Misr J. Ag. Eng., 36 (2): 689 - 722 BIOLOGICAL ENGINEERING

THERMAL AND MECHANICAL ANALYSIS OF GRAIN STORAGE SILOS UNDER FORCED AERATION CONDITIONS USING ADVANCED MODELLING METHODS

Said Elshahat Abdallah*, **Wael Mohamed Elmessery**** and
Asmaa Elsayed Sherif ***

ABSTRACT

The most important storage problems in wheat silos are heat and moisture accumulation and there are no early warning systems to know the occurrence of heat and humidity generation. Silo wall and bottom stresses changes are investigated to be suitable indicators for early warning and controlled aeration. Aeration is a popular tool, used to treat and modify the microclimate of grain bulk. A model silo with three horizontal and vertical load cells was constructed for heat and moisture transfer studying under the influence of three different airflow rates and patterns of aerations with three unlike heights of stored wheat during winter season of 2016 in the laboratory of Agricultural Process Engineering, Agricultural Engineering Department, Faculty of Agriculture, Kafrelsheikh University. The three vertical load cells were homogenously distributed to measure the stresses from the three longitudinal prism sections on bottom layer which provides information about mass transfers among longitudinal sections. As by same technique the horizontal load cells afford data about mass transfer among horizontal layers. For heat transfer monitoring, three vertical thermocouples were installed at equal heights. Storage quality indicators are temperature gradient among wheat layers and loads differences among longitudinal and horizontal sections, as the storage system keeps the temperature gradient and vertical loads differences to be at lower levels, and then the system has higher storage efficiency.

KEYWORDS: *Grain Silo, aeration system, response surface method and State Space Representation.*

***Professor, Agricultural Engineering Department, Faculty of Agriculture, Kafrelsheikh University, Egypt**

****Associate Professor, Agricultural Engineering Department, Faculty of Agriculture, Kafrelsheikh University, Egypt**

*****M.Sc. Student, Agricultural Engineering Department, Faculty of Agriculture, Kafrelsheikh University, Egypt**

The obtained experimental data were analyzed using Response Surface Method for optimal operating parameter specifications. The optimum operating specifications was acknowledged based on heat and moisture behavior, which is the third pattern of aeration, airflow velocity of 24m/s and height to diameter ratio of one. State Space Representation (Multiple Input Multiple Output) was used to model and simulate the grain storage silo system under variant enthalpies of aerating air. The model results indicate that the specific enthalpy of aerating air above 43kJ/kg can efficiently maintain the optimum storage conditions at inside. The developed model can predict and simulate the grain silo system performance under variant ambient conditions.

NOMENCLATURE

A	System matrix
AP	Aeration pattern
AP1, AP2 and AP3	First, second and third pattern of aeration process, respectively
AS	Aeration system state of turning ON or OFF
AV	Airflow velocity
AV12, AV18, AV24	Airflow velocity of 12, 18 and 24m/s, respectively
b, c, e, f, g, j	Parameters of equation 1
B	Input matrix
C	Output matrix
D	Feed forward matrix
H	Aerating air specific enthalpy, kJ/kg
HD	Silo height to diameter ratio
H/D1, H/D1.6, H/D2	Silo height to diameter ratio of 1, 1.6 and 2
HL15, HL40 and HL95	Horizontal grain pressures measuring locations at silo heights of 15, 40 and 95cm, respectively
S1, S2 and S3	Vertical grain pressures at the circular perimeter of silo hopper transition at angle of 120° between each determined location of 1, 2 and 3, respectively
ST	The summation of three vertical grain pressures
TL15, TL40 and TL95	Grain temperature measuring locations at silo heights of 15, 40 and 95cm, respectively
U	Input or control vector
$u_i(h)$	Input variable, the subscript *i*, denotes the input variable number
VAR	Variance
Y	Output vector
y_o	Output variable the subscript *o*, denotes the output variable number
x_n	State variable the subscript *n*, denotes the state variable number

INTRODUCTION

Wheat is one of the most important components of Egypt's food security. Wheat storage is practiced from the era of pharaohs. Egypt produces 8.45 million metric tons of wheat in marketing year (2018/2019) and imports 12 million metric tons **(Egypt today, 2018)**. The production of wheat crops is seasonal; harvest was completed by early June. Egyptian government established a company for wheat storage called General Company for Silos and Storage (GCSS) at the year of 1888 belonged to Ministry of Supply and Internal Trading. The Company owns silos in various ports and inside the republic that serves food security in Egypt **(GCSS, 2018)**. Storage quality control in silos is done indirectly through the control of moisture and air movements. Aeration system reduces the deterioration of the stored grains. The cooling of grain during storage by aeration with air has received increasing attention in recent years **(Wilkin *et al.*, 1990)** and has been widely used in stored-grain management (**Edde, 2012; Jayas, 2012; Navarro, 2012**). It offers the possibility of controlling insects with reduced levels of pesticide applications (**Yang *et al.*, 2017**). Moisture exchange is an important management process because grain adsorbs or desorbs moisture under changing environmental conditions. Moisture migration happens within the stored bulk due to heat-induced natural convection currents **(Smith and Sokhansanj, 1990; Thorpe *et al.*, 1991)**. Temperature gradient is the main factor for air convection currents induction. **(Gough *et al.*, 1990)** detect temperature gradient in metal maize silos. Laboratory experiments done by (**Close and Peck, 1986; Gough *et al.*, 1987**) emphasizes that the temperature gradient makes moisture-carrying convection currents. Mass diffusion occurs in the inter-granular air and on grain bulk surface. Natural convection current aids diffusion to be a principal mechanism of moisture transfer. Accurate prediction of grain temperature and moisture during storage is desired in order to develop the suitable aeration strategies (**Lopez *et al.*, 2008**). Many of mathematical models have been developed to simulate heat and moisture transfer in bulk stored grains with aeration system **(Metzger and Muir, 1983; Wilson, 1988; Chang *et al.*, 1993; Chang *et al.*, 1994; Sinicio *et al.*, 1997; Jia *et al.*, 2001; Iguaz *et al.*, 2004)**. The use of ambient air to cool grain that is stored in silos during autumn is an important management practice throughout many temperate regions (**Lopes *et al.*, 2006; Arthur *et al.*, 2001)**. Simulation modeling using documented weather data is an important tool to develop optimum controlled aeration for microorganism's population suppression in stored wheat **(Arthur and Flinn, 2000)**. **(Dussadee *et al.*, 2007)** developed a mathematical model to predict the paddy bed temperature in the silo with the hybrid aeration–thermo syphon. The model can determine periods of its blower from the simulation. Response Surface Methodology (RSM) is a compilation of mathematical and statistical methods, helpful for fitting the models and analyzing the problems in which quite a lot of independent parameters control the dependent parameter (s) (**Montgomery, 2003; Myers *et al.*, 2009**). The empirical mathematical modeling for any performance characteristic is fitted with the correlating parameters. This process will not only determine optimum conditions, but also gives the information necessary to design a process. State Space Representation (SSR) is a uniform platform for representing time-invariant systems, time-varying systems, linear systems as well as nonlinear systems which can describe the dynamics in almost all systems (mechanical, electrical and biological systems). SSR is a convenient tool for Multiple Input Multiple Output (MIMO) systems. **(Yao *et al.*, 2019)** used SSR to improve the modeling efficiency of heating, ventilation and air conditioning and validate the dynamic system model by transient response experiments. Aeration in winter season with ambient air for grain cooling purposes is investigated in the present paper. This concept of aeration in wintertime is an introductory study for aeration by chilled air in summertime; due to there are no literatures studying the feasibility of applying refrigerated air in summertime for cooling grain under Egyptian climatic conditions. Grain aeration management with automatic controllers is ideal with more complex strategies; usually based on temperatures and humidity. There are many studies to develop the suitable strategy of aeration automatic controller (**Agridry, 2014; Lopez, 2008**). The aeration control strategy in this paper is based on grain-stored stresses of vertical and horizontal direction integrated with temperature gradient.

From this view point, the main aim of the current study is to investigate how the aeration process works to prevent convection currents and condensation from occurring by reducing the temperature gradient and moisture migration of the stored wheat. The following specific objectives were followed to accomplish the main aim:

1. Studying the effect of aeration pattern, airflow velocity and silo geometric shape (height to diameter ratio) on heat gradient and moisture behavior,
2. Representing the obtained data by Response Surface Method for optimal operating conditions attaining,
3. Developing a convenient model for whole system representation and further simulation under variant ambient air conditions.

MATERIALS AND METHODS

This study was carried out in the laboratory of Agricultural Process Engineering, Agricultural Engineering Department, Faculty of Agriculture, Kafrelsheikh University, Kafr Elsheikh governorate, Egypt. Grain storage experiments were conducted during winter season of 2016, with minima and maxima air temperatures around 9 and 25°C, respectively. Air relative humidity did not exceed 70%.

Model silo and aeration system

The model silo consists of vertical cylindrical part (silo body), conical part (hopper) and roof manufactured from galvanized steel S320GD (zinc coated) of minimum tensile stress of 390MPa. The reinforcement rings of hopper and roof were of 50mm wide and 10 mm thick. The silo can be considered as a rigid, smooth walled steel silo. The silo dimensions are of 1m height and 0.5m diameter and hopper wall has an inclination angle of 15 degrees with a height of 0.3 cm and discharging opening diameter of 0.33m. The aeration system consists of a blower, vertical perforated pipe centrally located at the inner for air inlet distribution along the silo height, airflow rate regulator valve. Airflow rate was measured by Flow Sensor FS300A G 3/4” (flow rate range 1-60 ℓ/min, maximum pressure 2MPa and Relative humidity 35-90%). Airflow rate was regulated by a manual gate valve of 2cm in diameter to be at three levels of airflow velocity (12, 18 and 24) m/s, **Figure 1**. The three levels of airflow velocities were established according to discoverial experiment of air flow ability determination through the grain bulk in the silo. The maximum airflow velocity been achieved is 24m/s. So the other two levels were chosen to represent if the reduction in flow velocity has a significant effect on storage process performance or not.

Stress, temperature and relative humidity sensors

Stress measurement device is composed of three vertical (S type) and horizontal (L type) load cells which are calibrated at laboratory of concrete test, Faculty of Engineering, Kafrelsheikh University. The vertical forces were measured by three tension/compression (S type) located at 120˚ apart around the circumference of silo-hopper transition, La, Lb and Lc as depicted in **Figure 1**. Temperature sensor of LM35 (accuracy 0.5°C and range of -55 to 150°C) was used to measure the grain temperature inside the silo at three different heights on the silo, including the hopper part, **Figure 1**. Two sensors of HDT-11 (accuracy of 5%RH and range of 20-90%) were used to measure relative humidity with temperature simultaneously at two locations: the first sensor centrally positioned inside the hopper part of the silo for gauging temperature and relative humidity of the occulted air at inter-granular spaces and the second sensor was sited at outside for ambient measurements. Measurements were taken at three different timings: before, during and after aeration process of each time of treatment, **Figure 2**. At all aeration patterns AP1, AP2 and AP3; the aeration process starts at three different day times at 10:00AM, 1:00PM and 4:00PM and continue for 30, 60 and 90minutes for each time of aeration initiation, respectively. Aeration patterns were conveniently settled to recondition the grain silo microclimatic. It is important to reduce the energy consumed for this purpose without any effect on grain storage quality.

