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OPTIMIZING HEATED AIR CIRCULATION IN SILO/BIN DESIGN: A PARAMETRIC APPROACH

***Okorie, Uche Nelson and Oluka, Sylverster Ike**

Agricultural and Bioresource Engineering, Faculty of Engineering, Enugu State University of Science and Technology, Enugu State

*Corresponding authors' email: uchenelson@yahoo.com

ABSTRACT

Aeration is one of the most essential processes after harvest in guaranteeing food security since it is often employed for grain cooling while the physical qualities of the stored grains are sustained. Aiming to address issues of storage inefficiencies, the research reviewed "Optimization of Heated Air Circulation in Silo/Bin Design: A Parametric Approach." The method adopted for the study was systematic review of journal articles, conference proceedings, books and other relevant materials. Furthermore, the main method used to find relevant publications for the study was keyword searches in electronic databases such as Research Gate, Web of Science, Google Scholar and Scopus. Hence, the study ascertained that at an optimal temperature range between 10 - 15°C, grain storage facilities can effectively mitigate the risks of moisture accumulation, insect infestation, and microbial growth. More so, the study revealed that the rate of airflow ranging from 0.05 to 0.1 $m^3 min^{-1} t^{-1}$ are usually utilized in tall steel bins and concrete silos containing small grains, again measurements ranges from 0.1 to 0.2 meter cubed per minute per tonne were suggested for horizontal storage for huge grains. However, the study suggests that SSR model seems to be the most suitable model for optimization of heated air circulation in silo/bin among all the reviewed models because it is capable of describing nearly all the systems' dynamics.

Keywords: Air, Analysis, Bin, Circulation, Design, Silo

INTRODUCTION

Food grain storage has been seen as a vital element in security of food, particularly in developing countries where a sizable section of the populace makes their living from agriculture. Globally, every year, about twelve to sixteen million mt (metric tons) of grain products spoil as a result of no suitable post-harvest management for them (Singh *et al*., 2017). Post-harvest food loss has an adverse effect on the environment, the economic power of the nation, and society (Bisheko *et al*., 2023). Ali *et al.* (2021) observed that greenhouse gas (GHG) emissions and the waste of natural resources such as water, energy, and land used in crop production are a few environmental implications of post-harvest loss. Again, a good number of countries face several challenges in sustainable food grain management system, resulting in significant losses and food insecurity (Das *et al*., 2023) and Nigeria forms an integral part of such nations. These challenges also lead to financial losses for farmers and traders, exacerbating the issue of food security. According to Lorini (1993), 20% of food grain has been wasted as a result of bad storage buildings and insufficient storage techniques; these losses have a significant global economic and numeric impact (Rezende, 2002). Grain wreckage research is crucial for maintaining productivity and safety in the agricultural industry, considering that damaged grains are not solely deficit for producers/farmers. It also lowers yields including the products' quality (Nurmagambetov *et al*., 2024). More so, Food and Agricultural Organization (2021) observed that the average annual loss of grain was estimated at 11 - 15% of total output, or roughly 27.5 - 37.5 MT of grain. However, it has been proven by several studies that efficient storage of food grains is essential to ensure that they remain edible and nutritious for a long time (Banga *et al*., 2018; Hagstrum, 2017; Guru and Mridula, 2021; Das *et al*., 2023). Unfortunately, sustainable food grain management may be difficult in many developing nations because of low resources (Bhattacharya and Fayezi, 2021), insufficient infrastructure (Gunasekera *et al*., 2017), and other considerations like design of appropriate storage systems. Inappropriate system of storage causes food grain contamination (Sashidhar *et al*., 1992).

It has been noted that farmers benefit from off-season price increases of roughly 10 - 20% of the market price since grain can be stored using contemporary storage structures like silos and bins (Edwards, 2013). The preservation of agricultural products depends greatly on the types of storage facilities and storage management used (Singh *et al*., 2017) however, in different region and states in Nigeria, several inefficient, ancient and local storage methods are adopted in storage of grains resulting into huge losses. It is therefore paramount that a good number and capacity safe and advanced storage structures like silos and bins should be used for storage of grains with increasing food grain production in recent time. In order to feed the world's expanding population, effective and well-designed storage structures are essential for reducing food grain losses and maintaining grain safety during storage by reducing the impact of rodents, microorganisms, and environmental factors (Jakcob *et al*., 2006; Kendall and Pimentel, 1994).

However, the amount of modern practices and advanced storage structures required to store the world's entire surplus of food grains is still insufficient. As a result, a significant portion of the world's annual food grain production roughly 10 - 20% went to waste (Kendall and Pimentel, 1994; Singh and Satapathy, 2003). The creation of effective storage structures that can impede the growth of microorganisms and insect pests while preserving the quality of stored food grains with extended shelf lives is greatly aided by advanced technologies and thorough research. Therefore, in order to prevent grain infestation and store food grains safely for extended periods of time, an enhanced and long-lasting storage structure is paramount (Singh *et al.*, 2017).

