CERTIFICATE

This is to certified that the work contained in the thesis titled **"Drying of particulate materials and ceramic materials"** by **Mr. Dhiraj kumar** (Roll No. **15031004**), in partial fulfillment of the requirement for award of degree of **Doctor of Philosophy** at **Indian Institute of Technology (B.H.U) Varanasi,** is a record of his own work carried out under my supervision and guidance and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

Supervisor

Prof. Ram Pyare

Professor

Department of Ceramic Engineering

Indian Institute of Technology

(Banaras Hindu University)

Co-Supervisor

Prof. M. Prasad

Professor

Department of Mechanical Engineering

Indian Institute of Technology

(Banaras Hindu University)

DECLARATION BY THE CANDIDATE

I **Dhiraj Kumar** (Roll No.15031004) certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of *Prof. Ram Pyare* and *Prof. M. Prasad* from 2015 to 2021, at the **Department of Ceramic Engineering**, Indian Institute of Technology Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied from any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, theses, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

Date: Signature of the Student

Place: Varanasi **(Dhiraj Kumar)**

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of our knowledge.

Supervisor
Prof. Ram Pyare
Professor
Department of Ceramic Engineering
IIT (BHU) Varanasi

Co-Supervisor
Prof. M. Prasad
Professor
Department of Mechanical Engineering
IIT (BHU) Varanasi

Head of Department

भारतीय प्रौद्योगिकी संस्थान
काशी हिन्दू विश्वविद्यालय

IIT INDIAN INSTITUTE OF TECHNOLOGY
BANARAS HINDU UNIVERSITY

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: Drying of particulate materials and ceramic materials

.

Name of the Student: Dhiraj Kumar

Copyright Transfer

Date: Signature of the Student

Place: IIT BHU, Varanasi (**Dhiraj Kumar**)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for author's personal use provided that the source and the Institute's copyright notice are indicated.

Acknowledgment

I wish to express my sincere gratitude to my supervisor **Prof. Ram Pyare,** Department of Ceramic Engineering, Indian Institute of Technology (BHU), for his awe-inspiring guidance, kind cooperation, and constant support throughout this research work. I also wish to express my deepest sense of respect and sincere gratitude to my co-supervisor, **Prof. M. Prasad,** Department of Mechanical Engineering, Indian Institute of Technology (BHU), for his able supervision, constant help and kind assistance. Without their supervision and cooperation, this work would not have been possible to finish.

I am grateful to my research progress evaluation committee (RPEC) members **Dr. Manas Ranjan Majhi**, who is also my programme coordinator, Department of Ceramic Engineering, Indian Institute of Technology (BHU), and **Dr. Arnab Sarkar**, Department of Mechanical engineering, Indian Institute of Technology (BHU) for their kind succor during the research work. I am also thankful to **Prof. Vinay Kumar** (Head, Department of Ceramic Engineering IIT (BHU) and **Prof. Devendra Kumar** (Former Head, Department of Ceramic Engineering IIT (BHU) for providing the necessary facilities in the department to endure the research work.

I am thankful to **Dr. Anil Kumar**, **Dr. Preetam Singh**, and other teaching faculties of the Department of Ceramic Engineering. I am also grateful to **Dr. Jahar sarkar and Dr. S.S Mondal,** Department of Mechanical Engineering, for their support and cooperation.

I have obliged all the technical staff, especially Mr**. Bhagmal Singh**, **Mr. Shailendra**, **Mr. Pawan Kumar**, **Mr. Vinod Kumar, Mr. Mansa Ram, Mr. Madan,** and **Mr. Raj Kumar Mishra** for their assistance during the research activity.

I wish to thank my seniors, **Dr. Vikash Kumar Vyas, Dr. Vijay Yadav, Mr. Vipul Saxena,** and colleagues and juniors **Dr. Akher Ali, Mr. Nayan Kr Debnath, Mr. Satyendra Kumar Singh, Mr. Debajyoti Mahapatra**, for their help and support.

I would like to thank **Prof. Abanti Sahoo,** Department of Chemical engineering, National Institute of Technology Rourkela**,** for their tremendous help and support in carrying out my experimental work. I am thankful to all of my friends, seniors, and juniors who always believed in me and supported my decisions.

I am thankful and indebted to my family members, especially my grandfather, father, mother, and wife **Er. Roshani Kumari** and my beloved son, **Rudra Bhardwaj,** for their unconditional support in doing my research.

Finally, I would like to thank the most powerful, the **GOD**, the creator of this universe, for giving me this opportunity, strength, and courage to accomplish this research work.

Date:

Place: Varanasi Dhiraj Kumar

My thesis is dedicated to

My Beloved Family

Their Blessings and Prayers are enduringly with me to succeed in my life cycle.