Measurements data acquisition circuits

Open source of Arduino board was used to acquire the measurements data from the different sensors. Arduino board circuit has a human-computer interface which displays the acquired data on the personal computer. Each sensor has its connection configuration illustrated at **Figure 3**.

Determinations of aerating air specific enthalpy

On-line psychrometric chart program **(Psychrometrics, 2018)** was used to determine the specific enthalpy of aerating air based on the consideration of 10.2m altitude, relative humidity and dry bulb temperature. The results are within the scope of ANSI/ASHRAE 41.6-1994. In this study, the specific enthalpy was preferred to thermodynamically express of the variant aerating air conditions (ambient air was used for aeration without any pretreatments). The advantage of using air specific enthalpy is due to information which be obtained about the whole heat that the air contains, the summation of latent and sensible heat.

Grain moisture content

Samples of grain were collected from the silo every day for moisture content measuring by a device of Hydrometer GANN G88 (Elektronik-Feuchtmesser) at the laboratory of Grain Quality, Rice Research and Training Center.

Experimental procedures

The optimum operating conditions were determined by investigating three independent variables of silo filling height, airflow velocity and aeration pattern. Three different heights of silo filling of 100, 80 and 50cm which represents corresponding values of silo height to diameter ratio of 2, 1.6 and 1, respectively; to characterize three different types of silos according to **(EN 1991-4, 2006)** as slender, intermediate slenderness and squat silos, respectively. Three different aeration process patterns were investigated in this experiment of 30, 60 and 90 minutes repeated three times daily at 10:00AM, 1:00PM and 4:00PM, **Figure 2**. Three different ambient airflow velocities are of 12, 18, 24 m/s (under variant ambient conditions). Silo storage quality indicators were recognized by temperature gradient and moisture transfer among horizontal and vertical sections. The vertical or longitudinal prism sections are acknowledged by three vertical load cells, and the horizontal ones by three horizontal load cells, **Figure 1**.

Variance as a performance efficacy indicator for temperature and moisture controlling process

Temperature and moisture controlling by aeration and silo geometry was evaluated according to two principles of steady state of acquired data and the variance among measurements obtained from different locations.

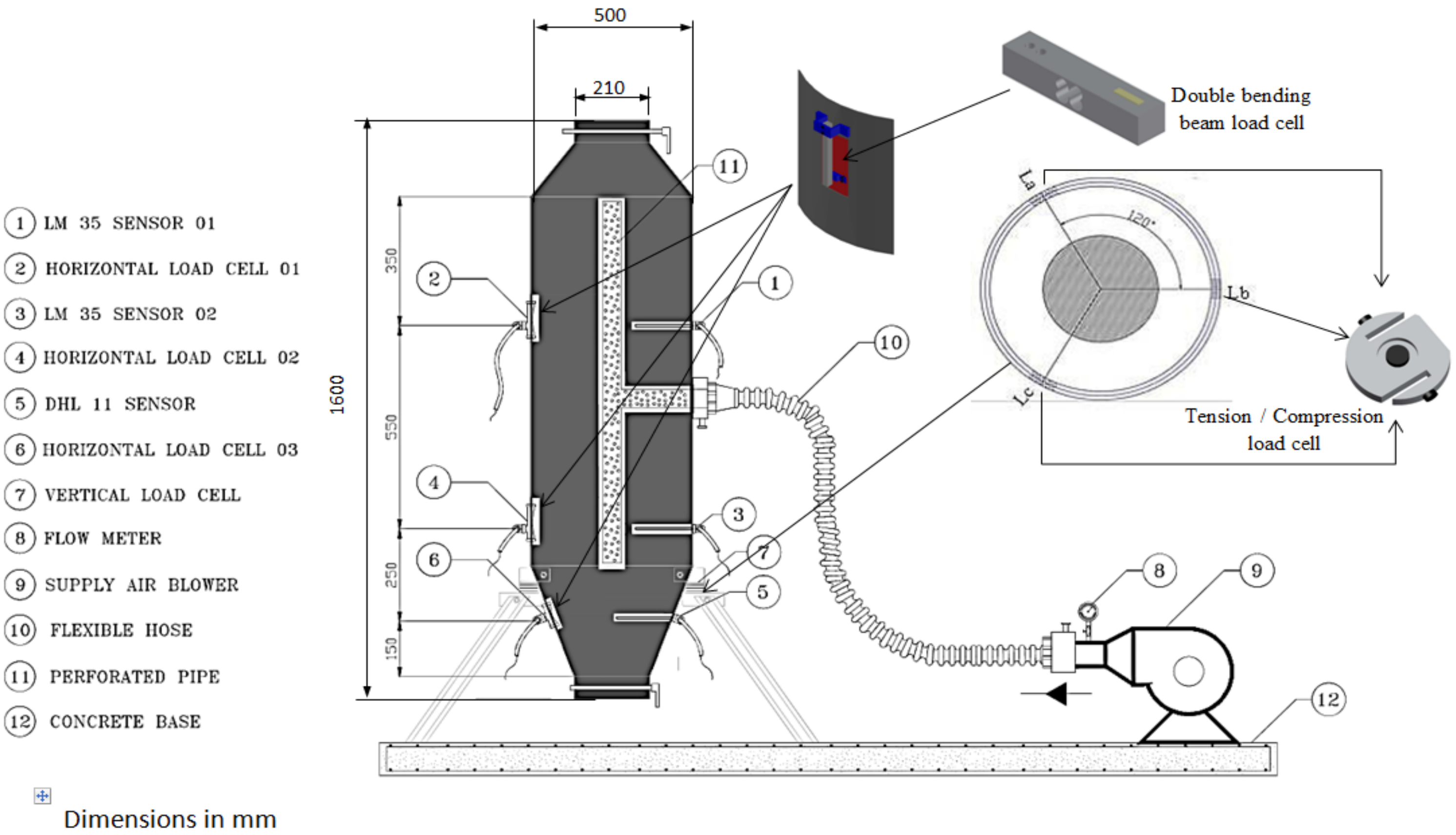

Figure 1. Schematic draw of the experimental wheat silo

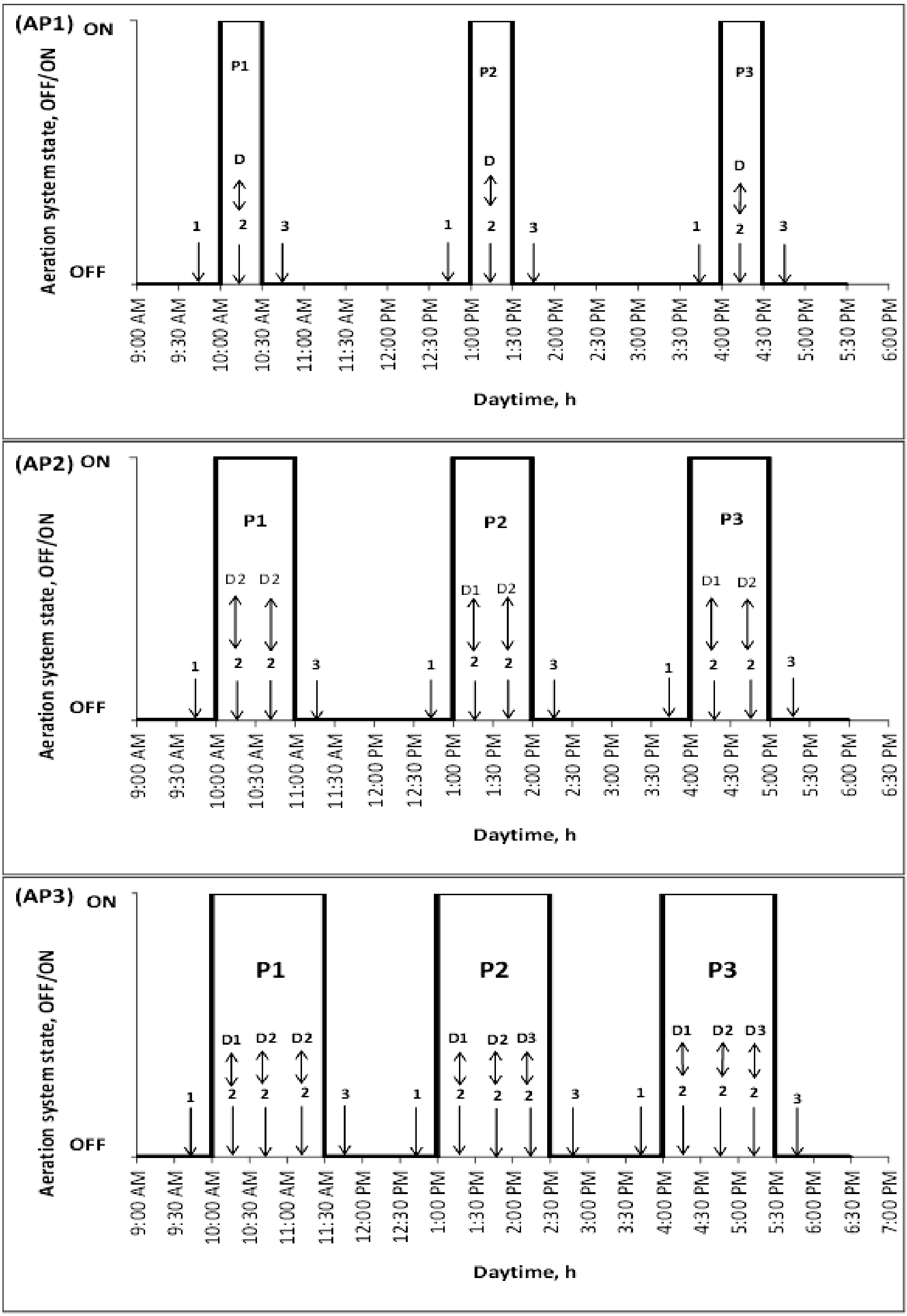

Figure 2. Aeration patterns AP1, AP2 and AP3 under investigation. D, D1, D2, D3 are measuring timings during aeration process. 1 and 3 are measuring timings before and after aeration process, respectively

