CAF2020 Paper No. P-2-3-16

Panigrahi SS, Singh CB, Fielke JM (2021) Integrated CFD-based on-farm stored grain aeration model to predict the fan hours and investigate factors affecting the cooling potential. Pp. 54-61. In: Jayas DS, Jian F (eds) Proceedings of the 11th International Conference on Controlled Atmosphere and Fumigation in Stored Products (CAF2020), CAF Permanent Committee Secretariat, Winnipeg, Canada.

Integrated CFD-based on-farm stored grain aeration model to predict the fan hours and investigate factors affecting the cooling potential

Shubham S Panigrahi[1], Chandra B Singh[2*], John M Fielke[1]

[1]School of Engineering, University of South Australia, Mawson Lakes, Adelaide, SA 5095, Australia.
[2]Agricultural Engineering and Technology, Lethbridge College, Lethbridge, AB, Canada.
*Corresponding author's email: chandra.singh@lethbridgecollege.ca

Abstract

Physical velocity-based finite volume method was used to model the aeration cooling and re-wetting process in an on-farm silo (13.47 m high and 12.8 m diameter) filled with 1,000 tonnes of barley in Balaklava, South Australia. The 3-D transient model was validated with grain temperature (°C) and moisture content (% wb) data obtained from OPI Blue sensors (2018-19 storage season). Due to the Mediterranean climate, the initial grain conditions varied between 21.7-32°C temperature and 9.9-12.4% wet basis (wb) moisture content (mc). Thus, initial grain condition was sub-divided into 36 different sections (using User-Defined Functions) based on the number of cable sensors that eventually contributed to the accurate sorption (adsorption and desorption) process upon transient simulation. Heat of wetting (a primary component of heat of sorption), was added into the model to calculate the heat that would be released when water gets adsorbed into the grain capillaries. A grain domain mesh independency test and an appropriate time-step size analysis were conducted for solution optimization. The effect of solution methods such as pressure-velocity coupling schemes, spatial discretization schemes, and transient formulation schemes were investigated on the heat and moisture transfer in the stored grain ecosystem. The standard error of prediction (SEP) and percent mean relative deviation (MRD) for prediction of grain temperature and moisture content were 1.39°C and 0.15% wb; and 5.1% and 1.2%, respectively for the grain bulk which represents reasonable accuracy for the consideration of further facility optimization purposes. Heat of wetting showed a decreasing profile (magnitude wise) at a validated data point due to an increase in moisture value. ANSYS Fluent macros (DEFINE_EXECUTE_AT_END and DEFINE_PROFILE) were incorporated to formulate an air inlet control system, taking into consideration grain temperature and moisture from a certain height (inside grain bulk), that could work as a fan control for any allotted strategies.

Keywords: Physical velocity, Finite volume method, Aeration, Cooling and re-wetting, Heat of sorption, Fluent Macros, Inlet control

Introduction

Grain storage has undergone a major shift from bulk handlers to on-farm facilities in the past decade in Australia (GRDC, 2017). Farmers are keen on investing in their own storages for gaining higher return values, rather than directly selling to the bulk handlers. This has led stored-grain industries to expand the field of focus from a single type of storage unit to diverse structural facilities that can accommodate the increasing harvest in any given season.

Stored grain must be maintained at optimum conditions (defined by the grain temperature and moisture content) throughout the storage period in order to obtain a higher return value. This requisite is most-often achieved through implementing a common but crucial, non-chemical technique called aeration. Tropical and Subtropical regions prefer aeration (natural air) drying, while Temperate and Mediterranean regions prefer grain cooling to mitigate the insect habitat as quickly as possible via controlled moisture content (12-14% wb depending on grain type) (Panigrahi et al., 2019).

Although aeration remains the preferred technique over other chemical-based solutions, its efficiency is highly dependent on the ambient conditions. Knowing how the grain ecosystem is affected by any of these differences would assist in making more strategic use of any of the given prevailing conditions. To better understand and make management decisions, stored grain researchers have developed numerical models that have shown the intrinsic factors contributing to variations in grain temperature and moisture content during the aeration process. Different methods of modeling such as finite element (FE), finite volume (FV), and finite difference (FD) have been widely used for this purpose (Lawrence et al., 2013; Thorpe, 2008, 1997). However, the model's application directly depends on its level of accuracy. Accuracy level is further influenced by the method undertaken for modeling specific management processes. Panigrahi et al. (2019) have shown that the finite volume method (FVM) provides the best prediction during the aeration process. Ranjbaran et al. (2014) and Liu et al. (2016) have simulated drying and aeration cooling for paddy using FVM based Computational Fluid Dynamics (CFD) tool. Though they predicted outcomes with reasonable accuracy, the model was limited to the heat of vaporization that contributes to only the phase change process. However, in a large-scale storage silo, because of uneven initial grain conditions both adsorption and desorption take place during aeration cooling. Thus, there is a need to include the associated factors contributing to the above phenomena.

