac{\partial^2 c}{\partial X^2} = \frac{\partial c}{\partial t} \qquad (5\text{-}7)$$

Equation (5-7) has been solved for many shapes. Becker (1959), by applying boundary conditions for wheat kernels (immersed in the water) and integrating in terms of concentration, developed the following equation:

$$c = \frac{c - c_s}{c_o - c_s} = 1 - \frac{2}{\sqrt{\pi}} Z + BZ^2 \qquad (5\text{-}8)$$

Equation (5-8) can be written in terms of moisture content:

$$\overline{M} = \frac{M - M_s}{M_o - M_s} = 1 - \frac{2}{\sqrt{\pi}} Z + BZ^2 \qquad (5\text{-}9)$$

Where:

$$Z = \frac{A}{V} \sqrt{Dt} \qquad (5\text{-}10)$$

With a second-order approximation, equation (5-9) can be written as:

$$\frac{M - M_s}{M_o - M_s} = 1 - \frac{2}{\sqrt{\pi}} Z \qquad (5\text{-}11)$$

Becker (1959, 1960), who developed and tested equation (5-11) for wheat kernels, Chung _et al_. (1961), on the basis of Fick's law and the development similar to the diffusion process, developed equation (5-12) for volume increase, which was successfully tested.

$$\overline{V} = \frac{V - V_s}{V_o - V_s} = 1 - \frac{2}{\sqrt{\pi}} V + BZ_v^2 \qquad (5\text{-}12)$$

Fan _et al_. (1961) made a study of the diffusion coefficient for water absorption into the wheat kernels utilizing equation (5-9). The same equation was tested successfully by Fan _et al_. (1963, 1965) for dent corn, popcorn, sweet corn and sorghum.

An attempt was made to test the diffusion equation for the available moisture absorption data. Before applying the main equation, the numerical values of A/V (surface area to volume ratio), D (diffusion coefficient) and M_S (effective surface moisture content[1]) had to be determined.

The numerical quantity of A/V is calculated in Appendix C. If a constant value is also assumed for the diffusion coefficient, equation (5-11) can be written as:

$$M - M_o = K \sqrt{t} \qquad (5\text{-}13)$$

Where:

$$K = \frac{2}{\sqrt{\pi}} (M_S - M_o)\left(\frac{A}{V}\right) \sqrt{D} \qquad (5\text{-}14)$$

There should be a linear relationship between $M-M_o$ and the square root of time with a slope of K if equation (5-14) is correct. A linear regression was used, and the data is plotted in Figure 5. With a correlation

---

[1] The effective surface moisture content is the moisture content which saturates very fast the peripheral part of the grain. In developing the boundary condition, this factor enters into the equation.

at $t = 0$ $\quad M = M_o$

at $t > 0$ and at surface $\quad M = M_S$

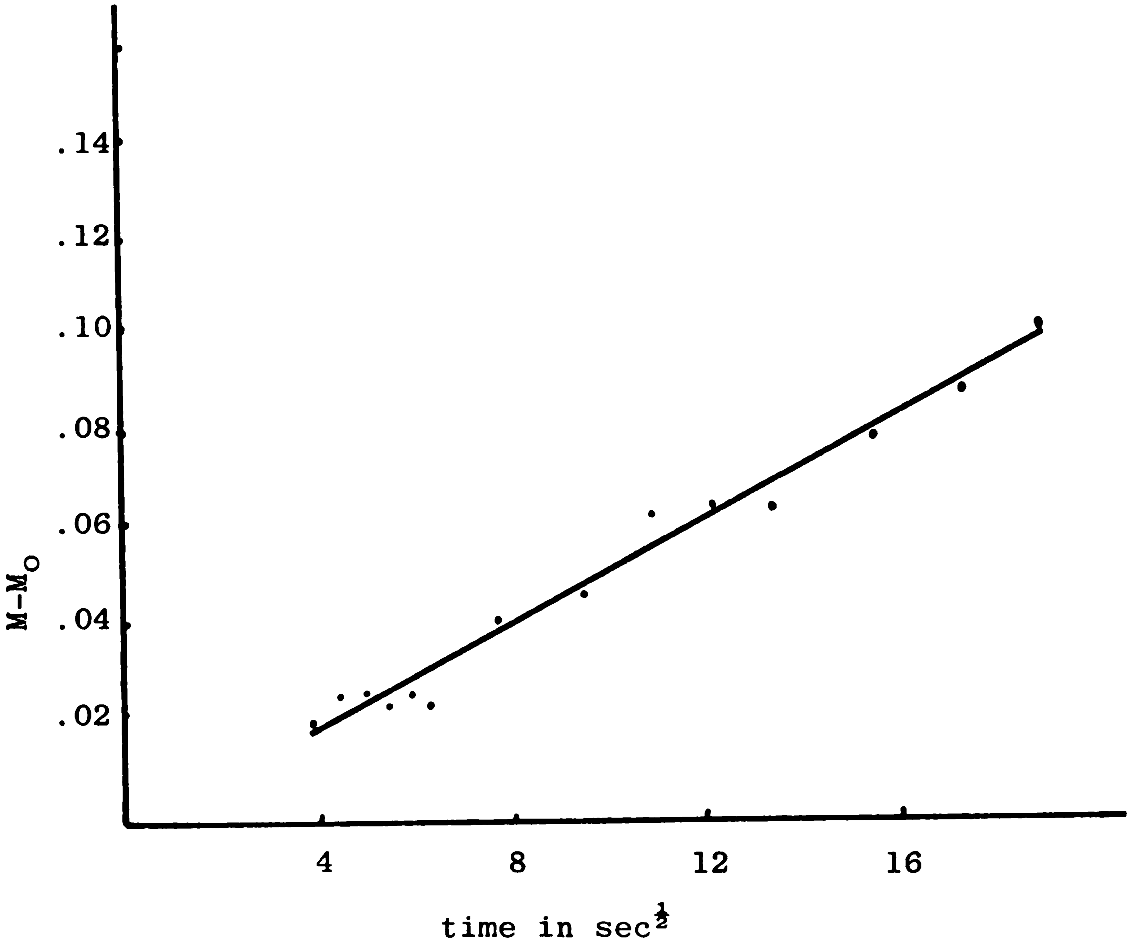

Figure 5. The change in moisture content as plotted versus the square root of time.

coefficient of .99, the linear relation can be written as:

$$M-M_o = .5332\sqrt{t} - .2975 \qquad (5\text{-}15)$$

Corn kernels of 28 percent MC (DB) treated with water at a temperature of 180°F were used for obtaining the data.

Equation (5-11) can also be written as:

$$M-M_o = K_A\ (M_s-M_o) \qquad (5\text{-}16)$$

Where:

$$-K_A = \frac{2}{\pi}\ (\frac{A}{V})\ \sqrt{Dt} \qquad (5\text{-}17)$$

Equations (5-16) and (5-17) show that if the diffusion time is kept constant, the quantity ($M-M_o$) is a linear function of M_o with a slope of $-K_A$. The value of M_o will be equal to M_s when $M-M_o$ equals zero. On the basis of this relationship, the value of M_s (effective surface moisture content) can be evaluated. This is done by plotting the values of ($M-M_o$) versus M_o and finding the intercept of the straight line with the x-axis where $M-M_o = 0$. Figure 6 is the corresponding plot at 140°F for a period of 90 seconds and Figure 7 for 180°F and 90 seconds. In the first case, a value of M_s equal to 44.05 percent MC (DB) is found, and for the second case, a value of 39.02 percent MC(DB).

