Climatic Humidity Effects on Controlled Summer Aeration in the Hard Red Winter Wheat Belt

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Abstract. *Aeration is an inexpensive way to improve grain storage conditions, but it can be difficult to implement immediately after harvest in much of the hard red winter (HRW) wheat belt due to high ambient temperatures. High nighttime relative humidity worsens this problem because the heat of condensation released during adsorption reduces aeration cooling, but the magnitude of this humidity effect is not well documented. A procedure was developed to calculate effective temperature (T_{eff}), which coupled dry-bulb temperature (T_{db}), wet-bulb temperature (T_{wb}), and grain moisture content to predict the actual final grain temperature after aeration. Hourly historical weather data were used to determine the available aeration hours below 24°C from mid-July through early August in Kansas, Oklahoma, Texas, eastern New Mexico, and eastern Colorado, along with nearby portions of surrounding states. Grain cooling was highly influenced by humidity. Actual available aeration hours averaged approximately 78% less during the periods studied compared to calculations based on T_{db} alone. Airflow rates higher than 0.1 m^3/min/t were found necessary to achieve sufficient grain cooling for the summer in Texas, Oklahoma, and southeastern Kansas. This effect was more pronounced in 10% than 12% moisture content wheat, because T_{eff} was always lower for grain at 12% moisture content.*

Keywords. *Climate, Controlled aeration, Grain storage, Humidity, Moisture, Wheat.*

Wheat (*Triticum* spp.) is the dominant grain of world commerce. The U.S. is the third largest wheat producing country in the world, and wheat is the third largest field crop in the U.S. behind corn and soybeans (USDA-FAS, 2006; USDA-NASS, 2006). Like any other grain, wheat is produced on a seasonal basis and may need to be stored for varying lengths of time. Therefore, maintaining grain quality during storage is a formidable task. Aeration is an effective, inexpensive tool to improve storage conditions by reducing grain temperatures and moisture migration, hence minimizing hot spots as well as mold and insect development, which may otherwise severely compromise the stored product quality (Noyes et al., 1995). However, aeration remains an underused tool in some situations, particularly with small grains in warm climates, such as in the central Plains states of the U.S. (Casada et al., 2002).

Aeration is an energy-efficient and economical method to reduce grain temperatures. Most hard winter wheat is grown in the Great Plains of the U.S., where the summers are typically hot and humid. Since aeration works best at relatively lower wet-bulb temperatures, in such locations aeration usually has to take place at night (Navarro and Calderon, 1982). The two primary objectives of aeration are to maintain a uniform temperature during storage and to keep the temperature below the limits for insect development (Noyes et al., 1995; Maier et al., 1996). Navarro et al. (2002) stated that development of stored-grain insects slows down below 27°C (81°F) and the insects thrive best at about 29.5°C (85°F). Aeration can slow the rate of deterioration of high-moisture grain, but most grains should be 14% (wet basis) or below for storing several months or longer (MWPS-29, 1999).

Reed and Arthur (2000) summarized the importance of aeration for reducing insect populations in stored grain. Computer simulation by Flinn et al. (1997) has shown that starting the aeration controller at harvest, rather than waiting until autumn, was more effective in cooling the grain and preventing insect infestation in Kansas, Oklahoma, and South Dakota. Aeration started at harvest was found to be effective in controlling insect growth in wheat stored in Kansas (Reed and Harner, 1998). Arthur and Casada (2005) reported that having a summer aeration cycle before the usual autumn cycles produced reduced temperatures in stored wheat as compared to temperatures with aeration only in autumn. However, previous research focused on the effect of dry-bulb temperature on aeration without explicitly accounting for the impact of relative humidity (RH) and grain moisture content on aeration temperatures.

Kansas grows more wheat than any other state in the U.S. Hard red winter (HRW) wheat, *Triticum aestivum* (L.), is also widely grown throughout the Great Plains (USDA-NASS, 2005). Benefits of early aeration following harvest have been investigated and reported (Sun and Woods, 1997; Reed and Harner, 1998; Casada et al., 2002). Typical central Plains weather in July and August affords sufficient hours below 24°C (75°F) for proper aeration (Arthur and Casada, 2005). Research on aeration management of stored grain (Arthur and Flinn, 2000; Arthur et al., 2001; Montross et al., 2004) that utilizes historical climatological data is available. However, such research solely considered dry-bulb temperature effects. Because aeration at night in these regions normally coincides

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with high ambient humidity (RH near 100% is common during the coolest part of the night), the heat of condensation from moisture adsorbed by the aerated grain has a significant effect that was not accounted for in previous research that looked only at dry-bulb temperatures and sensible heating effects. Using moisture equilibrium characteristics of the aerated grain, combined with psychrometric calculations, the temperature that the grain will reach after aeration can be calculated with latent heating included. This resulting aeration temperature, hereafter referred to as *effective temperature* (T_{eff}), will be higher than the ambient dry-bulb temperature when the air RH is higher than the grain equilibrium RH, and lower if the air RH is lower that the grain equilibrium RH.

The notion of controlling the seed wet-bulb temperature (SWBT) with aeration was investigated by Griffiths (1967) and Sutherland et al. (1971) and further developed by Wilson and Desmarchelier (1994). SWBT refers to the wet-bulb temperature of the interstitial air that is in moisture equilibrium with the grain. Previous control methods involved monitoring the ambient wet-bulb temperature and making control decisions based on comparison to the SWBT, but the effective temperature for aeration was not addressed. These researchers also did not look at historical climatological data across the region or at its implications for aeration system design.

Climatic conditions are not uniform across the large central Plains region. Average temperatures decline moving north because of normal latitude effects, but also decline moving west in much of the region as the elevation increases. Average humidity levels usually decrease moving west across this region as well.

The objectives of this study were: (1) to develop a protocol to calculate the effective temperature that accounts for the temperature and moisture conditions of the ambient air and the grain on the final aerated grain temperature, (2) to identify the number of early- and mid-summer available aeration hours in the U.S. HRW wheat states based on the effective temperature and compare the trends in contour plots to the apparent available aeration hours indicated by dry-bulb temperature, and (3) to evaluate required airflow rates for aeration system design based on available aeration hours in this region. The *available aeration hours* was defined as the number of hours accumulated in four weeks, in an average year, when HRW wheat could be cooled to 24°C or below with aeration.

Materials and Methods

Calculations were made for 50 years of weather data, and the available aeration hours from these years were averaged. Known psychrometric relations (ASHRAE, 1993) were used to determine other needed parameters based on the dry-bulb temperature and RH available in the weather data. The effective temperature is a function of both the ambient conditions and the grain moisture content. Two moisture contents were selected to cover the typical range for wheat stored in the region. The higher moisture content (12%) is typically near the upper limit that would be placed into storage. Designing for lower grain moisture requires larger fans than higher moisture and provides an additional safety factor for higher moistures; thus, it is unlikely to be desirable to design an aeration system for a higher moisture level than 12%. Similarly, the lower moisture content (10%) is near the lowest level likely to be stored in most of the region. With this range of typical storage moisture contents, interpolating for cases between the two moisture levels reported should provide sufficient accuracy for design purposes.