Table of Contents

LIST OF FIGURE

LIST OF TABLES

List of symbols

Nomenclatures:

Ar	Archimedes number
Area	Total Area of a bed element exposed to air interaction (m^2)
Cp_a	Specific heat of air (J/kg K)
Cp_v	Specific heat of vapour (J/kg K)
Cp_w	Specific heat of water (J/kg K)
Cp_m	Specific heat of material (J/kg K)
C_{jm1}	Water diffusion conductance between pair of nodes j and (j-1) in the spherical particle,(kg/s)
C_{jp1}	Water diffusion conductance between pair of nodes j and (j+1) in the spherical particle, (kg/s)
CS	Cross-sectional area of dryer (m^2)
D_{wg}	Diffusivity of water in the material particle,(m^2/s)
D_{wa}	Diffusivity of water in air,(m^2/s)
Dp	Diameter of grain (m)
Ga	Mass f low rate of dry air (kg/s)
Gm	Mass flow rate of dry material (kg/s)
h	Heat transfer coefficient (W/m^2 K)
h_{fg}	Latent heat of vaporization of free water, (kJ/kg)
h_{fgm}	Latent heat of vaporization of water contained inside material, (kJ/kg)

$[2502.2 - 2.39\,T_m)(1 + 0.5\,e^{-14.5\,X})]$ empirical formula of h_{fgm} for canola**[1]**

h_m Mass transfer coefficient (kg/m^2)

$H_{m,I}$ Material enthalpy at i node (J/kg)

$H_{m,i+1}$ Material enthalpy at (i+1) node (J/kg)

$H_{a,i+1}$ Air enthalpy at (i+1) node (J/kg)

$H_{a,I}$ Air Enthalpy at i node (J/kg)

$H_{a,\ in}$ Enthalpy of inlet air (J/kg)

$H_{a,\ out}$ Enthalpy of outlet air (J/kg)

H Height of the dryer bed (m)

J_d Mass transfer factor

Ka Thermal conductivity of air (W/m K)

LB Length of Bed (m)

LMTD Logarithmic Mean Temperature Difference

LMYD Logarithmic Mean Humidity Difference

M Dry mass of each element of a single particle, kg, [= $(4/3)_{\pi} r_o^3\ \rho_m$ /NEP]

m Total mass of the grains in the bed (kg)

NEB Number of elements along dryer length

NEP Number of elements along particle radius

Nu Nusselt number

P_{atm} Atmospheric pressure (Pa)

P_v Air vapor pressure (Pa)

P_{vs} Air saturation vapor pressure (Pa)

Pr Prandtl Number

r Particle radius, m

r_o Particle outer radius, m

R universal gas constant (k J/mol K).

R_o Radius of the particle (m)

R Radius at any point inside grain (m)

Re_p Reynolds number for particle based superficial velocity

RH Relative Humidity (decimal)

Sc Schmidt number

t Time (s)

T_m Temperature of material (°C)

T_{m1} Temperature of material at 1st node of dryer (°C)

T_{mi} Temperature of material at ith node of dryer (°C)

T_{amb} Ambient air temperature (°C)

T_{dp} Dew point temperature (°C)

T_{ain} Temperature of inlet air (°C)

T_{min} Temperature of inlet material (°C)

T_a Temperature of air (°C)

T_{a1} Temperature of air at 1st node of dryer (°C)

T_{ai} Temperature of air at ith node of dryer (°C)

Tdp Dew point temperature (°C)

Usup Superficial Velocity of air (m/s)

VG Volume of grain (m^3)

VB Bed volume, m^3, [Bed length x Bed width x Bed height]

W_m Mass flow rate of material (kg/hr) (wet basis)

W_a Mass flow rate of air (kg/hr) (wet basis)

X_{in} Inlet moisture content of material (kg water/kg dry basis)

X_{out} Outlet moisture content of material (kg water/kg dry basis)

Xm Distributed moisture content of grain (kg water/kg dry basis)

X_{m1} Value distributed moisture content at 1st node in grain (kg water/kg dry basis)

X Average moisture content in grain (kg water/kg dry basis)

x_1 Moisture content of center of grain (kg water/kg dry basis)

x_1^p Previous value of moisture content of grain at centre (kg water/kg dry basis)

x_j Moisture content of grain at intermediate point (kg water/kg dry basis)

x_j^p Previous value of Moisture content of grain at intermediate point (kg water/kg dry basis)

x_{NEG_+1} Moisture content of grain at outer surface (kg water/kg dry basis)

$x_{NEG_+1}^p$ Previous value of Moisture content of grain at outer surface (kg water/kg dry basis)

x_{NEBP1} Distributed Moisture content of grain coming out from dryer (kg water/kg dry basis)

