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Aeration Strategy Simulations for Wheat Storage in the Sub-Tropical Region of North India

Johnselvakumar Lawrence, *Kansas State University*
Dirk E. Maier, *Kansas State University*

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Abstract. *Ambient aeration is typically used in temperate climates to preserve grains by cooling, preventing moisture migration, and maintaining temperature as low and uniform throughout the grain mass as possible. However, the climatic factors for wheat bulk storage in the sub-tropical climate of north India are challenging for the grain preservation process. Low relative humidity with high temperature during daytime and high relative humidity with low temperature during nighttime is the common phenomenon. Five years of weather data were analyzed using the modified Chung-Pfost EMC equation for wheat. Fifteen different aeration strategies were formulated based on the weather data during the maintenance period (June to September) and cooling period (October to March). Strategies were selected based on combinations of the following parameters: temperature control; EMC control; 1 h, 2 h, or 4 h morning and/or evening aeration; and 0.11, 0.34, and 0.67 m^3 min^{-1} t^{-1} airflow rate. These 15 aeration strategies for the sub-tropical weather conditions of north India were studied using the 2D PHAST-FEM model developed at Purdue University. The initial grain temperature and moisture were assumed as 27°C and 12% (w.b.), respectively, based on typical harvest conditions. Dry matter loss (DML), insect development, fan run hours, and average grain temperature and moisture content for these aeration strategies were quantified based on weather data from 2000-2001 to 2004-2005. Aeration strategies were selected based on the optimum combination of low values of DML, insect development, grain temperature, moisture content, and fan run hours during both the maintenance and cooling periods . The best strategy was to operate fans 4 h during the morning and evening with an airflow of 0.11 m^3 min^{-1} t^{-1}, with EMC control but without temperature control during the maintenance period and with both EMC and temperature control during the cooling period (strategy 13).*

Keywords. *Aeration, Airflow rate, Dry matter loss, Fan run hours, Grain moisture content, Grain temperature, Insect population, Modeling, Strategy.*

Spoilage of grain during storage occurs due to insects, fungi, bacteria, and rodents and causes considerable economic losses to farmers and processors every year. In order to reduce insect damage, improved integrated pest management (IPM) techniques need to be developed by maximizing the effects of control strategies and developing new approaches for application. High insect infestation in the grain mass leads to insect damaged kernels (IDK) and dry matter loss (DML). Fungi growth results in DML and can lead to the production of mycotoxins in the grain mass. This can make grain unsuitable for human and livestock consumption. The factors that favor the growth of insects, fungi, and bacteria are grain temperature and moisture content. The temperature of stored grain should be reduced to 14°C or lower after harvest in order to slow the growth of most insects and pests (Banks and Fields, 1995). Navarro et al. (2002) stated that stored grain insects develop well at 27°C to 34°C and thrive at about 29.5°C. Mold can grow only when sufficient moisture content is available in the grain. The grain moisture content in equilibrium with a relative humidity of 65% is the lower moisture content limit for survival of most microorganisms in stored grains (Christensen and Meronuck, 1986). Moisture content of grain has to be lowered and maintained below the safe storage limit to suppress the growth of fungi and other organisms. Grain temperature has to be lowered below the safe storage limits to prevent the development or to kill insects and mites. If not controlled, the spoilage processes will disperse to unaffected areas.

Ambient aeration is a forced-convection grain preservation process in which air is pushed through the grain to reduce its temperature. Aeration reduces biological activity by cooling the grain, preventing moisture migration, and maintaining a relatively uniform temperature throughout the grain mass (Brooker et al., 1992). The main objective of aeration is to use air temperature that moves only the cooling front and avoids warm or moist air. Wilson and Desmarchelier (1994) used seed wet-bulb temperature (SWBT) to identify available cooling aeration periods. They stated that SWBT-controlled aeration systems have an advantage in warm climates with low wet bulb temperatures at night that can be used to cool dry grain. Such conditions are not frequently available in tropical or sub-tropical climates. In order to achieve effective aeration in these regions, a well defined aeration strategy needs to be developed. A good control sys-

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The authors are **Johnselvakumar Lawrence, ASABE Member,** Post-Doctoral Research Fellow, and **Dirk E. Maier, ASABE Member,** Professor and Head, Department of Grain Science and Industry, Kansas State University, Manhattan, Kansas. **Corresponding author:** Dirk E. Maier, Department of Grain Science and Industry, 201 Shellenberger Hall, Kansas State University, Manhattan, KS 66506; phone: 785-532-4052; fax: 785-532-7010; e-mail: dmaier@ksu.edu.

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tem for the operation of fans and monitoring of grain temperatures is also required. Selection of appropriate ambient air conditions to achieve optimum temperature reduction or maintenance is the basis of a successful aeration strategy. Poor aeration strategies can result in high costs for little or no gain, and can lead to substantial grain spoilage.

Most aeration studies have been conducted in the temperate region of North America. Harner and Hagstrum (1990) studied the effect of high airflow rates (>1.65 m^3 min^{-1} t^{-1}) for aerating wheat during warm summer months. They reported that wheat was cooled by an average of 6°C with approximately 9 h of fan operation. This grain temperature reduction was sufficient to reduce insect population growth by more than 80% in their simulations. Aerating with high-humidity air has potentially negative consequences if it causes condensation of moisture on cool grain, or if it results in excessive moisture adsorption in grain near the air inlets (Casada and Alghannam, 1999). The typical design airflow rate used for aeration is 0.11 m^3 min^{-1} t^{-1} or 0.1 cfm bu^{-1} (Holman, 1960). At an airflow rate of 0.11 m^3 min^{-1} t^{-1}, a minimum of 120 h was required to cool wheat from a high temperature to a desired threshold, whereas only 40 h was required with an airflow rate of 0.33 m^3 min^{-1} t^{-1} (Reed and Harner, 1998a, 1998b). The minimum time (h) required to move a complete temperature front through a grain bin is 16.5 divided by the airflow rate in m^3 min^{-1} t^{-1} (GEAPS, 1989). Arthur and Flinn (2000) studied aeration management for stored hard red winter wheat in the south central U.S. They found that 120 h of cooling aeration reduced rusty grain beetle populations more substantially than 40 or 60 h of cooling with an airflow rate of 0.11 m^3 min^{-1} t^{-1}.

Little aeration research has been done in sub-tropical regions. Aeration is challenging during the summer months in sub-tropical regions because few or no fan run hours are available to cool grain. Therefore, in order to take advantage of aeration during the hot sub-tropical summer, the maintenance aeration concept can be adopted. Maintenance aeration utilizes ambient air that maintains the grain temperature and moisture content in equilibrium with the average ambient conditions (temperature and RH). This technique prevents development of hot spots; removes heat produced due to the respiration of grain, insects, and molds; prevents moisture migration and surface crusting; prevents condensation on cold walls and floors; maintains the free-flowing characteristics of grain; and maintains uniform grain temperature and moisture content. Zeledon and Barboza (2000) found that early morning hours are suitable for aeration in the high-humidity regions of Costa Rica and Venezuela.