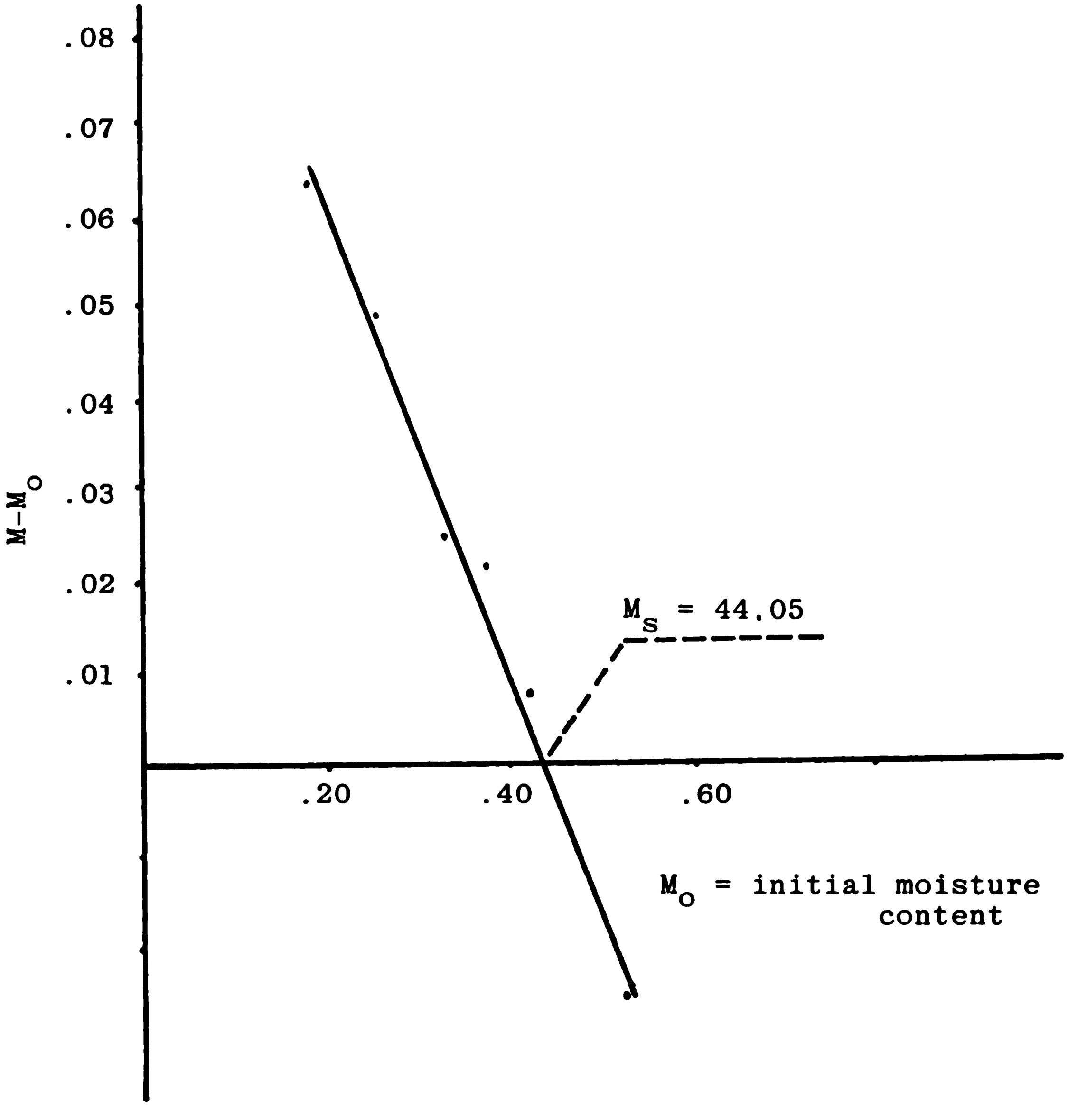

Figure 6. Moisture content difference versus initial moisture content for corn heated in 140^{o}F hot water for a period of 90 seconds.

M_s = effective surface moisture content

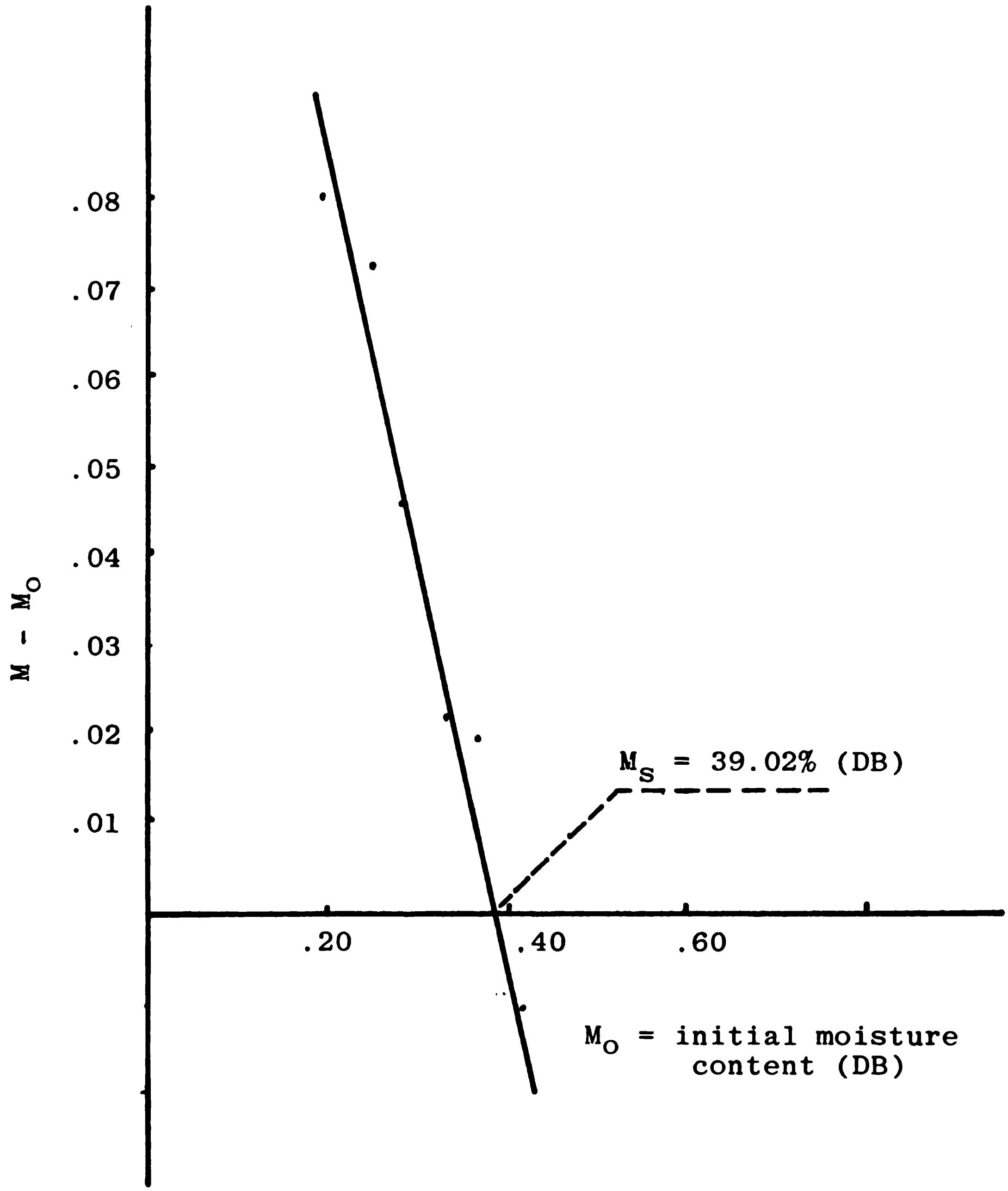

Figure 7. Moisture content difference versus initial moisture content for corn heated in 180°F hot water for a period of 90 seconds.

M_S = effective surface moisture content.

The value of the diffusion coefficient as a function of temperature can be determined from the following equation:

$$D = \left[\frac{K}{\frac{2}{\sqrt{\pi}} (A/V)(M_S - M_O)} \right]^2 \qquad (5\text{-}18)$$

or in terms of quantitative values:

$$D = \left[\frac{.5332}{\frac{2}{\sqrt{\pi}} (182)(39.02-28.2)} \right]^2$$

$$D = .575 \times 10^{-7} \ ft^2/sec$$

The value of K was found from the slope of line in Figure 7. With the values for D, K and A/V, a linear equation was developed as follows:

$$M = M_o + .53 \sqrt{t} \qquad (5\text{-}19)$$

The validity of equation (5-19) was tested for 28.2 percent MC (DB) corn. Figure 8 is a plot of the theoretical and experimental values. The difference between the two lines might be attributed to the following factors:

a) The surface area-volume ratio of the kernel during the heating process is not a constant.