Database Formation

Hourly historical weather data were obtained from the National Climactic Data Center (Asheville, N.C.) and EarthInfo, Inc. (Boulder, Colo.). The weather stations with data available continuously from 1952 through 2001 were selected (table 1). Dry-bulb temperature (°C) and relative humidity (%) were extracted from the Surface Airways hourly database. A FORTRAN 77 source code was developed to identify the missing fields. Missing hourly fields were interpolated by using the previous and following numerical values. Rare cases of several consecutive missing hourly fields were calculated by taking the average of the previous and following day. The

Table 1. Location, latitude, longitude, and elevation for individual weather stations.

Station	Latitude	Longitude	Elevation (m)
Dodge City, Kansas	37°46′	99°58′	787
Goodland, Kansas	39°22′	101°42′	1114
Russell, Kansas	38°52′	98°48′	566
Topeka, Kansas	39°04′	95°38′	269
Wichita, Kansas	37°39′	97°26′	403
Grand Island, Neb.	40°57′	98°19′	561
North Platte, Neb.	41°07′	100°40′	847
Omaha Eppley, Neb.	41°18′	95°54′	299
Scottsbluff, Neb.	41°52′	103°35′	1,202
Oklahoma City, Okla.	35°23′	97°36′	397
Tulsa, Okla.	36°12′	95°53′	198
Abilene, Texas	32°24′	99°41′	546
Amarillo, Texas	32°24′	99°41′	1,093
Austin Camp, Texas	30°19′	97°46′	205
Brownsville, Texas	25°54′	97°25′	6
Corpus Christi, Texas	27°46′	97°31′	12
Dallas-Fort Worth, Texas	32°54′	97°01′	171
El Paso, Texas	31°48′	106°22′	1,194
Midland, Texas	31°56′	102°11′	872
Lubbock, Texas	33°40′	101°49′	992
Port Arthur, Texas	29°57′	94°01′	5
San Angelo, Texas	31°21′	100°29′	584
San Antonio, Texas	29°32′	98°28′	247
Waco, Texas	31°36′	97°14′	152
Wichita Falls, Texas	33°58′	98°29′	314
Colorado Springs, Colo.	38°48′	102°42′	1,871
Grand Junction, Colo.	39°08′	108°32′	1,481
Albuquerque, N.M.	35°02′	106°37′	1618
Roswell, N.M.	33°18′	104°31′	1112
Tucumcari, N.M.	35°11′	103°36′	1239
Baton Rouge, La.	30°32′	91°09′	20
New Orleans, La.	29°59′	90°15′	1
Shreveport, La.	32°27′	93°49′	77
Fort Smith, Ark.	35°20′	94°21′	137
Little Rock, Ark.	34°43′	92°14′	79
Springfield, Mo.	97°14′	93°23′	384
St. Louis, Mo.	38°45′	90°22′	162
Des Moines, Iowa	41°32′	93°39′	292
Mason City, Iowa	43°09′	93°19′	373
Sioux City, Iowa	42°23′	96°22′	334

code automatically performed the necessary interpolations to produce a complete database for further calculations. Separate databases were built for each state.

Data on usual harvesting dates for winter wheat in each state were used to establish the appropriate periods to select for evaluating climatic conditions (USDA-NASS, 1997). That reference defined "most active harvesting periods," averaging about two weeks in length, for each state based on historical harvest data. The beginning aeration dates for each state were estimated as one week after the most active harvesting period begins because substantial amounts of grain should be binned in a given state one week into the most active period, while relatively little grain should be in storage a week earlier. To cover this range of harvesting dates in these states, four aeration periods of four weeks each were defined based on aeration starting one week after the most active harvesting period begins in each state. To use the results presented here, the aeration designer should select the period most appropriate for starting aeration in the design location. The four overlapping periods, each consisting of four weeks (672 h), were:

Period 1: June 17-July 14

Period 2: June 24-July 21

Period 3: July 1-July 28

Period 4: July 8-August 4

Data were included for four surrounding states (Louisiana, Arkansas, Missouri, and Iowa) to improve the accuracy of the contour lines all the way to the border of the HRW wheat states. Contour plots of available aeration hours were created using Surfer 7 (Golden Software, 1999), which used kriging as the gridding method to create these grid-based maps. The resulting contour maps were overlaid on a base map of the region that was outlined and exported from MapViewer 5 (Golden Software, 2002), and Surfer performed the scaling automatically. According to the Minnesota Association of Wheat Growers (MAWG, 2005), durum and soft red winter wheat are grown in those states, indicating that results can also be applied in those states. For those wheat classes, the small shift in equilibrium humidity isotherms compared to hard wheat would mean that the available aeration hours reported here would apply directly to slightly different moisture contents. Data on these moisture content differences are available in the literature and are presented in the discussion below.

Calculation of the Effective Temperature

A FORTRAN 77 code was developed to calculate T_{eff} for each station. The protocol was as follows:

1. Wet-bulb temperatures were calculated with the psychrometric equations in Section 1.5 of the ASHRAE *Handbook of Fundamentals* (ASHRAE, 1993) following Zhang et al. (1997). The input variables were relative humidity (decimal) and dry-bulb temperature (°C). The equations are summarized in table 2. The psychrometric calculation procedures are described in Zhang et al. (1997).
2. Equilibrium RH was calculated using the Chung-Pfost equation (*ASAE Standards*, 2003) for two different grain moisture contents (10% and 12% w.b.). Chung-Pfost equation constants were determined for moisture adsorption data in Pixton and Henderson (1981) from four varieties of hard red wheat. The Chung-Pfost equation requires moisture content in d.b.; therefore, w.b. was converted to d.b. moisture content for calculations. However, all moisture contents cited herein are w.b. The input temperature for the Chung-Pfost equation is T_{eff}, which is not known in advance; thus, the iterative procedure in step 3 was used.
3. With equilibrium RH and wet-bulb temperature being the starting values, effective temperature was calculated iteratively using ASHRAE equations 20 and 30 and the Chung-Pfost equation. For an initial guess for the iteration, the effective temperature was set 1°C higher than the dry-bulb temperature. The temperature where the constant wet-bulb temperature line intersected the equilibrium RH for the stored wheat (fig. 1) was defined as the effective temperature (T_{eff}).

Table 2. ASHRAE equations used to calculate wet-bulb temperature.