Sinicio and Muir (1996) studied aeration of wheat in Brazil using equilibrium and non-equilibrium models. The equilibrium model (Thompson, 1972; Metzger and Muir, 1983) uses equilibrium moisture content (EMC) equations to calculate the changes in grain moisture content during each time interval. The non-equilibrium model (Thompson et al., 1968) uses thin-layer drying and wetting equations to describe the rate of change in moisture content as a function of air conditions. Sinicio and Muir (1996) found that the non-equilibrium model was best for simulating aeration of stored wheat in Brazil. Sinicio and Muir (1998) also studied different aeration strategies for preventing spoilage of wheat stored in tropical and sub-tropical climates. They used a 1D non-equilibrium, forced convection, heat conduction model in the direction of the airflow to simulate aeration using ten years of weather data. This model did not account for the impact of solar radiation, which is the prime source of heat that affects grain temperature and moisture content during non-airflow periods. Casada et al. (2002) monitored grain temperatures and studied different aeration strategies for stored wheat in the Central Plains of the U.S. They evaluated three aeration strategies by monitoring grain temperature and relative humidity in the bin and found that a three-cycle aeration strategy was effective in reducing grain temperature compared to two other strategies (no aeration and controlled aeration at 15°C in early autumn and 7.2°C in late autumn). Arthur and Casada (2005) studied the feasibility of summer aeration to control insects in stored wheat and observed that populations were reduced in the aerated bins compared to bins that were not aerated.

Several heat and mass transfer models with various dimensions were developed during the past two decades to simulate grain temperature and moisture content during grain drying, aeration, and storage. Each model had its own merits and demerits. Thompson (1972) developed the first 1D computational heat and mass transfer model assuming equilibrium existed between the air and grain due to adiabatic heat and mass transfer. Two-dimensional heat and mass transfer models to predict temperature and moisture content in stored grain were developed by various authors (Metzger and Muir, 1983; Smith and Sokhansanj, 1990; Maier, 1992; Singh et al., 1993; Chang et al., 1994; Casada and Young, 1994; Khankari et al., 1994). These culminated in the research by Montross et al. (2002), who developed a 2D comprehensive heat, mass, and momentum transfer model (PHAST-FEM) using realistic boundary conditions such as solar radiation, wind speed, ambient temperature, and RH to predict grain temperature and moisture content.

The various factors that affect grain temperature and moisture content during storage are type of crop, initial grain temperature and moisture content, harvest date, bin size, bin wall material, solar radiation and ground reflection, and weather conditions (temperature, relative humidity, wind velocity and direction). In a sub-tropical region, cooler nighttime air with high RH and warmer daytime air with low RH is the common phenomenon. Additionally, solar radiation is also high. Thus, selection of suitable aeration opportunities for maintaining stored grain quality in a sub-tropical climate is very challenging. Computer simulation models are available to evaluate selected parameters that affect grain temperature and moisture content during storage. Appropriate aeration strategies need to be developed to identify the most suitable aeration conditions. The focus of this article is on developing aeration strategies for cooling wheat and preserving its quality during storage in large corrugated steel silos under sub-tropical weather conditions in north India.

Methods

Five years (2000-2001 to 2004-2005 crop seasons) of hourly weather data from Ambala, Haryana State, India (sub-tropical region; 30° 21′ N, 76° 52′ E) were acquired and entered into an Excel spreadsheet. The weather data consisted of ambient temperature and RH, wind speed, and solar radiation. Available aeration fan run times during various storage periods (three-month interval starting from April 1) were determined using the equilibrium moisture content and temper-

ature relationships. The ambient air EMC for soft red winter wheat was calculated using the modified Chung-Pfost equation (Chung and Pfost. 1967):

$$MC = 0.27908 - 0.042360 \times \ln(-T + 35.662) \times \ln(RH) \quad (1)$$

where MC is equilibrium moisture content of air (decimal dry basis), T is the temperature of ambient air (°C), and RH is relative humidity of ambient air (decimal).

Using the logical scheme ("if" condition), the fan run hours suitable for aeration were identified based on hourly weather data and equation 1. Calculated air EMC was compared against the upper and lower limits of desired grain moisture (MC) values. If the calculated air EMC was greater than the specified lower MC limit and less than the upper MC limit, and if the ambient temperature was greater than the specified lower temperature limit and less than the upper temperature limit, then the aeration logical statement was "true". If any of the above logical sequence was false, then the aeration logical statement was "false". Based on this concept, fan run hours available for aeration for different periods throughout the storage season were calculated. Based on the results of available fan run times, June to September was defined as the maintenance period, with the primary goal to preserve stored wheat quality, and October to March was defined as the cooling period, with the primary goal to lower stored wheat temperature.

Formulation of Aeration Strategy

Weather data analysis revealed that the fan run time available during the first four months of storage (i.e., June to September) was almost zero, and only a few fan run hours were available for aeration during October to March based on the desirable safe storage limit of 12% w.b. EMC and ≤15°C grain temperature. The primary concern with respect to no aeration between June and September was the rapid conductive heat transfer rate in the grain mass due to solar radiation and wind speed on the bin walls and roofs (i.e., structural boundaries). This heat transfer rate led to the development of temperature gradients in the grain, which would enable natural convection. Natural convection currents, although slow, can initiate intermittent moisture movement as well as condensation inside the grain mass (Montross, 1999). Nonuniformity of moisture content favors the increase of interstitial water activity in the grain mass above 0.65, which can result in mold growth. In order to minimize the development of natural convection currents inside the grain mass, the grain should be aerated in order to maintain bulk grain temperatures as uniformly as possible. Therefore, a maintenance aeration strategy consisting of a few daily fan run hours was included as one of the components of the aeration strategy options. A morning (6:00 to 9:00 a.m.) and evening (8:00 to 11:00 p.m.) period was found suitable for maintenance aeration. During this period, ambient temperature started increasing whereas RH started decreasing. At the crossover point, both air temperature and RH were suitable for aeration (fig. 1). Based on the weather data, both ambient temperature and relative humidity have optimum values during the specified time periods.

In order to cool the grain and maintain grain moisture content, temperature control and moisture control were included in the cooling aeration strategies. Temperature control was based on comparing the temperature in the center of the grain mass with the ambient air temperature. Whenever the ambient temperature dropped below the grain mass center temperature, the aeration fan was turned on for that hour; whenever the ambient temperature was higher, the fan was turned off. EMC control was based on comparing the ambient air EMC with the grain MC. Whenever the ambient air EMC was lower than the prescribed grain MC, the fan was turned on; otherwise, the fan was turned off. Aeration strategies were selected based on the combination of the following: temperature control; EMC control; 1 h, 2 h, or 4 h morning and evening timed aeration; and 0.11, 0.34, and 0.67 m^3 min^{-1} t^{-1} airflow rates. Fifteen different aeration strategies were developed for the evaluation of aerated wheat storage (table 1). The best aeration strategy was identified by finding the optimum combination of low values among the predicted DML, insect population, average grain temperature and moisture content, and fan run hours.