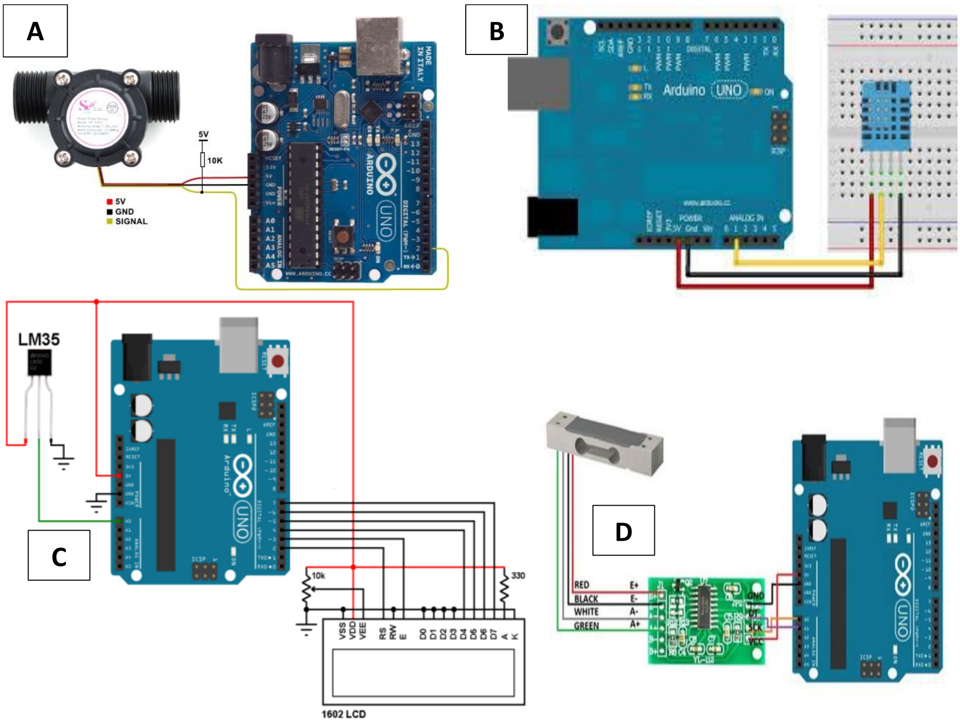

Figure 3. Sensors connection to Arduino board (A) Airflow sensor (FS300A G 3/4”), (B) Relative humidity sensor (HDT-11), (C) Temperature sensor (LM35), (D) Load sensor

When a steady state is achieved at any location of measurement, it means that the property is unchanging in time indicating that the whole energy or substance generated inside instantaneously removed or escaped. The variance indicates that there is a temperature gradient at silo, which can be calculated by using Microsoft Excel for each experimental run.

Response Surface Representation by Matlab software for optimal operating parameters determination

Matlab software package has a tool of response surface fitting. The variance data was used by this tool to build the response surface to the independent variables (aeration pattern, airflow velocity and height to diameter ratio) with the three different levels of each variable. The Response Surface Method tool built an interactive model between the independent variables and the variance among temperature measurements of different heights of silo (15, 40 and 95cm). After model architecting, it will be able to predict the variance at any set of operating parameters.

Developing the methodology for grain silos aeration control model

There are several mathematical models which formed from a well-known heat and mass transfer laws which developed from a lumped capacity analysis that assumes a uniform temperature distribution throughout the grain bed. These models are used to predict the grain bulk temperature inside different types of silos (**Dussadee et al., 2007**; **Lopes et al., 2006**; **Khatchatourian and Oliveira, 2006**). However in the current study the grain temperatures were acquired directly at three different locations to elucidate the grain temperature response to different strategies of aeration under an arbitrary thermal content of aerating air. The planned model can analyze the effect of specific enthalpy of aerating air on heat and moisture behavior inside grain silo under different regimes of aeration.

Model architecture

State Space Representation

A State Space Representation is a mathematical model in which a number of inputs, outputs and state variables are related by a series of first order differential equations that are combined in a single pair of differential equation matrices in which variables are expressed as vectors. This time domain approximation is compact and convenient to analyze systems with multiple inputs and outputs.

For continuous Linear Time Invariant (LTI) systems, the standard State Space Representation is given by the following equations with $'i'$ inputs, $'o'$ outputs and $'n'$ state variables, where the first equation is called state equation and the second one is outputs equation:

$$\{\dot{x}\}_{n,1} = [A]_{n,n}\{x\}_{n,1} + [B]_{n,i}\{u\}_{i,1}$$
$$\{y\}_{o,1} = [C]_{o,n}\{x\}_{n,1} + [D]_{o,i}\{u\}_{i,1}$$

where x is the vector of state variables, $\dot{x}$ is the air specific enthalpy derivative of the state vector, u is the input or control vector, y is the output vector, A is the system matrix, B is the input matrix, C is the output matrix, and D is the feed forward matrix is set to zero if the system model does not have a direct feed through.

For choosing a mathematical model typology to predict thermal and moisture behavior of grain storage the following assumptions were considered:

1. There is more than one engineering parameter (two parameters are related to silo aeration and the third one is belonging to silo geometry) that controlling heat and moisture sinking and migrating.
2. There are several points of measurement (three points of temperature and six points of grain pressures).
3. Psychrometric characteristics of the aerating air vary arbitrarily with time.

To model and simulate the aerated grain storage silo under arbitrary air ambient conditions, the following steps were followed;

1. Acquire thermal (grain temperatures at three different levels) and mechanical (silo wall pressures in both horizontal and vertical directions) data under different experimental runs.
2. Make a non-linear regression analysis on the acquired data to represent the most suitable differential equation for each variable under investigation.
3. Calculate the state space equations for thermal and mechanical states.
4. Create the m-file on MATLAB to simulate the model.
5. Model response analysis.

RESULTS AND DISCUSSION

The results obtained from a series of experimental runs on aerating the grain storage silo for moisture and temperature controlling under variable air ambient conditions at different aeration patterns, airflow velocities and silo geometry (height to diameter ratio) are illustrated by **Figures 4 to 6**. Heat and moisture transfer occurred inside the grain silo monitored by sensors located at heights of 15, 40 and 95cm symbolized by TL15cm, TL40cm and TL95cm and HL15cm, HL40cm and HL95cm for grain temperatures and horizontal pressures, respectively. However, grain vertical pressures designated by S1, S2 and S3. From the obtained data, the aeration process can limit any occurrence of thermal and moisture accumulation. The convergence and divergence among measurements of TL15cm, TL40cm and TL95cm and HL15cm, HL40cm and H L95cm and S1, S2 and S3 indicates system proficiency and deficiency, respectively, of heat and moisture removal regulator under the investigated operating parameters. Variance is used to illustrate the amount of convergence among temperature and load measurements as a performance efficacy indicator for temperature and moisture controlling process. In statistics, variance is defined as the measure of variability that represents how far members of a group are spread out. It finds out the average degree to which each observation varies from the mean. When the variance of a data set is small, it shows the closeness of the data points to the mean (higher convergence is higher performance efficiency) whereas a greater value of variance represents that the observations are very dispersed around the arithmetic mean and from each other (lower convergence is lower performance efficiency). Moisture migration can be acknowledged through vertical planes inconsistency by the horizontal load cells of HL15cm, HL40cm and HL95cm. However, the moisture fluxes through the horizontal planes can be identified by the vertical load cells of S1, S2 and S3. The aerating air characteristics are varying based on ambient air conditions, because the forced air is from ambient air without any treatment. **Figures 4, 5, 6 and 8** show the specific enthalpy of ambient air for each experimental run. **Figure 9 shows** the relationship between the specific enthalpy versus ambient air temperature and relative humidity. The ambient air specific enthalpy was read off from the no-line psychrometric chart based on air temperature and relative humidity and used as a determinant parameter for modelling thermal and moisture behavior inside grain silo storage. **Figure 4** shows the effect of aeration pattern on heat and moisture transfer. AP1 and AP2 nearly have the same effect of heat measurements variances of 1.79 and 1.82, respectively. However, AP3 has a higher variance of 3.26 which indicates that the first pattern of aeration is more suitable for grain storage silos of height to diameter ratio of 2. The effect of aeration pattern on vertical and horizontal pressures is shown at **Figure 5**. The third pattern of aeration AP3 has higher impact on moisture removal than other two patterns of aeration of AP1 and AP2. The effect of airflow velocity and height to diameter ratio was illustrated at **Figure 6**. As airflow velocity decreases from 24m/s to 18m/s, system performance efficacy declines, as variance units raise from 1.79 to 2.74. From **Figure 6C**, it was observed that at operating parameter of aeration pattern AP3, airflow velocity of 24m/s and silo height to diameter ratio of 1.6 has higher effect on system performance, the grain temperatures at the three different levels almost are the same indicating only there is a small amount of heat energy transferred from height 40cm to the top and the bottom of grain silo which noticed by the thermocouples located at heights of 15 and 95cm. Generally, as the grain temperatures at the different heights are the same, as the aeration system performance is efficiently operate.

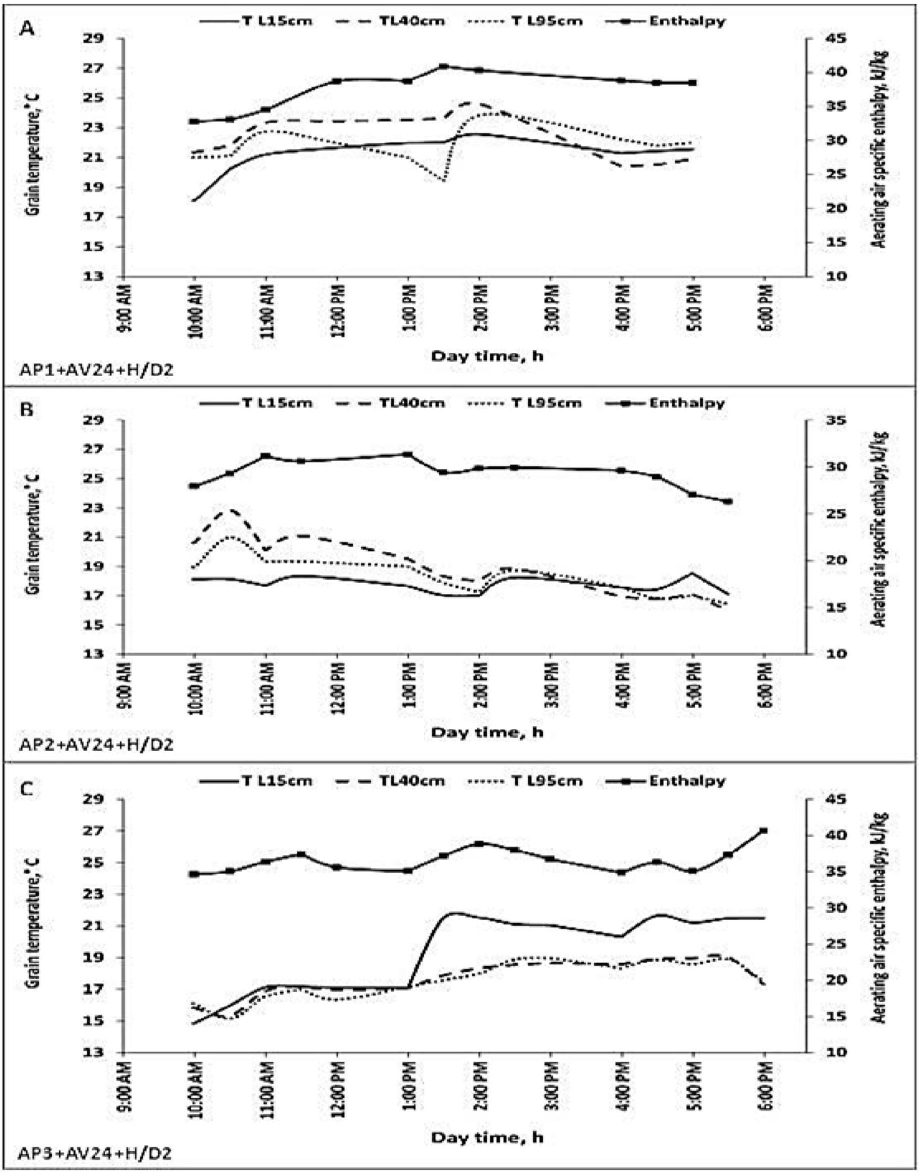

Figure 4. The effect of aeration pattern on stored grain temperature behavior at airflow velocity of 24m/s and silo height to diameter ratio of 2 under variant specific enthalpy of aerating air