Calculated Variable	Unit	ASHRAE Equation
Partial pressure of water vapor at saturation	kPa	3, 4
Humidity ratio of air/water vapor mixture	$kg_{water}/kg_{dry\ air}$	20
Dew point temperature	°C	35
Enthalpy of air/water vapor mixture	$kJ/kg_{dry\ air}$	30
Specific volume of air/water vapor mixture	$m^3/kg_{dry\ air}$	26
Degree of saturation of air/water vapor mixture (dimensionless)	--	12
Wet-bulb temperature	°C	33

The effective temperature is at the equilibration point that the ambient air reaches after passing through the shallow rewetting zone (the drying zone in the case of low-humidity air) after following the adiabatic saturation process (Henderson et al., 1997). It is the final temperature of all of the grain bulk, except the small amount of grain that experiences rewetting near the entrance, assuming there is no incident moisture change in the grain that the has not been subjected to the rewetting zone.

Foster (1967) indicated that the maximum theoretical drying incident to cooling by aeration will be less than 0.3 percentage points for cooling less than 14°C (25°F), which should always be the case with the small temperature changes possible during summer aeration. Thus, the assumption that there is no drying beyond the drying zone itself is reasonable. However, if desired, this small effect may be easily accounted for by using the grain moisture content after the incidental drying, rather than the initial storage moisture content. For example, if grain is placed in storage at 10.2%

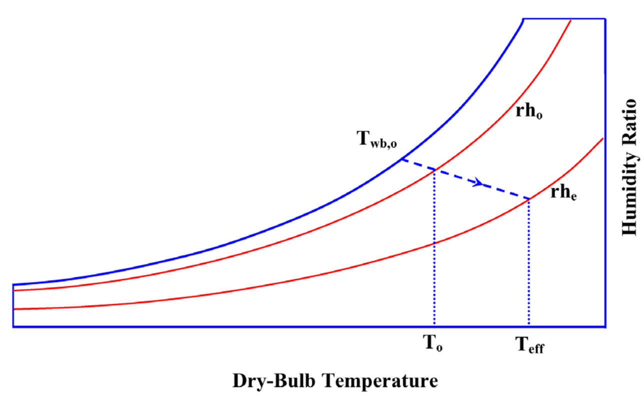


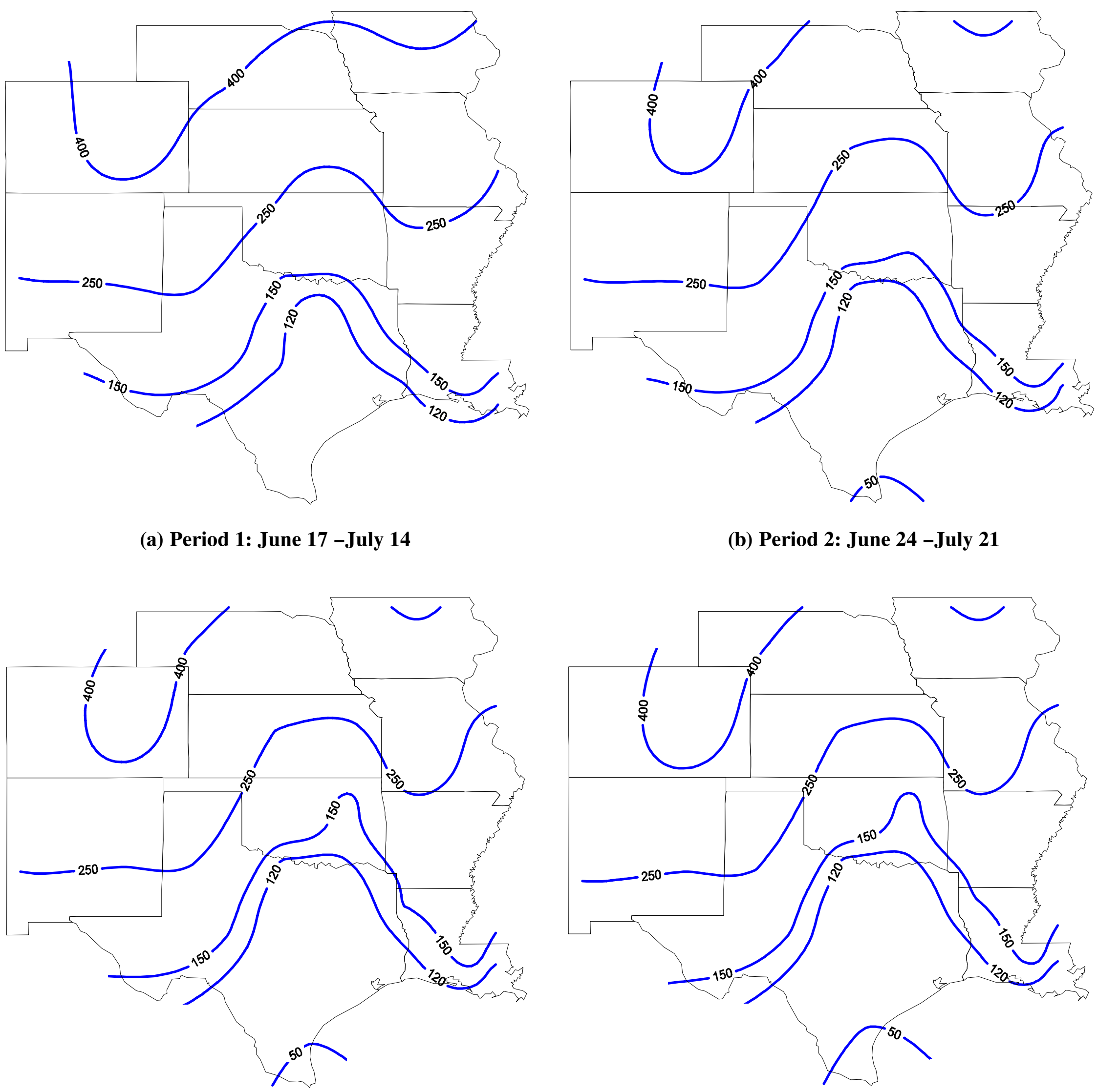
Figure 1. Psychrometric process when grain with an equilibrium relative humidity of rh_e at a temperature of T_{eff} is aerated with air at a relative humidity and dry-bulb and wet-bulb temperatures of rh_o, T_o, and $T_{wb,o}$, respectively, resulting in a final grain temperature of T_{eff}.

moisture content, and the designer determined that 0.2 percentage points of incidental drying will occur (following the method of Foster, 1967), then the results given here for 10.0% grain moisture content should be used.

This effective temperature is based on the same concept as the SWBT, defined by Griffiths (1967), which is the wet-bulb temperature in the interstitial spaces. However, effective temperature is the resulting grain temperature after aeration, when the heat of condensation from the adiabatic saturation process is accounted for during rewetting of the grain (or the heat of vaporization when there is a grain drying front during aeration), rather than a pre-existing wet-bulb temperature in the interstitial spaces, as is SWBT. Defining the effective temperature in this way makes it possible to evaluate weather data to see its total effect on aeration in one straightforward term, T_{eff}.