Furthermore, in both affluent and developing nations, food security is significantly impacted by storage. This is particularly crucial because the majority of cereals are grown seasonally, and in many regions, there is only one harvest each year, which could be unsuccessful in and of itself (Proctor, 1994). Huge losses occur over the course of harvesting, post-harvest, and storage processes in many developing nations (Aulakh *et al*., 2013; Olayem *et al*., 2010). This can majorly be linked to inadequate post-harvest infrastructure and inferior post-harvest practices (Aulakh *et al*., 2013; Habanyati *et al*., 2022). Variations in supply occur on a global, regional, national, or household level due to seasonal output. The erratic supply stands in stark contrast to the year-round and regional stability of demand. Thus, there is urgent need to design and construct silos and bins for storage of agricultural grains produced in Nigeria and numerous other countries. Again, in order to assist in achieving the goal outlined in SDG 12.3, food losses will be tracked by the Food and Agricultural Organization's index for food loss (FLI). Some researchers investigated on losses at the farmer level in the production of pulses, especially dry beans, which are crucial to the food security of millions of families in underdeveloped nations (Arong *et al*., 2023). Others examined how the quality of grains changed during different storage times, as well as how well the grain mass' active ventilation cooled the grain under varied climate circumstances (Toffolo *et al.*, 2018) but the topic of study has received little or no attention . However, the objective of the study is to conduct a narrative literature review on optimization of heated air circulation in silos/bins design following parametric approach.

MATERIALS AND METHODS

These research questions served as a guide for the investigation:(i) How will a bin's or silo's design be enhanced to guarantee efficient heated air circulation? (ii)What are the importance of silos and bins in storage of grains? (iii)What are the role of air circulation in maintaining the quality of stored materials? (iv) What are temperature optimization-related effects? A narrative literature review methodology was used to attempt and provide answers to the problems raised above. Such reviews typically offer an intellectual overview, justification, and critique in addition to offering a critical perspective on several of the most important stories in the literature, with the goal of assisting readers in developing a more comprehensive knowledge of the background and present state of the subject (Bisheko *et al.*, 2023).

Strategies for Literature Search

The method adopted for the review study was in line with the method proposed by Ferrari (2015). His study suggested a systematic step by step approach of searching the screen and analyzing journal articles and other useful materials that were included in the review. Once more, a methodical keyword search of an electronic database and a screening procedure were carried out to discover pertinent journal articles, books, conference papers, and other helpful materials that are relevant to the topic of study in order to represent a broad, varied, and unbiased collection of articles. More so, several keywords were combined together and even interchanged with each other in order to gather a significant amount of documents (journal articles, conference proceedings, books and others) that are relevant to the topic of study. About ninety four journal articles were obtained from the electronic databases during the search while four books were retrieved. In addition to the journal articles and books retrieved, three conference papers and three published articles relevant to the topic were as well obtained. About 104 articles were obtained during the literature search.

Used databases and keywords for the Study

Specifically, Scopus, Google Scholar, Web of Science, and Research Gate keyword searches were used to find relevant studies that should be included in the study. The selection of the 4 information systems, namely Research Gate, Scopus, Google Scholar and Web of Science was based on their established ability to encompass a broad spectrum of scientific study materials. A review of a few published articles revealed some subject-related phrases to be interchangeable. The study's list of keywords were therefore merged to obtain a sizable quantity of pertinent articles from the internet information systems. In line with the goal of the research, "Optimizing Heated Air Circulation in Silo/Bin Design: A Parametric Approach," eight additional keywords were also deployed in the search process: Efficiency, Grain, Heated, Optimization, Parametric, Storage, System and Temperature. Table 1 displays the list of keywords used to retrieve articles in electronic databases.

Table 1: Databases and keywords utilized

Databases	Keywords
Research Gate, Scopus, Google Scholar and Web of Science.	Air circulation in silos/bins, Parametric analysis of silos/bins, Air temperature optimization in grain storage, Grain storage system, silos/bins desin, Temperature Optimization, Effects of heated air on stored grains, Effective air circulation and Improvement of silos/bins efficiency.

Criteria for Including an Article and Exclusion of an Article

A range of inclusion and exclusion criteria were employed in the selection of pertinent publications for the narrative review as shown in Table 2. Firstly,the evaluation procedure considered journal research publications,books, conference paper and other relevant publications. The second criterion was based on the language of the publication, non English Language published articles were not included because the authors have no knowledge and understanding of such languages. The study considered also year of publication, journal papers and useful publications that were published between 1990 and 2024 were deployed for the study. Thereafter, each paper's title, abstract, and complete text were carefully reviewed, and the study included the relevant aspects of the subject. The third criterion involve the screening process, during the screening, about 41 papers were excluded. Publications that are not research oriented, articles that were not reported in English Language, publications made earlier than 1990 and articles not useful to the subject matter were excluded. Hence, about 63 articles were selected in this stage. The next step or stage was eligibility, in selection of eligible articles, the title and abstract of the 63 articles were carefully reviewed. As a consequence, 30 articles or papers were rejected because they did not capture the key words and as well not relevant to the topic of study while 33 articles were reviewed and adopted for the study.

