Mathematical Modelling of Drying Kinetics of Wheat in Electron Fired Fluidized Bed Drying System

Dayananad N. Deomore¹, Ravindra B. Yarasu²
¹Assistant Professor, D.Y. Patil College of Engineering and Technology, Kolhapur (MS), India.
²Associate Professor, Government College of Engineering, Nagpur (MS), India.
E-mail: d_deomore@msn.com

Abstract. The conventional method of electrical heating is replaced by electron firing system. The drying kinetics of wheat is studied using electron fired fluidized bed dryer. The results are simulated by using ANSYS. It was observed that the graphs are in agreement with each other. Therefore, the new proposed electronic firing system can be employed instead of electrical firing. It was observed that the drop in Relative Humidity in case of Electrical heating is 68.75% for temp reaching up to 70°C in 67 sec for pressure drop of 13 psi while for the electronic Firing system it is 67.6% temp reaches to 70°C in 70 sec for pressure drop of 12.67 psi. As the results are in agreement with each other it was concluded that for the grains like wheat which has low initial moisture content both systems can be used.

1. Introduction
Solid particles, when suspended in a liquid or gas, behave like a fluid. This physical process is called as fluidization. The media used for fluidization is generally gas (gas-solid), but liquid-solid system is also important area of research. Drying is the oldest and most commonly used operations in process industry. The applications of drying can be found in diverse fields such as agricultural, chemical, food, pharmaceutical, pulp and paper, mineral, polymer, ceramic, and textile industries. Industrial dryers consume a significant fraction of the total energy used in many manufacturing process on average some 12%. For an individual dryer, energy costs account for the bulk of the overall costs, typically some 60-70% [1]. The strategy of modelling followed by system optimization and overall experimental validation of the results is a cost-effective and efficient method for furthering drying technology.
Electron firing is a novel concept. Conventionally the air is heated by means of electrical heating and the hot air is flown through the bed comprising drying material. In electron firing air is flown over electrodes which will carry free electrons along with it. When the electrons come in contact with bio-material (wheat in our case), due to effect of ionization heat is generated which in turn is responsible for drying of grains. The modelling is done by assuming the physics behind this process by using ANSYS and the results were compared with experimental results obtained by conventional electrical heating system. Also, mathematical modelling is done for the same parameters by using MATLAB. All the results were compared with each other to check the feasibility of employing electron firing system.

¹ To whom any correspondence should be addressed.
2. Electron Firing System
Free electrons in a vacuum can be manipulated by electric and magnetic fields to form a fine beam.

Where the beam collides with solid-state matter, electrons are converted into heat or kinetic energy. This concentration of energy in a small volume of matter can be precisely controlled electronically, which brings many advantages without any damage in its bio properties [2]. Figure 1 incorporated with electron direction, its bombardment on biomass body and related fire point. This effect remains for some specific time for specific area, which increases the specific heat area of biomass solid for some specific time period, and this particular area makes more heat gain from surrounding for some specific time. Independent of time component the area makes solid mass to gain heat around the mass. This also makes solid mass to gain equal heat in all direction. [3]

We had proposed the model shown in figure 2 to employ the same. The inner diameter of the fluidized bed heater is 0.2 m and the total height 3.5 m allowing bed depths up to 0.5 m. The fluidization air is preheated electrically during the startup operation. This we called as an ELECTRON FIRE SYSTEM or pre heating chamber as shown in figure 3. During the test runs both the air-preheated systems are turned off. The bed material consists of sand with a particle size ranging from 1 to 1.5mm and 95% silica content. The bed height (static state) was 25 cm. Heating element/material fed pneumatically or manually at the above of the Pre-heater chamber from a hopper mounted on a weighting scale through a variable speed screw feeder. In order to study the influence of different parameters in removing moisture content of rice husk, the tests were done in different operating conditions. The modified variables were the furnace temperature and the fluidization velocity. The preheating chamber consists of a pipe having three tungsten carbide rods, which act as heating elements. Tungsten rod is used as it has melting point of 3200°C. Either we can use aluminum alloy instead of tungsten. The rods are heated by passing a 12V D.C. supply through it. 240V, 50 Hz A.C. supply is converted to 12V D.C. supply using a rectifier, regulator and filter. To trigger the heating the electric arc gets generated which further leads to ionize the air around it. A nozzle is used through which ionized air is passed which increases the velocity of the air input to the main heating chamber. It triggers the heating of bio element on the basis of hot ionized bed. Once heating gets at its higher side the electric supply to the pre-heating chamber is disconnected. The temperature controller will measure the internal energy of the main heating chamber. The pre-combustion chamber is also disconnected from the main heating chamber using a gate valve. Hence the advantage of advanced electron fire bed system/heater is that in this system continuous electric supply is not required, which results into electricity conservation,
which is the need of present hour. Pre-heating chamber also gives us an advantage of automation i.e. automatic ON-OFF regulator. The heated secondary air is introduced at below pre-heating levels through two pipes fabricated tangentially to main heating chamber to ensure swirl and to increase heating coefficient. It increases electron kinetic energy, electron fire flash point, i.e. electron associated with solid heat.