When a pressure (upward flow) aeration system is used with farm-size bins, there will be a small amount of sensible heating of the air by the fan. This fan heat will raise the dry-bulb temperature of the entering air a small amount and will raise the effective temperature. The effective temperature does not increase quite as much as the dry-bulb temperature because the entering air has a slightly lower RH due to the sensible heating. However, suction (downward flow) aeration systems are preferable in the HRW wheat region because they offer better control of insects at the top of the bin (Noyes and Kenkel, 1999; Reed and Harner, 1998). Thus, this analysis was based on a suction aeration system without any addition of fan sensible heat. A pressure aeration system would have slightly fewer total available aeration hours because the entering air temperatures would always be slightly higher.

Aeration cooling of grain is a deep-bed process in which a cooling front moves through the bed of grain. To move a temperature front completely through a bin of grain, the estimated time required to run the fan would be 150 h for 10% moisture content wheat at temperatures <24°C at the frequently recommended airflow rate of 0.1 m^3/min/t (GEAPS, 1989). For wheat at a higher moisture content, the cooling front will



(a) Period 1: June 17 –July 14

(b) Period 2: June 24 –July 21

(c) Period 3: July 1 – July 28

(d) Period 4: July 8 – August 4

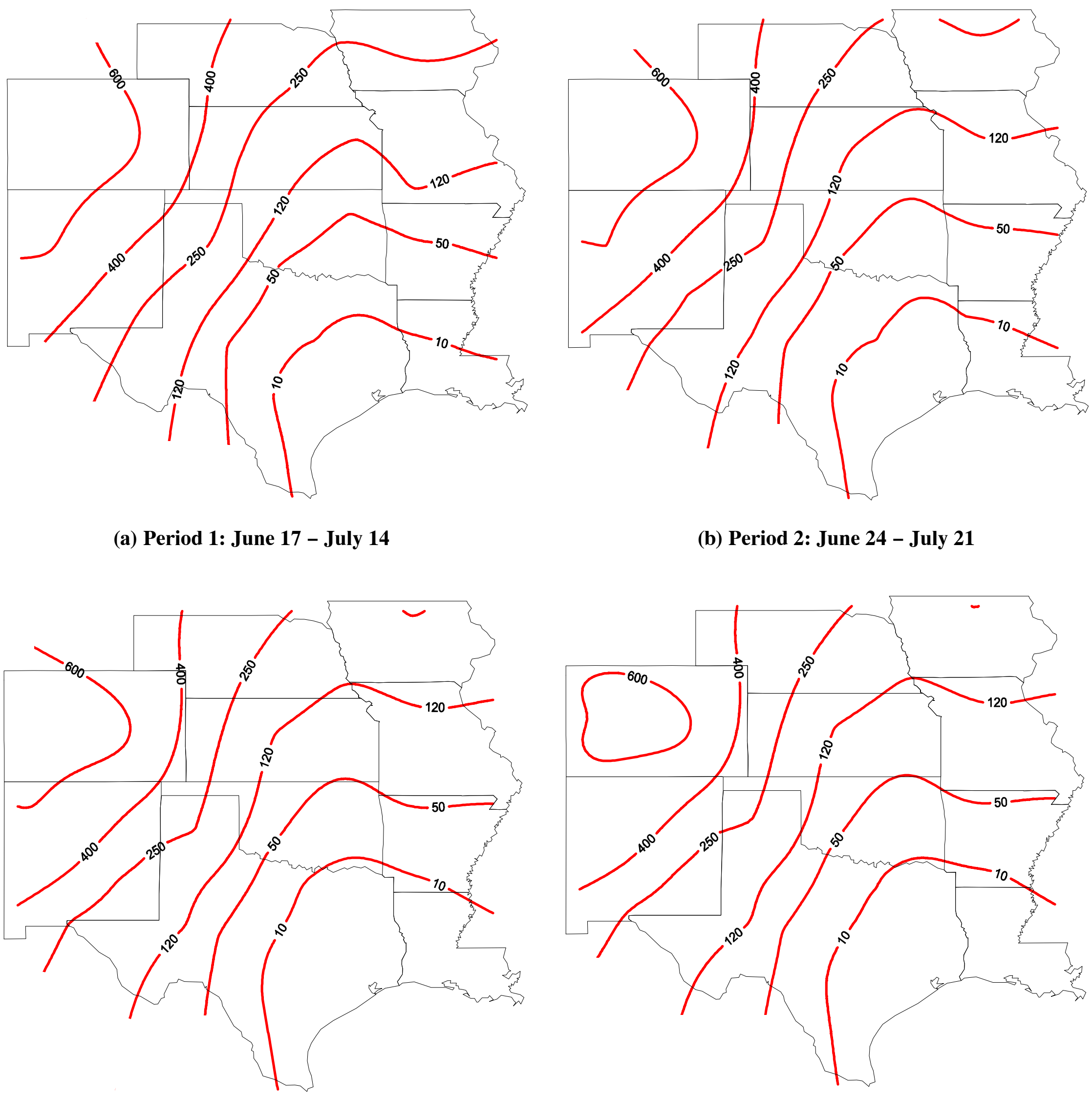
Figure 2. Apparent available aeration hours for summer aeration of hard wheat based on dry-bulb temperatures below 24°C and neglecting the heat of condensation released during rewetting.

move faster because more evaporative cooling will result from the greater amount of drying in wetter grain (with air at the same condition as for the drier grain). Thus, for wheat at 12% moisture content, about 120 h would typically be required to move the cooling front through the bin (Foster, 1967; Kline and Converse, 1961). The contour plots of the available aeration hours include contours for 120 and 150 h for reference for this common aeration rate (0.1 m^3/min/t). However, these times, while typical of these summer conditions, are selected for illustration only. Because of the wide variation in cooling times, the aeration system designer must determine the appropriate cooling time for the design conditions, and use that actual time in conjunction with the available aeration hours reported here. Since the relationship between airflow rate and speed of the cooling front is approximated very well by a linear relationship (Foster and Tuite, 1992), other airflow rates can also easily be evaluated with the figures. For example, an airflow rate that is three times higher (0.31 m^3/min/t) in 10% wheat under identical conditions would require approximately 50 h to complete a cooling cycle. Thus, the 50 h contour is useful for evaluating this higher airflow rate.

Results and Discussion

Available Aeration Hours, Dry-Bulb Temperature Only

During period 1 (fig. 2), there was a strong influence of latitude on the apparent available aeration hours following the increasing trend of dry-bulb temperature moving south in the region. As the periods progressed into mid-summer (periods 2 through 4), the contour lines were more influenced by both latitude and longitude as the drier high-elevation areas, such as New Mexico and Colorado, typically have more cooler nights and early mornings suitable for aeration (temperature <24°C) compared to the states that typically have warmer and more humid summers.