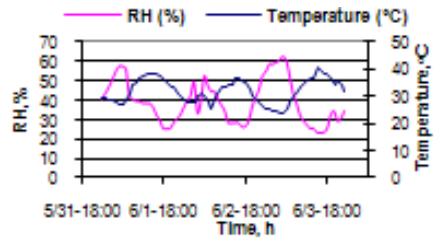

Figure 1. Temperature and RH pattern between 1 and 3 June 2005 at Ambala, Haryana, India.

Modeling

The two-dimensional PHAST-FEM computer simulation model (Montross et al., 2002), which is based on the finite element method, was used to predict the grain temperature and moisture content under realistic boundary conditions such as ambient temperature and relative humidity as well as solar radiation and wind speed. The 2D governing equations used to predict the grain temperature and moisture content are summarized by Montross et al. (2002). The 2D grain domain was meshed with elements (100) and nodes (341) using ANSYS. The procedure for running the 2D stored grain ecosystem model is given by Montross (1999). The Food Corporation of India (FCI) has awarded a 20-year contract to Adani Agri Logistics Ltd. to store at least 200,000 metric tonnes of wheat each year in large steel tanks at two base depots in India (Moga in Punjab and Kaithal in Haryana) and ship the wheat in bulk rail cars to bulk grain storage locations near four major population centers (Mumbai, Bangalore, Chennai, and Kolkata). At the base depots, each tank has a capacity of 12,500 metric ton with a size of 32 m (105 ft) diameter and 17 m (56 ft) eave height. The computational domain for modeling was taken as the equivalent to the size of one silo.

Dry matter loss (DML) of wheat after a period of storage depends on the temperature and moisture content of the grain. The DML for wheat was calculated based on the procedure explained by Morey et al. (1981), which is an indirect method of calculating DML based on DML equations for corn. The same procedure was used by Maier (1992), who used 0.5% DML as the maximum allowable storage level for wheat based on the work of Kreyger (1972). Morey et al. (1981) argued that wheat is easier to store than corn for the same storage conditions. Therefore, we have taken 0.25% DML as a reasonably safe storage level criterion for wheat. The insect

Table 1. Aeration strategies studied for wheat stored in large steel tanks in north India.

Strategy	Airflow Rate, m^3 min^{-1} t^{-1} (cfm bu^{-1})	June to September				October to March			
		EMC Control[a]	Temp. Control[b]	MA (h)[c]	EA (h)[d]	EMC Control[a]	Temp. Control[b]	MA (h)[c]	EA (h)[d]
1	0.11 (0.1)	Yes	Yes	na[e]	na	Yes	Yes	na	na
2	0.34 (0.3)	Yes	Yes	na	na	Yes	Yes	na	na
3	0.67 (0.6)	Yes	Yes	na	na	Yes	Yes	na	na
4	0.11 (0.1)	No	Yes	2	2	No	No	2	2
5	0.34 (0.3)	No	Yes	2	2	No	No	2	2
6	0.11 (0.1)	No	Yes	4	4	No	No	4	4
7	0.34 (0.3)	No	Yes	4	4	No	No	4	4
8	0.11 (0.1)	No	No	2	2	Yes	Yes	na	na
9	0.34 (0.3)	No	No	2	2	Yes	Yes	na	na
10	0.11 (0.1)	No	No	1	1	Yes	Yes	na	na
11	0.34 (0.3)	No	No	1	1	Yes	Yes	na	na
12	0.67 (0.6)	No	Yes	2	4	No	No	2	4
13	0.11 (0.1)	Yes	No	4	4	Yes	Yes	na	na
14	0.34 (0.3)	Yes	No	4	4	Yes	Yes	na	na
15	No	No	No	na	na	No	No	na	na

[a] EMC control: Yes= fan will turn on only if ambient EMC is ≤12% w.b., and No = no control over EMC (fan will turn on for all EMC values).
[b] Temperature control: Yes = fan will turn on only if ambient temperature is less than innermost grain core temperature, and No = no control over temperature (fan will turn on for all temperature values).
[c] MA = morning aeration: 1 h = fan will turn on only between 7:00 and 8:00 a.m. if the temperature and EMC control are satisfied, 2 h = fan will turn on only between 6:00 and 8:00 a.m. if the temperature and EMC control are satisfied, and 4 h = fan will turn on only between 5:00 and 9:00 a.m. if the temperature and EMC control are satisfied.
[d] EA = evening aeration: 1 h = fan will turn on only between 8:00 and 9:00 p.m. if the temperature and EMC control are satisfied, 2 h = fan will turn on only between 8:00 and 10:00 p.m. if the temperature and EMC control are satisfied, and 4 h = fan will turn on only between 7:00 and 11:00 p.m. if the temperature and EMC control are satisfied.
[e] na = no fan run.

population in the wheat bin after a specified period of storage was predicted using Throne's (1994) maize weevil model, which is based on the temperature and moisture content of the grain. The maize weevil model was used only to compare the results of the strategies; it provided comparative values, not actual values. The results found using this model may not represent the actual insect population for conditions in India, as the immigration rate of 12 insects per day was taken from Montross (1999) and the work was done in West Lafayette, Indiana. In addition, determining the insect immigration rate in a grain bin is complex and depends on weather and sanitation factors.

Multiple simulations using five years of weather data were run for 15 different aeration strategies (table 1) starting on June 1 and ending on March 20. June was initially taken as the start time for simulation because the wheat was purchased and collected from farmers in bags and stored temporarily in godowns (warehouses used for bag storage) before transferring the bagged wheat into bulk storage bins. In north India, this process typically takes about two months (i.e., April to May). After unbagging, the bulk wheat is fumigated in treatment silos equipped with closed-loop fumigation systems before it is transferred to large storage silos. Therefore, the initial insect population was assumed zero for each simulation scenario. The wheat temperature during bagging is typically 27°C, which was set as the initial grain temperature for the simulations. The parameters used to run the 2D PHAST-FEM model are summarized in table 2. During post-processing, the DML and insect populations were calculated based on the average grain temperature and moisture in the "bulk" and "periphery" regions. The periphery region included grain within 1.6 m of the silo wall, and the bulk region referred to the rest of the grain mass. The statistical analysis of five years of predicted data was done using SAS (version 9.1, SAS Institute Inc., Cary. N.C.). Strategies that were not significantly different were grouped together using Tukey schemes. Per the FANS program (FANS, 1996), a bin size of 32 m (105 ft) diameter and 17 m (56 ft) height requires around 52 kW (69.6 hp) of power to obtain an airflow of 0.11 m^3 min^{-1} t^{-1} at a static pressure of 6.8 cm of water, as compared to 544 kW (729 hp) for 0.34 m^3 min^{-1} t^{-1} at 23.9 cm of water, or 8 times more, as compared to 2592 kW for 0.67 m^3 min^{-1} t^{-1} airflow at 56.9 cm of water, or 250 times more, which is excessively high.