![Figure 2. Electron Fired Fluidized Bed Dryer](image1.png)  
![Figure 3. Combustion Chamber](image2.png)

3. Experimental Setup:

For present study, a laboratory scale fluidized bed dryer system was fabricated [4]. The setup comprises of a fluidized bed column, electric heater and blower. Air is supplied via a root blower and then passed through a Nichrome heater. The fluidization air was supplied by a blower with flow rate measured by air flow sensor connected at the outlet of blower. The orifice plate for fluid flow in closed conduits was designed as per ASME standards. The blower was set to deliver steady state discharge. The temperature of fluidized air was measured, which was approximately 40°C. A distributor plate was designed to distribute the air evenly into the system. The plate has 2 mm diameter holes drilled on a 6-mm square pitch. This gives 8.0% open area on the plate. The pressure drop across the distributor plate and the bed was measured by another differential transducer. The bed pressure drop was measured across the freeboard and 3 cm above the distributor plate. The data was displayed in an LCD display unit attached to the system. And readings were tabulated at regular interval of time.

The cylinder bed column is made of Cast iron with 7mm wall thickness, 175mm internal diameter with overall length of 1200 mm. A digital thermometer was used to measure the temperature at inlet and outlet of the bed. The wall temperature was measured at 60 mm above the distributor plate on the inner side of the column. All digital thermometers were same type and specifications are given in Table 1.

Humidity transducer was located before the exit to measure relative humidity of exit air. The specifications of relative humidity are given in Table 2.

| Table 1. Specifications of Digital Thermometers. |
|----------|--------|------|------|------|----------|
| Type     | Material          | Probe Diameter | Maximum Temperature | Length | Junction Type |
| DS18B20  | High quality stainless steel tube encapsulation | 1/8 inch | 125°C | 4 inch | enclosed   |
Table 2. Specifications of Humidity Transducer

| Type     | RH-Range | Temperature | Accuracy | Sensor   | Output Signal |
|----------|----------|-------------|----------|----------|---------------|
| DHT11    | 20-90%   | 0-50°C      | ±5% RH   | DF Robot | 4-20 mA       |
| DHT11    |          |             |          |          |               |

The wheat sample was taken from middle region of well mixed bed to determine its moisture content. The granule samples were analysed for moisture content with moisture analyser.

4. Material and Methodology

One of the test materials used was Indian Hexaploid wheat. The shape of wheat grain is ellipsoidal, the thread being in the direction of longer diameter. In this study, however, for simplicity the numerical solution of the wheat is assumed to be spherical with an average diameter of 3.66 mm and density of 1215 kg/m³.[5]

The moisture diffusion coefficient \( (D) \) of wheat is given by Becker [6]

\[
D = \frac{1}{130.5} \exp\left[\frac{-6140}{T_P}\right]
\]  

(1)

Thermal Conductivity \( (k_t) \) and Specific Heat \( (C_P) \) of Wheat are given as [7]

\[
k_t = 0.1167 + 0.1318 \left(\frac{M_p}{1+M_p}\right)
\]  

(2)

\[
C_P = 1398.3 + 4090.2 \left(\frac{M_p}{1+M_p}\right)
\]  

(3)

4.1 Method of Grain Conditioning

The grains taken for the experiment had moisture content of 10-18% on a dry basis initially. In order to raise the moisture content to 21-40% and simulate condition of newly harvested grain, water was added to the material [8]. The conditioning procedure used in this work was carried out by filling a plastic bucket with necessary amount of grain. The calculated amount of water was added to raise the moisture content to the desired value and at the same time the grain was mixed with a mechanical agitator. The grain was stored at room temperature for 48 hours with repeated mixing at periodic intervals. The bucket of the grain is then stored in a refrigerator at 5-7 degree centigrade until drying time to prevent degradation or germination of the grain. Generally, the storage time was 5 days and after that sample was used in the experiment.

