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Energy efficiency investigation of intermittent paddy rice dryer: Modeling and experimental study

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ABSTRACT

In this study, energy consumption of intermittent drying of paddy rice is considered. Firstly, a mathematical model consists of two parts is established to describe the moisture distribution within a grain for both drying and tempering stages. The model, which is solved analytically, is proposed based on Fick's second law of diffusion within a sphere. Effects of different parameters namely air temperature and velocity are experimentally investigated utilizing a lab-scale fluidized bed dryer. Thereafter, moisture diffusivity is estimated in Arrhenius form using experimental results. Finally, the model is utilized in an optimization problem to minimize the total energy consumption. Based on experimental results, impact of air velocity on drying characteristics is found to be negligible. The optimization results shows that employing the tempering stages substantially reduces the energy consumption. Not only that, it dictates a process beginning with longer drying stages and lower temperatures while the subsequent stages are shorter with higher temperatures.

Keywords: Mathematical modeling; Intermittent drying; Energy consumption; Optimization; Drying characteristics; Paddy rice

1. Introduction

Rice is the third largest crop, behind maize and wheat. Paddy rice is harvested with relatively high moisture content normally ranging from 0.18 to 0.35 kg H_2O/kg dry solid (Bunyawanichakul et al., 2007; Tirawanichakula et al., 2004). Having this moisture level, paddy is susceptible to deteriorate rapidly. Hence, delaying in drying would lead to germination of the grains. It would mean that, drying is the most essential treatment after harvesting paddy rice. Hot air drying is the most common method for drying of paddy rice all over the world. Generally speaking, thermal drying is an energy-intensive operation. It accounts, on average, for up to 15% of all industrial energy consumption. This amount varies from 5% for chemical process industries to 35% for paper making operations (Mujumdar, 2007). The main function of an efficient cereal dryer is to reduce the moisture content of grains to a safe level for storage with minimum cost, time and maximum yield.

Since the drying of paddy rice mostly occurs in the falling rate period, there is not enough surface moisture after long drying periods. Therefore, it is advisable to stop drying thereby facilitating moisture migration from the inner layers to the surface to evaporate. The described process is an intermittent drying in which a set of subsequent periods of drying and tempering (resting) is implemented. Tempering periods have remarkable effects on the drying characteristics of the paddy grains. Improvement of the product quality, increasing drying rate as well as reduction of energy consumption in the subsequent drying stages are the main advantages of applying tempering stages to the drying process (Steffe et al., 1979; Steffe and Singh, 1980a; Franca et al., 1994; Li et al., 1998; Yang et al., 2002; Thakur and Gupta, 2006; Kowalski and Pawłowski, 2010).

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Nomenclature

A	cross sectional area, m^2
c	vector of constraints
c	specific heat capacity, kJ/kg °C
D_0	Arrhenius factor, m^2/s
D_{eff}	effective moisture diffusivity, m^2/s
E_a	activation energy, kJ/kg mol
$f(r)$	initial moisture profile for drying stage
$f'(r)$	initial moisture profile for tempering stage
J	objective function
M	grain moisture content kg H_2O/kg dry solid
N	number of drying stages
Q	total energy consumption, MJ
r	radial coordinate for the grain
R	universal gas constant, kJ/kg mol K
R'	radius of a grain in spherical form, m
RH	relative humidity
t	time, s
T	temperature, °C
u	input variable
x	vector of state variable
Y	absolute humidity of the air, kg/kg (db)

Greek letters

λ	eigenvalue
ν	velocity, m/s
ρ	density, kg/m^3

Subscripts

a	air
ave	average
D	drying stage
eq	equilibrium
f	final
opt	optimum
T	tempering stage
0	initial

At the present, most of the rice mills in Iran use a traditional paddy drying method with low efficiency. In this method, large amounts of paddy is put into a deep bed and hot air is blown from the bottom of the bed through a perforated plate distributor. In some cases, the bed is continuously exposed to hot air even for 10 h. There is not adequate mixing inside the dryer as the bed is completely fixed. Besides, the bulk of grains do not dry uniformly as a result of non-uniform distribution of the hot air. Since the continuous drying forms a sharp moisture gradient in the grains and produces tensile stress at the surface as well as compressive stress in the inner layers of the grains, head rice yield is low (Nishiyama et al., 2006). These stresses may cause the kernels to fissure and crack. Moreover, huge amount of the hot air is wasted to the surroundings without removing much of the grains' moisture (Golmohammadi, 2010). The energy carrier prices in Iran have drastically risen in the recent years due to reforming energy subsidies; as a result, the paddy rice processing industries have encountered with a serious crisis. In this regard, modification of out-dated drying methods in this sector are vital. For this purpose, a lab scale fluidized bed was designed and manufactured in order to investigate the characteristics of an intermittent drying of Iranian paddy rice.

Fluidized bed is a relatively appropriate method for drying of grains as complete mixing ensures uniform heat and mass transfer for all grains in the dryer so faster drying rate with shorter drying time can be achieved. Many researchers have investigated the fluidized bed drying operation. Palancz (1983) proposed a mathematical model for continuous fluidized bed drying based on the two-phase model of fluidization. Thakur and Gupta (2006) examined drying of high-moisture paddy experimentally within stationary and fluidized bed dryers with and without intervening resting periods. Their results reveal that fluidization reduces the energy requirement approximately 50% compared with continuous drying for the stationary beds. Sangdao et al. (2011) proposed a fluidized bed micro-wave drying system for paddy rice. They examined different temperatures and reported an efficiency of 615% for this system. Hatamipour and Mowla (2006, 2007) and Golmohammadi et al. (2012b) investigated the effect of air velocity on drying rate of agricultural products. They reported that the air velocity has no significant effect on drying curves.

Some research works have been conducted regarding the optimization of drying process.

Some researchers have focused on product quality (Ongrat et al., 2011) while many others have considered energy consumption of the process (Bon and Kudra, 2007; Kudra et al., 2009). Kudra et al. (2009) developed an excel-based tool to investigate the energy performance of convective dryers in which energy efficiency is defined as ratio of the energy used for moisture evaporation to the total energy. Their algorithm accounts for different modes of operation and is capable of identifying major sources of dryer inefficiency. Baker and McKenzie (2005) considered energy consumption, including heat and electricity, of industrial spray dryers. They developed a model enabling comparison between performance of a particular dryer with that of its ideal adiabatic counterpart and estimated energy loss. Soponronnarit et al. (2001) designed, constructed and tested a commercial-scale vibro-fluidized bed paddy dryer. In their research, they took the specific energy consumption into account and also established a cost analysis to find the optimal operating conditions. Olmos et al. (2002) combined a mathematical model for drying and quality degradation with a dynamic optimization algorithm in order to determine the air temperature and relative humidity as a function of time. Their optimization results proposes a mild drying condition. Moreover, the optimal control strategy was shown to be very sensitive to the initial moisture content and water activity of the product. Bon and Kudra (2007) formulated an optimization problem using the enthalpy gain definition. They showed that the optimization of intermittent drying improves the energy performance.

This study aims to: (1) present a mathematical model for intermittent drying process, including drying and tempering stages together with its analytical solutions; (2) investigate different drying parameters namely air temperature and velocity and evaluate moisture diffusivity inside grain based on the model and experiments; (3) optimize the process from an energy consumption point of view and find the optimal combination of time durations and temperatures of drying/tempering stages.

2. Mathematical modeling

A mathematical model is developed to be used in the optimization problem. The model consists of drying and