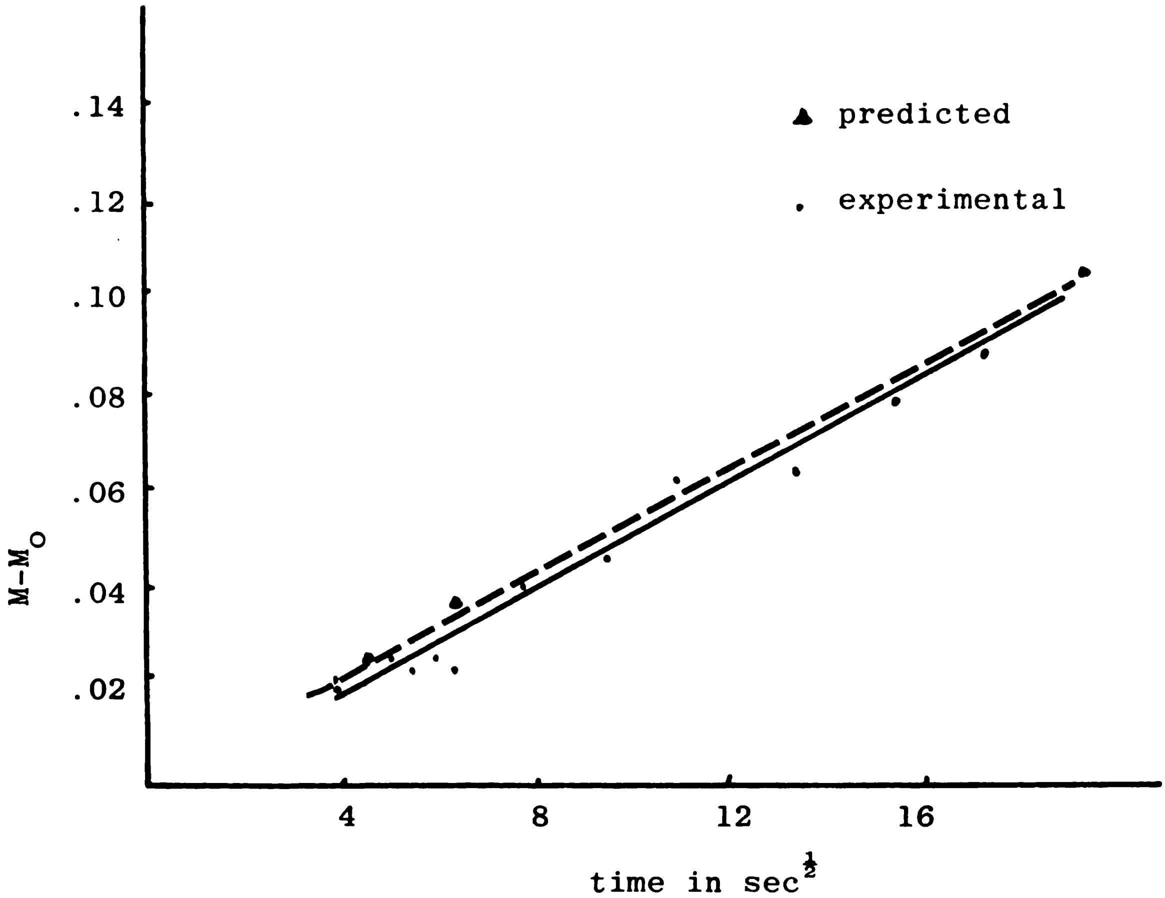

Figure 8. The correlation of experimental data and predicted values of moisture content change versus time.

b) The applicability of the constant value of M_s (Fan et al., 1967) is questionable.

The results obtained from the analysis show that experimentally measured absorption data obey the Fick's law of diffusion. Kumar (1973) proposed an empirical equation for the relationship between soaking time and final moisture content:

$$T = A_S(M)^{A_t} \qquad (5\text{-}20)$$

Where A_s and A_t are constants for different parts of a corn kernel. Equation (5-20) was tested with available data. The result is not in agreement with the experimental values. It can be concluded that the equation is not applicable within short periods of time of absorption.

Germination

In general, time, temperature and initial moisture content are factors affecting germination of the corn when it is immersed in a constant-temperature water bath. This is in agreement with previous grain quality investigators (Rali, 1960; Ives, 1968; Bakker-Arkema et al., 1972; Sinha and Muir, 1973; Anderson, 1973; Gygax, 1974). The following conclusions can be drawn:

a) Temperatures in the 140°F range do not affect germination of corn at lower moisture contents.

In fact, these temperatures may improve germination compared to the control samples. This may be due to activating certain enzymes which are responsible for breaking the dormancy of the embryo. Temperatures above 140°F reduce germination and at 180°F no germination is detected for moisture contents above 16 percent (WB).

b) Length of heating time affects the viability of the corn, but it is not as strong as temperature effect.

c) As the initial moisture content of the corn increases, the viability will decrease. This is in agreement with findings of other investigators (Zotova et al., 1960; Bakker-Arkema et al., 1973).

Stress Cracks and Damage Test Result

The following is a summary of the observations from the damage tests:

a) The hull is the most vulnerable part of a corn kernel. In moisture contents above 25 percent (WB), it is soft and easily separable from the kernel.

b) The point of silk attachment that is on germ side is slightly prolonged.

c) Multicracks and checks are mostly along the interface of germ and horny endosperm. This is in agreement with Wolf (1952) and Kumar (1973). They indicated that a difference in the rate of water absorption by the germ and endosperm generates cracks in their interface.

d) More damage was detected at temperatures of 180^{o}F than at 140^{o}F.

e) In some cases in the high moisture content ranges, the hull is wrinkled.

f) At temperatures of 180^{o}F, most of the tip caps are removed and the dark hilar layer can be seen. It should be noted that the tip cap is not a permanent part of the kernel. It may be separated from the corn kernel during shelling or subsequent mechanical handling.

Chemical Tests

The objective of the tests was to detect possible extraction of chemical substances from corn kernels during heating with hot water. The results of three tests for starch, protein and ash are given in Tables 7, 8 and 9.

Starch

In order to obtain a basis to compare the readings in transmittancy or absorbency with the starch concentration in the solution, series of known concentration samples were prepared. These samples were examined with the same instrument settings which were used to determine transmittancy in the original samples. The concentration of .005 percent (50 PPM) was detectable by spectrophotometer which indicated a transmittancy of 89 percent. As Table 7 shows, all the transmittancy values are above 89 percent, meaning that starch concentration is less than 50 PPM in the solution.

Protein

Table 8 gives the amount of nitrogen in the water solution. The percentage of nitrogen has been multiplied by 6.25 to obtain protein. Protein in the grain is calculated based on 9.9 percent weight basis average protein content in the corn kernels. It should be noted that the range of dctectable nitrogen for the ammonia electrode is about ±2 percent (Orion, 1972). As the figures in Table 8 show, all the values are well below 2 percent.

Ash

Although in some tests, minor quantities of ash were detected (Samples C2, D3, F1 and F4), no firm conclusion can be drawn from the tests.

VI. COUNTERFLOW HEATING AND DRYING

Proposed Dryer

The dryer consists of three major sections: the heater, the cooler and the heat exchanger. Accessories like a screw for moving grain, a pump for recirculating water, a fan for air movement, are also part of the system.