4.2 Moisture Content Determination of the Grain

Before starting experiment moisture content of the grains were determined. The moisture content of the grain was determined by a standard method developed by American Society of Agricultural Engineers, ASAE standard: S352.2. Table 3 shows the sample weight and temperature and time of drying.

Table 3. ASAE standard for drying of the grains

| Grain | Weight of Sample | Temperature(±6°C) | Drying Time |
|-------|------------------|-------------------|-------------|
| Wheat | 10 g             | 130               | 19 hours    |
Weights of the dry gains were taken before and after conditioning for determination of the moisture content of the gain. All moisture content refers to in this work are on a dry basis. The moisture content on a dry basis is calculated by:

\[ M_p = \frac{W_{B} - W_A}{W_A} \]  

(4)

\( W_B \) = Weight of grain before drying  
\( W_A \) = Weight of grain after drying  
\( M \) = Moisture content of a grain on a dry basis

The moisture content on a wet basis is given by

\[ M_{PW} = \frac{M_p}{1+M_p} \]  

(5)

4.3 Experimental Conditions

The range of moisture for wheat is between 22 to 5 ± 1 wt %. Experiments were carried out for the same range of moisture content. The experiment was started with 10 gm of weight and 20 wt % moisture of wheat. Readings were taken for relative humidity, pressure drop, temperature and time. The data collected was recorded for two minutes.

4.4 Drying Run Procedure

Initial moisture content of the sample was determined before drying. In order to attain a uniform working condition, hot air is blown through the bed for five minutes before charging with the material. The air supply and power to heater was turned off as bed reached required temperature, the material was charged into bed as quickly as possible. The air supply and heat power are then reinstated and the pressure drop across the distributor and the bed at the corresponding gas velocity was measured. Temperature, pressure, humidity, and velocity are taken continuously at regular interval of time through LCD display attached to the system. Since the digital thermometers and the humidity transducer were exposed to hot air before the start of the drying process, there might be some experimental errors in the initial reading of them.

5. Results and Discussion

5.1 Experimental Results

| Values                                | Temperatures |
|---------------------------------------|--------------|
|                                       | 30°C | 40°C | 50°C | 60°C | 70°C |
| Time (sec)                            | 0     | 15   | 30   | 40   | 67   |
| Relative Humidity at Bed Height       | 61%   | 54%  | 42%  | 25%  | 25%  |
| Relative Humidity of Exit Air         | 1.60% | 2.56%| 3.48%| 4.38%| 5.23%|
| Pressure (psi)                        | 8     | 8    | 8    | 13   | 13   |

Table 4. Experimental Results Obtained for Wheat
Table 5. Results Obtained from CFD analysis of Electron Fired System

| VALUES                  | TEMPERATURES |
|-------------------------|--------------|
| Time (sec)              | 20°C  | 33.8°C | 41.9°C | 52.7°C | 62.08°C | 74.3°C |
| Relative Humidity at Bed Height | 81.20% | 65.80% | 52.30% | 42.20% | 29.80% | 26.30% |
| Pressure (psi)          | 0.8   | 6.85   | 7.33   | 8.49   | 11.34  | 12.67  |

5.2 Results Obtained by CFD

- **Solution Methods**

  In the Spatial Discretization section of the Solution Methods pane, change the Gradient to Green-Gauss Node Based. This gradient method is suggested for tetrahedral meshes.

  The VOF model can model two or more immiscible fluids by solving a single set of momentum equations and tracking the volume fraction of each of the fluids throughout the domain. Typical applications include the prediction of jet breakup, the motion of large bubbles in a liquid, and the motion of liquid after a dam break, and the steady or transient tracking of any liquid-gas interface.