Table 2: Including and Excluding Criteria (Selection Criteria)

Standards	Requirements	Articles not included
Categories of writing/Literature genres	Published journal articles, books, conference papers and other research articles	Non research articles, publications made in languages that are not English Language, articles published earlier than 1990, and articles not useful to the subject matter.
The language used	English Language	Articles that were not written in English Language
Year of research	Articles publish from 1990 to 2024	If published before 1990
Intervention	Articles focusing on optimization of heated air circulation for silos and bins' design.	If the article is not relevant to the subject matter

Useful articles, journal papers and other materials that were used for the study were selected based on different inclusion and exclusion criteria as given in Table 2. Firstly, the review aspect of the study considered only published journal articles, book related to the study, conference papers and other research articles. The next criterion for inclusion and exclusion was based on the language of the publication. The authors considered research articles published in English Languge alone because that is the language they communicate fluently with. Again, Kitinoja *et al*. (2011) noted that attention on postharvest research increased in 1990s and has increased significantly over the last two decades (Baributsa *et al*., 2014; Moussa *et al*., 2011), hence, the authors included only research articles published between 1990 and 2024. The last criterion was based on consideration of research articles focusing on optimization of heated air circulation for silos and bins' design.Similarly, parameters for analysis were selected and modeled based on the fact that studies have shown that optimization of heated air circulation in silos and bins requires accurate estimation of grain temperature and moisture all through the storage period (Lopez *et al*., 2008). Thus, equation that explains heat and mass transfer in a system was deployed for the model process.

Role of Air Temperature and Air Circulation in Maintaining Stored Grains in Silos and Bins

Indirect storage quality management in silos is achieved by managing moisture and airflow (Abdallah *et al.*, 2019). The aeration system slows down the grains' degradation during storage. A study has shown that it is possible to manage insects with fewer pesticide applications when grains are cooled by air or by an aeration process (Yang *et al*., 2017). Again, since grain absorbs or releases moisture in response to varying environmental conditions, moisture exchange in silos and bins is a crucial management procedure (Abadallah *et al*., 2019).

Moisture movement occurs within the stored bulk due to natural convection currents caused by heat (Smith and Sokhansanj, 1990; Thorpe *et al*., 1991). It is also well known that the induction of air convection currents is mostly dependent on temperature gradients. Mass diffusion is more prevalent on the bulk surface of grains and in the inter-granular space. One of the main mechanisms of moisture transfer is diffusion, which is facilitated by natural convection current. It has also been observed that when the typical air volume is at least 10 m^3/hr, active ventilation has the greatest impact on the grain mass (Toffolo *et al*., 2018).

According to Kechkin *et al*. (2020), altering the thickness of the grain layer can guarantee that the necessary air volume is supplied, as it is not dependent on the equipment and design of the silo or the grain crop that is being kept. Their results demonstrated that with a thinner layer thickness, a bigger volume of air was delivered. Their research also revealed that, as a result of heat produced from the grain mass' deep layers, the temperature outside steel silos dropped while the temperature above the grain rose. Condensate formed in the upper section of the silo as a result of the grain's moisture being expelled along with the heat. With regard to the pressure drop over the silo height in this instance, natural ventilation of the grain mass occurs at low air speeds; therefore, optimized hot air circulation within the silos is necessary for increased efficiency. Again, studies have shown that when storing grains in metal silos, condensate accumulates on the grain mass' surface and then in the upper layer's depth (about 70 mm), which lowers the grain's resistance during storage (Kechkin *et al*., 2020). In this kind of circumstances, ventilation of the area beneath the roof and above the grain is necessary to ensure grain safety. Large capacity metal silos, according to Bonner and Alavanja (2017), produce the worst storage conditions in the upper section of the grain embankment. This is as a result of the storage system's insufficient air circulation and temperature. Similarly, the findings of the research on the quality of wheat kept in huge, 15.2 m-diameter metal silos supported the necessity of grain cooling. According to the study, wheat may be stored for up to a year at 10 °C and 11 - 15% humidity without losing any of its quality markers (Kechkin *et al*., 2021). Again, at temperature of 20°C it can be stored without compromising the quality for twelve months only with a moisture content not more than 12% (Oates *et al*., 2017). On the other hand, grain with a moisture content of 13 - 14% exhibited certain signs of deterioration after three months of storage (such as sowing characteristics, a drop in dehydrogenase activity, and an increase in the acid number off), and after nine months, the respiration rate increased by about two-fold. Grain storage without deterioration at 30 °C was noted for two months, with a maximum moisture level of 13%. In the first month of storage, quality degradation began at 13 to 14% humidity. According to Oates *et al*. (2017), their investigation revealed that after three months, the quality indicators had substantially declined, including the natural mass, germination energy, and germination rate. Their findings thus showed that the storage system's air circulation and temperature were not kept at an appropriate level. Berezina and Vlasenko (2020) found that as humidity increased, the amount of time needed for the product to be stored for quality was shortened. Hassan et al. (2023) noted also that in high ambient temperatures of the tropics that fresh fish can spoil within twelve hours. Therefore, it is crucial to develop a temperature mode that complies with the legal specifications for different kinds of cereal or legume storage. Ordinarily,ventilation systems assist in resolving the humidity issue by preserving the essential grain properties (temperature and humidity). Determining the methods of periodic layer blowing is the goal of appropriate storage organization in order to avoid moisture condensation and spontaneous grain combustion that could occur on the inside surfaces of the walls and silo roof (Lawrence *et al*., 2012). Investigation on how long it takes for the layer to cool to room temperature depending on the air velocity and starting temperature has been carried out. Thus, the study revealed that, air velocity had the biggest impact on how long cooling lasted (Berezina and Vlasenko, 2020). Additionally, their research showed that in metal silos, an increase in air velocity from 0.5 m/s to 0.1 m/s speeds the layer cooling by 92%. They further stated that compared to cooling at a speed of 0.5 m/s, cooling occurred 2.6 times faster at a subsequent speed increase to 2 m/s.