Table 2. Key variables and parameter values used to run the 2D PHAST-FEM model for five storage seasons (2000-2001 to 2004-2005).

Variable	Values
Grain type	Soft wheat
Initial moisture content (d.b.)	13.63% (12% w.b.)
Initial temperature	27.0°C
Permeability[a]	0.596e-8 m^2 s^{-1}
Density	772 kg m^{-3}
Thermal conductivity (W m^{-1} K^{-1})	0.117 + 0.0011MC[b]
Specific heat (J kg^{-1} K^{-1})	1240 + 36.2MC[b]
Insect parameters	
Re-infestation	12 adults per day[c]
Initial number of immature insects	Zero insects per 30 kg
Initial number of adult males	Zero insects per 30 kg
Initial number of preoviposition females	Zero insects per 30 kg
Initial number of adult females	Zero insects per 30 kg

[a] Source: Khankari et al. (1995).
[b] MC = moisture content (% w.b.).
[c] Six males and six females.

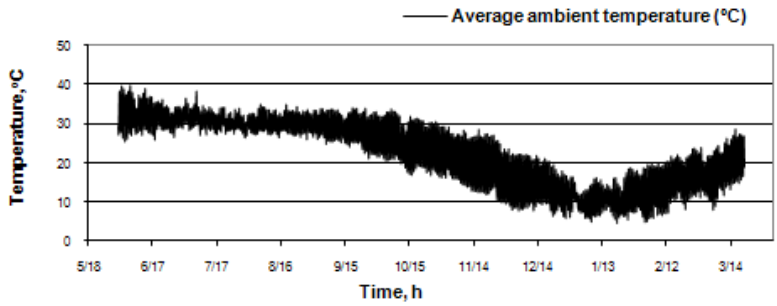

Figure 2. Five-year average hourly ambient temperature at Ambala, Haryana, India, from June to March.

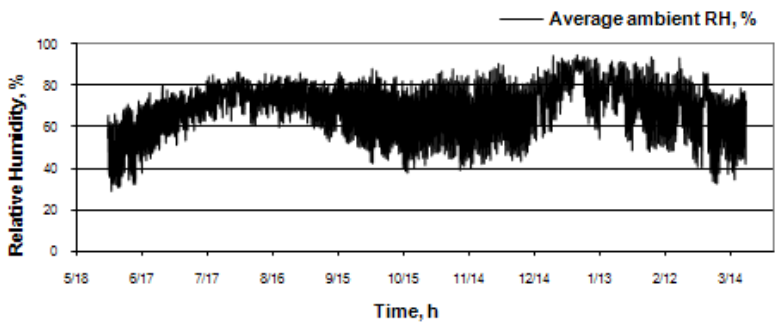

Figure 3. Five-year average hourly ambient RH at Ambala, Haryana, India, from June to March.

Results and Discussion

Weather Data Analysis

The five-year hourly average ambient temperature and relative humidity from June to March calculated from 2000-2001 to 2004-2005 weather data are given in figures 2 and 3. During June to September, ambient temperatures were in the range of 27°C (nighttime) to 33°C to 35°C (daytime). During October, night temperatures reached 20°C and began to decrease in subsequent months. The ambient relative humidity during June was between 30% and 65%. During the second week of July, the average relative humidity was between 70% and 80%. This high RH period falls into the high rainfall monsoon season of north India and lasts until the second week of September.

The potential average fan run hours calculated using the EMC model for different periods of the year from 2000-2001 to 2004-2005 are given in table 3. During April to June, the fan run hours available for aeration were fewer than 17 h below the 16% EMC limit and 15°C temperature limit. Using the typical design airflow rate of 0.11 m^3 min^{-1} t^{-1}, at least 120 h would be required to cool the wheat to below a specified temperature. To speed up the cooling aeration process, the airflow rate would have to be increased from 0.11 m^3 min^{-1} t^{-1} (0.1 cfm bu^{-1}) to 0.67 m^3 min^{-1} t^{-1} (0.6 cfm bu^{-1}) in order to cool the wheat below 15°C within about 40 h. After May, the ambient temperature increased to above 20°C even at night, with humidity levels mostly above 65%. Those conditions would not have been suitable to achieve cooling using aeration. No fan run hours were available to cool the grain below 15°C until the first week of October for all five years with an upper EMC limit of 20% and upper temperature limit of 15°C. Only maintenance aeration would have been possible during these periods, with sufficient fan run hours for an upper EMC limit of 14% and an upper temperature limit of 27°C. Between October and December, the available fan run time accumulated to 62 h with a 12% upper EMC limit and 20°C temperature limit and 72 h with a 14% upper EMC limit and 15°C temperature limit, which would not have been sufficient to cool the wheat to below 20°C at 0.11 m^3 min^{-1} t^{-1}. Instead, an airflow rate of 0.33 m^3 min^{-1} t^{-1} would have been required. During the January to March period, the fan run hours available were 99 h with a 12% upper EMC limit and 20°C temperature limit. During that period, using 0.11 or 0.33 m^3 min^{-1} t^{-1} airflow should have been sufficient to cool the wheat to below 20°C with an upper EMC limit below 14%. As the upper temperature limit was increased, the available fan run hours also increased for a constant EMC control window. Likewise, when the upper EMC limit was increased, the available fan run hours increased for a constant temperature control window.

The temperature and RH patterns for three representative days are given in figure 1. When the ambient temperature was above 30°C, the RH was below 30%. Likewise, when the ambient temperature was below 20°C, the RH was above 80%.

Table 3. Potential average fan run hours at Ambala, India, predicted for different periods of the year from 2000-2001 to 2004-2005.

	Upper Temperature Limit[a]								
	15°C			20°C			27°C		
	Upper EMC Limit (% w.b.)			Upper EMC Limit (% w.b.)			Upper EMC Limit (% w.b.)		
Period	12%	14%	16%	12%	14%	16%	12%	14%	16%
Apr.-June	0.4	4	17	17	65	96	215	397	480
July-Sept.	0	0	0	0	0	0	6	79	241
Oct.-Dec.	6	72	342	62	331	758	254	728	1314
Jan.-Mar.	16	206	637	99	536	990	238	769	1240
Total	22	282	996	178	932	1844	713	1973	3275

[a] No lower limits were specified for temperature and EMC.