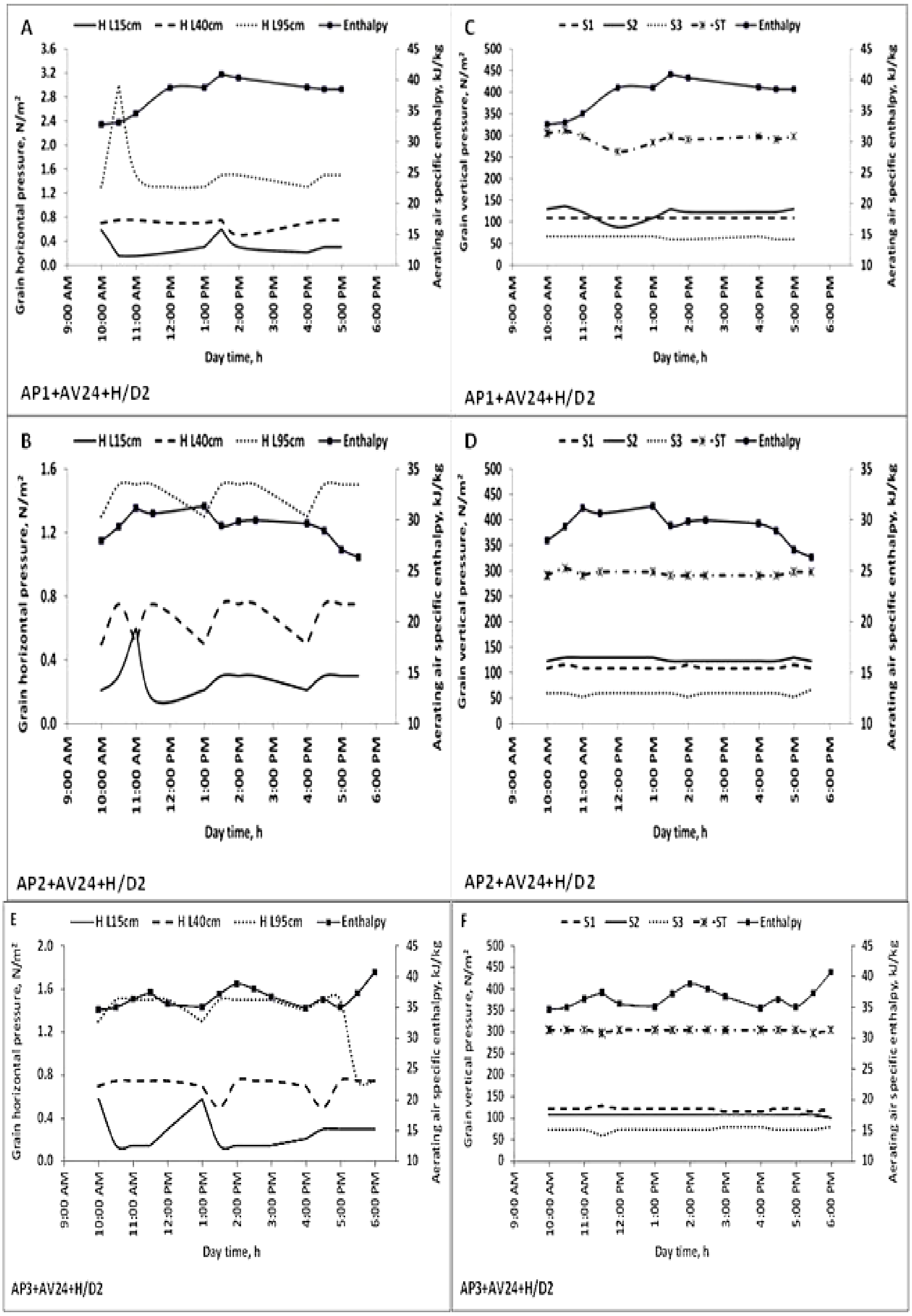

Figure 5. The effect of aeration pattern on grain silo horizontal and vertical pressures behavior, respectively, at airflow velocity of 24m/s and silo height to diameter ratio of 2

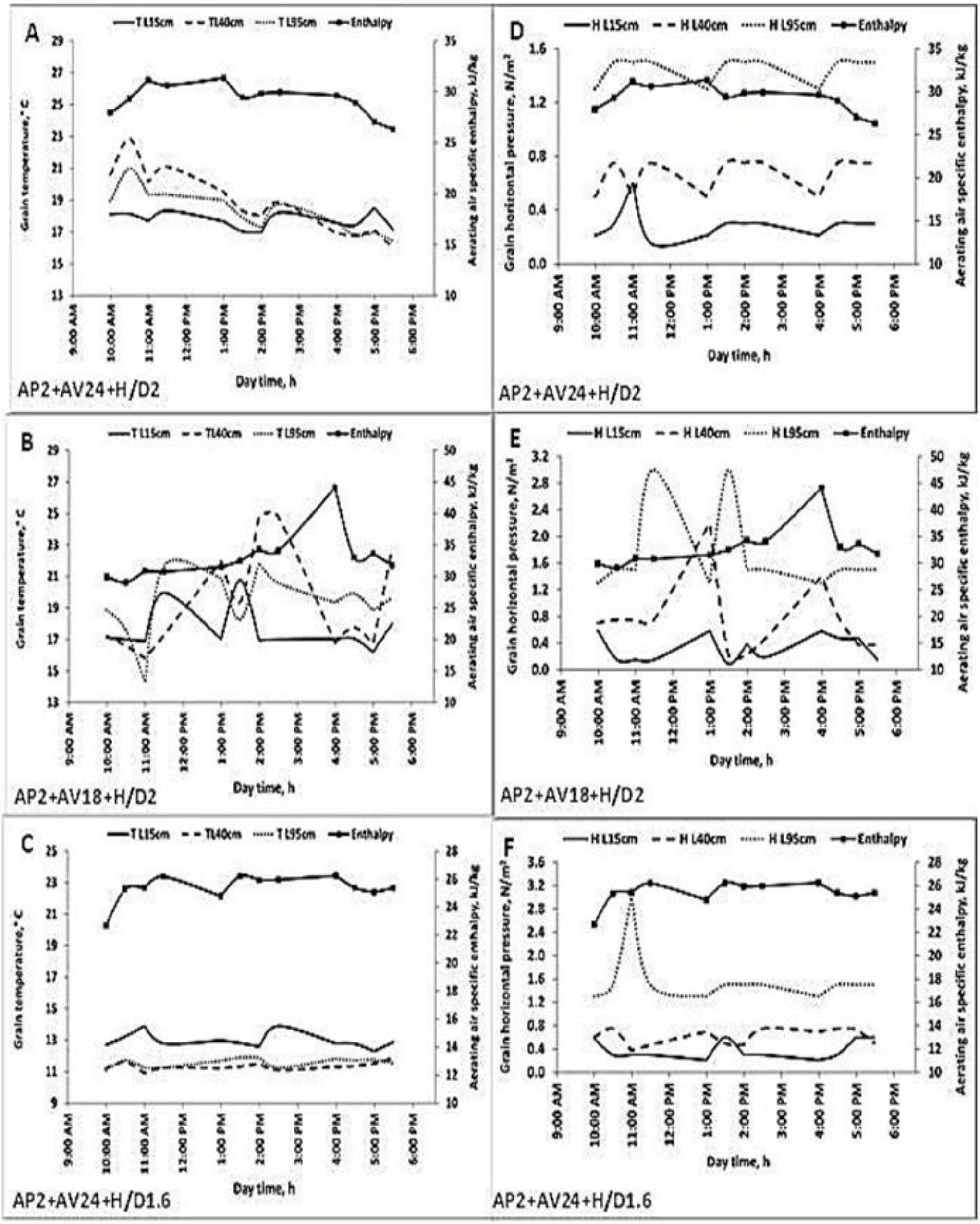

Figure 6. The effect of airflow velocity and height to diameter ratio on temperature and grain silo wall horizontal pressures behavior

Graphical representation of Response Surface Method

Approaching the optimum specifications of grain storage silo prototype needs to investigate the impact of independent variables on thermal and moisture controlling; hence the present study is primarily calculate the variance among temperature and pressure measurements for each experimental run. **Figure 7** shows the response surface which fit the variance values of temperatures under the investigated operating parameters. The advantage of response surface, it gives a prediction about the performance of grain silo under unlimited operating conditions be set in determined operating parameters boundaries. For example airflow velocities form 12 to 24m/s, height to diameter ratio from 1 to 2 and aeration pattern from 1 to 3. The variance values were automatically calculated by Matlab program after fitted model creation. So it can be inferred from the surface response, **Figure7**, that at height to diameter ratio of 1 the lowest variance value of 0.051 were achieved at the third pattern of aeration AP3 and airflow velocities from 18 to 21m/s. However, at height to diameter ratio of 1.6 and 2 the minimum variance obtained were 0.207 and 1.0198 at operating parameters of first pattern of aeration (AP1) and airflow velocity of 12m/s (AV12) and second pattern of aeration (AP2) and airflow velocity of 12m/s (AV12), respectively. Grain storage silo performance rating for each experimental run according viewpoint of thermal behavior and moisture behavior are summarized at **Table 1.** The operating parameters of AP1, AV18 and height to diameter ratio of 1 recorded the best thermal control over other operating parameters. However, for moisture control documented the ninth. So the most optimum performance suitable for both of temperature and moisture control was obtained at operating parameters of AP3, AV24 and H/D1 or AP2, AV24 and H/D1, as given by **Table 1.**

Temperature and moisture behavior at optimum operating parameters of AP3, AV24, H/D1 was illustrated in **Figure 8**. It is observed that the closeness amount among lines of temperature and vertical pressure measurements is the highest.

Empirical model development

The first step in the control design process is to develop appropriate mathematical models of the system to be controlled. This model is derived from experimental data. The State-Space Representation of grain silo was introduced as a dynamic system. Then this model is going to be introduced to MATLAB for further analysis.

