

Three-dimensional modeling of heat and mass transfer and hygroscopic swelling in rice grains during moisture absorption and desorption using finite element analysis approach

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(コメの吸水・乾燥過程における熱物質移動および形状変化の有限要素法解析)

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論 文 内 容 の 要 旨

The cracking of rice kernel during moisture absorption affects the textural characteristics of the cooked rice. Similarly, rapid moisture loss and wide temperature gradients inside the kernel during drying induces stress that leads to fissuring. The presence of fissures in the kernel often results in the breakage of the grains during milling. The objective of this study is to understand the moisture absorption and desorption characteristics in rice grains and its subsequent effect on the development of cracks in the kernel. This study employed the principles of finite element analysis to simulate the penetration of moisture in the grain in two and three dimensions (2D and 3D) and the consequent swelling because of moisture absorption. Homogeneous and heterogeneous diffusion of moisture in rice grains were numerically modeled and tested. In the same manner, a computer simulation to investigate the temperature distribution and moisture loss in a layer of grains during forced-air convective drying was also performed. The simulation experiments were conducted at 25, 35, 45 and 55 °C, respectively. The purpose of this study was to understand the synergistic effect of temperature and rate of moisture absorption on the cracking of rice grains during soaking. In the modeling, several mathematical models were tested and compared. Peleg's equation, Fickian and non-Fickian diffusion models were tested using the analogy of the Fourier's law of heat transfer. Moreover, the Navier-Stokes and Fourier's equation was used to analyze heat and mass transfer during drying. Results of the experiment showed that certain boundaries of the grain served as major entry site for moisture. The penetration of moisture escalated due to the presence of cracks that developed after 10-15 minutes of soaking. Temperature was also found to be related in both the moisture absorption and hygroscopic swelling characteristics in grains. The rate of moisture absorption is comparatively higher in grains that were soaked at higher temperature than those at lower temperature. The degree of swelling varied directly with the soaking temperature. Results of the modeling revealed the non-Fickian diffusion model was the best model to describe the 3D moisture diffusion and hygroscopic swelling characteristics. The non-Fickian diffusion model had the lowest RMSE values among the three models. The RMSE values for the moisture diffusion in all the temperature levels ranged from 0.98 to 2.55 % d.b. while for the volumetric change due to hygroscopic swelling were 1.62×10^{-10} to $7.17 \times 10^{-10} \text{ m}^3$. Analysis from the simulation also revealed that several locations on the grain with high stresses were found at the mid-section and embryo attachment region of the endosperm. In modeling the heterogeneous

moisture diffusion, the model described the moisture diffusion characteristics satisfactorily with the incorporation of the logistic function into the diffusivity equation of the non-Fickian diffusion equation. The RMSE values of the moisture content were very low that only ranged from 0.50 to 1.18% d.b.. The model for the heat and mass transfer during drying of grains revealed that the temperature distributions in the air and brown rice grains were significantly influenced by the direction of flow of the heated air. Air gaps in between grains and the periphery of the drying chamber affect the rate and direction of airflow.