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Research Paper

Validation of CFD models for the deep-bed drying of rice using thermal imaging

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Validation is one of the most important steps in modelling the drying process of cereal crops. Once a simulation model is validated, it can be used for further practical applications. This study examines the potential of the thermal imaging technique to validate computational fluid dynamic (CFD) simulation models developed for describing the deep-bed drying process of rough rice and to visualise the temperature profiles throughout the bed under different drying conditions. A laboratory forced-air convective dryer was designed and fabricated to dry the rough rice in deep layers and thermal images of the rough rice inside the drying bin were directly acquired during drying process. The predicted data of the CFD models for moisture and temperature distributions through the deep bed during drying were verified against the experimental results. The results revealed that the CFD model developed for predicting moisture content exhibited good correlation with a coefficient of determination $R^2 = 0.96$. The model was also very accurate for predicting the temperature of rough rice in the deep-bed dryer with coefficients of determination > 0.90 and low RMSE (<5 °C). A fair agreement was also obtained between the temperature values recorded by the thermocouples and those exported from the thermal images with a coefficient of determination of 0.94.

1. Introduction

Among the main challenges in the rice production, improving the overall quality to meet export requirements and secure suitable shares of national and international markets is a continuing challenge. There is an urgent need to improve the rice quality and minimise the losses during handling, especially during drying processes (Khir, 2008). Rough rice has a high moisture content at harvest, and if it is not subjected to an appropriate drying process, it decays due to infestation and mould growth (Duangkhamchan & Laohavanich, 2014; Hacihafizoğlu, Cihan, Kahveci, & de Lima, 2008). In general, two kinds of methods are commonly used to dry grains, convective drying methods using ambient or heated air and radiation drying using either solar or infrared radiation (ElGamal, Ronsse, Radwan, & Pieters, 2014). As commercial rough rice dryers are usually deep-bed dryers, it is very important to study the moisture and temperature distributions through these dryers to improve and optimise the drying process.

Mathematical modelling and computer simulation of food processing operations, including drying process, have been used successfully to minimise the cost and time-required for

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experiments and to allow better understanding of all thermal and physicochemical phenomena associated with the drying process (Duangkhamchan, Ronsse, Siriamornpun, & Pieters, 2015; Hemis, Singh, Jayas, & Bettahar, 2011; Istadi & Sitompul, 2002; Aghbashlo, Kianmehr, Khani, & Ghasemi, 2009; Naghavi, Moheb, & Ziaei-rad, 2010). The application of computer modelling and numerical simulation for understanding the dynamics of thermal transport during drying process of rice grain is extremely significant for the quality control of rice grains (Izadifar, Baik, & Simonson, 2006; Perez, Tanaka, Tanaka, Hamanaka, & Uchino, 2015). Predicting drying parameters could help design more efficient dryers as well as improve the performance of the existing systems (Zare & Chen, 2009).

Validation is one of the most important steps in modelling the drying process. Once a simulation model is validated, it can be used for practical applications. Many researchers have developed mathematical models to describe the deep-bed drying process of grain. However, fewer have conducted experimental studies to validate their models (Harchegani, Moheb, Sadeghi, Tohidi, & Naghavi, 2012; Hemis et al., 2011; Perez et al., 2015; Tohidi, Sadeghi, Mousavi, & Mireei, 2012; Wongwises & Thongprasert, 2000; Zare, Minaei, Zadeh, & Khoshtaghaza, 2006). Furthermore, most developed models have been validated based on experimental data only collected from authenticated references. Such approach has been used primarily where the main objective was limited to the development of models rather than their application (Chueaprasat & Chitsomboon, 2008; ElGamal, Ronsse, ElMasry, & Pieters, 2015; Izadifar et al., 2006; Jia, Sun, & Cao, 2000; Mandas & Habte, 2002; Naghavi et al., 2010; Ranjbaran, Emadi, & Zare, 2014; Sitompul, Istadi, & Widiasa, 2001). In fact, moisture and temperature distributions through a deep bed of grain during drying are not explicitly covered because drying parameters were principally calculated from fundamental equations rather than experimentally measured. Thus, it is important in grain drying research to obtain reliable experimental data under a wide range of conditions to validate numerical simulation models.