Model development is the first phase for creating a foundation for better management decisions other than relying on past experiences. As aeration efficiency depends on the strategic use of the local weather conditions, there is also a need to implement control measures to the model so that it can work as an integrated system for the desired aim. Lawrence and Maier (2011) used the 'if' logical scheme in Microsoft Excel to identify the desired ambient conditions and then used this information as an inlet to the developed 2D PHAST-FEM model. This was limited to the initial grain conditions and did not consider the changing grain condition during the aeration process. Thus, there is a need to integrate an automatic inlet control system to make the simulation more sophisticated and operate based on both changing grain and ambient conditions. Considering all the above issues, the study aimed to cool the grain more efficiently based on modelling approaches.

The objectives were as follows: a) to develop a 3D transient FVM model to predict grain temperature and moisture content during aeration cooling in a 1,000-t silo; and b) to develop and integrate an automatic inlet control system based on the changing grain conditions.

Materials and methods

On-farm storage silo

The on-farm grain storage structure was a flat-bottomed corrugated steel silo located at Balaklava, South Australia, Australia (34° 7' 26.22" S, 138° 27' 41.58" E) (Fig. 1). The silo was 12.8 m in diameter and 13.47 m high with an eave height of 10.06 m (Cyclone Model 4233CA, Newcastle, Australia). The silo floor had a V-shaped in-floor aeration duct of 10.4 m length and 0.9 m width. The grain had a peak height and diameter of 12.41 m and 12.8 m, respectively; with an angle of repose of 21^{o} and eave height of 9.91 m. The silo was filled with barley.

The silo was equipped with one OPI Blue moisture sensing cable (M1/T1) having 10 RH and temperature sensors (near the central lid of the silo) and three temperature sensing cables (T2, T3 and T4) having 9 temperature sensors. Cable T2 was near the vents, and the other two were at the south (T3) and west (T4) corners (2 m in from the silo wall). The OPI system used registered equilibrium moisture content (EMC) curves to determine moisture content of the grain. Aeration cooling was operated for 24 h whenever the ambient temperature was lower than the grain temperature (lower bulk). A volumetric flow rate of 0.954 m^3/s and back pressure of 663 Pa was observed in the transition duct of a 3kW aeration fan during the aeration period.