- **The Donor-Acceptor Scheme**

  In the donor-acceptor approach, the standard interpolation schemes that are used in ANSYS Fluent are used to obtain the face fluxes whenever a cell is completely filled with one phase or another. When the cell is near the interface between two phases, a “donor-acceptor” scheme is used to determine the amount of fluid advected through the face. This scheme identifies one cell as a donor of an amount of fluid from one phase and another (neighbor) cell as the acceptor of that same amount of fluid, and is used to prevent numerical diffusion at the interface. The amount of fluid from one phase that can be convected across a cell boundary is limited by the minimum of two values: the filled volume in the donor cell or the free volume in the acceptor cell.

  The orientation of the interface is also used in determining the face fluxes. The interface orientation is either horizontal or vertical, depending on the direction of the volume fraction gradient of the qth phase within the cell, and that of the neighbor cell that shares the face in question. Depending on the interface's

  A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases. The momentum equation, shown below, is dependent on the volume fractions of ρ and μ

  \[
  \frac{\partial}{\partial t} (\rho \bar{v}) + \nabla (\rho \bar{v} \bar{v}) = \nabla \rho + \nabla [\mu (\nabla \bar{v} + \nabla \bar{v}^T)] + \rho \bar{g} + \bar{F} \quad (6)
  \]

  One limitation of the shared-fields approximation is that in cases where large velocity differences exist between the phases, the accuracy of the velocities computed near the interface can be adversely affected.

  Note that if the viscosity ratio is more than 1x10^3, this may lead to convergence difficulties. The compressive interface capturing scheme for arbitrary meshes (CICSAM) (The Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM) is suitable for flows with high ratios of viscosities between the phases, therefore solving the problem of poor convergence.

  When the electric potential solver is enabled, ANSYS FLUENT solves the following electric potential equation
∇(σ∇φ) + S = 0 \hspace{1cm} (7)

where

φ = Electric Potential
σ = Electric Conductivity in a solid Zone or Ionic Conductivity in Fluid Zone
S = Source Term

In the iterative scheme, all the equations are solved iteratively, for a given time-step, until the convergence criteria are met. Thus, advancing the solutions by one time-step normally requires a number of outer iterations as shown in Figure. With this iterative scheme, non-linearity of the individual equations and inter-equation couplings are fully accounted for, eliminating the splitting error. The iterative scheme is the default in ANSYS Fluent. Figure 7 shows, when the air is passed through the electrodes, it carries free electrons with it. The mathematical equations are used to simulate the phenomenon in ANSYS. When the electrons come in contact with bio-mass, they emit heat energy. The rise in temperature is seen to be 75.2 °C. Figure 8 shows the relative humidity of the air which in turn is responsible for drying of grain.

Various trials are run by using the concept of electronic firing. The first trial is after 2 sec when the temperature of grain is 300°C and the relative humidity is 81.25%. The results are shown in figure 9 (a). From figure 9 (b) it is clear that with time the temperature of grain goes on increasing while the relative humidity goes on decreasing. After 80 sec of trials run the temperature is raised to 172°C while the relative humidity is dropped to 23.24%.

Figure 4. Ionization of Electrons
Figure 5. Interaction of Free Electrons with biomass

Figure 6. (a) Temperature and Relative Humidity after 2 sec

Figure 6. (b) Temperature and Relative Humidity after 80 sec.
5.3 General Agreement

Drying tests were carried out on the wheat particles to obtain complete and reliable experimental results for comparison with the results of mathematical model. Different types of data are collected during each experiment run. These are: temperature at different bed heights, humidity of outlet air, bed pressure drop, air velocity, and moisture content of material at different times. These data compare reasonably well with the results of the mathematical model. Temperatures namely 49.5 °C and 65.0 °C to show the degree of agreement between the model and experimental data. For all practical purposes, the most important aspect of the drying result is the agreement of moisture content between prediction and experimental data. However, other parameters are also very useful for understanding the nature of drying and its physiochemical properties.