Table 4 . Predicted five-year average grain temperature at key dates, and five-year average means and standard deviations of grain temperature for maintenance (June to September) and cooling (October to March) aeration strategies during the storage period.[a]

Strategy	September 30	December 31	March 31	Mean (SD) June-September	October-December	January-March
1	29.5 bcd	19.1 b	17.9 b	28.6 i (0.7)	23.3 bc (3.4)	17.8 d (0.8)
2	29.0 bcde	17.2 cde	16.6 bc	28.2 j (0.7)	21.8 e (3.6)	16.1 h (0.8)
3	28.5 cde	16.4 de	16.2 bc	27.7 k (0.8)	20.8 g (3.8)	15.5 i (0.8)
4	29.4 bcd	15.7 e	13.4 cd	29.9 d (1.1)	22.3 d (4.4)	12.7 j (1.1)
5	28.1 def	13.1 f	13.1 cd	29.8 e (1.5)	20.6 g (4.6)	11.7 l (1.0)
6	27.7 def	12.8 f	12.6 d	29.6 f (1.4)	20.3 h (4.7)	11.9 k (1.0)
7	26.2 f	10.8 g	10.9 d	29.6 f (1.7)	16.7 j (4.9)	8.4 n (0.9)
8	29.5 bcd	19.1 b	17.7 b	31.6 c (1.6)	23.1 c (3.4)	18.9 b (0.9)
9	28.2 def	17.1 de	16.6 bc	31.6 c (1.7)	21.5 e (3.8)	17.2 e (0.8)
10	30.5 abc	19.1 b	17.7 b	31.5 c (1.7)	23.3 b (3.4)	18.6 c (0.9)
11	29.0 bcde	17.2 cde	16.5 bc	31.5 c (1.6)	21.2 f (3.6)	17.1 f (0.8)
12	27.2 ef	11.8 fg	11.8 d	29.1 h (1.5)	19.6 i (5.1)	10.6 m (1.0)
13	32.1 a	18.9 bc	17.8 b	32.0 b (1.4)	23.4 b (3.6)	17.8 d (0.9)
14	30.5 abc	17.6 bcd	17.3 b	32.2 a (1.7)	22.5 d (3.7)	16.6 g (0.8)
15	30.5 a	29.5 a	29.4 a	29.2 g (0.7)	30.7 a (0.4)	29.6 a (0.3)

[a] Values within the same column followed by the same letter are not significantly different ($p > 0.05$).

This type of weather pattern occurs during the June to September months. Crossover periods of ambient temperature and RH occur during morning and evening hours. The morning and evening hours during which the crossover period occurred that provided the best conditions for aeration during maintenance aeration (June to September) were 5:00 to 10:00 a.m. and 7:00 to 11:00 p.m.

Temperature and Moisture Prediction

The predicted five-year average grain temperature and moisture content during the maintenance and cooling periods for the 15 different aeration strategies at various times at Ambala, Haryana, India, are given in tables 4 and 5. At the end of September, average grain temperatures of around 26°C to 32°C were predicted in all aeration strategies. At the end of December and March, the predicted average grain temperatures and moisture contents varied with the different aeration strategies. For strategy 7, the predicted average grain temperature at the end of December was around 10.8°C, which was the lowest among all aeration strategies whereas non-aeration (strategy 15) predicted the highest grain temperature of around 30°C. For strategies 7 and 12, the predicted average grain moisture content (>13.0%) was the highest among all aeration strategies, whereas strategy 14 predicted the lowest grain moisture content of 11.1%. High moisture gain was observed during strategies 7 and 12, and high moisture loss was observed during strategies 1, 3, 13, and 14. The higher moisture content predicted by strategies 7 and 12 was not acceptable, as this would favor mold growth and cause spoilage loss of stored wheat.

The predicted average grain temperature and moisture content variations during the maintenance and cooling periods for the different aeration strategies at Ambala, Haryana, India, for one example year (2003-2004) are given in figures 4 to 7. The high airflow aeration strategies predicted high moisture gain compared to the low airflow aeration strategies. Fluctuations were observed in moisture content prediction due to strategies that did not have EMC control windows during the maintenance period. During October to mid-November, all aeration strategies except non-aeration predicted decreasing grain temperature and moisture content. The first week of October started the cooling period for all years of simulation. The grain temperature began decreasing from this period onward and was maintained until March. The standard deviations of average grain temperature during October-December were in the range of 3°C to 5°C for all aeration strategies except for non-aeration (table 4). There was no major change in the moisture content during June to September for all strategies except for the high airflow strategies (7 and 12).

Dry Matter Loss Prediction

The predicted five-year average DML for maintenance (June to September) and cooling (October to March) aeration strategies at various times is given in table 6. The maximum allowable DML for wheat was assumed to be 0.5% (Morey et al., 1981). Therefore, DML of less than 0.25% was assumed to represent an optimum level for aeration strategy selection. At the end of September, strategies 1, 2, 3, and 15 predicted a low DML of less than 0.1%, as compared with strategies 7, 9, and 12 that were all above 0.2%. It was observed that DML increased by about 70% to 80% during the

Table 5. Predicted five-year average grain moisture content for maintenance (June to September) and cooling (October to March) aeration strategies at key dates during the storage period.[a]

Strategy	September 30	December 31	March 31
1	11.9 de	11.5 ef	11.4 de
2	11.9 de	11.4 efg	11.5 d
3	11.9 de	11.4 fg	11.3 de
4	12.0 cde	11.7 cdef	11.6 cd
5	12.3 bc	12.2 b	12.3 b
6	12.2 cd	12.0 bcd	12.0 bc
7	12.7 a	12.9 a	13.1 a
8	12.1 cde	11.6 def	11.6 d
9	12.2 cd	11.8 cde	11.7 cd
10	12.1 cde	11.6 ef	11.5 de
11	12.1 cd	11.6 ef	11.6 d
12	12.7 ab	12.8 a	13.1 a
13	12.0 cde	11.4 efg	11.3 de
14	11.7 e	11.1 g	11.1 e
15	12.0 cde	12.0 b	12.0 bc

[a] Values within the same column followed by the same letter are not significantly different ($p > 0.05$).