In the first stage, water and grain move in opposite directions. The grain has a relatively low temperature when it enters from one end while the water has a higher temperature as it enters from the other end. The hot water exchanges heat with the grain, while flowing in a counterflow configuration. As a result, the grain will almost be heated to the inlet water temperature and the water cooled to the inlet grain temperature (Figure 9). The warm grain from the heater stage enters the second stage or cooler by gravity and moves down. A stream of air in a counterflow direction is blowing upward through the bed of grain particles. The air cools the hot grain and at the same time carries away the moisture. For a perfect heat and mass transfer, the saturated outlet air

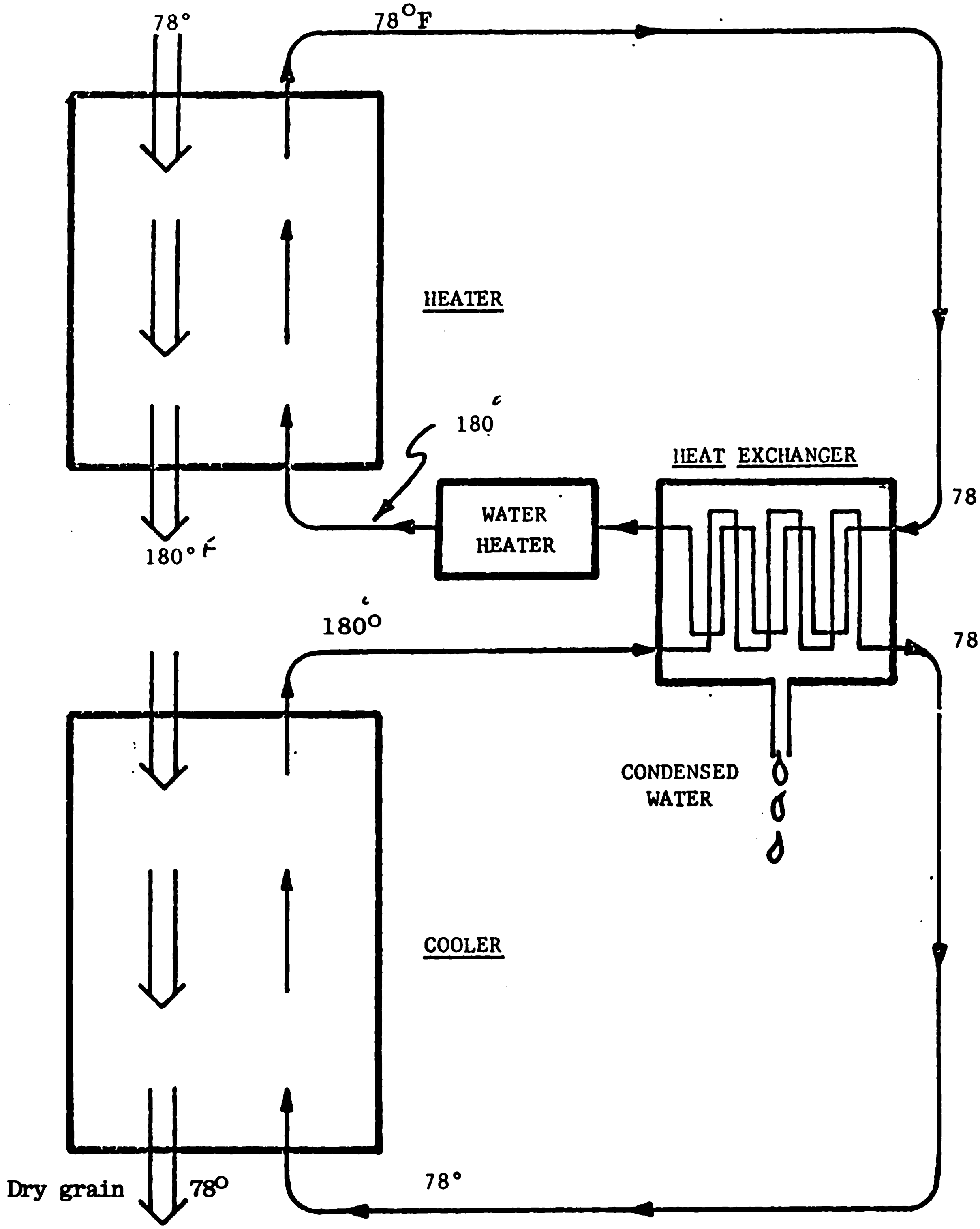

Figure 9. Two-stage recirculating counterflow dryer utilizing water as a heating medium.

will have the inlet temperature of the corn. The water from the first stage and the air from the second stage are circulated through a heat exchanger which is located between the two stages. The saturated hot air gives off its energy to the cold water flowing in the opposite direction in the heat exchanger. As a result of cooling, the water vapor in the air will be condensed and the cold air restores its drying capacity. Water at the exchanger outlet which has the inlet air temperature will be recirculated by a pump to the heater section. The cold air from the exchanger will also be blown by a fan to the cooler and dryer section. The condensed water from the air can be recirculated into the main water stream to compensate for any possible water losses from the system. Therefore, theoretically, no energy is required in an ideal situation. However, some BTUs are required to compensate for possible losses, inefficiencies and start-up period. Figure 10 is a sketch of the physical arrangement of the components of the system.

Water As a Heating Medium

Water in all of its phases has been a favorite agent for heat transfer in the chemical process industry. It is nontoxic, inexpensive, nonflammable and its technology is well understood.

When the air is used in the first stage of the process

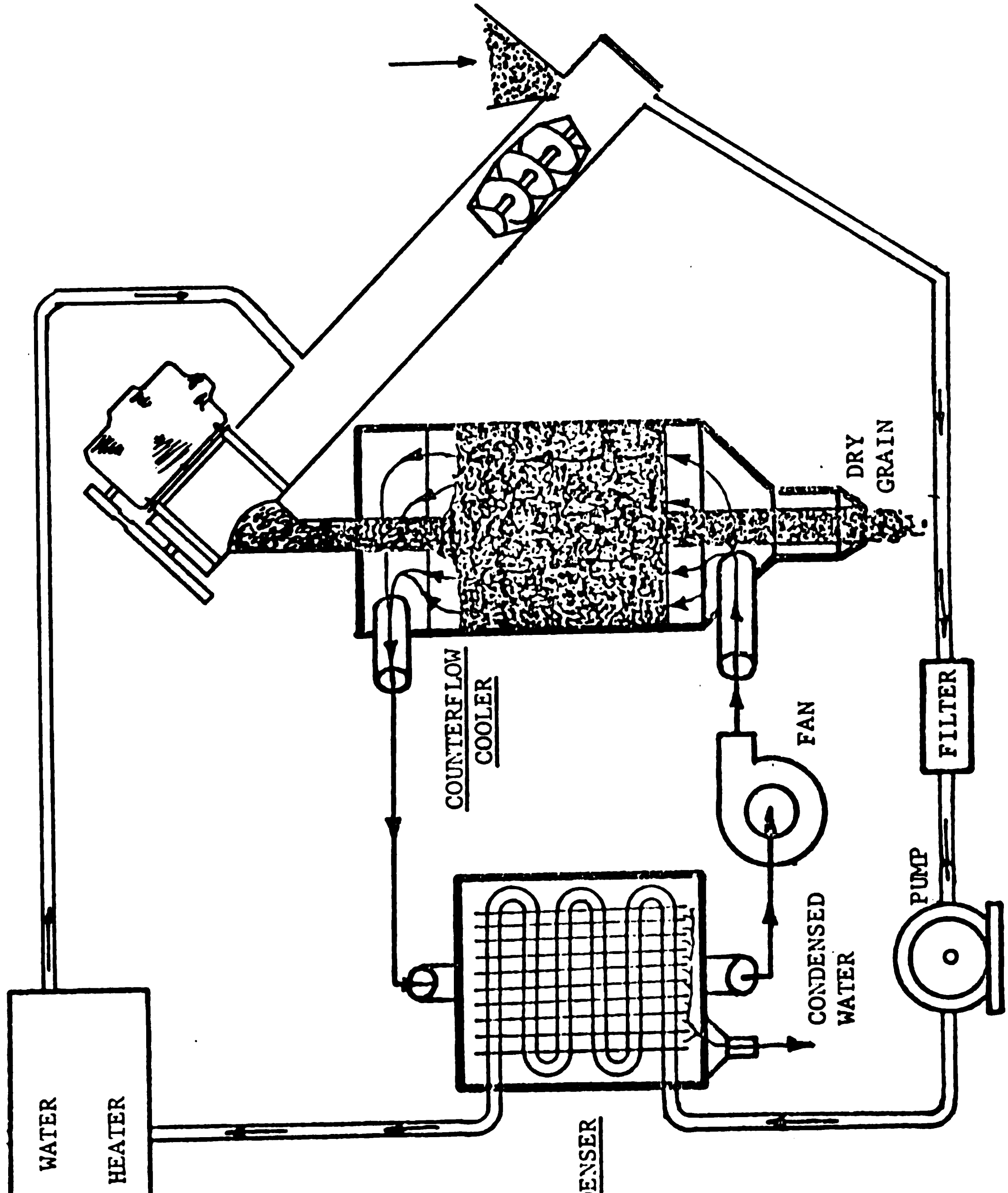

Figure 10. A two-stage recirculating counterflow dryer using water as the heating medium.

which consists only of heating, some grain drying in the inlet area and condensation near the outlet is inevitable. As a result, the process will not be efficient (Mitch et al., 1973) and the corn quality is questionable. Simultaneous counterflow heating and drying of the grain is a detrimental process to corn quality (Anderson, 1972; Bakker et al., 1973).

