CHAPTER 2

LITERATURE REVIEW AND OBJECTIVE

To improve material quality and safe storage time, the process of drying grains and ceramics has been a subject of study for quite a long time. As the drying process is governed by fundamental equations of heat and mass transfer, extensive research has been done to investigate the effect of various parameters and obtain a model for getting materials of desired quality. A number of research papers have been published showing the effect of initial moisture content, drying air temperature, and air velocity on final moisture content. Various governing equations have been solved with suitable assumptions, and a model was developed to obtain materials of desired quality.

The list of published literature on simulation and experimental studies of different types of dryer and materials is driers being rather large, and a brief mention is made to some representative works in the area in the following paragraphs.

2.1. Literature survey for oil seed drying.

[Pathak et al., 1991] showed thin layers drying model for rapeseed at room temperature and elevated temperature ranging from 50°C to 200°C. They developed a mathematical model on the basis of Page's equations. [LIAO et al., 2007] studied the effect of microwave drying on rapeseeds without undermining the mathematical equations involved in the dehydration process. [Duc et al., 2011] also studied the thin layer drying characteristics of rapeseeds. They calculated the effective moisture diffusivities and drying activation coefficients for a spherical shape using Fick's Law.[Pabis & Jayas, 2007] developed a mathematical model for a radial, continuous-cross flow dryer. Their mathematical model was in close agreement with the experimental values limiting only to thin-layer drying. [Tayel et al., 2015] conducted experimental work to study and simulate the high-temperature short-time drying behavior of peanut pods.[Gamea et al., 2019] evaluated the effect of accelerated drying on seed's moisture content.

2.2. Literature survey for deep bed rice drying.

[Pabis & Jayas, 1993] presented a comprehensive review of various deep bed drying models for grain drying. Different theoretical, semi theoretical, and empirical models have been discussed, but all are limited to thin layer or batch type drying. Many researchers have developed various simulation models but only for thin-layer drying or batch type dying for paddy [Zare & Chen, 2009; Dong et al., 2009; Naghavi et al., 2010; Abe et al., 1997.;Srivastava & John, 2002;Istadi et al., 2002]. [Sarker et al., 2002.; Luthra et al., 2021] investigated the impact of drying temperature, effects of ambient air dehumidification, and airflow on the quality of rice on deep bed dryers; experimentally. Numerical simulation has not been done.[Izadifar & Mowla, 2003] also developed a mathematical model to simulate moist paddy drying for cross-flow continuous fluidized bed dryer. Researchers have also investigated the drying characteristics and milling quality of rough rice and tempering, but they have used a thin-layer drying model [G. O. Ondier et al., 2010;Doungporn et al., 2012.G. Ondier et al., 2012]. [D. Zare et al., 2012] have developed a computer program and dimensionless model for drying rough rice in a deep bed batch dryer, not a continuous dryer. [Torki Harchegani et al., 2012] implemented a non-equilibrium model for the numerical simulation of rice drying in a deep-bed dryer; they conducted specific experiments on deep bed drying; however, the drying model used in not clearly mentioned.[El Gamal et al., 2015] Analysed the drying behavior of rough rice in a deep bed by solving the heat and moisture transfer equations numerically that is not suitable for continuous drying. [Mukhopadhyay & Siebenmorgen, 2018] worked on continuous cross-flow deep bed drying of paddy.

[Taghinezhad et al., 2020; Chokphoemphun & Chokphoemphun, 2018] studied the quality property of paddy in different types of dryer and moisture content prediction of paddy drying in fluidized bed dryer respectively by mathematical modeling but using ANN(artificial neural network) assessment. [Pati et al., 2016]experimentally studied mass, heat, and momentum transfer in vortex chambers for drying paddy. [Beigi et al., 2017; Tohidi et al., 2012]have done exergy analysis and energy and quality aspect analysis of paddy in laboratory-scale deep bed convective dryer at different inlet drying air temperatures and flow rates experimentally not numerically. [Li et al., 2020] analyzed heat loss in the multistage, deep bed counter-flow paddy drying process. [Jha & Tripathy, 2021] studied numerical modeling and heat and mass transfer during solar drying of paddy, and the simulation studies were performed using COMSOL software. [Kumar et al., 2021] developed a mathematical model and computer program for continuous deep bed drying, but he has not studied tempering and second stage drying processes.