Silos/ Bin Design for Effective Storage of Grains

Grain silos are essential buildings/structures made specifically to store grain crops effectively. These structures are important because they offer the best conditions for maintaining grain quality throughout storage. According to Petre and Popa (2020), a typical silo has the following components: a circular concrete distribution system, floor support, air outlet, grain intake, silo top, walls, fan, air duct, and perforated floor. When it comes to grain quality, it is critical to maintain proper grain conditions as well as create safe, functional storage and handling facilities that guarantee dependable, effective operations (Roberts, 1994).

Bucklin *et al*. (2019) placed some parameters as priority in design of grain storage system. They noted that agricultural materials are bulk materials that flow freely and that structural design typically does not account for grain cohesion. Their research went on to say that when grains are handled or stored incorrectly, especially when there is a lot of moisture present and mold grows, the grains may become cohesive. Grain bins and hoppers are typically not made to handle cohesive materials, so in order to keep grain in a free-flowing state, a well planned and run grain handling system will be required. Once more, research has shown that aeration chilling and aeration drying are the two sorts of operations that the systems designed for aeration of grains are intended to accomplish. Small airflow rates of two to three liters per second per tone can be used to accomplish aeration cooling. Fans that deliver 15 to 25 L/s/t can be used to achieve aeration drying (Gaceu and Apostol 2019). In order to maintain heat balances inside the grain storage system, Hammami *et al.* (2016) established a mathematical model based on mass and heat balances in their study, "Modelling and simulation of heat exchange and moisture content in a cereal storage silo." The equations governing heat and mass transfer (equations of mass and energy conservation) were adopted for the study. However, the mathematical models for the enthalpy of air balance within the storage or control system came to light. These equations were obtained by the thermodynamic laws (Mabrouk, 1999; Mabrouk *et al*., 2006; Welty *et al*., 2008). Thus, the equation is stated as {Δ internal energy of the air inside the silo} = {Enthalpy flow of the air entering into the silo} − {Enthalpy flow of the air leaving the silo} − {Heat exchange by convection between the air and the layer of grain} − {convective heat flow between the air and the silo wall}. However, it can be stated mathematically as given in equation 1.

$$\rho_a v_a c_a \frac{dTa}{dt} = m_a c_a (T_{ai} - T_a) - h_{cag} A_g (T_a - T_g) - h_{ca,w} A_w (T_a - T_w) \quad (1)$$

In accordance with Hammami *et al*. (2016), ρa, density is constant (kgm^{-3}) in equation 1, where Va is the silo's volume measured in meter cubed, Ca is the air's specific heat measured in J kg^{-1} ^{o}C^{-1}, Ta and Tai are the interstitial and entering (ventilated) air temperatures in ^{o}C, ma is the air mass flow rate in kgs^{-}1, Tg and Tw are the wall and grain temperatures in ^{o}C, and Ag and Aw are the corresponding areas (m^2) of the grain and wall layer. Furthermore, equation 2 expresses the convective heat transfer coefficient (hca,g) between the grain layer and the air inside the silo (Welty *et al.*, 2008).

$$h_{cag} = Nu \frac{\lambda a}{D} \quad (2)$$

The Nusselt number (Nu), which provides information about the nature of flow is computed using the Reynolds number, Re. D, the characteristic diameter of the control volume was measured in meters, while λa (the air's thermal conductivity) was measured in W m^{-1} ^{o}C^{-1}. Additionally, Welty *et al.* (2008) proposed that equation 3 can be used to calculate the convective heat transfer coefficient between the air within the silo and the silo wall.

$$h_{ca,w} = Nu \frac{\lambda a}{D} \quad (3)$$

Reynold's Number which are known to be dimensionless number that are used to determine the the state of flow in a system can be determined using equation 4.

$$Re = \frac{U_a D}{V} \quad (4)$$

Where equation 5 can be used to determine the Nusselt number, Nu, where ua is the air velocity (m.s^{-1}) and υ is the kinematic viscosity of air (m^2.s^{-1}). (Welty *et al.*, 2008; Xu and Burfoot, 1999) u_a is the air velocity (m.s^{-1}), υ is the kinematic viscosity of air (m^2.s^{-1}) while Nu, the Nusselt number can be obtained using equation 5 (Welty *et al*., 2008; Xu and Burfoot 1999).

$$Nu = 0.023 Re^{0.8} pr^{0.4} \quad (5)$$

Where the Prandtl number (Pr) of air is = 0.7.

According to Hammami *et al.* (2016), during extended storage, ambient relative humidity variations and seasonal weather temperature have the greatest effects on grain temperatures close to the silo walls. The capillary tube system of their method allows cold water to flow through a double-walled silo that has a capillary ex-changer built around the interior wall. As a result, maintaining the targeted wall temperature and grain temperature at a safe level was achieved. A cylindrical grain storage silo with a humidifier is shown in Fig. 1. The humidifier recycles moist air at the system's exit, lowering the moisture content of the grain and maintaining a safe humidity level and appropriate temperature throughout. The dehumidifier's outlet blows dry air into the silo through a ventilation system.