In the heat exchanger, the process of heat transfer, in case of air to air, is inefficient when compared to water and air. In the first case, the overall heat transfer coefficient is 5-50 and in the second case, 200-700 BTU/hr - $^{O}F\text{-}ft^2$ (Peters et al., 1968).

Freid (1973) has developed a heat-transfer efficiency factor (HTEF). This can be considered as an expression of the ratio of the heat-transfer coefficient to the frictional energy expended pumping the fluid:

$$HTEF = 19.75 \frac{C^{.333}\ K^{.667}\ \rho^{.572}}{\mu^{.524}}$$

HTEF values for water and air from 80^{O} to $180^{O}F$ are plotted in Figure 11. In spite of the high thermal properties, water has some limiting factors. At temperatures above $120^{O}F$, the formation of mineral scales from water tends to become excessive. Liquid mixtures that contain solids tend to foul heat exchangers very rapidly because the solids can

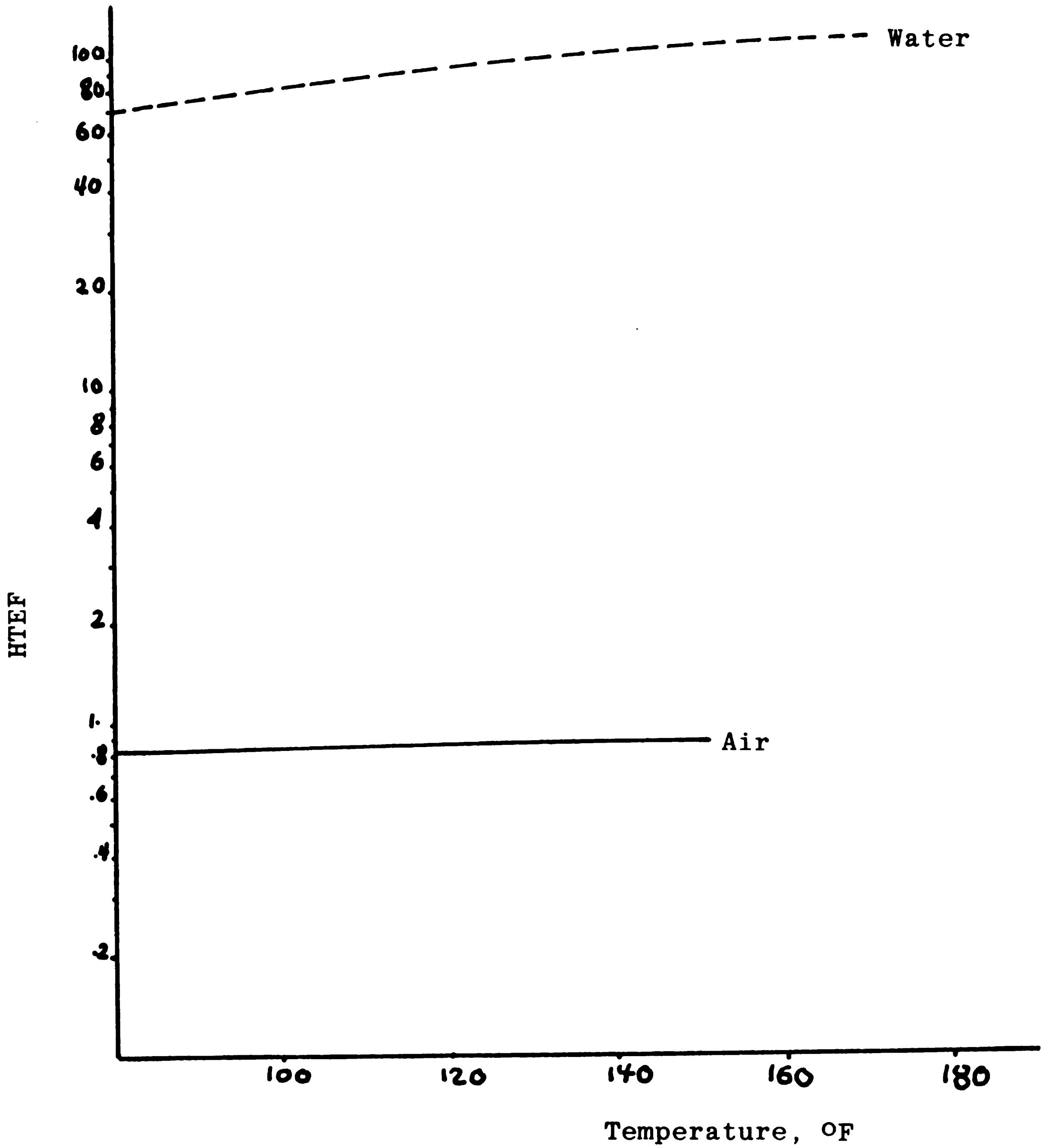

Figure 11. Heat transfer efficiency factor for water and air.

settle out and foul the hot walls. The difficulty can be reduced by:

a) Providing a filter for water before entering the heat exchanger.

b) Giving the water a velocity of at least 3 feet per second to keep the solids in suspension (Peters et al., 1968).

Simulation of a Counterflow Grain Heater

Bakker-Arkema et al. (1973a) and Roth et al. (1973) have developed models describing mass and heat transfer in a moving porous bed ventilated by air. The same principles can be employed when water is substituted for air. The physical variables which are relevant to the system are water temperature and bed temperature. Energy balances and convective heat transfer between the bed and water leads to steady-state equations, which can be solved for $T(x)$ and $\theta(x)$, water and grain temperature, respectively (Roth, 1973):

$$T(x) = \frac{C_T \left[T(o) - \theta(o)\right]}{C_T + C_\theta} \left[\exp(-x(C_T+C_\theta)) - 1\right] + T(o) \tag{6-1}$$

$$\theta(x) = \frac{C_\theta \left[\theta(o) - T(o)\right]}{C_T + C_\theta} \left[\exp(-x(C_T + C_\theta))-1\right] + T(o)$$

(6-2)

Where:

$$C_T = \frac{ha}{V_w \rho_w C_w} \quad (6\text{-}3)$$

$$C_\theta = \frac{ha}{V_p \rho_p (C_p + MC_w)} \quad (6\text{-}4)$$

The subscripts w and p denote the corresponding values for the water and the grain, respectively.

The counterflow system requires special consideration because of its boundary conditions. It can be observed that θ in the above equation at $x = 0$ is not known, while $\theta(L)$ which is the inlet condition of the grain is given (L is the length of the system). Equation (6-2) can be rearranged and solved for $\theta(0)$:

$$\theta(0) = \frac{\theta(L)(C_T + C_\theta) + C\, T_{(0)} \exp(B)}{C_T + C_\theta (\exp(B) + 1)} \quad (6\text{-}5)$$

Where:

$$\exp(B) = \exp\left[-L(C_T + C_\theta)\right] - 1 \quad (6\text{-}6)$$

Having $\theta(0)$ and $T(0)$ as initial conditions, the values of $\theta(x)$ and $T(x)$ can be found along the length of the system.