(a) Period 1: June 17 – July 14

(b) Period 2: June 24 – July 21

(c) Period 3: July 1 – July 28

(d) Period 4: July 8 – August 4

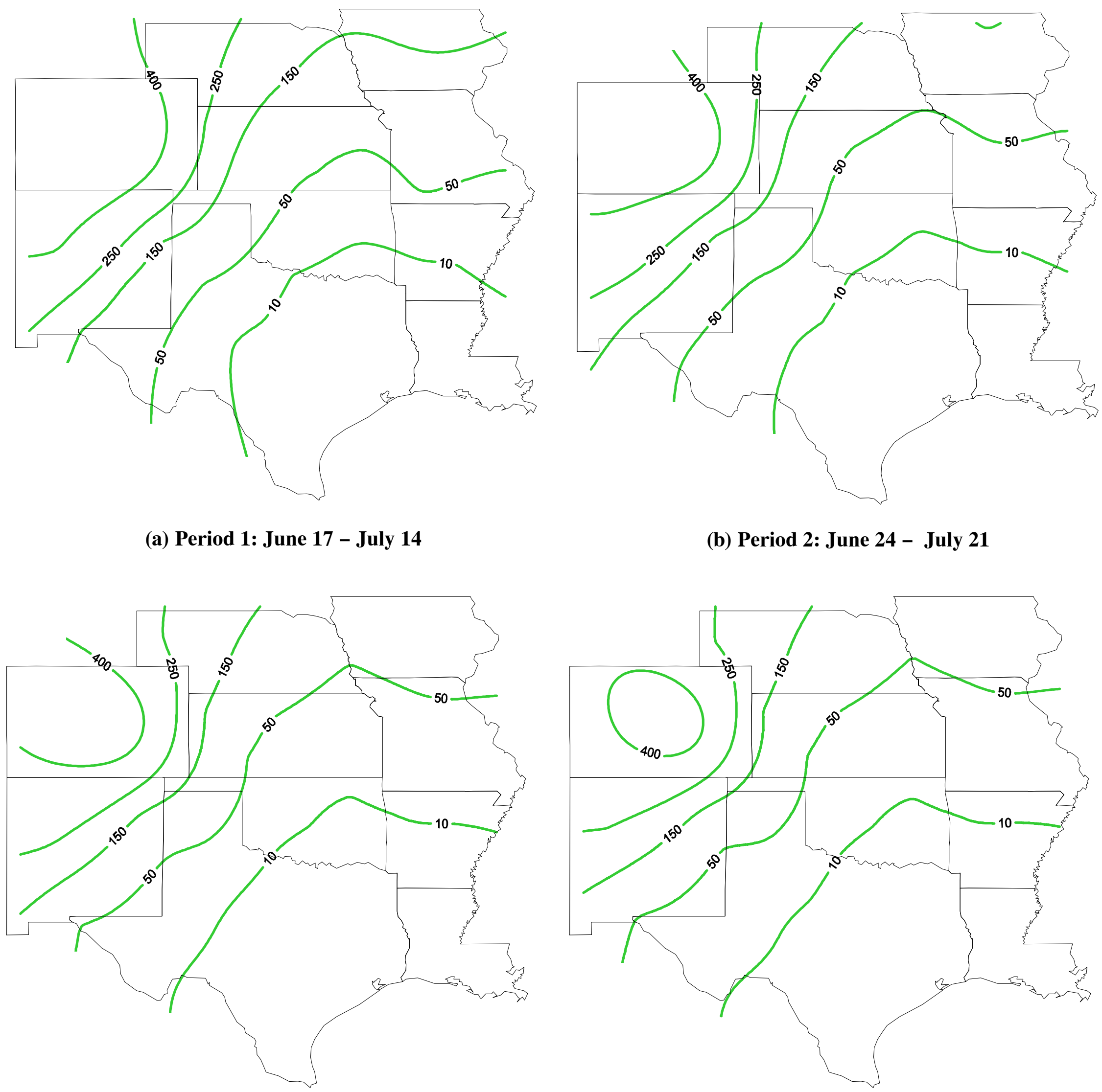
Figure 3. Available aeration hours for summer aeration of hard wheat at 12% moisture content based on reaching 24°C or lower after accounting for the heat of condensation released during rewetting.

The results based on dry-bulb temperature alone indicate that almost all of the HRW wheat region can successfully move a summer aeration front through stored grain with low airflow rates, 0.1 m^3/min/t (0.1 cfm/bu) or slightly higher, during a four-week period immediately after harvest during a normal year. However, since this method of calculation overestimates the time available for actually cooling the grain to the desired temperature, airflow rates actually needed may be higher. Since results like these, based on dry-bulb temperature alone, have previously been considered in most of the literature, they are used here as a standard of reference. The results that account for the effective temperature of the aeration air, discussed below, indicate that higher rates are needed to move aeration fronts through stored wheat during these four-week periods.

Available Aeration Hours with Humidity Effect

Available aeration hours for summer aeration shown in figure 3 for grain at 12% moisture content are significantly reduced compared to the hours shown in figure 2, which were based on dry-bulb temperature alone. For example, for period 2, the 120 h contour for the dry-bulb temperature results shows only a portion of central and eastern Texas below this critical limit where there are sufficient hours for aeration at the low flow rate. When the true effective temperature is determined (fig. 3), most of Texas and Oklahoma and more than half of Kansas are below the 120 h limit. This contour continued to move slightly farther toward the northwest in later time periods, but most of the central Plains and mountainous states had temperatures adequate to complete summer aeration with a low airflow rate at any given period when wheat moisture content was 12%.

Aeration of high-moisture grain results in greater cooling than low-moisture grain because the heat of condensation is reduced. For example, aeration of 12% grain results in temperatures approximately 3°C cooler than aeration of 10% grain with the same ambient air dry-bulb temperature and RH. As a result, aeration of grain at higher moisture content



(a) Period 1: June 17 – July 14

(b) Period 2: June 24 – July 21

(c) Period 3: July 1 – July 28

(d) Period 4: July 8 – August 4

Figure 4. Available aeration hours for summer aeration of hard wheat at 10% moisture content based on reaching 24°C or lower after accounting for the heat of condensation released during rewetting.

(e.g., 12% versus 10%) produces more available aeration hours, since the effective temperature is always lower for grain at the higher moisture content. Despite this advantage with higher moisture grain, the available aeration hours are much lower than the apparent available aeration hours indicated by dry-bulb temperature alone in figure 2.