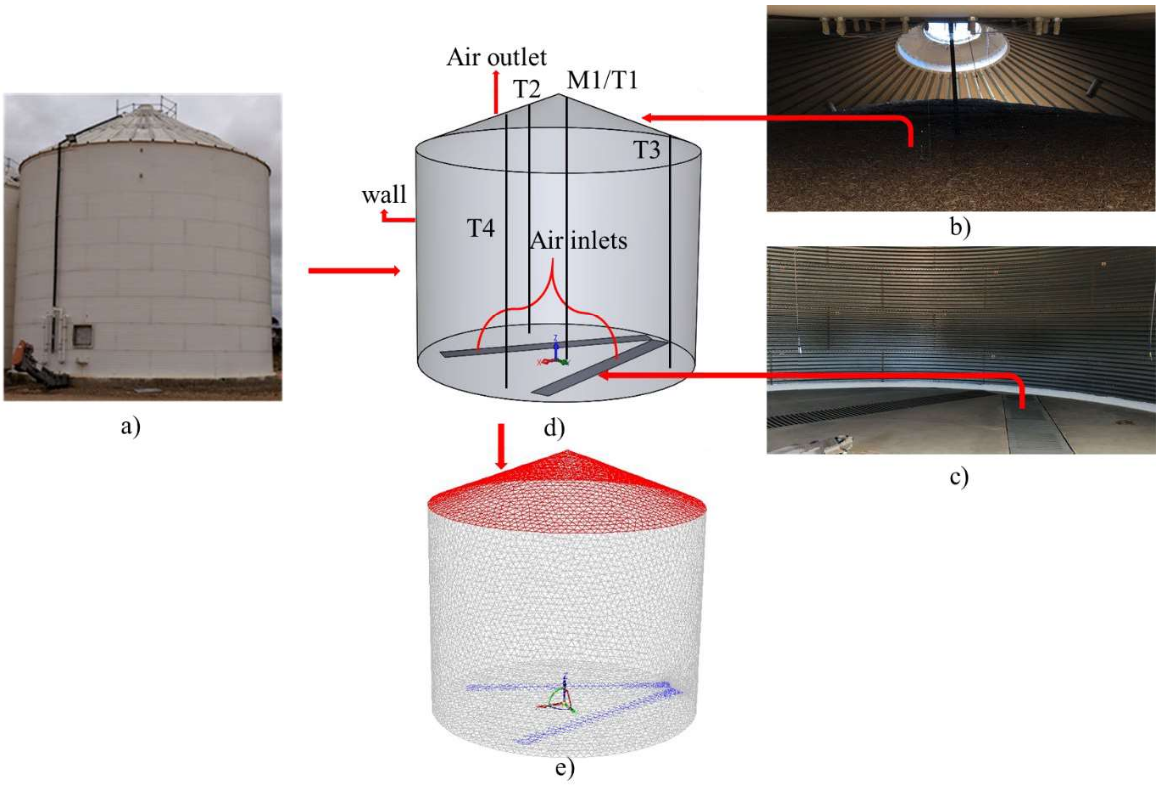

Fig. 1. On-farm grain storage silo: a) Experimental silo; b) Top grain surface; c) Aeration duct; d) 3D CAD model; e) Meshed (tetrahedral) geometry.

The flow rate and the duct surface area were used to determine the inlet face velocity (0.051 m/s). This system logged the ambient and grain temperature and moisture content with 1 h interval.

Model /control development

Local thermal equilibrium condition and laminar flow was assumed during the aeration process. Heat, moisture, and momentum conservation laws were incorporated with physical velocity formulations to account for the anisotropic porous medium across the radial direction. User Defined Scaler (UDS) was used to model the moisture transfer in the grain with absolute humidity of air as the scalar quantity. The moisture source term during the aeration cooling was based on Thorpe (2008) formulation with the inclusion of heat of sorption in the heat source term for the governing equation. The isosteric heat of sorption was derived from the combination of Clausius-Clapeyron equation and ideal gas law with the consideration of similar grain and free water temperature.

The following process was used to determine the differential heat of wetting:

$$h_w = h_v - h_s \quad (1)$$

Where h_w is differential heat of wetting (J/kg); h_v is latent heat of vaporization (J/kg) and h_s is heat of sorption (J/kg).

Respective constants associated with the source terms were used accordingly to the best fitted moisture adsorption or desorption process during aeration cooling.

Thermo-physical property equations such as bulk density, specific heat capacity and thermal conductivity for grain were formulated with temperature and moisture dependency functions (Alagusundaram et al., 1991; Otten and Samaan, 1978). For air, all property equations were a function of temperature and RH of the humid air (Basunia and Abe, 2005; Tsilingiris, 2008).

The on-farm silo was discretized into control volumes using tetrahedral elements to best represent the heaped surface of the peaked grain configuration (Fig. 1.e). The curvature and proximity mesh sizing and outlet face sizing criteria were opted to generate smaller size elements near the start of the V-shaped duct and at the domain outlet, respectively, in order to improve the mesh quality. Initial grain conditions were modeled as per 36 sensors in the silo. An assumption was made that the temperature is uniform within a zone (denoted by cable M1/T1, T2, T3 and T4, Fig. 1.d). Hourly ambient air temperature and absolute humidity data were used at the inlet and were linearly interpolated (to every second) during the simulation.

Mesh independency tests were conducted using 0.5, 0.35, 0.275 and 0.25 m element size. Time step size analysis was conducted using 1, 2, 4, 6, 8, 10 and 12 s for 24 h simulation. SIMPLE and COUPLED algorithms were opted as the pressure-velocity schemes to examine the difference in solution convergence and numerical solutions. Green-Gauss Node based and Least Squares Cell based interpolations were examined for Gradient discretization. Second order and PRESTO! methods were examined for pressure discretization. Second order scheme for momentum was employed, while first and second order for energy and UDS discretization were opted consecutively for examination. Both first and second order implicit transient formulations were examined to analyze the computational time and accuracy in the numerical solution. The absolute criteria for continuity, x, y and z-velocity, and for UDS were set at 0.0001; while 0.000001 was set for energy.