For developing an appropriate expression for h, the convective heat-transfer coefficient, Bird et al. (1960) will be followed. The Colburn J factor for convective heat transfer can be written as follows:

$$J_H = \frac{h}{C_w G_w} (Pr)^{2/3} \qquad (6\text{-}7)$$

The value of J_H as a function of the Reynolds Number (Re) can be obtained from the following empirical relations:

$$Re < 50 \qquad J_H = .91\ R_e^{-.51}\ \psi \qquad (6\text{-}8)$$

$$Re > 50 \qquad J_H = .61\ R_e^{-.41}\ \psi \qquad (6\text{-}9)$$

Where ψ is a shape factor which for corn kernels is estimated as .67 (See Appendix C). The Reynolds number can be defined as:

$$Re = \frac{G_e}{a\ \mu\ \psi} \qquad (6\text{-}10)$$

Eliminating J_H from equations (6-7) and (6-9) for $R_e > 50$ will give:

$$\frac{h}{C_w G_w} (Pr)^{2/3} = .61 \left(\frac{G_e}{a \mu \psi}\right)^{-.41} \psi \qquad (6\text{-}11)$$

Solving equation (6-11) for h and substituting numerical values for Pr, C_w, ψ and μ gives:

$$h = .181(G_e)^{.59}\ (a)^{.41} \qquad (6\text{-}12)$$

Similarly, for cases where $R_e < 50$:

$$h = .253(G_e)^{.49}(a)^{.51} \qquad (6\text{-}13)$$

Where G_e is the apparent mass velocity of the grain. Also:

$$G_e = \rho_p V_e \qquad (6\text{-}14)$$

Where V_e is the apparent velocity and may be estimated from:

$$V_e = V_p + V_w = \frac{G_p}{\rho_p} + \frac{G_w}{\rho_w} \qquad (6\text{-}15)$$

The bulk density of the grain, $_p$, can be estimated as 35-40 percent of the bulk density for a packed column bed (Hicks <u>et al</u>., 1972).

Equations (6-1) through (6-15), along with equation (5-19), have been solved simultaneously by a Fortran computer program. The main objective was to select both flow rates of grain and water so that:

a) The most efficient heat transfer takes place.

b) The time of grain and water contact does not exceed 90-100 seconds.

The Fortran program, which has been written for Michigan State University CDC 6500 is in Appendix G. Figure 12 is a numerical output, and Figure 13 is a graph of water and grain (corn) temperatures along the length of the heater. As it is shown in the sample outputs, the grain and water flow rates, along with the bed lengths, were adjusted in order to obtain a narrow temperature difference and minimum water absorption. However, these values will be recomputed when the flow of grain in the cooler-dryer was determined.

INPUT

WATER FLOW RATE	GA	LB/SQ FT-HR	710.00
GRAIN FLOW RATE	GP	LB/SQ FT-HR	835.00
LENGTH	XL	FEET	1.20
INITIAL WATER TEMP	TIN	OF	180.00
INITIAL GRAIN TEMP	THIN	OF	73.00
INITIAL MC(DB)	XMI	PERCENT	29.00

OUTPUT

REYNOLDS NO.	RE		15.05
CONV. HEAT TRANSF.	H	BTU/SQ FT-OF-HR	89.41
TOTAL TIME	TT	SECONDS	101.05

TIME	LENGTH	WATER TEMP	GRAIN TEMP	GRAIN MC
101.1	0.00	180.0	174.5	.33
95.0	.06	174.9	169.1	.33
90.9	.12	169.6	163.7	.33
85.9	.18	164.2	158.1	.33
80.8	.24	158.8	152.6	.33
75.8	.30	153.3	147.0	.33
70.7	.36	147.8	141.4	.32
65.7	.42	142.3	135.9	.32
60.6	.48	136.9	130.5	.32
55.6	.54	131.6	125.2	.32
50.5	.60	126.4	120.0	.32
45.5	.66	121.3	115.0	.32
40.4	.72	116.3	110.1	.31
35.4	.78	111.5	105.4	.31
30.3	.84	106.8	100.8	.31
25.3	.90	102.4	96.5	.31
20.2	.96	98.1	92.4	.30
15.2	1.02	94.1	88.4	.30
10.1	1.08	90.2	84.7	.30
5.1	1.14	86.5	81.3	.29
.0	1.20	83.2	78.0	.29

Figure 12. Sample output of the Fortran program describing a counterflow grain heating by hot water.

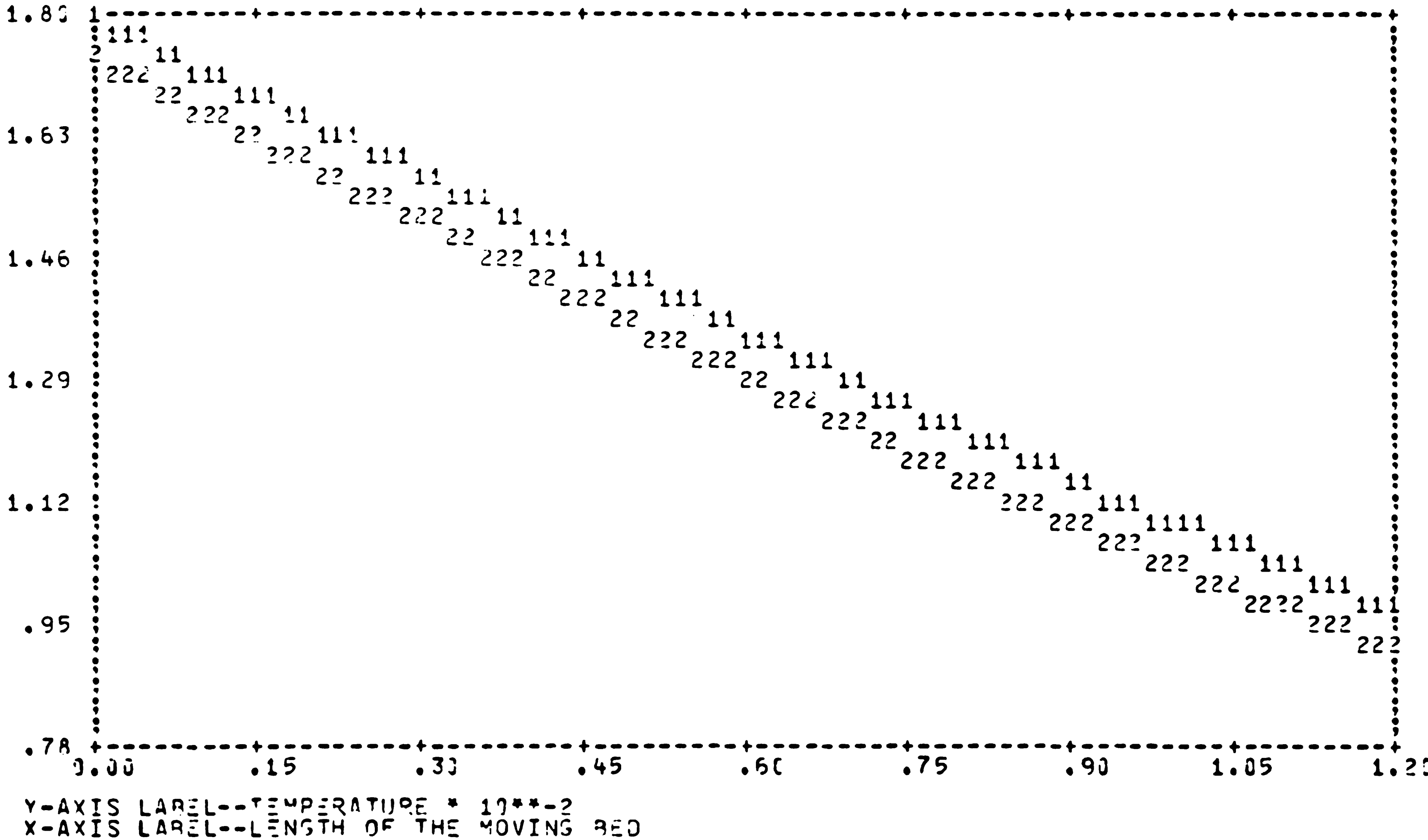

Figure 13. Water temperature (1) and grain temperature (2) along a 1.2 feet length of a screw conveyor. The instantaneous difference between water and grain temperature is about 5°F.