5.4 Effect on Relative Humidity with Respect to Time

Figure 10 and figure 11 present a comparison of the model prediction for the relative humidity with the experimental results. As can be seen from the figures, a very good match was observed between electron fired system, the experimental and theoretical results. The drying rate is very high at the initial stage due to rapid evaporation of surface moisture. But it decreases exponentially when all the surface moisture evaporate and the drying front diffuses inside the particle. Usually, surface moisture evaporates very fast due to high heat and mass transfer coefficient in fluidized bed systems. A constant rate drying period is not seen for the given condition.

Model prediction is in good agreement with experimental results except for the initial stage of drying. This can be explained by the fact that the high drying rate at the initial stage is very short lived and its detection by experimental devices is difficult.

As seen in the figure, after the initial stage of drying, the variation of exit humidity is very small. At the initial stage of drying, a difference between experimental and numerical results is obvious. This may be attributed to the initial response time of humidity transducer. Before the start of the test, the value of humidity is very low (equal to the inlet relative humidity) it then undergoes through a fast change, so the transducer may not have enough time to respond quickly to these changes. Furthermore, the existence of a filter on the transducer probe which prevents from contacting particles with the tip of the probe, makes the response time even longer.

The relation between the relative humidity and the temperature obtained from the study is shown in the figure 10, and figure 11. As it is evident from the graph that the results obtained are very good match for electron fired system and experimental study. At the initial stage, there is a large decrease in relative humidity with increase in temperature this is due to the presence of surface moisture which is easy to remove but as the surface moisture decreases it becomes hard to remove the moisture from beneath the surface thus the decrease in relative humidity at the later part of the study is less.

![Figure 7. Experimental Observation for Variation in Relative Humidity with Temperature](image-url)
Figure 8. Variation in Relative Humidity with Temperature using Electron Firing System

Model prediction is in good agreement with the experimental observations but there are some discrepancies with the electron fired system at intermediary stages which can be due to the fact that experimental results were recorded at a fix time interval but the electron fired results were generated at every instance.

6. Conclusions

- The drop in Relative Humidity in case of Electrical heating is 68.75% in 67 sec while for the electronic Firing system it is 67.6 % in 70 sec.
- The drop in relative humidity for Conventional system is 68.75 % for temp reaching up to 70°C in 67 sec, while for electron firing system it is 67.6% and temp reaches to 70 °C in 70 sec
- The drop in Relative Humidity in case of Electrical heating is 68.75% for pressure drop of 13 psi while for the electronic Firing system it is 67.6 % for 12.67 psi.
- The drying rate of electrical heating fluidized bed and electron fired fluidized bed are in good agreement with each other. Therefore, the conventional system can be replaced by electron fired system.

References

[1] R. E. Bahu, “Energy Consumption in Dryer Design,” Elsevier Science Publishers, pp. 553-557, 1991.
[2] D. C. Joy, “http://web.utk.edu,” [Online]. Available: http://web.utk.edu/~srcutk/htm/interact.htm. [Accessed 21 2 2014].
[3] “http://cas.sdss.org,” Sky Server, [Online]. Available: http://cas.sdss.org/dr6/en/proj/advanced/spectraltypes/energylevels.asp. [Accessed 24 5 2015].
[4] D. N. Deomore and R. B. Yarasu, “Mathematical Modelling and Simulation of Fluidized Bed Drying System,” International Journal of Application or Innovation in Engineering & Management (IJAIEIM) , vol. 6, no. 1, pp. 52-60, 2017.
[5] E. Hajidavaloo and F. Hamdullahpur, “Thermal Analysis of a Fluidized Bed Drying Process for Crops. Part 2: Experimental Results,” International Journal of Energy Research, vol. 24, pp. 809-820, 2000.
[6] H. A. Becker and R. A. Isaacson, “Wheat Drying in Well Stirred Batch and Continuous Moving Bed Dryers,” Can J., Chem. Eng., vol. 48, pp. 560-567, 1970.
[7] E. A. Kazarian and C. W. Hall, “Thermal Properties of Grain,” Transaction of the ASAE, vol. 8, pp. 33-37, 1965.

[8] H. A. Becker, “A Study of Diffusion in Solids of Arbitrary Shape, with Application to the Drying of the Wheat Kernel,” Journal of Appl. Polym. Sci., vol. 1, pp. 212-226, 1959.