For 10% grain moisture, a prominent trend among the periods for each weather station was the decreasing mean available aeration hours as the periods progressed from June into the beginning of August. Period 1 had the highest number of available aeration hours, while period 4 had the least number (fig. 4). This was because the weather becomes hotter and more humid in the HRW wheat region as summer progresses. As previously mentioned, the estimated time to move a temperature front completely through a bin of grain is 150 h for 10% moisture content wheat at an airflow rate of 0.1 m^3/min/t and 120 h for 12% moisture wheat. At a grain moisture content of 10%, compared to 12%, a larger section of Texas, Oklahoma, and Kansas falls below the required aeration criterion (120 h and 150 h, respectively) as summer progresses into hotter months (fig. 4), with essentially all of these states below the limit for period 2 and after. Thus, in those states, the low airflow rate of 0.1 m^3/min/t is expected to be inadequate for cooling 10% moisture content wheat within the four-week period in an average year. Aeration systems would have to be designed with larger fans to move an aeration front through the grain in four weeks. If faster cooling is desired, the fan size would have to be proportionately larger to complete the aeration cycle in less than four weeks.

Inspection of the effective daily temperature data revealed that the highest number of available aeration hours was accumulated from late night to early morning, peaking at 5:00 to 6:00 a.m. This trend consistently occurred independent of the region. The minimum available aeration hours were accumulated from 3:00 to 5:00 p.m. for more humid areas and from 1:00 to 2:00 p.m. for less humid areas, such as New Mexico and Colorado. The daily temperature variation that leads to these results is illustrated in figure 5, which shows the temperatures for a summer day in Wichita, Kansas. The dry-bulb temperature dropped below the target of 24°C at about 9:00 p.m., while the effective temperature for 12% wheat did not reach that level until much later, about 1:30 a.m. For 10% moisture wheat, the effective temperature never dropped below the target level that night. Thus, the effect of humidity to raise the effective aeration temperature shifted the temperature curve and reduced the hours below the target each day. The temperature shift was greater for lower moisture grain and resulted in the elimination of all available aeration hours below the target on some days.

The diurnal temperature variation will produce a series of fronts in the aerated grain that finally yield an average of the temperatures of the interacting fronts wherever they overlap (Sutherland et al., 1983). Each temperature front will be at the effective temperature corresponding to each ambient condition and the moisture content of the grain. For controlled summer aeration, all of the fronts will be below whatever target temperature is achieved by the control system; thus, the final average temperature will be below the target temperature. However, this interacting front phenomenon does not effect the accumulation of available aeration hours reported here, but simply produces small temperature variations in the grain after aerating during those accumulated hours.

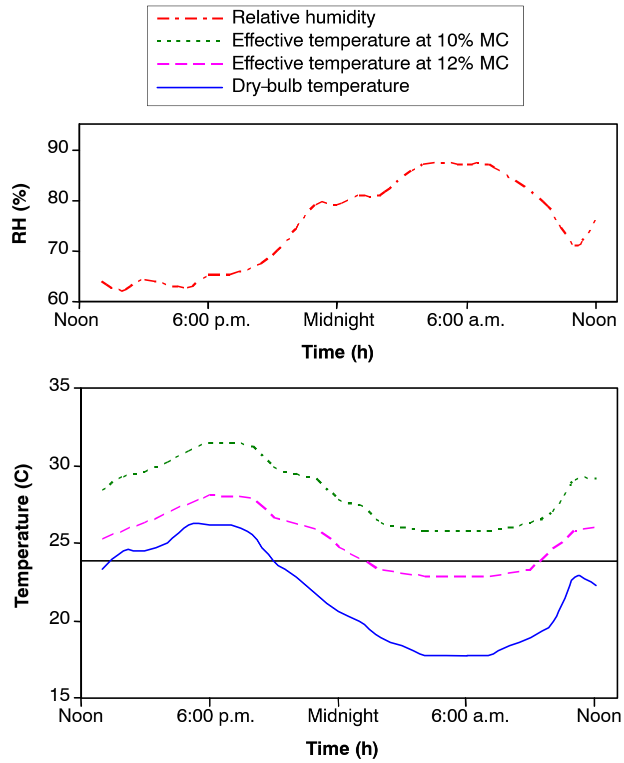


Figure 5. Temperatures and relative humidity during a typical 24 h period in Wichita, Kansas, during 28-29 July 1981.

Evaluation of Humidity Effects

A comparison of the available times in table 3 showed that, with a few exceptions at high elevations, higher humidity lowered the actual available aeration hours throughout the region compared to the apparent available aeration hours, based on dry-bulb temperature alone. The reduction at low and moderate elevations was usually greater than 50% and averaged nearly 70% for the four periods for 12% moisture wheat. This is reasonable because in summer, in all but extremely dry or cool parts of the region, desirable aeration temperatures occur mostly at night concurrent with the highest relative humidities of the day. As indicated in table 4, the reduction was even greater for 10% moisture content grain. The average reduction, excluding high elevations, was almost 90%, which shows why it is difficult to cool low-moisture wheat with summer aeration in these warm, humid climates despite the many misleading hours with low dry-bulb temperatures at night.

With results for wheat at 12% in southern Missouri, Arkansas, Louisiana, southeastern Kansas, and much of Texas and Oklahoma all below the typically required 120 h of aeration during periods 2 and 3 (fig. 3), it is clear that the 0.1 m^3/min/t rate is not adequate for summer aeration in those locations. The contours show that this area had approximately 60 available aeration hours or less during any of the four-week periods. When only 60 h are available, as opposed to 120 h, doubling the rate to 0.21 m^3/min/t is required, following from the linear relationship between aeration rate and cooling time. Thus, the higher airflow is needed in most of the HRW wheat growing sections of that area, and even higher rates would be needed in years with above-average temperatures. This problem was worse for dryer wheat at 10% moisture (fig. 4), with the same region having less than 40 h available for

Table 3. Mean number of available aeration hours for individual weather stations based on a threshold temperature of 24°C (75°F) and below.