Although knowledge of the temperature variation in the bed during drying is very important since it influences rice fissuring and overall quality (Woźniak, 2001; Iguaz, Rodriguez, & Virseda, 2006), most studies have focused only on determining moisture gradients throughout the bed rather than temperature variations. In convective drying, the quality of grains may be deteriorated due to overheating at high temperatures and rapid moisture loss. The efficiency of a dryer is usually related to the temperature of heated air as well as exposure time (Inprasit & Noomhorm, 2001). The typical method to record the grain temperature during drying is the use of thermocouples connected to a data logger. This method is limited by the number of probes that can be inserted along the bed height without affecting the air flow and influencing the drying process through the grain bed. A more advanced method based on thermal imaging could be used as an alternative to the traditional thermocouple measurements for recording the change in the surface temperature (Ishimwe, Abutaleb, & Ahmed, 2014; Vadivambal & Jayas, 2011). In thermal sensing, the invisible radiation patterns of grains during drying process are converted into temperature data without establishing a contact with the grains. These data are then visualised as pseudo colour images representing temperature levels and are called thermograms or thermal images. By using thermal imaging, it is possible to obtain temperature mapping of any particular area in the deep bed. This is not possible with thermocouples or other similar temperature sensors. Besides being a non-contact technique used to determine thermal profiles, thermal imaging does not require an illumination source unlike many other imaging methods (Prakash, 2000). There is a lack of experimental data on rice drying in general, and on the temperature profile through the bed of rice in particular. Therefore, there is a need to establish new techniques to record the temperature distribution through the grain bed during the drying process.

In our previous study, a computational fluid dynamic (CFD) model for deep-bed drying of rice was developed (ElGamal et al., 2015). The developed model was used successfully to predict the moisture contents and temperatures of the rough rice at different heights in the bed under different conditions of drying process. Although the model prediction for moisture contents was verified against the experimental data of Zare et al. (2006) and there was close agreement between the model and experiential data, there is still a need to verify the accuracy of the model for predicting temperature distributions based on experimental measurements and under various operating conditions.

The ultimate goal of this study was to examine the potential of thermal imaging technique for validating the CFD models previously developed by ElGamal et al. (2015) and to provide a new method to visualise the temperature profiles throughout the whole depth of a bed of rough rice during the drying process. To the best of our knowledge, this is the first study to employ the thermal imaging technique for validation the CFD models developed for deep-bed dryers.

2. Materials and methods

2.1. *Experimental setup and measurements*

2.1.1. *Preparation of rough rice samples*

Rough rice (Giza 181 a long grain variety) was provided by the Agricultural Research Centre, Ismailia, Egypt. All rough rice samples used in this study were freshly harvested without any artificial conditioning prior to the tests. Rice samples were sealed in plastic bags and stored in a freezer at -5 ± 1 °C to prevent moisture loss and inhibit the fungal growth. One day before each experiment, the samples were taken out from the freezer and kept in a refrigerator at 10 ± 1 °C for approximately 12 h and then kept in the room temperature for 6 h in a sealed plastic bag in order to thermally equilibrate rice samples with the surrounding environment directly prior to conducting the experiments. The ambient air temperature and relative humidity of the drying experiments were 18 ± 1 °C and 57 ± 3%, respectively. The initial moisture content of the rough rice sample was 30 ± 1% (d.b) determined using oven-drying method conducted at 130 °C for 24 h (ASAE Standards, 2000).

2.1.2. *Deep-bed dryer*

The system of the forced-air convective dryer used in this study to dry the rough rice in deep layers was designed and