FLUENT macro DEFINE_EXECUTE_AT_END was used to determine the grain temperature at 1.5 m (coincident with first sensor of T1 cable) high from the silo floor. The above macro was also used to calculate the average inlet temperature and UDS value. These values were determined after every time-step, and based on the strategy "inlet temperature ≤ grain temperature". The inlet velocity was switched on with DEFINE_PROFILE macro.

FLUENT's parallel solver was used for computational processes. The UDF's developed aeration model (considering all functions and properties) was incorporated with #if PARALLEL… #endif arguments for calling out the sequence. All the simulations were run in parallel processing with 8 core dual Intel Xeon Gold 5215, 2.5 GHz, 192 GB memory with a bus speed of 2 ×10.4 GT/s. Model evaluation for all the simulations were based on the standard error of prediction (SEP) and mean relative deviation (MRD) for each of the sensor points. The analysis procedure was as follows: first SEP and MRD were calculated for a single sensor point (over the transient basis) followed by averaging with rest of the sensor points on a single cable. Then, the respective SEP and MRD for each of the cables were averaged (4 cables) and denoted as a single data.

Results and discussion

Simulation results showed that the inlet was operating with 0.051 m/s velocity throughout the 24 h cooling period. This was nearly coincident with the actual fan operation when the ambient temperature was less than the grain temperature (data not shown).

Considering the least values of computational time (2.25 h), SEP (1.39°C and 0.15% wb) and MRD (5.1% for temperature and 1.2% for moisture) among all the solution methods, the following were optimized: pressure discretization- PRESTO!; pressure-velocity scheme- SIMPLE; gradient- least square cell based; energy discretization- first order; UDS discretization- first order; and transient formulation- first order. These errors were significantly lower than the previous works, particularly for MRD values (Ranjbaran et al., 2014). It was also observed that second-order schemes took a significantly longer time than first order schemes; however, there was no significant difference in temperature and moisture error during aeration. This showed that opting for a scheme is "model-specific" and cannot be assumed instinctively. A 0.35 m element size (Panigrahi et al., 2020) and 4 s time-step size were observed to provide the least solution deviation for the 1,000-t storage silo configuration. These values should not be used in a general way when simulating a *different* storage structure. However, these values could be assumed the same for other types of grains stored in a *similar* silo structure. The transient temperature and moisture variation (M1/T1 cable) over the 24 h aeration period is shown in Fig. 2 for the best fitted validated model. Results for other cables are not shown.

The errors observed could be due to the assumption of uniform grain moisture across the thin layer. This could have altered the heat of sorption released during the adsorption process due to the tortuous flow path in anisotropic porous media. Moreover, the isotherm constants used in this model were different from the OPI's values which could result in a different value at the same validation point.