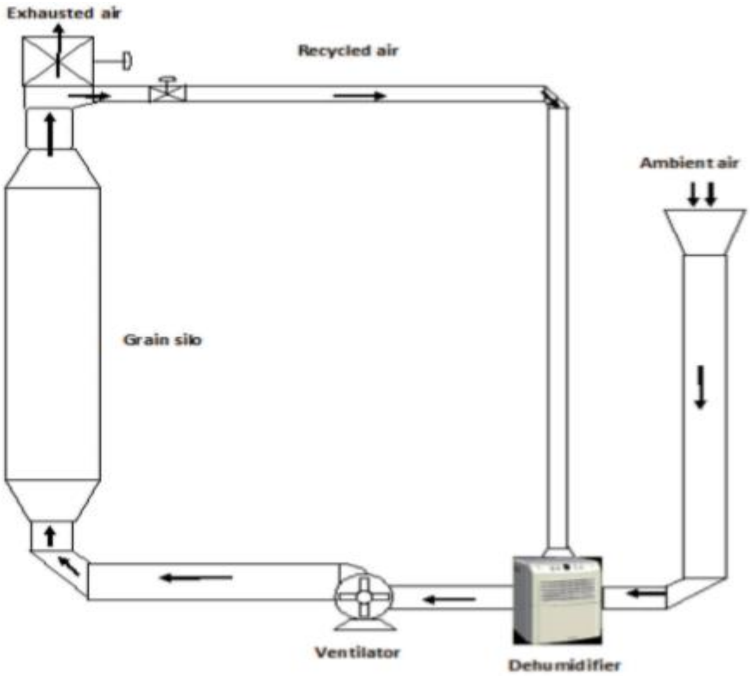

Figure 1: Design of a Cylindrical Storage System for Grains Having a Forced Ventilation System and Dehumidifier for Temperature Optimization
Source: Hammami *et al*. (2016)

Again, Berezina and Vlasenko (2020) in their study, developed a model for solving the problem associated with internal heat and moisture exchange in metal silos during grain storage in a dense bed. Their model contains linear differential equations of the 1st order with two variables (τ, the grain cooling time and z, the height of the granary refilling) that are independent to each other. Numerical Euler method was used in resolving the problems while Matlab Simulink software was utilized for the simulation work. Their model allows the determination of parameters of the kinetics of heat and mass transfer of thermal moisture treatment for grain mass. These parameters influenced the choice of the air parameters with active ventilation. Their model was capable of predicting the air temperature at the exit of the grain layer as well as the grain temperature after cooling. The effects of the different factors, air velocity, initial air temperature and the granary refilling height on the layer warm up time was described as given in Fig. 2. The system was designed based on thermal and mass balance for air and for grain in an elementary grain layer of height dz.

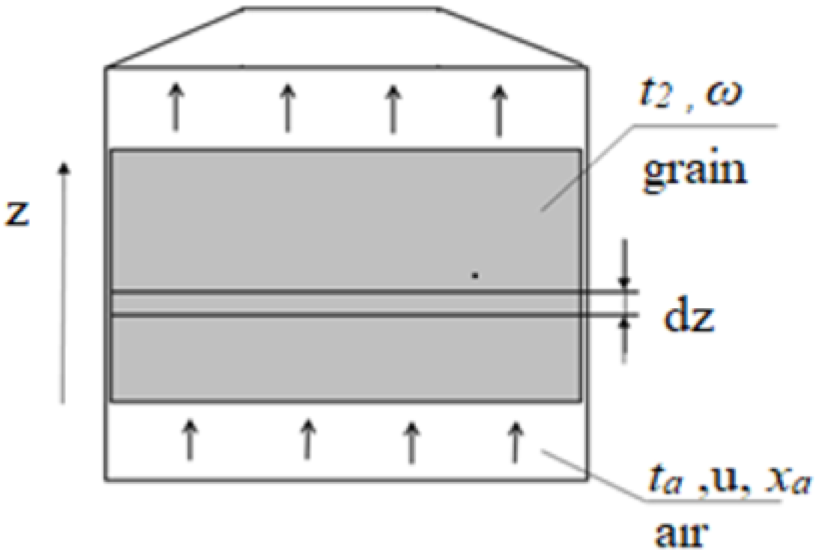

Figure 2: Design for Modeling of Active Ventilation in Silos for Grain Storage
Source: Berezina and Vlasenko (2020)

The dz (elementary grain layer), z (silo height), ta (temperature of the air), $t_2 = \theta(\tau)$ (the temperature of the grain), the absolute grain humidity (ω), the absolute air humidity (xa), and the air velocity (u) are all represented in the system (Fig. 2). Their study's findings showed that as ventilation occurs, grain temperature gradually drops to that of the cold air that is brought in from the outside during the first layer's formation. Furthermore, because of air saturation in the lowest layers of the grain mass, higher layers cool more slowly. Due to the fact that moisture moved from the hotter higher regions to the cooler lower regions, the total moisture content of the grain layers dropped. Consequently, the cooler the air temperature, the more dry the grains become and subsequently the more severe the mass transfer that occurs between airflow and the grain will become. According to Rao (2013), the finite element model (FEM) has been effectively investigated as a means of adequately expressing boundary irregularities in engineering problems linked to heat conduction. Equation 6, which was presented for the transient heat transmission within the bulk grain storage silo is a three-dimensional partial differential (PD) equation developed by Alagusundaram *et al*. (1990) in a cartesian coordinate system. Simulation study similar to that of 3 dimensional partial differential equation was carried out for non aerated grain bulks (Jayas *et al.*, 1994).

$$\delta(K_x \frac{\delta T}{\delta x}) + \delta(K_y \frac{\delta T/\delta y}{\delta y}) + \delta(K_z \frac{\delta T/\delta z}{\delta z} + q = \rho c \frac{\delta T}{\delta t} \quad (6)$$