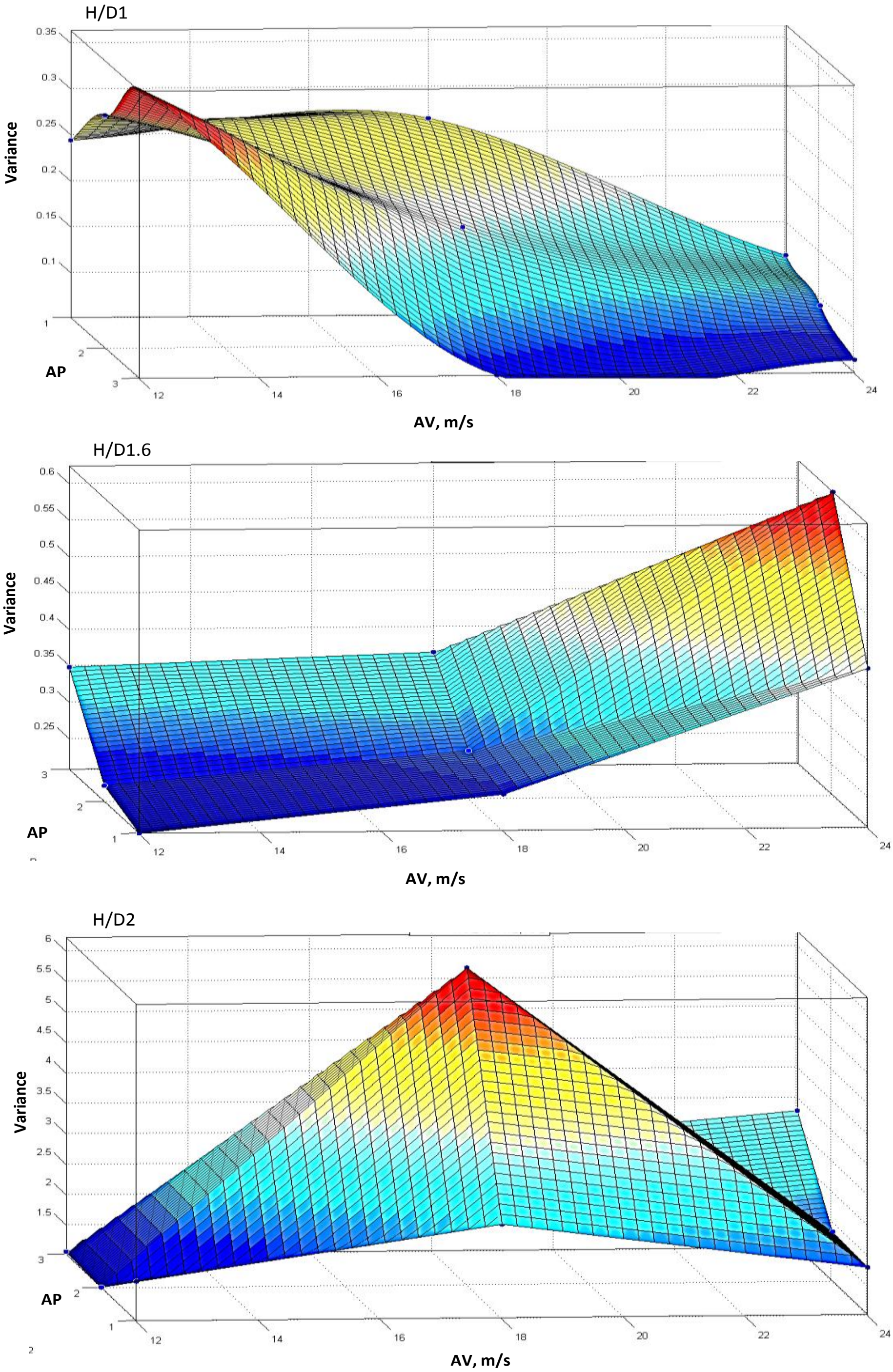

Figure 7. The effect of aeration operating parameters on temperature measurements variance for H/D ratios of 1, 1.6 and 2

Table1: Operating parameters rating in-order of aerated grain storage silo

Operating parameters			Grain storage system performance rating in-order based in viewpoint of	
Aeration pattern	Airflow velocity, m/s	Height to diameter ratio	Thermal behavior	Moisture behavior
3	18	1	1st	9th
3	24	1	2nd	3rd
2	24	1	3rd	2nd
1	24	1	4th	8th
2	18	1	5th	1st
1	12	1.6	6th	20th
2	12	1.6	7th	24th
1	12	1	8th	7th
1	18	1.6	9th	21st
1	18	1	10th	5th
2	18	1.6	11th	21st
2	12	1	12th	4th
3	12	1.6	13th	17th
3	12	1	14th	6th
3	18	1.6	15th	15th
1	24	1.6	16th	22nd
3	24	1.6	17th	16th
2	24	1.6	18th	18th
2	12	2	19th	14th
3	12	2	20th	10th
1	12	2	21st	11th
1	24	2	22nd	23rd
2	24	2	23rd	27th
1	18	2	24th	12th
3	18	2	25th	26th
3	24	2	26th	13th
2	18	2	27th	19th

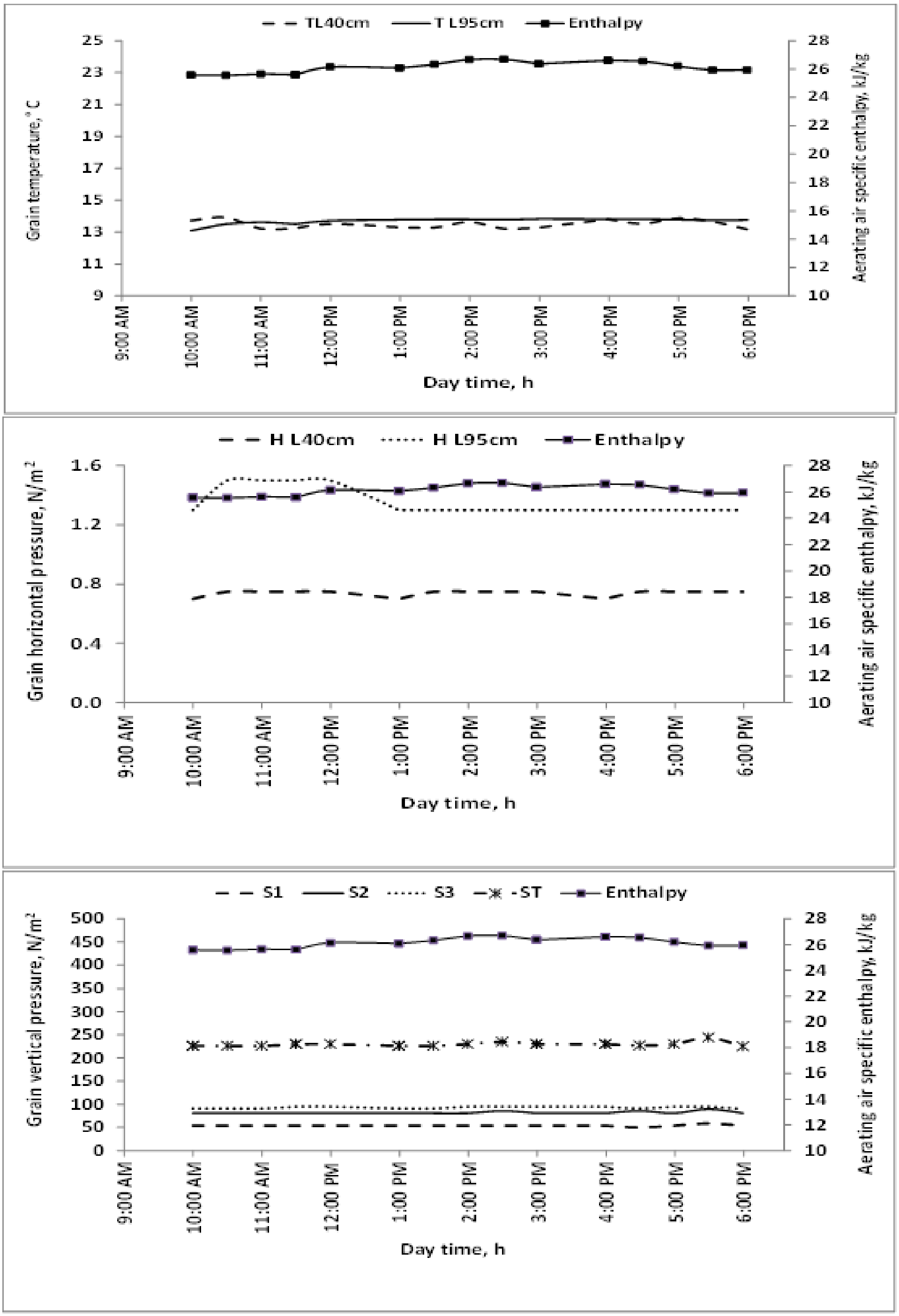

Figure 8: Heat and moisture behavior under optimum operating conditions (AP3, AV24, H/D1)

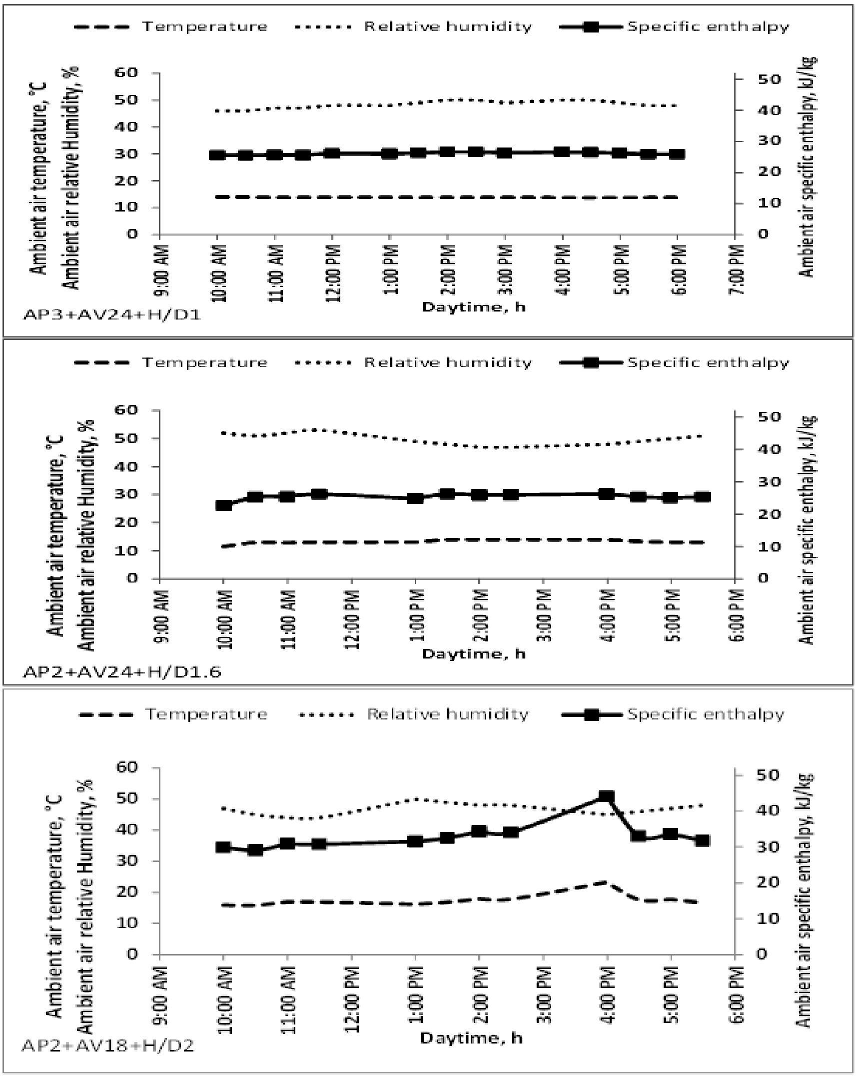

Figure 9: Ambient air characteristics used to aerate grain storage silo

To describe the aeration dynamics of grain storage silos, three different differential equations (equations 2 to 4) and other seven ones (equations 5 to 11) to represent both thermal and mechanical states, respectively. That is created in a standard form for state space representation as equation 1**.**

Thermal state modeling

The acquired experimental data of stored grain temperature was used to develop the thermal behavior model. The general equation form of the developed differential model can be expressed by **equation 1**. However, the empirical thermal model was articulated by **equations** 2, 3 and 4.