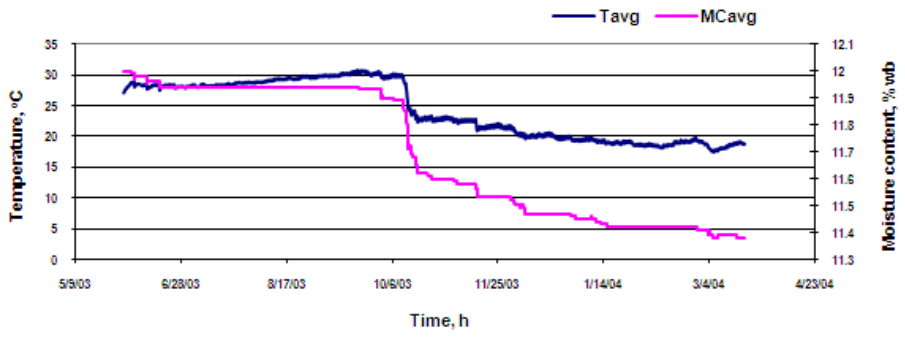

Figure 4. Predicted average grain temperature and moisture content for temperature and EMC controlled aeration with 0.11 m³ min⁻¹ t⁻¹ (0.1 cfm bu⁻¹) airflow rate from June 2003 to March 2004 (strategy 1).

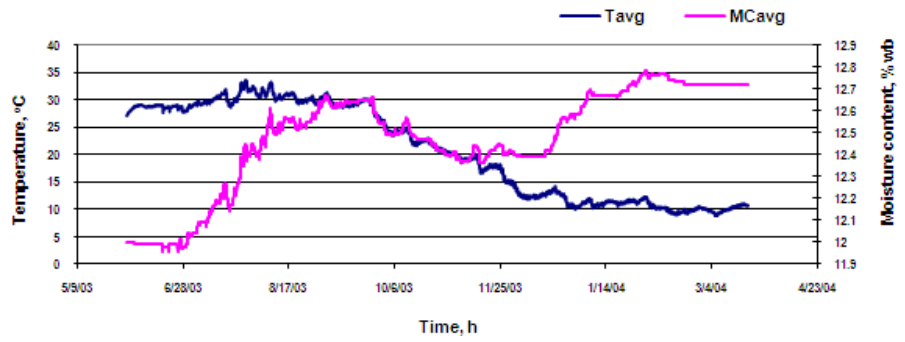

Figure 5. Predicted average grain temperature and moisture content for 4 h morning and 4 h evening aeration with 0.33 m³ min⁻¹ t⁻¹ (0.3 cfm bu⁻¹) airflow rate and temperature control simulated from June 2003 to March 2004 (strategy 7).

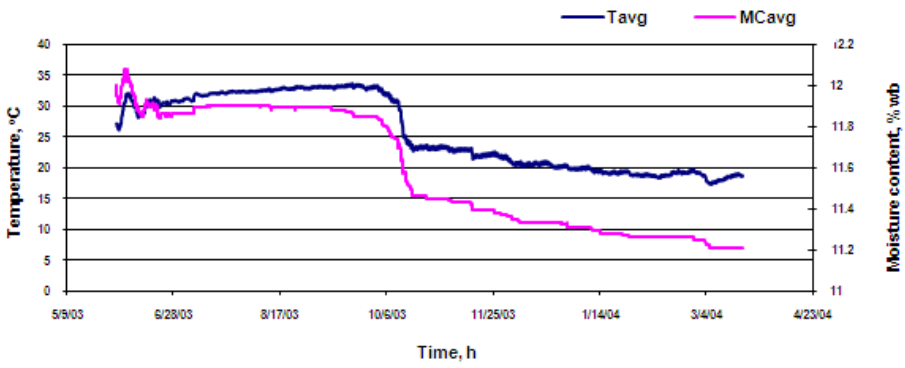

Figure 6. Predicted average grain temperature and MC for 4 h morning and 4 h evening aeration with 0.11 m³ min⁻¹ t⁻¹ (0.1 cfm bu⁻¹) airflow rate and EMC control, and without temperature control from June 2003 to September 2003 and with temperature and EMC control from October 2003 to March 2004 (strategy 13).

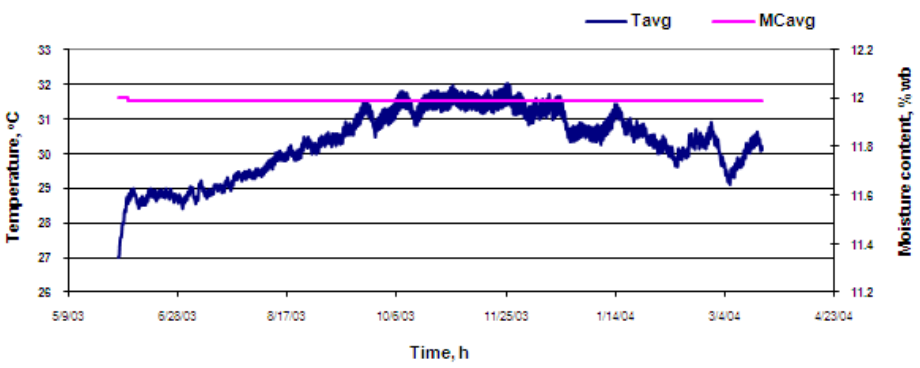

Figure 7. Predicted average hourly grain temperature and moisture content for non-aeration from June 2003 to March 2004 (strategy 15).

Table 6. Predicted five-year average DML (%) for maintenance (June to September) and cooling (October to March) aeration strategies for 27°C initial grain at key dates during the storage period.

Strategy	DML, % (SD)[a]		
	September 30	December 31	March 31
1	0.09 ef (0.01)	0.13 de (0.01)	0.14 def (0.01)
2	0.09 ef (0.01)	0.12 e (0.02)	0.12 ef (0.01)
3	0.09 ef (0.01)	0.12 e (0.01)	0.12 f (0.02)
4	0.15 bcdef (0.02)	0.20 cde (0.03)	0.22 cdef (0.03)
5	0.17 abcdef (0.05)	0.24 abcd (0.05)	0.28 abc (0.05)
6	0.14 cdef (0.04)	0.19 cde (0.03)	0.21 cdef (0.04)
7	0.23 ab (0.08)	0.32 ab (0.11)	0.37 ab (0.11)
8	0.19 abcd (0.02)	0.24 abcd (0.02)	0.26 bcd (0.02)
9	0.21 abc (0.04)	0.26 abc (0.05)	0.28 abc (0.05)
10	0.18 abcde (0.02)	0.23 abcd (0.03)	0.24 cde (0.03)
11	0.19 abcd (0.02)	0.24 abcd (0.03)	0.25 bcd (0.03)
12	0.24 a (0.10)	0.34 a (0.13)	0.39 a (0.13)
13	0.16 abcdef (0.02)	0.19 cde (0.02)	0.21 cdef (0.02)
14	0.14 bcdef (0.02)	0.17 cde (0.03)	0.17 cdef (0.03)
15	0.1 edf (0.01)	0.22 bcd (0.03)	0.29 abc (0.04)

[a] Values in the same column followed by the same letter are not significantly different ($p > 0.05$).

maintenance aeration period in all aeration strategies except non-aeration. During the cooling period, acceleration of DML was slowed in all strategies except for non-aeration, which showed a steep increase. This was due to the benefit of grain cooling, which suppresses the development of insects and mold. At the end of March, strategies 1-4, 6, 10, 13, and 14 predicted the lowest average DML of less than 0.25%. The high airflow strategies (7 and 12) predicted higher DML due to excessive moisture gain during aeration.