Both studies included boundary conditions for convection and radiation heat transfer components that took into account the impacts of the storage structure's head space and bin wall, correspondingly. Due to the existence of a function (Rao, 2013) that was minimized over each finite element (linear and quadratic) in the domain to produce a general matrix equation, the PD equations were solved using a variation method. Therefore, the thermal conductivity of the grain in the x coordinate is Kx; in the y coordinate is Ky; while in the z coordinate is Kz. Grain temperature is T, grain density is ρ, grain specific heat is c, duration is t, and internal heat generation in the element is q. Hence, the Nusselt number was found using equation 7.

$$Nu = 0.227(Re^{0.633}) \quad (7)$$

In equation 7, Re stands for Reynold's number, while Nusselt's number was represented by Nu. Nevertheless, the model failed to give details for the natural convection inside the grain bulk with latent heat exchange, internal heat of respiration and presumed stable thermal characteristics of the grain. Thus, impacting significantly the predicted temperatures when validated using varying diameter (constant) to height (varied) ratios of canola and barley storage (Subrot *et al.*, 2019). Once again, Jia *et al.* (2000) provided a model that simulated temperature variations brought on by internal heat generation and the convection mechanism of transfer of heat. Accounting for the transfer of heat caused by the generated heat flux on the walls of the bin as well as the heat between the top surface of the grain and the bin roof, a 2 D equation in a cylindrical coordinate system was presented as given in equation 8.

$$k(\frac{\delta^2 T}{\delta z^2} + \frac{1}{r}\frac{\delta T}{\delta r} + \frac{\delta^2 T}{\delta r^2}) + q = \rho c \frac{\delta T}{\delta t} \quad (8)$$

In equation 8, the grain's temperature was represented by T, its thermal conductivity was represented by k while r and z represent the radial and vertical distances in the cylindrical coordinate respectively. More so, the variables q, ρ, c, and t represent internal heat generation, grain density, specific heat, and time, respectively, in an element. However, it was supposed that the bottom surface was adiabatic. For the purpose of producing heat during their investigation, a 0.5kW/220 V electric heater covered in wire mesh was placed in the middle of the bin. The nonlinear equation with complicated boundary condition and all necessary parameters was solved using the FEM. Due to the wheat's low thermal conductivity, the study indicated that there was a high likelihood of grain deterioration close to the internal heat source, regardless of location. Consequently, the temperature around the grain storage system's center needs to be optimized. According to their analysis, during the first stage of the validations, the measured temperature and the projected ones agreed well.

Discrete element modeling (DEM) has been studied further and developed to represent non-spherical particles and to present inter-particle contacts and actual pores between them, thereby improving the particle handling capability of the FEM (Horabik and Molenda, 2016). The particulate system was simulated using discrete element modeling as a vast assemblage of a finite number of discrete solids interacting through contact forces in accordance with physical rules. According to Mostofinejad and Reisi (2012), DEM takes into account every force that a particle experiences as a function of boundary conditions, gravity, and inter-particle interactions. Depending on the kinds of configurations, these forces were measured using contact models whose mathematical formulations include one or more of the following laws: the rolling movement law, the normal contact force-displacement law, and the tangent contact force-displacement law (Markauskas *et al.*, 2015). Fig. 3 shows DEM's explanation of the phenomenon involving heat transfer in a bulk storage system.

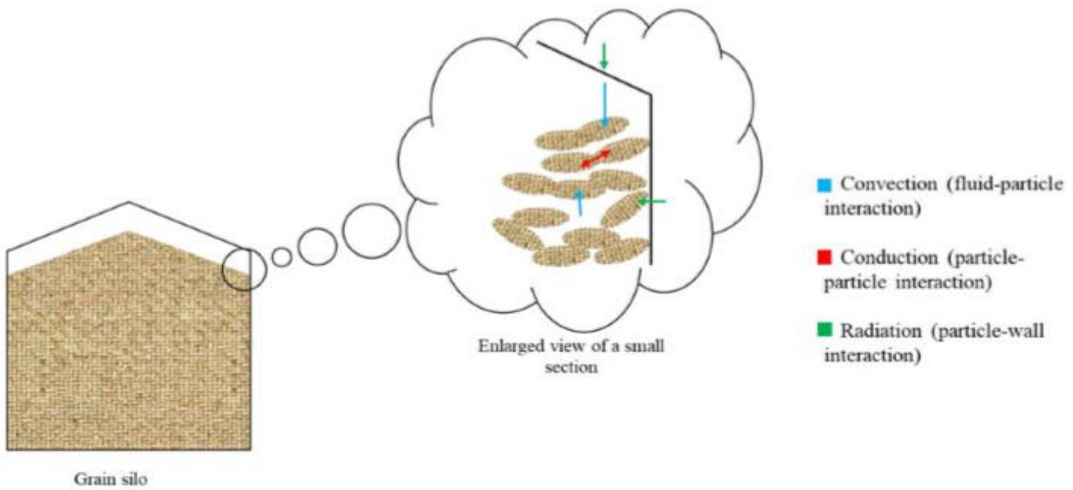

Figure 3: Schematic Representation of the Phenomenon Involving the Transfer of Heat and Mass in a Bin/Silo
Source: Subrot *et al*. (2019)

