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Research Paper

# Models to predict the thermal state of rice stored in aerated vertical silos

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The thermal state of the rice mass in steel vertical silo with an aeration system, located in a rice storage facility in Rio Grande do Sul State, Brazil, was studied. Data obtained by thermometry system were compared with the predicted data obtained from four one-dimensional models. The first model was based on the hypothetical division of the deep bed into a limited number of thin layers with identical temperatures of the grain and the passing air. The second model presented the system of two partial differential equations, describing the heat transfer and conservation of energy for air and for grain mass. The third model used the generalised dependence between dimensionless temperature and homochronous number and was adapted to conditions when both a variable temperature of the ventilation air inlet and an initial non-uniformity of the grain mass temperature existed. The fourth model was intermediate between the thermal state problem of a body made up of two different materials (with fixed boundary) and the Stefan problem in which a moving boundary separates the different phase domains. The velocity of the moving boundary and thermal diffusivities of each domain were obtained experimentally. Each of the proposed models satisfactorily described the thermal state of the studied silo. The use of the last data reading obtained as a new initial condition increased simulation accuracy. In the case of a significant transverse temperature inhomogeneity, a hypothetical division of the silo into independent vertical cylinders centred on the respective thermometry cables increased accuracy.

## 1. Introduction

The State of Rio Grande do Sul is the main producer of rice in Brazil (CONAB, 2017). The most common method of storing rice in large quantities is bulk storage in cylindrical silos with aeration. To preserve the quality of rice and prevent unnecessary losses, it is important to provide the conditions for safe storage. The temperature condition inside the grain silo with aeration depends on ambient temperature, air flow rate, the temperature of the grain in neighbouring layers and the

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**Nomenclature**

| | |
|---|---|
| $A$ | surface area, $m^2$ |
| $a$ | ratio of grain surface area $A_g$ to grain volume $V_g$ (1/hydraulic radius), $m^{-1}$ |
| $a_q$ | thermal diffusivity, $m^2\ s^{-1}$ |
| $a_j$ | weighting coefficients ($j = 1, 2$), dimensionless |
| $b_j$ | empirical coefficients ($j = 1, 2, 3$), dimensionless |
| $c_g$ | specific heat of dry grain, $J\ kg^{-1}\ K^{-1}$ |
| $c_{pa}$ | specific heat of dry air, $J\ kg^{-1}\ K^{-1}$ |
| $c_{pv}$ | specific heat of water vapour, $J\ kg^{-1}\ K^{-1}$ |
| $c_{pw}$ | specific heat of liquid water, $J\ kg^{-1}\ K^{-1}$ |
| $\Delta y$ | layer depth, m |
| $Ho$ | homochronous number, $Ho = vt/y$ , dimensionless |
| $H_v$ | latent heat of water vaporisation, $J\ kg^{-1}$ |
| $H$ | grain mass height, m |
| $k_v$ | proportionality coefficient, dimensionless |
| $M$ | grain moisture content, d.b. |
| $s$ | mobile boundary location, m |
| $R$ | silo radius, m |
| $r$ | radial coordinate, m |
| $T$ | temperature, °C |
| $t$ | time, s |
| $V$ | volume, $m^3$ |
| $v$ | air velocity, $m\ s^{-1}$ |
| $y$ | coordinate along airflow axis, m |
| $\alpha$ | heat transfer coefficient, $W\ m^{-2}\ K^{-1}$ |
| $\varepsilon$ | porosity factor, dimensionless |
| $\tau$ | integration variable, s |
| $\lambda$ | thermal conductivity, $W\ m^{-1}\ K^{-1}$ |
| $\rho$ | density, $kg\ m^{-3}$ |
| $\Phi_m$ | mass flux between air and grain, $kg\ m^{-2}\ s^{-1}$ |
| $\Phi_h$ | heat flux between air and grain, $W\ m^{-2}$ |
| $\Psi$ | temperature ratio, dimensionless |
| $\Omega$ | integration domain |

*Subscripts*

| | |
|---|---|
| a | air |
| g | grain |
| h | relating to heat |
| m | mass, average |
| v | vapour |
| w | water |
| 0 | initial |

application time of aeration (Navarro & Noyes, 2001). Unevenness of temperature occurs not only along the height of the silo, but also in its cross-section. This is due to uneven external temperature conditions associated with exposure to solar radiation on the outer surface of the silo, with non-uniformity in the distribution of ventilation air entering into the grain mass as well as other factors associated with the presence of impurities in the grain mass. Usually, to check the humidity and temperature inside the silo it is recommended to use an automatic system with sensors and computer control of the aeration (Lopes et al., 2008).

Under these conditions, it is difficult to predict the effects resulting from aeration, because the risk area in the silo, i.e. the grain subdomain with higher temperatures, can be displaced, reduced or even increased depending on the grain, air temperature and airflow direction. Theoretically, the installation of a very large numbers of temperature sensors in the interior of the silo could allow a safe mode of aeration to be selected. However, in practice, the number of sensors that can be installed is heavily limited. Modelling the dynamics of temperature of the grain mass allows it to be predicted each point of the silo. However, with time and changes in boundary conditions, the difference between the measured and the calculated temperature becomes too large. Therefore, a combination of modelling of thermal state of grain mass with the use of the sensors to obtain new initial data for simulation appears to be a suitable strategy for the complete control of the temperature of the grain mass at each point in time.

Simulation of the thermal state of the grain mass during aeration is a relatively difficult problem. In the case of a solid body, or a porous mass without airflow, the thermal state can be relatively easily produced using the effective thermal conductivity. However, in the case of a porous mass with an internal airflow, determining the effective thermal conductivity is meaningless, since its value varies both in time and in space and it also depends on the values of the velocity and temperature of the ventilation air.

There are models that satisfactorily describe airflow in silos under isothermal conditions (Khatchatourian & Savicki, 2004). Also, the simulation of the thermal state of a silo for non-isothermal conditions presents some difficulties related to the absence of reliable data for heat transfer coefficients between grain and air, the coefficients of thermal diffusivity of the grain itself and that of the grain layer.

The thermal state of the grain mass can be calculated applying the so-called “drying models”, described in Boyce (1966), Burrell and Laundon (1967), Henderson and Henderson (1968), Sutherland, Banks, and Elder (1971), Bakker-Arkema, Lerew, DeBoer, and Roth (1974), Brooker, Bakker-Arkema, and Hall (1974), Ingram (1979), Hunter (1988), Sanderson, Muir, and Sinha (1988), White (1988), Sun and Woods (1997), Montross and Maier (2000), Lamrani, Boulard, Roy, and Jaffrin (2001), Ranalli, Howell, Jr., Arthur, and Gardisser (2002), Kurpaska, Slipek, Bozek, and Fraczek (2004), Khatchatourian, Vielmo, and Bortolaia (2013). However, during the prolonged storage of grain using an aeration system, the variation of grain moisture content over time is negligible compared to the variation of the grain temperature. In these conditions, to calculate the temperature field, a model that neglects moisture transfer can be used. Some of these models were presented by Schumann (1929), Furnas (1930), Bakker-Arkema and Bickert (1966), Foster (1967), Khatchatourian and Oliveira (2006), Oliveira, Khatchatourian, and Bihain (2007).

The main objectives of the present work are:

1. To study experimentally the dynamics of temperature variation of the grain mass inside a full-scale silo fitted with an aeration system;
2. To adapt four mathematical models to calculate the thermal state of the grain mass inside the silo.
3. To compare simulation results with experimental data and choose the most adequate model.