Insect Population Development Prediction

The predicted five-year average insect population growth for the maintenance (June to September) and cooling (October to March) aeration strategies at various times at Ambala, Haryana, India, is given in table 7. At the end of December, aeration strategies 4, 5, 6, 7, and 12 predicted relatively high insect populations (>0.22 kg^{-1}) as compared to the other strategies. After December, the insect population in the periphery region increased to higher levels than in the core region of the grain mass, which remained at lower temperature. Strategies 2, 4, 8, 9, and 15 predicted high insect population development by the end of March. Insect population development was low during the maintenance aeration period in all aeration strategies. During the cooling aeration period, strategies 5, 7, 12, and 15 showed higher increases in insect population development than the other strategies. This was due to the higher moisture content caused by these strategies, which favors insect growth during the cooling period. At higher moisture, the numbers of insect survival for the various stages (egg, larva, pupa, and adult) are higher (Throne, 1994). At 20°C, only six insects develop from egg to adult at 43% RH, as compared to 37 insects at 75% RH (Throne, 1994).

For strategy 14, the insect population was predicted as 0.06 kg^{-1} in the periphery and 0.01 kg^{-1} in the bulk region. The non-aeration strategy (strategy 15) predicted the highest insect population of 2.28 kg^{-1} in the bulk region by the end of March. While the absolute values may not be accurate because the actual rate of insect infiltration into the wheat storage silos was unknown, the relative values allow for a comparison of efficacy among strategies. In particular, leaving the wheat at elevated temperatures and not aerating after October (strategy 15) may result in sufficiently large insect development rates to warrant fumigation for control. In the U.S., the presence of more than two live weevils per kg of grain results in rejection of wheat at the first point of sale.

Fan Run Hours

The predicted five-year average fan run hours for the maintenance (June to September) and cooling (October to March) aeration strategies are given in table 8. The optimum fan run period was defined as the fan run hours available to allow for at least three cooling cycles (i.e., based on 120 h required to move one cooling front through the grain mass) during the storage period. The maximum number of fan run hours was available for strategy 6, and the lowest number was available for strategy 3. The optimum fan run hours were available for strategies 4, 5, and 9 to 14. The lower fan run hours observed in strategies 1, 2, and 3 were due to the tem–

Table 7. Predicted five-year insect population (kg^{-1}) for maintenance (June to September) and cooling (October to March) aeration strategies at key dates during the storage period.[a]

Strategy	Insect Population (adults plus immature stages of weevils), kg^{-1} (SD)					
	September 30		December 31		March 31	
	Periphery	Bulk	Periphery	Bulk	Periphery	Bulk
1	0.01 cde (<0.01)	<0.01 d (<0.01)	0.05 def (0.05)	0.02 c (0.01)	0.27 b (0.33)	0.04 bc (0.03)
2	<0.01 ef (<0.01)	0.02 a (0.01)	0.22 abcd (0.10)	0.20 a (0.07)	0.64 ab (0.37)	0.23 bc (0.11)
3	0.01 def (<0.01)	0.02 a (0.01)	0.15 bcdef (0.07)	0.15 ab (0.07)	0.34 b (0.18)	0.13 bcd (0.08)
4	0.01 cde (<0.01)	0.01 ab (0.01)	0.30 abc (0.2)	0.19 a (0.11)	0.70 ab (0.44)	0.16 bc (0.09)
5	0.01 cd (<0.01)	<0.01 cd (<0.01)	0.23 bcde (0.09)	0.06 bc (0.05)	0.42 b (0.23)	0.04 bc (0.04)
6	0.01 bc (<0.01)	0.012 bcd (0.01)	0.25 bcde (0.22)	0.07 bc (0.07)	0.36 b (0.36)	0.05 bc (0.05)
7	0.02 a (<0.01)	0.01 abc (<0.01)	0.41 a (0.11)	0.07 bc (0.01)	0.45 b (0.17)	0.05 bc (0.01)
8	<0.01 ef (<0.01)	<0.01 d (<0.01)	0.12 bcdef (0.05)	0.04 c (0.02)	0.56 ab (0.39)	0.08 bc (0.06)
9	0.01 cd (<0.01)	<0.01 d (<0.01)	0.15 bcdef (0.04)	0.04 c (0.02)	0.54 ab (0.28)	0.05 bc (0.03)
10	<0.01 f (<0.01)	<0.01 d (<0.01)	0.06 cdef (0.03)	0.03 c (0.01)	0.38 b (0.29)	0.06 bc (0.07)
11	0.01 cd (<0.01)	<0.01 d (<0.01)	0.06 cdef (0.03)	0.02 c (<0.01)	0.16 b (0.09)	0.02 d (0.01)
12	0.02 ab (0.01)	<0.01 d (<0.01)	0.28 ab (0.15)	0.02 c (<0.01)	0.36 b (0.18)	0.01 d (0.01)
13	<0.01 f (<0.01)	<0.01 d (<0.01)	0.04 def (0.05)	0.02 c (0.03)	0.20 b (0.30)	0.06 b (0.09)
14	<0.01 f (<0.01)	<0.01 d (<0.01)	0.02 ef (0.02)	0.01 c (0.01)	0.06 b (0.05)	0.01 d (0.01)
15	<0.01 f (<0.01)	<0.01 d (<0.01)	0.01 f (0.01)	0.06b c (0.01)	1.02 a (0.59)	2.28 a (0.36)

[a] Values in the same column followed by the same letter are not significantly different ($p > 0.05$).

Table 8. Predicted five-year average fan run hours for 15 maintenance (June to September) and cooling (October to March) aeration strategies.[a]

Strategy	Maintenance Period		Cooling Period		Total	
	Duration, h (SD)	Fan Run Time (%)	Duration, h (SD)	Fan Run Time (%)	Duration, h (SD)	Fan Run Time (%)
1	18 d (12)	0.6	159 efgh (9)	3.6	177 g (8)	2.4
2	15 d (7)	0.5	80 fgh (10)	1.8	95 g (8)	1.3
3	13 d (5)	0.4	54 h (8)	1.2	67 g (7)	0.9
4	133 c (65)	4.5	394 bc (69)	9.0	527 de (43)	7.2
5	214 c (69)	7.3	329 cd (87)	7.5	543 d(33)	7.4
6	400 ab (163)	13.7	706 a (67)	16.2	1106 a (115)	15.2
7	386 ab (144)	13.2	509 b (134)	11.7	895 b (54)	12.3
8	488 a (0)	16.7	194 ef (32)	4.4	682 c (32)	9.3
9	488 a (0)	16.7	69 gh (10)	1.6	557 cd (10)	7.6
10	244 bc (0)	8.3	159 efgh (5)	3.6	403 ef (5)	5.5
11	244 bc (0)	8.3	117 efgh (14)	2.7	361 f (14)	4.9
12	197 c (64)	6.7	240 de (61)	5.5	437 def (77)	6.0
13	220 c (90)	7.5	183 efg (22)	4.2	403 ef (73)	5.5
14	220 c (89)	7.5	127 efgh (61)	2.9	347 f (127)	4.8
15	na[b]	--	na	--	na	--

[a] Values in the same column followed by the same letter are not significantly different ($p > 0.05$).
[b] na = no fan run and not applicable.