Airflow Rate Optimization

Technology, machinery, and storage systems must be continuously developed and improved in order to support modern agricultural and grain processing. Airflow optimization of bins and silos is one of the key elements of this technique. One key technique for developing the best controlled aeration for suppressing the growth of microorganisms in stored wheat was stimulation modeling utilizing verified meteorological data (Arthur and Flinn, 2000). In order to forecast the temperature of paddy bed in the silo using hybrid aeration-thermo syphon, Dussadee *et al.* (2007) developed a mathematical model. The developed simulation can be used by the model to determine the blower's periods. For silos and bins airflow rate optimization, Response Surface Methodology (RSM), a collection of mathematical and statistical techniques, is helpful for fitting the models and evaluating the issues in which quite a few independent variables control the dependent parameter(s) (Montgomery, 2003; Myers *et al*., 2009). The correlating parameters are used to suit the empirical mathematical model for any performance characteristic. In addition to identifying ideal conditions, this procedure provides the data required for establishing a process (Abdallah *et al.*, 2019). The uniform platform known as State Space Representation (SSR) can be used to represent time-varying, time-invariant, linear, and nonlinear systems. Since SSR is capable of describing nearly all systems' dynamics including biological, electrical and mechanical systems, it can be applied for optimization of airflow rate in bins and silos. In terms of MIMO (Multiple Input Multiple Output) systems, SSR is a useful tool. Yao *et al.* (2019) validated the dynamic system model using transient response experiments and employed SSR to increase the modeling efficiency of heating, ventilation, and air conditioning. Furthermore, the on-line psychrometric chart software, Psychrometrics (2018) is very important in determination of the specific enthalpy of aerating air in conformity with the consideration of 10.2 m altitude, relative humidity and dry bulb temperature. Furthermore, Binelol *et al*. (2019), noted that an effective aeration system can be achieved with the use of mathematical models and software designed to predict the dispersion of 3D airflow in horizontal bulk storage bins during the aeration process under non-homogeneous and anisotropic conditions. The study's recommendation for an improved aeration inlet air pressure profile aimed to improve the local specific flow distribution's consistency. According to their proposal, the airflow variance could be reduced by 85.3% using a theoretical air inlet profile; however, the maximum intake pressure of the air at the center of the storage bin would need to be increased by 150%.

Hence, this could serve as a guide for designing new aeration system (Binelo *et al*., 2019), in order to optimize airflow rate in silos and bins. Again, the kind of storage container/unit, depth of grain, and type of grain are the main determinants of the specific airflow rate in an aeration system. Airflow rates ranging from 0.05 to 0.1 $m^3 min^{-1} t^{-1}$ are commonly employed in tall steel bins and concrete silos used for the storage of tiny grains in temperate regions. Airflow rates between 0.1 and 0.2 $m^3 min^{-1} t^{-1}$ are advised for huge grains and horizontal storage (Navarro *et al*., 2020). A study revealed that airflow rates ranging from 0.03 to 0.05 $m^3 min^{-1} t^{-1}$ may be necessary when grain depth surpasses 30 m, leading to potentially excessive power requirements. In particular, airflow rates between 0.2 and 0.25 $m^3 min^{-1} t^{-1}$ should be taken into account in areas with limited cooling time (Newman, 1996). It is crucial to note that while fan power increases by a factor of more than four, the needed static pressure increases by a factor of three when the airflow rate is doubled (Navarro and Noyes, 2001).

Temperature Optimization

Grains are a great thermal insulator and may retain heat without aeration for a very long time, according to Gaceu and Apostol (2019). However, metabolism continues for a considerable amount of time during storage, and temperature and air humidity interactions are important (Gastón *et al*., 2009). At temperature lower than 15 ^oC, storage temperatures can prevent the development of insects (Arthur and Casada 2010; Akdogan and Cascada, 2006). Accordingly, one of the most crucial thermodynamic factors in storage that affects the quality of stored grains and their market value is temperature (Wang *et al*., 2010). In a study,"Modeling and simulation of heat exchange and moisture content in a cereal storage silo," Hammami *et al*. (2016) observed that a rise in air temperature defines the interstitial air's evaporative power, which shortens the rise time. During the summer, when the outside temperature fluctuates between 30 ^oC and 40 ^oC, the temperature of the grain changed in lockstep with the changes in the outside temperature. However, the temperature of the wall will increase once more, reaching a range of 40 °C to 50 °C. Thus, the center of the silo and the vicinity of the walls will be the grain's high-temperature accumulation areas during the summer. Their research however indicated that the grain temperature varies and that the 40 ^oC peak is followed by a slow decline. After five hours, the grain temperature dropped to almost the vented air's temperature before reaching its peak at a steady 25 °C (Hammami *et al*., 2016). Therefore, it is crucial to remember that grains farther from the air intake area cooled more slowly than grains closer to the air inlet location. Hence, the simulation results at various baseline grain temperatures showed that the grain temperature has significantly improved. More so,the study's findings were consistent with those of other studies since air temperature affects how grain moisture content varies (Wang *et al.*, 2010; Aregba *et al*., 2005; Corrêa *et al*., 2011). It is advised to equip the interior of the grain mass by the temperature monitoring system with an alarm or a device that automatically turns on fans when the temperature rises above 7 °C for two to three days with two or more sensors in order to prevent the development of the grain self-heating process (Stankevych *et al.*, 2018). Consequently, the storage system's temperature will be optimized. Ensuring safe active ventilation of grain in steel silos, the silo's exterior temperature must be at least 5 °C lower than the grain's temperature (Kechkin *et al*., 2020). Three temperature ranges are important for the development or mortality of insects found in stored goods. The fastest rate of growth for insects occurs between 25 and 32 °C. Development slows down at sub-optimal temperatures (13 to 24 °C and 33 to 35 °C), and insects cease feeding and develop more slowly and eventually die at life-threatening temperatures (below 13 °C and above 36 °C). According to David *et al*. (2012), they perish more quickly in temperatures that are too high.