VII. SUMMARY

Corn heating in a counterflow heater using water as a heating medium was investigated. This system is part of a two-stage recirculating counterflow dryer which promises a lower energy consumption.

Heating time, moisture absorption, germination and chemical losses (starch, protein and minerals) were determined by immersing shelled yellow corn into the hot water. Corn with different initial moïsture contents, water with initial temperatures and different time periods were selected variables in the experiments.

The following major conclusions can be drawn:

1) A period of 60 to 90 seconds is sufficient for corn to reach equilibrium temperature with water, when the water temperature is kept constant.

2) Moisture absorption during the selected process time (60-90 seconds) is through the basal end of corn kernels and will be considered as a free water. The absorption behavior agrees well with Fick's law of diffusion; consequently, a linear model for water absorption was developed.

3) Starch, protein and mineral losses are negligible in the experimental conditions.

4) Germination was improved at 140^{o}F, but it drops rapidly at higher temperatures. Germination is almost zero at 180^{o}F.

VIII. FUTURE WORK

Based on the present work, it can be concluded that heating the corn kernels by hot water is an efficient heat-transfer process, and it is also safe with respect to corn quality. However, the other parts of the system (the cooler and heat exchanger) still have to be investigated.

The author recommends the following points to be considered for further investigations and implementation of the project:

1) The economics of the new design has to be studied carefully. A thorough quality test for all types of end uses of corn is required after the completion of the drying process.

2) Manufacturing a prototype of the dryer while simulating the process through the models is recommended.

3) More investigation to determine the pattern of water movement in and out of the corn kernel within the short periods of time applicable with the present conditions.

4) Determining the most effective types of heat exchanger, filter, pump, heater and a device to remove, mechanically, additional water from grain after the first stage.

5) Applying the system to other crops such as wheat, rice and beans.

APPENDICES

APPENDIX A

Crop	Year	Michigan	U.S.A.	Iran	World
Corn	1972	4002	141053	25	301392
	1971	4236	237806	25	305612
	1970	3241	105463	25	261312
Wheat	1972	642	42043	4500	347603
	1971	535	44030	3612	353822
	1970	562	36784	4262	318437
Rice	1972	--	3863	1200	295377
	1971	--	3890	877	309096
	1970	--	3801	1350	308767
Total Cereals	1972	4975	228093	6766	1275138
	1971	4236	237806	5396	1315702
	1970	4292	186851	6751	1212948

Table A-1. Selected cereals production in Michigan, U.S.A., Iran and World, in 1000 metric tons.

Source:

For Michigan: Michigan Agricultural Statistics, 1974.

For Others: FAO Production Yearbook, 1972.

	Estimated Fuel Consumption, gal./acre	
Operation	Diesel Fuel	Gasoline
Tillage (plow, disc twice)	3.34	4.36
Planting	0.77	1.10
Cultivating (twice)	1.54	2.20
Harvesting (field shelled)	0.88	1.16
Transporting to Storage	--	0.125
Drying (high temperature)	13.9*	
Transporting to Market	--	1.00

* LP-gas expressed as fuel oil equivalent. Assumed 100 bushel/acre of corn at 26.5 percent moisture dried to 14 percent moisture with 2000 BTU utilized per pound of water removed.

Table A-2. Energy requirements of selected corn production operations.

Source: (Isaacs, 1973).

	Unit	Mich.	U.S.A.
Corn Production	Mil.Bu.	133.5 [1]	5670 [2]
Heat Dried	Percent	61.2 [1]	75 [3]
Quantity Dried[4]	Mil.Bu.	81.7	4250
Water Removed	Mil.Lb.	580	30130
Energy Consumed[5]	BTU	1.16×10^{12}	60.3×10^{12}
Propane Equivalent[6]	Mil.Gal.	12.87	670

Table A-3. Estimated energy consumed in U.S. and Michigan to dry corn crop of 1973.

Notes:

1 Michigan Crop Reporting Services (1974).

2 Estimated (Johnson, 1973).

3 Johnson (1973).

4 From a moisture content of 25 percent to 15.5 percent WB.

5 Based on 2000 BTU per pound of water to be removed.

6 About 90-95 percent of heated-air dryers work on LPG (Hansen, 1973). Fuel heating value of propane is 21680 BTU per pound (Hall, 1967).

Type of Dryer	BTU/Lb	Specific Conditions	Source
Layer Drying 6 inches deep (wheat)	1900 - 3700	Inlet air 32°C Inlet humidity ratio .0085	Woodforde and Lawton (1965)
Bach Drying 2 feet deep (wheat)	1260 - 2300	Inlet air 59°F DB	Clark and Lamond (1968)
Cross Flow Cross Modified	3320 1640	 Air partially recycled	Converse (1972)
Cross Flow (Modified)	3017 1329	The grain was dried from 22.0 to 15.5 percent	Lerew *et al.* (1972)
Concurrent Flow with counterflow cooler	1500	Corn temp. 64.4°F drying from 21.7 to 16.4 percent inlet air 61°F DB 72 percent RH	Anderson (1972)

Table A-4. Energy requirements of different types of dryers to evaporate one pound of water from the grain.

APPENDIX B

SAMPLE	MC	Ml Water	Temp °F	Time Sec	SAMPLE	MC	Ml Water	Temp °F	Time Sec
A1		86.79	140	50	D1		82.21	140	50
A2		78.93	140	90	D2		88.25	140	90
A3	15.66	78.24	180	50	D3	27.38	79.83	180	50
A4		72.86	180	90	D4		76.64	180	90
B1		85.74	140	50	E1		78.89	140	50
B2	20.48	72.28	140	90	E2	29.78	84.41	140	90
B3		80.62	180	50	E3		80.61	180	50
B4		72.28	180	90	E4		76.08	180	90
C1		87.45	140	50	F1		89.40	140	50
C2	25.00	81.65	140	90	F2	34.47	92.45	140	90
C3		72.77	180	50	F3		73.33	180	50
C4		79.29	180	90	F4		87.20	180	90

Table B-1. Sample number, initial moisture content and quantities of water used in the experiments.

APPENDIX C

DIMENSIONAL CHARACTERISTICS OF CORN

1. The dimensions of the corn kernel used in the experiments are based on the average of 50 kernels:

   a = .3937 inch

   b = .2925 inch

   c = .1614 inch

   d = .1969 inch

2. Volume to surface area ratio.

   According to Becker et al. (1959), V/A can be calculated from:

$$\frac{V}{A} = \frac{r}{3} \frac{4\pi r^2}{A}$$

The factor $4\pi r^2/A$ is the ratio of the surface area of a sphere of equal volume to the surface area of the solid. This ratio is called shape factor, and commonly is known as the sphericity and denoted by ψ. According to Mohsenin (1970), the percentage of sphericity in corn kernels can be calculated from:

$$C = \frac{100(a\ b\ c)^{1/3}}{a} = .67$$

Therefore, the ratio of V/A can be estimated from:

$$V/A = r/3\ \psi$$

By having 2r as the diameter of the smallest diameter of the circle which circumscribes the kernel, i.e., a/2, the value of V/A will be:

$$V/A = \frac{(.3937)(.67)}{(2)(3)(12)} = .0036\ ft^{-1}$$

3. A geometric mean diameter is defined for the corn kernel for cases where a chacteristic dimension is needed, as follows:

$$dm = (a\ b\ c\ )^{1/3} = .0221\ ft$$

APPENDIX D

Property	Unit	Air[1]	Water[2]	Corn[3]	
				Bulk	Single kernel
Heat Capacity C	$\frac{BTU}{lbm^{o}F}$	.2400	.998	.567	≈.5
Density P	$\frac{lbm}{ft^3}$	.0747	62.270	44.3	80.7*
Viscosity	$\frac{lbm}{ft\text{-}hr}$	.0440	2.370	--	--
Thermal Conductivity K	$\frac{BTU}{hr\ ft^{o}F}$	.0149	.349	.0982	1.2**
Thermal Diffusivity	$\frac{ft^2}{hr}$	.0831	.0056	.00344	.0262
Prandtle Number Pr	--	.710	6.780	--	--

Table D-1. Thermal properties of air, water and shelled corn (24.7% MC WB) at 70^{o}F.