Y Humidity of air (kg water/ kg dry air)

Y_{eq} Equilibrium humidity of air (kg water/ kg dry air)

Y_{in} Inlet air humidity (kg water/ kg dry air)

Y_i Humidity of air at i node (kg water/ kg dry air)

Y_{i+1} Humidity of air at i+1 node (kg water/ kg dry air)

$Y_{eq,I}$ Equilibrium humidity of air at i node (kg water/ kg dry air)

$Y_{eq,i+1}$ Equilibrium humidity of air at i+1 node (kg water/ kg dry air)

Z	Coordinate in vertical direction (along bed height)
E	Voidage (decimal)
φ	Sphericity (%)
ρ_p	Density of material (kg/m^3)
$(\Delta T)_m$	Logarithmic mean temperature difference for heat transfer from air to grain for a dryer element,(°C),
$(\Delta Y)_m$	Logarithmic mean air moisture concentration difference for mass transfer from grain to air for a dryer element, (kg/kg),
ρ_a	Dry air density,(kg/m^3)
ρ_m	Dry particle density,(kg/m^3)
ϵ	Void fraction (Fraction of bed volume occupied by ait)
μ_a	Dynamic viscosity of air (kg/m-s)
ΔP	Pressure Drop (Pa)
ΔH_S (i)	Heat of sorption of material with X(i) moisture content,(kJ/kg), [= $h_{fgm} - h_{fg}$]

Preface

Drying is essential in many sectors, such as food and ceramic materials. For the food sector, drying is used as a method of preservation. The vaporizing of water provokes a cracking of ceramic materials during firing at high temperatures. So the water used for forming must imperatively evacuate before firing, so the necessity of the drying operation. Hence, in this thesis, an investigation has been carried out to analyze coupled heat and mass transfer phenomena during steady-state and different drying modes. To carry out this study, a non-equilibrium drying model and related computer program have been developed for different drying processes considering other materials like biological and ceramic. Governing equations include moisture mass balance, enthalpy balance, heat transfer rate, an element's mass transfer rate, along bed height. And diffusion equation of moisture inside a single kernel has also been solved simultaneously through an implicit scheme using TDMA (Tri-Diagonal Matrix Algorithm). An iterative approach has been used to solve the governing equations for a selected geometry of the dryer. The rating analysis can be used for arriving at improved quality and higher dryer efficiency. The simulation program developed is fairly general and can be used for any material. The detailed performance prediction results can be used to arrive at an optimum design. To quantify the enhanced performance characteristics and fulfill the research gaps, numerical and experimental investigations have been done on a different type of dryer using different kinds of material.

This thesis is divided into 11 Chapters.

Chapter 1 introduces the thesis work, including the background related to drying and drying phenomena. It describes different drying techniques, other types of dyer, the need for drying, and their application for biological and ceramic materials.

Chapter 2 includes the literature review and objective of the investigations. The literature review sought the recent drying trend like different drying models for different dryers, different types of drying materials, and different drying mechanisms. The objective of the present study includes the importance of a new mathematical model and related computer programs.

Chapter 3 describes the experimental procedure and preparation of materials and a brief description of the instruments used and characterization techniques.

Chapter 4 depicts the mathematical modeling in detail for different types of dryers.

Chapter 5 reports Performance analysis of deep bed drying of canola seeds using a numerical technique in detail. And full drying performance and rating analysis of deep bed dryers have been investigated, and numerical study has also been validated with experiment.

Chapter 6 presents a sequential numerical technique for efficient utilization and quality improvement of rough rice using multistage deep bed drying with tempering. This study investigates the effect of tempering in drying, and multistage drying has been studied in detail. And the experiment has been done to validate the mathematical results.

Chapter 7 presents a sequential numerical technique for analyzing coupled heat and mass transfer phenomena during fluidized bed drying of particulate materials with exhaust gas recirculation and application to wheat drying. In this chapter, the performance of a fluidized bed dryer has been studied. The effect of recirculation on the drying performance of the dryer has been investigated in detail. An experiment has also been done to validate the program.

Chapter 8 describes the design analysis of continuous counter-current deep bed drying of corn through modeling and simulation.

Chapter 9 explains an experimental and sequential numerical technique to study the effect of environmental conditions during fluidized bed drying of kaolin clay. The effect of drying rate on the quality of the product has also been examined. And the experiment has been done throughout the year in different sessions to test the mathematical model.

Chapter 10 The outcome of the entire investigation was summarized. This chapter also includes the future scope, a suggestion based on the results, and explanations acquired in this effort.

Chapter 11 Summarizes the overall general conclusions covering chapter 6 to chapter 10 and future scope of the drying.