2.3. Literature survey for fluidized bed wheat drying.

Recirculation of exhaust air has been found to be suitable to make fluidized bed drying economical for wheat, as reported by [Giner & de Michelis, 1988]

Whereas, a number of mathematical modeling and experimental works have been reported on fluidized bed drying of particulate materials [Haron et al., 2017. Sivakumar et al., 2016.; de Souza et al., 2012; Sundaram et al., 2016; Khanal et al., 2013] , no general numerical algorithm has been revealed in the published literature for the solution of the set of governing equations which are highly implicit in nature containing coupled heat and mass transfer equations.

[Jittanit et al., 2010; Hemis et al., 2009] worked on thin layer fluidized bed drying of wheat. [Abu-Hamdeh & Othman, 2004] designed and constructed a fixed bed dryer, and drying experiments of wheat were carried out under various conditions.[Jittanit, Srzednicki, & Driscoll, 2010] studied the effect of two-stage fluidized bed drying of wheat. [Turhan et al., 2001] dried wheat by forced and natural convection at different temperatures. Magnetic resonance images have been taken periodically during drying, which indicates Fick's diffusion is not applicable to describe the moisture transfer during drying of wheat grains. [Gong et al., 1997] developed a two-dimensional finite element simulator for the drying of wheat for jet spouted beds. [Jittanit, Srzednicki, & Driscoll, 2010] modified Page's model and the two-compartment model by adding the drying temperature term. These models predict the drying curves under a wider range of temperatures with a root mean square of the difference between model-predicted and experimental values of less than 0.035.

2.4. Literature survey for corn drying.

[Bruce et al., 1993.] Developed a mathematical model of grain drying for counter flow beds along with an investigation of crossover of air and grain temperatures. They performed the validation of the crossover effect in a bench-scale counter-flow dryer under appropriate experimental conditions selected using the simulation model.[Valença et al., 2000] designed and verified mathematical models and computational methodologies for parallel flow grain drying analysis. They used a steady-state model to replicate the Concurrent flow drying. A better method based on simulation of the operation beginning from initial transient conditions was developed to address mathematical problems that appeared in the modeling of countercurrent flow drying under the operating condition that leads to thermodynamics equilibrium in any segment of the dryer level. They put the mathematical models and numerical methodologies to the test by comparing computed results to experimental data for corn drying.

By considering coupled heat and mass transmission within grains, [Sitompul et al., 2001] created a heterogeneous model for deep bed cereal dryers based on a two-phase model. They also take into account axial mass and heat dispersion in the fluid phase, solving the dynamic two-phase equations by finite difference with an alternating direction implicit method algorithm, and then applying the results to simulate temperature and humidity profiles of drying gas across dryers, as well as grain moisture levels and temperature.

. [Srivastava & John, 2002] proposed a grain drying model. They have used the thin layer semi-empirical equations for predicting the air humidity, air temperature, and grain temperature with the variation of the height of a fixed bed of grains in the unsteady state. They also incorporated the effects of air velocity and voidage. The coupled partial and ordinary differential equations were solved by a backward implicit numerical scheme and the Runge-Kutta method.[Istadi et al., 2002] developed a comprehensive mathematical and numerical model of deep-bed grain drying. The models involve momentum, energy, and mass conservation into account inside the grain and drying air phases. They solved the two-dimensional dynamic equations of mass and energy conservation numerically using the finite-difference method (FDM) and the interchanging direction implicit algorithm inside the seed and drying air phases, while momentum conservation was solved using the finite difference method and the Semi-Implicit Method for Pressure-Linked Formula (SIMPLE) algorithm. [Mandas et al., n.d.] Developed a computer program for the simulation of a non-equilibrium numerical method for static-deep-bed barley drying As a consequence of mass and energy balances and heat transfer equations, the model is composed of four non-linear partial differential equations, as well as a suitable diffusion equation. They used a finite-difference technique using a 2nd order iterative predictor-corrector process and a 1st order iterative procedure to solve the equations. [Sitompul, 2003] Ram created two-dimensional models of deep-bed grain dryers that took into account momentum, heat, and mass transfer during the drying stage, as well as coupled heat and mass balance in the particle phase. The finite-difference technique is used to solve the dynamic equations numerically. The pressure drop and velocity field of the drying air across the bed are simulated using momentum equations.[Lacerda et al., 2005.] The heat and mass transmission between air and soybean seeds in a countercurrent moving bed drier was investigated using a two-phase model. They established the numerical results to the model by employing a computer code based on BDF techniques (Backwards Differentials Formulas). The experimental results for air humidity and temperature, as well as seed moisture levels and temperature at the dryer output, were matched to the model values, and there was a satisfactory agreement.[Aregba et al.,2006.] Ram conducted a comparison study among a logarithmic model and the Giner's differential model for simulating fixed deep bed drying of a material. The application range of the logarithmic model looks to be more restricted than Giner's model; nonetheless, it is far more parsimonious than the numerical estimates of the differential model, and it may be employed by decision system for the construction of driers.