[1] Source: Villa (1973).
[2] Source: Holman (1972).
[3] Source: Kazarian et al. (1963).
* Source: Mohsenin (1970).
** Source: Hall (1967).

APPENDIX E

- Corn Kernel
  - Pericarp (fruit coat):
    - 1-Epidermis cutinized
    - 2-Mesacarp
    - 3-Cross cells
    - 4-Tube cells
  - Seed
    - Seed coat (Testa, spermoderm, integument)
    - Endosperm:
      - Aleuron layer
      - Starch storage parenchyma
    - Embryo
      - Scutellum:
        - Epiderm
        - Oil storage
        - Vascular tissue
      - Embryonic Axis:
        - Plumule
        - Mesocotyle
        - Primary root

Figure E-1. Corn kernel structure (Wolf et al., 1952).

Starch	71.50%
Protein	9.91%
Fat	4.78%
Ash (oxides)	1.42%
Fiber (crude)	2.66%
Sugars total	2.58%
Total carotenoids	30.00mg/kg

Table E-1. Approximate analysis of corn grain at moisture level of 16.7% (wet basis).

Source: Matz (1969)

Endosperm	81.7
Horny	54.2
Floury	27.5
Germ	11
Hull	5.8
Tip cap	1.4

Table E-2. Percentage(weight basis)of the different parts of a corn kernel.

Source: Wolf et al. (1952)

APPENDIX F

```
PROGRAM    WATHEAT                                    CDC 6500 FTN V3.0-P376 OPT=1  08/13/74
          PROGRAM WATHEAT(INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT)
C*****PROGRAM WATHEAT IS TO SIMULATE HEATING OF THE GRAIN WITH HOT WATER
C******IN A COUNTERFLOW MANNER IN AN AUGER
          COMMON MAXNO,Y(101,2),T(101),TH(101),TXM(101)
          DATA CA,CP,SA,RHOP,RHOW/1.,.5,120.,20.,61./
          NX=100
          MAXNO=2
          READ 1,GA,GP,XL,THIN,TIN,XMI
        1 FORMAT(6F5.1)
C******COMPUT APPARANT MASS VELOCITY OF THE GRAIN,GO
          GO=(GP/RHOP+GA/RHOW)*RHOP
          RE=1.56*GO/SA
C******CHECK THE CONDITION IF REYNOLDS NUMBER IS GREATER OR LESS THAN 50
C****** ,FOR CALCULATING CONVECTIVE HEAT TRANSFER COEFFICIENT,H
          IF(RE.GT.50.) GO TO 5
          H=.253*GO**.49*SA**.51
          GO TO 6
        5 H=.191*GO**.59*SA**.41
        6 HA=H*SA
C******FIND THE TOTAL TIME OF HEATING,TT
          TT=7200.*XL/GP
C******COMPUTE FINAL MOISTURE CONTENT
          XM=(XMI+.53*SQRT(TT))/100.
          CTH=-HA/(GP*(CP+CA*XM))
          CT=HA/(GA*CA)
          EXPX=EXP(-XL*(CT+CTH))
C******FIND THE OUTLET GRAIN TEMPERATURE
          THO=(THIN*(CT+CTH)+TIN*CTH*(EXPX-1.))/(CTH*EXPX+CT)
C******CALCULATE DISTANCE AND TIME INTERVAL
          DX=XL/NX $ D=0
          DT=TT/NX
          TMTH=TIN-THO
C******MONITOR GRAIN AND WATER TEMPERATURE ALONG THE FLOW LENGTH
          DO 20 I=1,101
          D=I*DX
          TIME=I*DT
          TXM(I)=(XMI+.53*SQRT(TIME)) /100.
          CTH=-HA/(GP*(CP+CA*TXM(I)))
          EXPX=EXP(-D*(CT+CTH))
          T(I)=(CT*TMTH*(EXPX-1.))/(CT+CTH)+TIN
          TH(I)=-(CTH*TMTH*(EXPX-1.))/(CT+CTH)+THO
       20 CONTINUE
```

Figure F-1. A Fortran program written for the MSU CDC 6500.

```
C******PLOT THE TEMPERATURES
      CALL GRAF(0)
      X=XMIN
      Y(1,1)=TIN
      Y(1,2)=THO
      DO 10 K=2,101
      Y(K,1)=T(K)
      Y(K,2)=TH(K)
      X=K*DX
   10 CONTINUE
      CALL GRAF(-1)
      PRINT 2,GA,GP,XL,TIN,THIN,XMI,RE,H,TT
    2 FORMAT(*-*,20X5HINPUT//
     125X15HWATER FLOW RATE7X2HGA4X11HLB/SQ FT-HR8XF6.2/
     225X15HGRAIN FLOW RATE7X2HGP4X11HLB/SQ FT-HR8XF6.2/
     325X6HLENGTH15X2HXL4X4HFEET15XF6.2/
     525X18HINITIAL WATER TEMP3X3HTIN4X2HOF17XF6.2/
     425X18HINITIAL GRAIN TEMP2X4HTHIN4X2HCF17XF6.2/
     625X14HINITIAL MC(DB)7X3HXMI4X7HPERCENT12XF6.2///
     720X6HOUTPUT//
     825X12HREYNOLDS NO.11X2HRE21XF8.2/
     925X18HCONV. HEAT TRANSF.6X1HH4X15HBTU/SQ FT-OF-HR2XF8.2/
     A25X10HTOTAL TIME13X2HTT4X7HSECONDS10XF8.2///
     B23X4HTIME5X6HLENGTH5X10HWATER TEMP5X10HGRAIN TEMP5X8HGRAIN MC//)
      D=TIME=0
      PRINT 3,TT,D,TIN,THO,TXM(101)
      DO 30 K=5,100,5
      D=K*DX
      TIME=TT-(K*DT)
      PRINT 3,TIME,D,T(K),TH(K),TXM(101-K)
    3 FORMAT(22XF5.1,5XF4.2,2(9XF5.1)10XF3.2)
   30 CONTINUE
      END
```

```
C******PLOT THE TEMPERATURES
      CALL GRAF(0)
      X=XMIN
      Y(1,1)=TIN
      Y(1,2)=THO
      DO 10 K=2,101
      Y(K,1)=T(K)
      Y(K,2)=TH(K)
      X=K*DX
   10 CONTINUE
      CALL GRAF(-1)
      PRINT 2,GA,GP,XL,TIN,THIN,XMI,RE,H,TT
    2 FORMAT(*-*,20X5HINPUT//
     125X15HWATER FLOW RATE7X2HGA4X11HLB/SQ FT-HR8XF6.2/
     225X15HGRAIN FLOW RATE7X2HGP4X11HLB/SQ FT-HR8XF6.2/
     325X6HLENGTH16X2HXL4X4HFEET15XF6.2/
     525X18HINITIAL WATER TEMP3X3HTIN4X2HOF17XF6.2/
     425X18HINITIAL GRAIN TEMP2X4HTHIN4X2HOF17XF6.2/
     625X14HINITIAL MC(DB)7X3HXMI4X7HPERCENT12XF6.2///
     720X6HOUTPUT//
     825X12HREYNOLDS NO.11X2HRE21XF8.2/
     925X18HCONV. HEAT TRANSF.6X1HH4X15HBTU/SQ FT-OF-HR2XF8.2/
     A25X10HTOTAL TIME13X2HTT4X7HSECONDS10XF8.2///
     B23X4HTIME5X6HLENGTH5X10HWATER TEMP5X10HGRAIN TEMP5X8HGRAIN MC//)
      D=TIME=0
      PRINT 3,TT,D,TIN,THO,TXM(101)
      DO 30 K=5,100,5
      D=K*DX
      TIME=TT-(K*DT)
      PRINT 3,TIME,D,T(K),TH(K),TXM(101-K)
    3 FORMAT(20XF5.1,5XF4.2,2(9XF5.1)10XF3.2)
   30 CONTINUE
      END
```

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