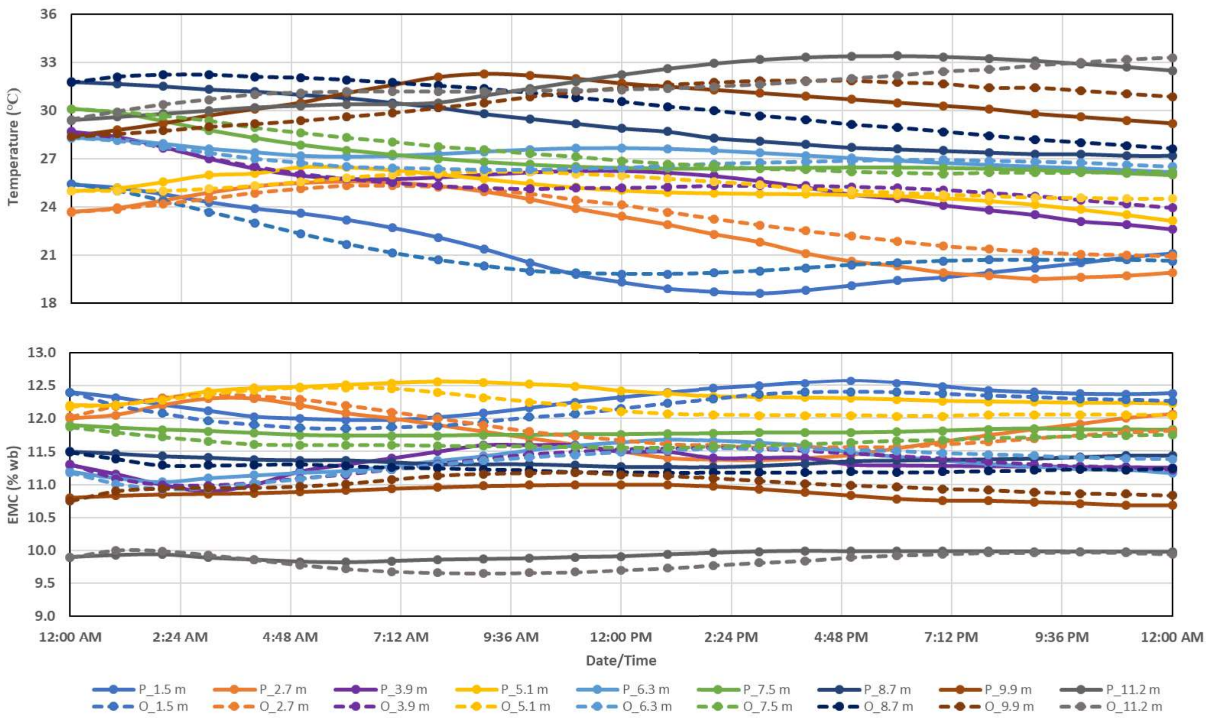

Fig. 2. Comparison of predicted and observed data during 24 h aeration cooling period.

Results showed that the cooling and moisture adsorption rate decreased along the bulk height. This was attributed to the loss in the release of the heat of wetting up the bulk (Fig. 3.). Negative values signified that h_v was less than h_s during the aeration cooling period due to extra heat taken to absorb the moisture into the grain.

However, negligible changes were observed above 8.5 m resulting in negligible moisture changes. During the cooling and re-wetting period, a linear decrease in h_w was observed at a particular grain depth (Fig. 4.), thus illustrating the decreasing cooling effect of the interstitial air along the height. The linear trend could be due to the assumption of constant moisture across the thin layer that might not be true as the grain moisture also depends on the temperature at every zone.

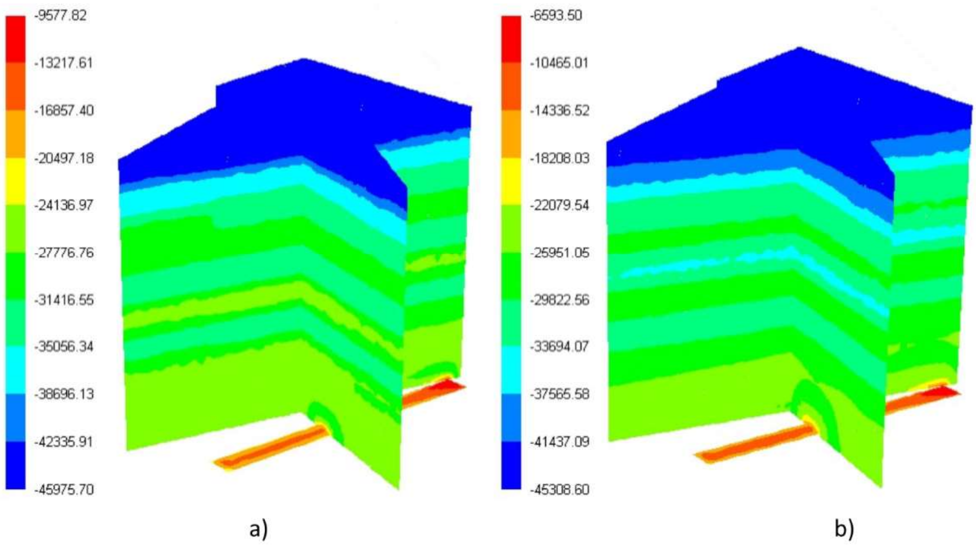

Fig. 3. Contour plots of heat of wetting (J/kg): a) Before start of the aeration; b) After 24 h aeration.