$\frac{dy^2}{dx} + b\frac{dy}{dx} + cy = eu_1(h) + fu_2(h) + gu_3(h) + ju_4(h)$	R^2	Eqn 1
$\frac{d(TL15)^2}{dh} + \frac{d(TL15)}{dh} + (TL15) = -0.037AP + 3.299AS - 0.195AV + 10.458HD$	0.98	Eqn 2
$\frac{d(TL40)^2}{dh} + \frac{d(TL40)}{dh} + (TL40) = -0.381AP + 0.589AS - 0.058AV + 8.631HD$	0.91	Eqn 3
$\frac{d(TL90)^2}{dh} + \frac{d(TL90)}{dh} + (TL90) = -0.139AP + 0.62AS - 0.049AV + 8.36HD$	0.92	Eqn 4

Mechanical state modeling

Moisture migration behavior can be indicated by horizontal and vertical pressures on silo wall (gaining or losing) for two dimensions, the vertical moisture migration was revealed by horizontal load cells and the horizontal one by vertical load cells that can be calculated by **equations** from 5 to 7 and from 8 to 11, respectively.

$\frac{d(HL15)^2}{dh} + \frac{d(HL15)}{dh} + (HL15) = 0.004AP + 0.095AS - 0.004AV + 0.102HD$	0.91	Eqn 5
$\frac{d(HL40)^2}{dh} + \frac{d(HL40)}{dh} + (HL40) = 0.048AP + 0.384AS - 0.016AV - 0.462HD$	0.89	Eqn 6
$\frac{d(HL90)^2}{dh} + \frac{d(HL90)}{dh} + HL90 = -0.0015AP - 0.586AS + 0.035AV + HD$	0.93	Eqn 7
$\frac{d(S1)^2}{dh} + \frac{dS1}{dh} + S1 = -5.603AP - 41.726AS + 2.412AV + 43.022HD$	0.94	Eqn 8
$\frac{d(S2)^2}{dh} + \frac{d(S2)}{dh} + (S2) = 1.223AP - 12.45AS + 0.809AV + 20.519HD$	0.92	Eqn 9
$\frac{d(S3)^2}{dh} + \frac{d(S3)}{dh} + (S3) = -3.148AP + 49.397AS - 2.943AV - 1.646HD$	0.95	Eqn 10
$\frac{d(ST)^2}{dh} + \frac{d(ST)}{dh} + (ST) = -7.527AP - 4.78AS + 0.278AV + 61.895HD$	0.95	Eqn 11

State space representation of the empirical thermal state model

State space representation is a mathematical tool that was used in this study to convert the developed empirical model of thermal energy behavior (dissipation or acquisition) to predict the system performance response under different levels of aerating air specific enthalpy.

Symbols definitions

$y_0 = TL15, y_1 = TL40, y_2 = TL95$ and

$u_1(h) = AP, \quad u_2(h) = AS, \quad u_3(h) = AV, \quad u_4(h) = HD$

The 6-Dimensional space definition

The co-ordinate axes (state space) are $x_1, x_2, x_3, x_4, x_5, x_6$

The state variables definitions

$$\begin{array}{lll} x_1 = y_0 & x_2 = \dot{y}_0 & x_2 = \dot{x}_1 \\ x_3 = y_1 & x_4 = \dot{y}_1 & x_4 = \dot{x}_3 \\ x_5 = y_2 & x_6 = \dot{y}_2 & x_6 = \dot{x}_5 \end{array}$$

State equations

$$\dot{x}_1 = x_2 \qquad \text{Eqn 12}$$

$$\dot{x}_2 = -x_2 - x_1 - 0.037u_1(h) + 3.299u_2(h) - 0.195u_3(h) + 10.458u_4(h) \qquad \text{Eqn 13}$$

$$\dot{x}_3 = x_4 \qquad \text{Eqn 14}$$

$$\dot{x}_4 = -x_4 - x_3 - 0.381u_1(h) + 0.589u_2(h) - 0.058u_3(h) + 8.631u_4(h) \qquad \text{Eqn 15}$$

$$\dot{x}_5 = x_6 \qquad \text{Eqn 16}$$

$$\dot{x}_6 = -x_6 - x_5 - 0.139u_1(h) + 0.62u_2(h) - 0.049u_3(h) + 8.36u_4(h) \qquad \text{Eqn 17}$$

Therefore, the state space representation of the thermal state system becomes as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ -0.037 & 3.299 & -0.195 & 10.458 \\ 0 & 0 & 0 & 0 \\ -0.381 & 0.589 & -0.058 & 8.631 \\ 0 & 0 & 0 & 0 \\ -0.139 & 0.62 & -0.049 & 8.36 \end{bmatrix} \begin{bmatrix} u_1(h) \\ u_2(h) \\ u_3(h) \\ u_4(h) \end{bmatrix} \qquad \text{Eqn 18}$$

$$\begin{bmatrix} y_0 \\ y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} + [0] \begin{bmatrix} u_1(h) \\ u_2(h) \\ u_3(h) \\ u_4(h) \end{bmatrix} \qquad \text{Eqn 19}$$

State Space Representation of the empirical mechanical state model

Mechanical state model, equations 5, 6, 7, 8, 9, 10 and 11, can designate the generated grain pressures on silo wall and bottom. The generated pressures are related to aerating air and grain storage conditions. State Space Representation can benefit the available information for further aeration control designing.

Symbols definitions

$y_3 = HL15, y_4 = HL40, y_5 = HL90,\ y_6 = S1,\ y_7 = S2, y_8 = S3,$
$y_9 = ST$

The 14-Dimensional space definition

The co-ordinate axes (state space) are $x_7, x_8, x_9, \ldots, x_{18}, x_{19}, x_{20}$

The state variables definitions

$$\begin{array}{lll}
x_7 = y_3 & x_8 = \dot{y}_3 & x_8 = \dot{x}_7 \\
x_9 = y_4 & x_{10} = \dot{y}_4 & x_{10} = \dot{x}_9 \\
x_{11} = y_5 & x_{12} = \dot{y}_5 & x_{12} = \dot{x}_{11} \\
x_{13} = y_6 & x_{14} = \dot{y}_6 & x_{14} = \dot{x}_{13} \\
x_{15} = y_7 & x_{16} = \dot{y}_7 & x_{16} = \dot{x}_{15} \\
x_{17} = y_8 & x_{18} = \dot{y}_8 & x_{18} = \dot{x}_{17} \\
x_{19} = y_9 & x_{20} = \dot{y}_9 & x_{20} = \dot{x}_{19}
\end{array}$$

State equations

$$\dot{x}_7 = x_8$$
Eqn 20

$$\dot{x}_8 = -x_8 - x_7 + 0.004u_1(h) + 0.095u_2(h) - 0.004u_3(h) + 0.102u_4(h)$$
Eqn 21

$$\dot{x}_9 = x_{10}$$
Eqn 22

$$\dot{x}_{10} = -x_{10} - x_9 + 0.048u_1(h) + 0.384u_2(h) - 0.016u_3(h) - 0.462u_4(h)$$
Eqn 23

$$\dot{x}_{11} = x_{12}$$
Eqn 24

$$\dot{x}_{12} = -x_{12} - x_{11} - 0.0015u_1(h) - 0.586u_2(h) + 0.035u_3(h) + u_4(h)$$
Eqn 25

$$\dot{x}_{13} = x_{14}$$
Eqn 26

$$\dot{x}_{14} = -x_{14} - x_{13} - 5.603u_1(h) - 41.726u_2(h) + 2.412u_3(h) + 43.022u_4(h)$$
Eqn 27

$$\dot{x}_{15} = x_{16}$$
Eqn 28

$$\dot{x}_{16} = -x_{16} - x_{15} + 1.223u_1(h) - 12.45u_2(h) + 0.809u_3(h) + 20.519u_4(h) \qquad \text{Eqn 29}$$

$$\dot{x}_{17} = x_{18} \qquad \text{Eqn 30}$$

$$\dot{x}_{18} = -x_{18} - x_{17} - 3.148u_1(h) + 49.397u_2(h) - 2.943u_3(h) - 1.646u_4(h) \qquad \text{Eqn 31}$$

$$\dot{x}_{19} = x_{20} \qquad \text{Eqn 32}$$

$$\dot{x}_{20} = -x_{20} - x_{19} - 7.527u_1(h) - 4.78u_2(h) + 0.278u_3(h) + 61.895u_4(h) \qquad \text{Eqn 33}$$

Therefore, the state space representation of the mechanical state system becomes as follows

$$\begin{bmatrix} \dot{x}_7 \\ \dot{x}_8 \\ \dot{x}_9 \\ \dot{x}_{10} \\ \dot{x}_{11} \\ \dot{x}_{12} \\ \dot{x}_{13} \\ \dot{x}_{14} \\ \dot{x}_{15} \\ \dot{x}_{16} \\ \dot{x}_{17} \\ \dot{x}_{18} \\ \dot{x}_{19} \\ \dot{x}_{20} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \end{bmatrix} \begin{bmatrix} x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{16} \\ x_{17} \\ x_{18} \\ x_{19} \\ x_{20} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0.004 & 0.095 & -0.004 & 0.102 \\ 0 & 0 & 0 & 0 \\ 0.048 & 0.384 & -0.016 & -0.462 \\ 0 & 0 & 0 & 0 \\ -0.0015 & -0.586 & 0.035 & 1 \\ 0 & 0 & 0 & 0 \\ -5.603 & -41.726 & 2.412 & 43.022 \\ 0 & 0 & 0 & 0 \\ 1.223 & -12.45 & 0.809 & 20.519 \\ 0 & 0 & 0 & 0 \\ -3.148 & 49.397 & -2.943 & -1.646 \\ 0 & 0 & 0 & 0 \\ -7.527 & -4.78 & 0.278 & 61.895 \end{bmatrix} \begin{bmatrix} u_1(h) \\ u_2(h) \\ u_3(h) \\ u_4(h) \end{bmatrix} \qquad \text{Eqn 34}$$

$$\begin{bmatrix} y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \\ y_9 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{16} \\ x_{17} \\ x_{18} \\ x_{19} \\ x_{20} \end{bmatrix} + [0] \begin{bmatrix} u_1(h) \\ u_2(h) \\ u_3(h) \\ u_4(h) \end{bmatrix} \qquad \text{Eqn 35}$$

Grain silo system analysis and control design by Matlab

Once the whole storage system of grain silo is represented by four matrix equations, equations 18 and 19 and 34 and 35, Matlab program was used for the whole system analysis and control design.