Station	Apparent Available Hours from Dry-Bulb Temperature				Actual Available Hours for 12% Wheat MC				Actual Available Hours for 10% Wheat MC			
	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]
Dodge City, Kansas	295	274	270	273	224	186	166	156	97	68	54	50
Goodland, Kansas	386	368	366	371	417	376	348	335	240	193	164	152
Russell, Kansas	287	262	254	256	184	145	128	124	83	57	43	40
Topeka, Kansas	287	260	253	254	124	94	84	85	57	38	31	31
Wichita, Kansas	245	215	205	204	117	88	75	75	50	34	26	24
Grand Island, Neb.	362	340	339	342	269	220	196	196	142	104	84	80
North Platte, Neb.	410	389	384	387	362	322	299	292	220	178	154	144
Omaha Eppley, Neb.	331	304	301	305	199	157	137	135	98	67	53	49
Scottsbluff, Neb.	425	406	401	406	523	487	459	446	357	304	269	253
Oklahoma City, Okla.	222	199	184	184	63	47	36	38	21	16	12	12
Tulsa, Okla.	177	152	136	136	51	38	30	31	18	13	9	10
Abilene, Texas	155	144	132	130	47	42	35	40	12	10	6	9
Amarillo, Texas	304	291	288	294	293	264	249	238	112	86	72	67
Austin Camp, Texas	118	106	91	84	6	6	4	4	1	2	1	1
Brownsville, Texas	52	45	41	37	1	1	0	0	0	0	0	0
Corpus Christi, Texas	65	56	52	48	1	1	0	0	0	0	0	0
Dallas-Fort Worth, Texas	103	87	73	67	16	14	9	10	4	3	1	1
El Paso, Texas	162	166	175	184	347	278	232	209	136	84	54	42
Lubbock, Texas	256	247	243	250	188	165	151	146	50	38	29	29
Midland, Texas	215	211	208	207	144	133	128	134	34	28	24	27
Port Arthur, Texas	111	98	94	91	2	3	2	1	1	1	0	0
San Angelo, Texas	167	159	149	148	45	40	34	38	8	7	5	6
San Antonio, Texas	98	87	73	68	5	5	3	3	2	2	0	1
Waco, Texas	102	86	70	66	10	10	7	7	3	3	2	2
Wichita Falls, Texas	147	129	116	115	34	28	21	25	11	8	6	7
Colorado Springs, Colo.	465	454	459	472	666	663	659	654	583	553	527	506
Grand Junction, Colo.	311	292	285	287	648	630	611	595	520	464	415	373
Albuquerque, N.M.	298	300	309	322	629	604	579	553	422	346	288	243
Roswell, N.M.	239	234	232	239	300	254	232	217	116	83	69	58
Tucumcari, N.M.	295	291	294	302	373	327	291	268	157	112	85	68
Baton Rouge, La.	189	176	168	166	7	5	2	1	2	2	0	0
New Orleans, La.	124	117	107	103	3	3	1	1	1	1	0	0
Shreveport, La.	180	163	151	145	14	10	5	5	3	2	1	0
Fort Smith, Ark.	221	200	188	187	43	31	23	25	15	10	6	7
Little Rock, Ark.	199	182	168	168	41	29	20	19	12	8	5	5
St. Louis, Mo.	254	231	221	221	136	106	87	88	62	41	30	27
Springfield, Mo.	337	313	303	303	129	102	87	89	57	42	33	34
Des Moines, Iowa	366	339	333	333	239	192	173	171	129	92	73	69
Mason City, Iowa	451	429	425	427	329	281	260	253	202	158	140	132
Sioux City, Iowa	366	339	333	333	254	207	186	187	142	104	87	82

[a] Period 1: June 17-July 14.
[b] Period 2: June 24-July 21.
[c] Period 3: July 1-July 28.
[d] Period 4: July 8-August 4.

aeration. This amount of aeration time requires still higher airflows. To cool in 40 h in the typical situation, an airflow rate of 0.21 m^3/min/t would be required. In addition, the affected area is extended still farther toward the northwest for 10% moisture. As noted previously, the cooling time of 120 h for the 0.1 m^3/min/t aeration rate is typical for 12% moisture content wheat, but the aeration system designer needs to use the cooling times calculated for the specific conditions of the design in conjunction with the available aeration hours reported here.

These results are based on the common target aeration temperature of 24°C. Occasionally, an aeration designer may use a slightly higher target temperature; although the highest useful target is limited to only a few degrees above 24°C if the aeration is to provide useful suppression of insect population growth (Fields, 1992). Calculations based on a slightly higher target temperature would yield different values for reduction in mean available aeration hours; however, the general trend (i.e., that available aeration hours are greatly reduced compared to neglecting the latent heat effects due the temperature phenomena seen in fig. 5) would not change.

Application to Other Grain Types

To apply these results directly to soft or durum wheat grown in states surrounding the HRW wheat belt, without repeating the calculations for those grain types, the design moisture

Table 4. Reduction in mean available aeration hours for individual weather stations based on a threshold temperature of 24°C (75°F) and below compared to calculations neglecting heat of condensation.

	Percent Change (%) for 12% Wheat MC				Percent Change (%) for 10% Wheat MC			
Station	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]
Dodge City, Kansas	−23.9	−32.3	−38.5	−42.9	−67.1	−75.1	−79.9	−81.7
Goodland, Kansas[e]	8.1	2.1	−4.9	−9.5	−37.7	−47.5	−55.2	−59.0
Russell, Kansas	−35.9	−44.5	−49.8	−51.6	−71.0	−78.3	−83.1	−84.5
Topeka, Kansas	−56.7	−63.8	−66.9	−66.4	−80.0	−85.4	−87.6	−87.7
Wichita, Kansas	−52.4	−59.3	−63.2	−63.3	−79.7	−84.4	−87.5	−88.1
Grand Island, Neb.	−25.8	−35.2	−42.0	−42.7	−60.8	−69.5	−75.2	−76.6
North Platte, Neb.	−11.7	−17.3	−22.2	−24.5	−46.3	−54.4	−60.1	−62.7
Omaha Eppley, Neb.	−39.8	−48.4	−54.5	−55.8	−70.4	−78.0	−82.5	−83.8
Scottsbluff, Neb.[e]	23.0	20.0	14.6	9.9	−15.9	−25.1	−32.8	−37.6
Oklahoma City, Okla.	−71.7	−76.6	−80.4	−79.1	−90.3	−91.8	−93.7	−93.6
Tulsa, Okla.	−71.5	−75.2	−78.0	−77.5	−90.1	−91.7	−93.3	−92.9
Abilene, Texas	−69.5	−71.3	−73.4	−69.5	−92.4	−92.9	−95.5	−93.4
Amarillo, Texas[e]	−3.6	−9.2	−13.7	−18.9	−63.2	−70.3	−74.9	−77.2
Austin Camp, Texas	−94.8	−94.1	−95.8	−95.3	−98.8	−98.4	−99.0	−99.0
Brownsville, Texas	−98.1	−97.7	−99.6	−99.7	−99.6	−99.4	−99.7	−99.8
Corpus Christi, Texas	−98.2	−97.8	−99.7	−99.7	−99.8	−99.7	−100.0	−100.0
Dallas−Fort Worth, Texas	−84.2	−84.1	−88.3	−85.8	−96.6	−96.3	−98.6	−98.5
El Paso, Texas[e]	113.9	67.0	33.0	13.5	−16.0	−49.3	−69.1	−77.3
Midland, Texas	−26.4	−33.2	−38.0	−41.5	−80.3	−84.8	−88.1	−88.6
Lubbock, Texas	−32.7	−37.1	−38.2	−35.6	−84.0	−86.7	−88.4	−87.1
Port Arthur, Texas	−97.8	−96.6	−98.3	−98.5	−99.5	−99.2	−99.6	−99.6
San Angelo, Texas	−73.1	−74.9	−76.9	−74.3	−95.3	−95.5	−96.7	−96.1
San Antonio, Texas	−95.1	−94.7	−96.5	−95.2	−98.4	−98.3	−99.4	−99.0
Waco, Texas	−89.8	−88.2	−90.5	−89.1	−97.4	−96.5	−97.3	−97.2
Wichita Falls, Texas	−76.6	−78.7	−82.2	−78.1	−92.8	−93.4	−95.2	−93.8
Colorado Springs, Colo.[e]	43.2	46.0	43.5	38.7	25.3	21.7	14.9	7.2
Grand Junction, Colo.[e]	108.1	115.4	114.0	107.2	67.0	58.8	45.4	29.7
Albuquerque, N.M.[e]	111.3	101.1	87.6	71.7	41.6	15.1	−6.8	−24.4
Roswell, N.M.[e]	25.6	8.5	0.1	−9.2	−51.5	−64.8	−70.1	−75.5
Tucumcari, N.M.[e]	26.7	12.4	−1.1	−11.3	−46.8	−61.4	−71.3	−77.4
Baton Rouge, La.	−96.4	−97.2	−98.9	−99.2	−99.1	−99.1	−99.7	−99.8
New Orleans, La.	−97.4	−97.2	−99.2	−99.1	−99.6	−99.6	−99.9	−99.9
Shreveport, La.	−92.3	−93.8	−96.4	−96.6	−98.1	−98.5	−99.4	−99.8
Fort Smith, Ark.	−80.7	−84.6	−87.8	−86.8	−93.5	−94.8	−96.6	−96.4
Little Rock, Ark.	−79.6	−83.9	−87.8	−88.7	−94.0	−95.7	−97.0	−97.2
Springfield, Mo.	−46.6	−53.9	−60.5	−60.2	−75.8	−82.3	−86.2	−87.6
St. Louis, Mo.	−61.6	−67.4	−71.2	−70.7	−83.0	−86.6	−89.0	−88.7
Des Moines, Iowa	−34.7	−43.3	−48.1	−48.6	−64.9	−73.0	−78.0	−79.4
Mason City, Iowa	−27.0	−34.3	−38.9	−40.8	−55.3	−63.1	−67.0	−69.1
Sioux City, Iowa	−32.6	−41.1	−46.5	−46.7	−62.4	−70.3	−75.1	−76.5
Average (<1000 m only)	−63.7	−67.7	−71.2	−71.1	−84.4	−87.5	−89.9	−90.3

