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Research Paper

CFD modeling of air flow distribution in rice bin storage system with different grain mass configurations

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Poor airflow distribution in grain mass during in-bin aeration, drying and storage may lead to moisture content variations that could be detrimental to grain quality. The effects of grain mass configuration and porosity on airflow distribution inside a rice bin were investigated using three-dimensional computational fluid dynamics simulations and experiments. A finite volume method with porous media formulation was used to simulate air flow characteristics in peaked, inverted, and levelled grain mass configurations for long-grain rough rice with a porosity of 0.55, and mean particle size distribution of 2.94 mm. The airflows through the rough rice masses were simulated for airflow rates of 0.55, 0.825 and 1.1 m^3 min^{-1}[air] t^{-1} [rice]. The model was validated using a bench scale pressure drop system and an actual long-grain rice in-bin storage with peaked grain mass configuration having a capacity of 700 Mt. The results showed that long-grain rice has viscous and inertial resistance coefficients of 9.72E+06 and 36,185, respectively. Non-uniform airflow distribution dominated peaked and inverted grain mass configurations with peaked configuration having the highest restriction to airflow. Airflow at peak positions in the bed were significantly ($p < 0.05$) lower compared to other parts. The average non-uniformity coefficient (NUF) measured directly from the bin was 34% and those obtained from the model using constant and variable porosities were 19% and 71%, respectively. For inverted scenario, a maximum of 50 t of rice is needed to be removed from the rice storage bin to ensure an airflow distribution with an NUF <50%.

1. Introduction

The temperature and moisture content (MC) of freshly-harvested rough rice varies considerably as it comes into storage. To prevent spoilage and maintain grain quality, grain condition must be stabilised as soon as possible. Aeration is a process of forcing natural air from the bottom of the bin at relatively low airflow (1–2 s^{-1} [air] m^{-3} [grain]) through the bulk grain for the purposes of cooling, ventilation and

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Nomenclature

CFD	Computational Fluid Dynamics
NUF	Non-uniformity coefficient (%)
MC (s)	Moisture content (% wet basis)
UDF	Users Defined Function
MRD	Mean relative deviation (%)
DDP	Dimensionless Dynamic Pressure
DV	Dimensionless Velocity
SIMPLE	Semi-Implicit Method for Pressure Linked Equation
Symbols	
S	Source term for the momentum equation
D	Normal viscous resistance (m^{-2})
C	Inertial resistant coefficient (m^{-1})
ε	Porosity
ρ	Density (kg m^{-3})
u	Velocity (m s^{-1})
P	Pressure (Pa)
ΔP	Pressure drop (Pa)
L	Grain column depth (m)
μ	Viscosity (Pa s)
k	Turbulent energy (m^2 s^{-2})
g	Acceleration due to gravity (m s^{-2})
S	Mean modulus of the rate of strain tensor
σ	Turbulent based on Prandtl number
Q	Airflow (m^{-3} s [air] m^{-2})
Subscript	
bulk	Bulk density (kg m^{-3})
particle	Particle density (kg m^{-3})
i, j	Prescribed matrices
n	Normal component
t	Tangential component
ε	Turbulent dissipation rate constant

improving grain storability (Calderon, 1972; Foster, 1979; Navarro & Noyes, 2001). However, grain conditions can make the aeration process less effective by impeding uniform flow of air throughout the bed. Presence of fines and/or dirt in the grain (dockage), grain mass configuration, and the physical properties of the grain can produce less exposure to aeration in sections of the bin; areas of the grain mass subjected to high exposure to aeration could over-dry (Flinn, Hagstrum, & Muir, 1997). As a consequence, poor aeration is associated with problems of grain moisture build up, mould growth, insect attack and, spoilage (Bartosik & Maier, 2006; Khatchatourian & Binelo, 2008). There is need to understand airflow distribution and pattern at different bed conditions of grain for successful aeration to prevent the quality of rice deteriorating, mycotoxin contamination occurring, and to reduce economic losses.

Atungulu et al. (2013) investigated dockage in freshly-harvested rice of different varieties (M104, M202, M205, and M206) and harvest MCs that ranged from 18% to 27% wet basis and found that the dockage varied between 0.2% and 2.0% but the amounts could be more depending on harvester and weather conditions. When the grain is transferred to bin storage system, grain samples at the bin core tend to be associated with low porosity while that at the periphery (close to the wall) high porosity (Bartosik & Maier, 2006; Lawrence & Maier, 2011). Hence, during aeration lower specific air velocity passes through the core compared with the periphery of the grain mass. Airflow resistance as the result of the concentration of fines was investigated by Siebenmorgen and Jindal (1987) using a long-grain rough rice cultivar at varying MCs (12%, 18% and 24%) and fine material concentrations (0%, 5%, 10%, 15%, 20%, 25% and 30%) at airflow velocities ranging from 0.0135 to 0.387 m s^{-1}. They found a 1% increase in fine concentrations resulted in 0.87% increase in airflow resistance. A similar result was obtained by Chung, Maghirang, Kim, and Kim (2001) who also investigated the effect of fine content on rough rice at different MCs (12%, 13%, 15%, 16%, and 18%) and four levels of fine materials (0%, 1%, 3%, and 5%) at velocities ranging from 0.05 to 0.38 m^3 m^{-2} s^{-1}.

Loading of the bin from the centre of the roof can result in peak/cone shape grain mass configuration. As the grain drops into the middle of the bin, and spreads radially outward toward the bin wall, the grain follows the natural angle of repose (typically 30°). The formation of a peak configuration results in beds with non-uniform surfaces and unequal bed depth with surface grain close to the periphery being a few metres to several metres below the top of the peak. The extra grain depth in the centre of the bin increases air flow resistance. In particular, the region at the peak of the cone usually has low exposure to airflow which could cause grain at those locations to remain at high MCs for extended periods of time; grain quality reduction, mould development, and mycotoxin contamination may ensue (Bartosik & Maier, 2006). To reduce problems associated with peak grain mass configuration, producers use coring and levelling of the grain bed surface to improve airflow distribution within the grain. The coring process involves partially drawing out grain at the bin core. The coring process results in an inverted cone mass configuration with bottom of the inversion at several metres below the surface of the grain at the periphery.

A few experimental and modelling studies on airflow distribution in rice bins are reported in literature. Calderwood, Cogburn, Webb, and Marchetti (1984) studied the difference in viability reduction in long-grain rice stored in aerated and non-aerated bin for 30 months storage. They found that non aerated grains had zero viability. Using a corn bin, Bartosik and Maier (2006) found a reduction from 89% to 36% in non-uniformity factor (NUF) when a peaked grain mass configuration was changed to flatbed grain mass configuration. NUF is defined as (peripheral air velocity − central air velocity) × 100/(peripheral air velocity + central air velocity). De Ville and Smith (1996) presented an analytical solution for solving nonlinear air flow distribution through a bed of rapeseed, wheat, barley and corn. Lai (1980) presented three-dimension nonlinear partial differential equations that describe the axisymmetric airflow through a porous media using the Ergun equation. The core and the periphery of the grain mass were modelled using two different porosities (0.4 and 0.6). Similarly, Lawrence and Maier (2011) used the NUF to validate the work of Bartosik and Maier (2006). The author used Fluent computational fluid dynamics software with