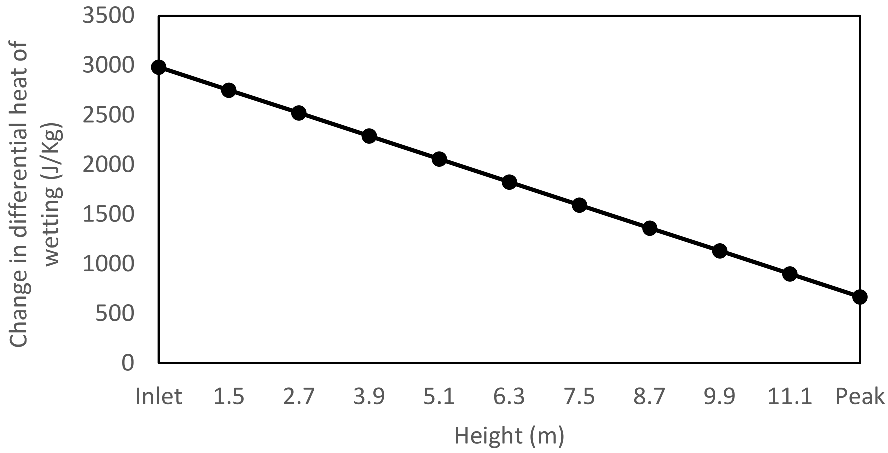

Fig. 4. Differential heat of wetting values between initial and final grain after 24 h aeration.

The above figure shows that to achieve efficient cooling along the height, the differential h_w should be maintained to a near-constant value. This can only be achieved by increasing the inlet velocity resulting in a higher temperature differential between incoming air and grain along the height.

Future work by the authors will include validating the above process on how the differential h_w varies with doubling the inlet velocity.

Conclusions

An integrated 3D CFD model was successfully developed with an inlet control system to predict the fan operation and the factors affecting the cooling potential in a 1,000-t storage silo. Mesh size, time-step size, and solutions methods were optimized for the above process. The optimized parameters resulted in a computational time of 2.25 h for simulating a 24 h real time aeration with SEP of 1.39℃ and 0.15% wb and MRD of 5.1% and 1.2%, for temperature and grain moisture, respectively. Results showed that opting a scheme was model-specific and could not be assumed based on another model's output. A decreasing trend in differential h_w was observed during the cooling and rewetting process.

Acknowledgements

Authors would like to thank South Australian Grain Industry Trust (SAGIT) for funding the computers and respective licenses, and the Commonwealth Govt.'s Higher Degree Research Scholarship for the study. The authors also thank OPI Systems Inc. (Calgary, Alberta, Canada) for providing the platform to monitor the grain conditions, and the Australian Growers Direct (AGD) for allowing us to use their on-farm grain silo to perform aeration experiments.

References

Alagasundaram K, Jayas DS, Muir WE, White NDG (1991) Thermal conductivity of bulk barley, lentils and peas. Trans ASABE **34**: 1784–1788.

Basunia MA, Abe T (2005) Adsorption isotherms of barley at low and high temperatures. J Food Eng **66**: 129–136.

GRDC (2017) GRDC Grain Storage GrowNotes National. Grain Res. Dev. Corp. Retrieved from https//grdc.com.au/__data/assets/pdf_file/0019/244045/GRDC-Grain-Storage-GrowNotes-National.pdf.

Lawrence J, Maier DE (2011) Aeration strategy simulations for wheat storage in the sub-tropical region of North India. Trans ASABE **54**: 1395–1405.

Lawrence J, Maier DE, Stroshine RL (2013) Three-dimenisonal transient heat, mass, momentum, and species transfer in the stored grain ecosystem: part II. model validation. Trans ASABE **56**: 189–201.

Liu Q, Yang G, Zhang Q, Ding C (2016) CFD simulations of aeration for cooling paddy rice in a warehouse-type storage facility. Trans ASABE **59**: 1873–1882.

Otten L, Samaan G (1978) Determination of the specific heat of agricultural materials: part II. experimental results. Can Agr Eng **22**: 25–27.

Panigrahi SS, Singh CB, Fielke J (2020) CFD modelling of physical velocity and anisotropic resistance components in a peaked stored grain with aeration ducting systems. Comp Elec Agric **179**, 105820.

Panigrahi SS, Singh CB, Fielke JM (2019) Effect of Mediterranean climatic condition during aeration and silo wall coating in on-farm grain storage in South Australia. Paper No. 1900976, St. Joseph, MI: ASABE.

Ranjbaran M, Emadi B, Zare D (2014) CFD Simulation of deep-bed paddy drying process and performance. Dry Technol **32**: 919–934.

Thorpe GR (2008) The application of computational fluid dynamics codes to simulate heat and moisture transfer in stored grains. J Stored Prod Res **44**: 21–31.

Thorpe GR (1997) Modelling ecosystems in ventilated conical bottomed farm grain silos. Ecol Modell **94**: 255–286.

Tsilingiris PT (2008) Thermophysical and transport properties of humid air at temperature range between 0 and 100°C. Energy Convers Manag **49**: 1098–1110.