A study has shown also that a three dimensional (3D) FDM model is capable of forecasting the temperature distribution caused by conduction within a bin holding rapeseed (Alagusundaram *et al.*, 1990). According to their study, the finite element approach was used to solve a three-dimensional heat conduction issue in a Cartesian Coordinate System in order to estimate the temperature distribution in grain storage bins. The model can replicate the temperature inside any shape of bin filled with grains at any given location.The result of their study showed that three dimensional finite-difference and three dimemsional finite-element models' predictions of temperatures compared favorably with one another. The temperature predictions made by three dimensional finite element model for both south and north part of the storage structure were found to differ significantly. When creating the optimal management plan to reduce spoilage risks related to grain temperature and moisture content, modeling the stored-grain ecosystem becomes an essential component of the grain industry (Subrot *et al*., 2020). Therefore, a simple and affordable way of predicting shifts in physical characteristics to evaluate the risk of spoilage and optimize the abiotic factors crucial for grain storage is to use adequate model for predicting transfer of momentum, heat and mass within the grain bulk.

Table 3: Summary of Some Models Adopted for the Study

Model	Objective	Limitation	Strenght and Remark
Modelling and simulation of heat exchange in a cereal storage silo (Hammami *et al*. 2016).	Development of a simulation model for prediction of grain temperature and moisture content in a wheat storage silo based on temperature and moisture dynamic balances. Again to validate their model against experimental data and to verify the effect of the humidifier on grain moisture content.	The model was adopted for different conditions of grains stored in silo without aeration only.	The model is able to propose the interaction of temperature and moisture content in the grain mass at critical storage conditions boundaries. The model can predict the evolution of temperature and moisture content of grains stored in critical condition. However, it is anticipated that the model may not function efficiently when used in aerated or ventilated silo/bin.
Modeling Grain Active Ventilation Process in the Silos (Berezina and Vlasenko, 2020).	Solving the problem of moisture exchange and internal heat modeling in metal silos when storing grain in a dense bed.	The study was for only non-stationary changes in temperature and moisture content of grain in a one-dimensional grain layer along with the height of a metal silo.	The model is capable of substantiating the safe grain storage modes in conditions of heterogeneity and temporal variations of standard parameters such as temperature and air humidity. Hence, it may not be applied for grain with stationary changes in temperature and moisture content having more than one dimensional grain layer in metal silo.
Finite Element Model (FEM), 3D	Prediction of temperature distribution in large storage bins.	Most FEM assume that silos walls are rigid, the assumption can only work for concrete silos. Another limitation is that it does not account for natural heat convection inside the grain bulk with latent heat exchange.	FEM can successfully be used when carrying out analysis related to heat conduction and and associated engineering problems linked to irregular boundaries (Rao,2013). However, error value of estimation are usually greater for linear elements rather than for quadratic elements. Again, it works well for concrete silos and not metal silos. The flexibility of metal silos lead to clear discrepancies in the predicted and actual performance of the silo.
Discrete Element Modeling (DEM) 3D	Prediction of self-heating phenomenon within a 2500kg capacity bin.	DEM assumes that it is only conduction heat transfer that occurs during the simulation. Therefore, other heat transfers methods in the system is not considered and accounted for.	DEM's predicted results are usually in agreement with the actual or measured values (Rusinek;Kobylka, 2014). DEM also takes into account every force that a particle experiences as a function of boundary conditions, gravity, and inter-particle interactions. However, DEM cannot be used to account for other heat transfers occurring in a system.

CONCLUSION

Studies have revealed that appropriate control and optimization of air temperature in grain storage silos and bins is a critical factor in ensuring the long-term preservation and quality of stored grains. Numerous academic studies have also demonstrated very important impact that air temperature plays in controlling the growth and metabolic processes of microorganisms, as well as the potential physical and chemical changes that might take place within the grain. In practical terms, the implementation of advanced air temperature control systems in grain silos and bins has been shown to have a profound impact on preserving the overall integrity and marketability of the stored grains. Maintaining the optimal temperature range typically between 10 - 15°C, grain storage facilities can effectively mitigate the risks of moisture accumulation, insect infestation, and microbial growth, all of which can significantly compromise the grain's end-use value. More so, the study revealed that most of the models adopted worked for a specific condition. When such models are adopted for different condition or silos and bins made with different materials there maybe variations in results obtained (Subrot *et al*., 2020).

RECOMMENDATION

It is recommended that utilization of airflow stimulation tools should be encouraged for optimization of the inlet pressure profile and airflow distribution within silos/bins.

It is also recommended that fludizers and airflow pads should be strategically installed along silos/bins' walls.

Use of materials that improves thermal efficiency and structural integrity should be encouraged

Aeration systems and temperature sensors of silos/bins should be regularly checked and maintained.

Training of operators, stakeholders and policy makers on the importance of proper silos/bins design, aeration techniques and monitoring technologies is very essential and highly recommended.

Lastly, further research is encouraged in modeling and design of silos and bins that combines different conditions such adiabatic and diabatic conditions. Again, designs and models involving both linear elements and quadratic elements can as well be studied.

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