Model prediction of aerating air specific enthalpy effect on moisture removing

From **Figure 10** it was observed that at as aerating air specific enthalpy increases from 40 to 43kJ/kg at optimum operating conditions, Pressures on vertical direction decreases tremendously to be nearly zero, which means that all moisture trapped before zeroing the load cells are removed as shown by ST. So that as aerating air specific enthalpy be above 43kJ/kg the aeration system can efficiently operate.

System stability analysis

To analysis the stability of the grain storage silo system, step input was used to test system response behavior and the time required to be stable or at steady state conditions for each input (operating parameters) on each output (temperatures and pressures), **Figure 11**. The outputs and inputs are defined at Table 2.

Table2: System inputs and outputs definitions

Input symbol	Input definition	Output symbol	Output definition
In(1)	Aeration pattern	To:out(1)	HL15
In(2)	Aeration turning state of On or Off	To:out(2)	HL40
In(3)	Airflow velocity	To:out(3)	HL95
In(4)	Silo height to diameter ratio	To:out(4)	S1
		To:out(5)	S2
		To:out(6)	S3
		To:out(7)	ST

It was observed that the system response has some delayed time to be stable at the input of aeration system turning state and silo geometrical shape. However the other two inputs behave as a zero order control systems with no time lag.

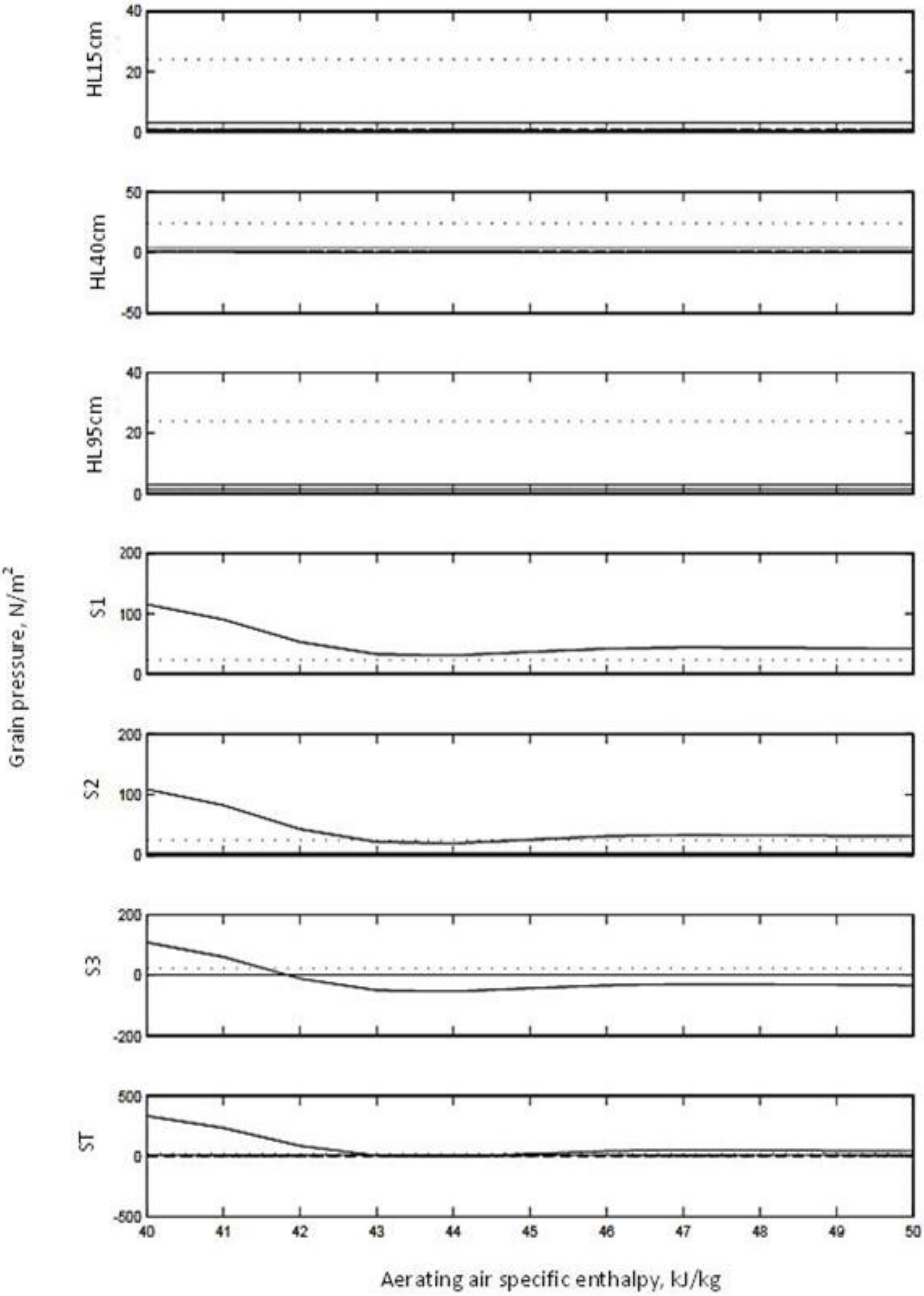

Figure 10. Predicted values of grain silo pressures that aerated by different specific enthalpies of air at AP3, AV24, H/D1.

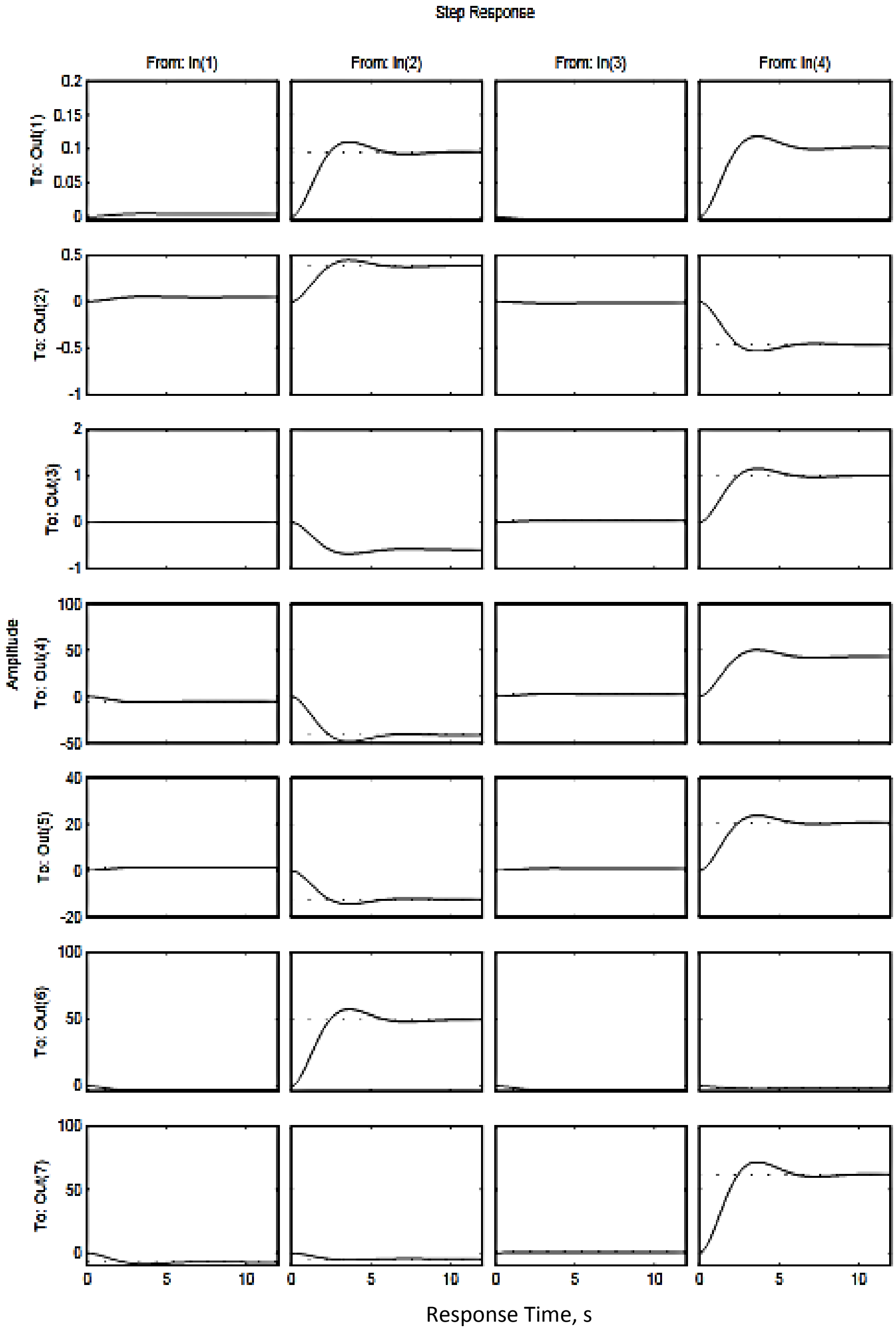

Figure 11. Grain silo system response to the step input of enthalpy at optimum operating parameter specifications of AP3, AV24 and H/D 1.

CONCLUSIONS

Temperature and moisture control methodology for grain storage silo has been presented by investigating different strategies of aeration process and geometrical shapes of silo. Variance, among temperatures measurements and grain's pressures over vertical and horizontal planes, with response surface methodology can efficiently represent the control system performance which aids for each operating parameters ranking. The thermal and mechanical model of the grain storage silo was developed from empirical measurement. The developed model can predict heat and moisture behavior of the grain storage silo with variant ambient aeration system at different specific enthalpies of aerating air. The most important achieved results are as follows:

1. The overall optimum operating parameters were obtained at
    a. Second and third pattern of aeration (AP2 and AP3) that is have an aeration period of 60 and 90 minutes three times daily, respectively.
    b. The aeration should initiate at 10:00AM, 1:00PM and 4:00PM every day.
    c. Airflow velocity of 24m/s and
    d. Height to diameter ratio of one.
2. The developed model predicted the optimum specific enthalpy of aerating air used for controlling moisture and heat will be at the range of 43-50 kJ/kg, which corresponding air temperatures from 20 to 27°C and relative humidity from 41 to 58%.
3. The dynamical system response simulation of grain storage silo shows that the inputs of aeration system turning state and silo geometrical shape has higher interactions than the other two parameters of aeration pattern and airflow velocity.