[a] Period 1: June 17-July 14.
[b] Period 2: June 24-July 21.
[c] Period 3: July 1-July 28.
[d] Period 4: July 8-August 4.
[e] Locations above 1000 m elevation not used in average.

content can be adjusted to the equivalent moisture content of hard wheat at the same RH level. Because the calculated values of T_{eff} are based on the equilibrium RH of the stored grain (fig. 1), different grains with the same equilibrium RH produce the same T_{eff} at different moisture contents. Typical moisture correction factors were calculated by subtracting the equilibrium moisture content of durum or soft wheat from the equilibrium moisture content of hard wheat at five levels of RH (table 5) from equilibrium data in the literature. A temperature of 25°C is reasonable for T_{eff} calculations with the common target temperature of 24°C; the 15°C column for durum wheat is included to illustrate the small temperature dependence of the moisture corrections.

If needed, a designer could generate correction factors for different temperatures or another grain type or cultivar using other appropriate equilibrium data. However, most design situations in the surrounding areas can be adequately based on the corrections in table 5. For example, to determine the available aeration hours for durum wheat at 11.25% moisture content when it is exposed to rewetting conditions from aeration air ranging from 55% to 95% RH, a designer should use hard wheat results for 12% moisture content. This

Table 5. Representative moisture content corrections (in percentage points, wet basis) for durum and soft wheat. To use, add the correction value to the actual durum or soft wheat moisture content to use hard wheat results in figures 2 through 4 and tables 3 and 4.

Relative Humidity (%)	Durum Wheat Correction[a]		Soft Wheat Correction[b]
	15°C	25°C	25°C
50	0.49	0.59	–0.16
60	0.55	0.76	0.49
70	0.68	0.92	0.89
80	0.72	0.87	1.28
90	0.52	0.45	1.45

[a] Data source: Pixton and Henderson (1981).
[b] Data source: *ASAE Standards* (2003).

moisture content was determined by adding the average correction factor of 0.75 percentage points (the mean of 0.76, 0.92, 0.87, and 0.45 from table 5, column 3) for the 60% to 90% RH levels of durum wheat at 25°C.

A study by Harner and Hagstrum (1990) in Kansas reported that airflow rates greater than 1.6 m^3/min/t (1.5 cfm/bu) could be utilized for aerating wheat with no adverse effects on test weight and moisture content. Our results show that moderately high airflow rates should be effective in western Kansas, but southeastern Kansas, along with areas south and east of there, would need the higher airflow rates for effective summer aeration with low-moisture wheat. In most of the mid-southern U.S., aeration rates between 0.8 and 2.2 m^3/min/t were found to provide sufficient time to cool wheat during July and August based on an evaluation of dry-bulb temperature. Higher airflow rates could be readily achievable in horizontal storage by limiting the eave height (or grain depth) or increasing fan power (Montross et al., 2004). For other than low-profile bins, i.e., with grain depths greater than 8 to 10 m, these high airflow rates may become impractical due to excessive fan power requirements.

This approach, evaluating T_{eff} from climate data, may be applicable to other crops and other regions such as the Atlantic coast or the southeastern U.S.

CONCLUSION

The available aeration hours reported in figures 3 and 4 and table 3 provide aeration design engineers with the necessary information to determine appropriate airflow rates for sizing aeration fans in the HRW wheat region and surrounding states. The following conclusions were based on results of this evaluation of historical weather data for this region:

- For most of the HRW wheat region, the effect of humidity to increase the effective aeration temperature resulted in actual available summer aeration times that were less than 50% of the time indicated by dry-bulb temperatures alone, averaging less than 30% for most of the region.
- For the central and some of the northern parts of the region, there are normally just enough available aeration hours immediately after harvest to complete an aeration cycle with low airflow rates such as 0.1 m^3/min/t. Thus, it is important to begin the aeration cycle immediately after filling the bins, and moderately higher airflow rates may be desirable to be effective in years with above-normal temperatures.
- For much of Texas, Oklahoma, and southeast Kansas, actual available aeration hours based on T_{eff} were much less than the 120 to 150 h typically needed for aerating at 0.1 m^3/min/t, even with higher moisture wheat (12% w.b.). Thus, much higher airflow rates would be required to take advantage of the very limited times of cool air for summer aeration in those locations. The affected area was extended farther to the northwest of the region for lower moisture content wheat.
- Neglecting the effect of humidity on reducing available aeration hours in summer caused large errors in most of the HRW wheat region. Required aeration rates in a normal year were typically two to five times greater than indicated by looking at dry-bulb temperature alone, but may be limited to low-profile bins (less than about 8 m tall).

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