Table 9. Predicted five-year average energy required (kWh) and fan operating cost for 15 maintenance (June to September) and cooling (October to March) aeration strategies based on U.S. \$0.1 kWh^{-1} (4.5 rupees kWh^{-1}) electricity charges in Haryana, India.

Strategy	Energy Required to Run Fans (kWh)			Operating Cost to Run Fans (U.S. \$)		
	Maintenance Period	Cooling Period	Total	Maintenance Period	Cooling Period	Total
1	936	8,268	9,204	94	827	920
2	8,160	43,520	51,680	816	4,352	5,168
3	33,701	139,987	173,687	3,370	13,999	17,369
4	6,916	20,488	27,404	692	2,049	2,740
5	116,416	178,976	295,392	11,642	17,898	29,539
6	20,800	36,712	57,512	2,080	3,671	5,751
7	209,984	276,896	486,880	20,998	27,690	48,688
8	25,376	10,088	35,464	2,538	1,009	3,546
9	265,472	37,536	303,008	26,547	3,754	30,301
10	12,688	8,268	20,956	1,269	827	2,096
11	132,736	63,648	196,384	13,274	6,365	19,638
12	510,693	622,164	1,132,857	51,069	62,216	113,286
13	11,440	9,516	20,956	1,144	952	2,096
14	119,680	69,088	188,768	11,968	6,909	18,877
15	na[a]	na	na	na	na	na

[a] na = no fan running and not applicable.

perature and moisture control limits prescribed for these strategies. The other strategies had combinations of temperature control, moisture control, and fixed morning and evening aeration in the maintenance and cooling periods. Fixed 4 h morning and evening aeration (strategies 6 and 7) had the highest fan run hours. This is due to no EMC control during the 4 h period, as only temperature was controlled. These strategies caused addition of moisture to the grain and could be used as an option for reconditioning overly dry wheat. The predicted five-year average fan operating costs for the maintenance (June to September) and cooling (October to March) aeration strategies are given in table 9. The fan operating costs for aeration strategies operating at 0.34 and 0.67 m^3 min^{-1} t^{-1} (0.3 and 0.6 cfm bu^{-1}) airflow are exorbitantly high and would be unfeasible for economic conditions in India. In addition, based on the FANS program, the aeration strategies operating at 0.67 m^3 min^{-1} t^{-1} (0.6 cfm bu^{-1}) airflow are not feasible because of the high static pressure and power required. The aeration strategies operating at 0.11 m^3 min^{-1} t^{-1} (0.1 cfm bu^{-1}) airflow are reasonable in cost, ranging from \$920 to \$3546 per year. The operating costs for aeration strategies operating at 0.34 m^3 min^{-1} t^{-1} airflow are 6 to 10 times higher in comparison.

Selection of Optimum Aeration Strategy

Fifteen different aeration strategies were studied for bulk wheat storage by predicting grain temperature, moisture content, DML, and insect population in north India (sub-tropical region) using 2000-2001 to 2004-2005 weather data. The optimum aeration strategy for the above climatic conditions was selected by first considering the predicted DML, insect population, and fan run hours. Low optimum values of DML and insect population development combined with reasonable fan run hours were used to preselect aeration strategies. Some aeration strategies may predict low DML but high insect populations, and vice versa. For example, strategies 2 and 3 predicted low DML of 0.12% but relatively higher insect populations of 0.13 to 0.23 kg^{-1}. This was due to the low

fan run hours available for these strategies. Higher fan run hours result in higher DML. Likewise, strategies 5, 7, 8, 9, 10, 11, and 12 predicted low insect populations of around 0.04 to 0.8 kg^{-1}, but with higher DML of more than 0.24%. A high-humidity, low-temperature grain aeration strategy (strategy 5) may result in low DML and insect population, but when the ambient temperature increases during storage or transport of higher-moisture wheat to a warmer location, mold growth may be triggered and cause damage to the wheat. Strategy 1 was found to be best in terms of grain temperature, moisture content, DML, and insect population, except for the fan run hours during the maintenance period. The five-year average fan run time of 18 h would not be sufficient to keep the grain temperature uniform during four months of storage without the danger of self-heating and hot spots. Therefore, this strategy was not selected. For the sub-tropical region of north India, strategies 13 and 14 were selected as the best aeration strategies based on the optimum combination of low values of DML (0.17% to 0.21%), insect population (0.01 to 0.06 kg^{-1}), grain temperature (17°C to 18°C), moisture content (11.1% to 11.3%), and reasonable fan run hours (5% to 6% fan run time). Strategy 13 consisted of aerating wheat with EMC-based fan control independent of ambient temperature, an airflow rate of 0.11 m^3 min^{-1} t^{-1}, and allowable operating windows of 4 h in the morning and evening during the maintenance period, and EMC- and temperature-based fan control during the cooling period at any time during the day or night time. Strategy 14 was the same as strategy 13 but with an airflow rate of 0.33 m^3 min^{-1} t^{-1}. Considering the difference in power requirement for fans to generate 0.11 versus 0.34 m^3 min^{-1} t^{-1}, strategy 13 would be the preferred strategy, given that it would require fan motors of about 1/12 the size as strategy 14. Smaller fans would cost substantially less to purchase and operate, even though the total fan run time would be about 116% more.

Conclusions

Fifteen different aeration strategies were formulated and studied for bulk wheat storage by predicting grain temperature, moisture content, dry matter loss (DML), and insect population. Grain temperature and moisture content, DML, and insect populations were simulated using the 2D PHAST-FEM model (Montross, 1999). The best aeration strategy was selected based on the optimum low values of grain temperature and moisture content, DML, insect population, and fan run hours. Based on this study, strategies 13 and 14 were found to be the best for the sub-tropical region of north India. Strategy 13 aerated wheat with an airflow of 0.11 m^3 min^{-1} t^{-1}, EMC control, no temperature control, and 4 h of morning and evening aeration during the maintenance period (June to September) and with EMC and temperature control during the cooling period (October to March). Strategy 14 was the same as strategy 13 but with an airflow rate of 0.33 m^3 min^{-1} t^{-1}. Strategy 13 would be preferred because it requires smaller fans and lower operating costs to maintain the desired stored wheat quality.

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