REFERENCES

Arthur, F.H. and P.W. Flinn. 2000. Aeration management for stored hard red winter wheat: simulated impact on rusty grain beetle (Coleoptera: Cucujidae) populations. Journal of economic entomology, 93(4):1364-72.

Arthur, J.D.; J.D. Cowart, and Dobash, A.A. 2001. Florida aquifer storage and recovery geochemical study: Year three progress report, Florida geological survey open file report, 83,46PP.

Agridry. 2014. http://www.grainsystems.com/products/agridry/

Chang, C. S.; H. H. Converse and J. L. Steele. 1993. Modelling of temperature of grain during storage with aeration. Transactions of the ASAE, 36(2): 509–519.

Chang, C. S.; H. H. Converse and J. L. Steele. 1994. Modelling of moisture content of grain during storage with aeration. Transactions of the ASAE, 37(6): 1891–1898.

Close, D.J. and M.K. Peck. 1986. Experimental determination of the behavior of wet porous beds in which natural convection occurs. Heat and mass transfer, 29: 1531-1541.

Dussadee, N. , T. Punsaensri and T. Kiatsiriroat. 2007. Temperature control of paddy bulk storage with aeration–thermosyphon heat pipe. Energy Conversion and Management, 48: 138–145.

Edde, P. A. 2012. A review of the biology and control of Rhyzopertha dominica (F.) the lesser grain borer. Journal of Stored Products Research, 48: 1-18.

Egypt Today. 2018.

http://www.egypttoday.com/Article/3/49959/Egypt%E2%80%99s-wheat-production-to-increase-4-3-YoY-in-2018 Accessed in May 2019.

EN 1991-4, the European Union per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC, Eurocode1, 2006. Actions on structures - Part 4: Silos and tanks.

GCSS, General Company for Silos and Storage, 2018. http://www.gcss-egypt.com/about.htm, Accessed in May 2019 .

Gough, M.C., C.B.S. Usio and C.J. Stigter .1987. Convection current in bulk grain. Tropical Science, 27: 29-37.

Gough, M.C., C.B.S. Uiso and C.J. Stigter.1990. Air convection currents in metal silos storing maize grain. Tropical Science, 30:217-222.

Iguaz, A.; C. Arroquie; A. Esnoz and P.V. Wrsida. 2004. Modelling and validation of Heat transfer in stored rough rice with aeration. Biosystems Engineering, 89(1): 69-77.

Jayas, D.S. 2012. Storing Grains for Food Security and Sustainability. Agricultural Research, 1:21-24.

Jia .J; D. Sun and C. Cao. 2001. Computer simulation of temperature changes in a wheat storage bin. Journal of Stored Products Research, 37(2):165-177.

Khatchatourian, O.A. and F.A. de Oliveira. 2006. Mathematical modelling of airflow and thermal state in large aerated grain storage. Biosystems Engineering, 95 (2): 159–169.

Lopes,D.C.; J.H. Martins, E.C. Melo and B.C.B. Monteiro. 2006. Aeration simulation of stored grain under variable air ambient conditions. Postharvest Biology and Technology, 42: 115–120.

Lopes, D.C.; J.H. Martins; A.F. L. Filho; E.C. Melo; P.M.B. Monteiro and D.M Queiroz. 2008. Aeration strategy for controlling grain storage based on simulation and on real data acquisition. Computer and Electronics in Agriculture, 63: 140–146.

Lopez, A. 2008. Storage stability of pineapple slices preserved by combined methods. Food Science Technology, 43: 289-295.

Lopez, A.B, J.V. Eck, B.J. Conlin, D. J. Paolillo and J. ONeill Li Li. 2008. Effect of the cauliflower Or transgene on carotenoid accumulation and chromoplast formation in transgenic potato tubers. Journal of Experimental Botany, 59: 213-223.

Metzger, J.F. and W. E. Muir. 1983. Computer model of two-dimensional conduction and forced convocation in stored grain. Agricultural Engineering, 25: 119-125.

Montgomery, D.C. 2003. Design and analysis of experiments. Wiley, New York, NY, USA.

Myers, R.H.; D.C. Montgomery and C.M. Anderson-cook. 2009. Response surface methodology: process product optimization using designed experiments, Wiley, New York, NY, USA, 3rd edition.

Navarro, S. 2012. The use of modified and controlled atmospheres for the disinfestation of stored products. Journal of Pest Science, 81:1-24.

Psychrometrics.2018.http://www.daytonashrae.org/psychrometrics_si.html.

Sinício, R., W.E. Muir and D.S. Jayas. 1997. Sensitivity analysis of a mathematical model to simulate aeration of wheat stored in Brazil. Postharvest Biology and Technology, 11(2):107-122.

Smith, E. A. and S. Sokhansanj. 1990. Moisture transport caused by agricultural convection in grain stores. Journal of Agricultural Engineering Research, 47: 23 - 34.

Thorpe, G.; J.A.O. Tapia and S. Whitaker. 1991. The diffusion of moisture in food grains II: Estimation of the effective diffusivity. J. of Stored Products Research. 27: 11 - 34.

Wilson, J.B.1988. A review of evidence on the control of shoot root ratio in relation to models. Annals of Botany, 61:433-449.

Wllkin, D. R , Armitage, D M., Cogan, P. M. and Thomas, K. P. 1990. Integrated pest control strategy for stored grain. Project Report No. 24, 87pp. Home-Grown Cereals Authority, London, UK.

Yang, Y.; L. T. Wilson; F. H. Arthur; J. Wang and C. Jia. 2017. Regional analysis of bin aeration as an alternative to insecticidal control for post-harvest management of Sitophilus oryzae (L.) and Rhyzopertha dominica (F.). Ecological Modelling 359, 165–181.

Yao Y.; J. Chen; J. Feng and S. Wang. 2019. Modular modeling of air-conditioning system with state-space method and graph theory. International Journal of Refrigeration, 99: 9-23.

الملخص العربي

التحليل الحراري والميكانيكي لصوامع تخزين الحبوب تحت ظروف التهوية الجبرية باستخدام طرق نمذجة متطورة

سعيد الشحات عبدالله [١] ، وائل محمد المسيري [٢] و أسماء السيد شريف [٣]

تعتبر حبة القمح مهمة جدا في تغذية الانسان لأنها مكون رئيسي في كثير من الأطعمة وبالتالي يجب تخزينه بطريقة ملائمة تمنع تلف القمح وجعله متاحاً على مدار العام. أهم طريقة للحفاظ على القمح المخزن هي باستخدام الصوامع نظرا لفوائدها المتعددة. تتمثل أهم مشاكل التخزين في صوامع القمح في تراكم الحرارة والرطوبة ولا توجد أنظمة إنذار مبكر لمعرفة حدوث توليد الحرارة والرطوبة. يتم فحص التغييرات في الضغوط السفلية والجدارية لتكون مؤشرات مناسبة للإنذار المبكر والتهوية المتحكم فيها. التهوية هي أداة شائعة ، تُستخدم لتعديل المناخ الداخلي أو المحلي لمعظم الحبوب.

تم إنشاء نموذج صومعة تحتوي على ثلاث خلايا حمل أفقية وعمودية لجلب بيانات انتقال الحرارة والرطوبة تحت تأثير ثلاث معدلات وأنماط مختلفة من التهوية مع ثلاث ارتفاعات مختلفة من القمح المخزن خلال فصل الشتاء من عام ٢٠١٦. تم توزيع خلايا الحمل العمودي الثلاث لقياس الضغوط القادمة من القطاعات المنشورية الطولية الثلاثة على الطبقة السفلية والتي توفر معلومات حول الانتقال الكتلي بين المستويات الرأسية. ووفقًا للتقنية نفسها ، توفر خلايا الحمل الأفقية بيانات حول الانتقال الكتلي بين المستويات الأفقية. لمراقبة انتقال الحرارة أو الانحدار في درجات الحرارة، تم تثبيت ثلاث مزدوجات حرارية على ارتفاعات متساوية من جدار الصومعة. مؤشرات جودة التخزين هي مقدار الانحدار في درجة الحرارة بين طبقات القمح المختلفة والاختلافات في الأحمال أو الضغوط بين المقاطع الطولية والأفقية ، لكي يتمتع نظام التخزين بكفاءة تخزين أعلى يجب أن يحافظ على الانحدار في درجات حرارة والاختلافات في الأحمال الرأسية والأفقية عند مستويات أقل. في هذا البحث تم تقديم منهجية جديدة للتحكم في درجة الحرارة والرطوبة لصوامع تخزين الحبوب من خلال دراسة الاستراتيجيات المختلفة التي يمكن تطبيقها على عملية التهوية والأشكال الهندسية للصوامع. تم استخدام التباين مع طريقة مسطح الاستجابة للحكم على أداء نظام التحكم والذي يساعد على تصنيف وتقييم كل عوامل التشغيل تحت الدراسة. تم تطوير نموذج رياضي حراري وآخر ميكانيكي لصومعة تخزين الحبوب مستنبط من القياسات التجريبية. يمكن أن يتنبأ النموذج المتطور بسلوك الحرارة والرطوبة في صومعة تخزين الحبوب مع نظام تهوية ذو الهواء المحيطي المتغير الخصائص.

---

١. أستاذ - قسم الهندسة الزراعية - كلية الزراعة - جامعة كفرالشيخ - كفرالشيخ ٣٣٥١٦ - مصر

٢. أستاذ مساعد - قسم الهندسة الزراعية - كلية الزراعة - جامعة كفرالشيخ - كفرالشيخ ٣٣٥١٦ - مصر

٣. طالبة ماجستير - قسم الهندسة الزراعية - كلية الزراعة - جامعة كفرالشيخ - كفرالشيخ ٣٣٥١٦ - مصر

وكانت أهم النتائج المحققة هي كما يلي:

١. تم الحصول على عوامل التشغيل المثلى على وجه العموم من خلال النمط الثاني والثالث للتهوية وسرعات تدفق الهواء ٢٤ م/ث ونسبة الارتفاع إلى القطر واحد.

٢. تنبأ النموذج المتطور بأن المحتوى الحراري النوعي الأمثل لهواء التهوية المستخدم للسيطرة على الرطوبة والحرارة سيكون في حدود ٤٣-٥٠ كيلو جول / كج، وهو ما يقابل درجات حرارة الهواء من ٢٠ إلى ٢٧ درجة مئوية والرطوبة النسبية من ٤١ إلى ٥٨ ٪ .

٣. يوضح محاكاة استجابة النظام الديناميكي لصوامع تخزين الحبوب تأثير المدخلات تحت الدراسة أن مدخلي حالة تشغيل أو ايقاف نظام التهوية والشكل الهندسي للصوامع لها تفاعلات أعلى من العاملين الأخريين لنمط التهوية وسرعة تدفق الهواء.