[Dariush Zare & Chen, 2009] developed a numerical model for fixed-bed batch drying of rough rice in order to predict the profiles of grain average moisture content, grain temperature, air temperature, and air humidity during the drying process. In order to evaluate the validity of his model, they designed and fabricated a laboratory-scale fixed bed batch dryer and carried out comprehensive experiments. A good agreement was found between the numerical results and the experimental results. They enhanced the dryer performance after validating the model by reducing specific energy usage under identical evaporation of water using the simulation model.

2.5. Literature survey for kaolin drying.

A strong research effort focused on coupled heat and mass transfers and the mechanical behavior of materials during drying has been done. Researchers [Hammouda & Mihoubi, 2014a]worked on the equilibrium isotherm of clay material [Zagrouba et al., 2002] proposed mathematical modeling for drying of clay. [Mihoubi et al., 2002] also developed a mathematical model for different drying modes for kaolin, [Pourcel et al., 2007] investigated the crack formation during drying. [Hammouda & Mihoubi, 2014b] studied different isotherm models for kaolin drying. [Vid Baumann & Keller, 1975] studied mechanical properties like the density of the kaolin clay. [Basma et al., 1994] investigated the effect of the drying method on the engineering and physical and engineering property of clay. [Oliveira et al., 2018] studied different thin-layer model for drying of clay material. [Saleh. N Ahdiri et al., 2017] investigated the physical property of kaolin clay. [Peter et al., 1992] unsaturated the behavior of soils and the mechanics of cracking during drying. [Y. Li et al., 2017] found the relationship between water drop penetration time and soil water content and found how water drop penetration time effect wetting processes and drying processes. [Prime et al., 2016; Hasatani et al., 1993; Hu et al., n.d] did an experimental investigation on the effect of drying on shrinkage of the clay. [D. Mihoubi et al.] Developed a two-dimensional drying model for clay material that deals with heat and mass transfer and the accompanying deformation of the dried material. [Ketelaars, 1994]studied Shrinkage and Moisture concentration gradients in the ceramic material and which led to drying stresses. [Manel et al., 2014] studied the effect of induced strain stress within deformable media at different drying conditions and also investigated the drying kinetics, and the energy consumption during drying.

2.6. Outcome of literature review:

From the above literature survey, we find that simulation studies on a different type of dryer are being carried out. It is observed from the list of above literature that researchers have been using models of varying levels of complexity for simulation and experimental studies of different bed dryers. Most of the models reported in the literature are based on thin-layer drying, batch type using a fixed bed model or deep bed cross-flow drying; however, no work has been reported on deep bed continuous counter-flow drying of canola and rice and work reported on ceramic material is also in very less. The thin-layer drying model does not simulate water vapour mass transfer phenomena at the outer surface of the particles accurately since the surface moisture content and temperature of the drying air get changed continuously with time during the drying process. Therefore, the present work simulates the convective mass transfer boundary condition at the particle's outer surface in an exact numerical manner where the mass transfer potential changes with time during the passage of material in the dryer.

Also, the available general software capable of solving coupled heat and mass transfer cannot be comfortably used for analysis and design of each product/equipment’s combination; therefore, an individual appropriate computer program is needed for individual cases. Hence, to cater to the need, an algorithm has been developed and is being reported for the present study. It has been used to analyze the drying behaviour of different materials in a continuous counter-flow deep bed dryer and other types of the dryer. The proposed model provides scope for accurate simulation of change in boundary conditions at the outer surface of the particle, such as that occurring during the use of drying air with a different temperature and/or moisture content after a period of time. The present model has the advantage of incorporating the variation in the diffusion coefficient of moisture inside the particle with temperature and moisture content.

2.7. Objectives

The objective of the present study is to report a comprehensive algorithm for the sequential solution of five governing equations to be solved simultaneously, including (i) moisture mass balance between material and air, (ii) convective heat transfer rate from air to material, (iii) enthalpy balance between the material and the drying air, and (iv) convective moisture mass transfer rate from material to air. The fifth equation is a partial differential equation for moisture diffusion inside the particle, from center to outer surface, with particle radius and time as independent variables. The latter is directly proportional to the distance traveled along the bed length. An implicit discretization of the partial differential equation for mass diffusion through particle is considered, and a tri-diagonal matrix algorithm (TDMA) is used for its solution. And also to analyze the effect of exhaust air recirculation and tempering for drying in dryer and conduct experiments to validate the proposed model.