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A Study of Efficient Drying Parameters for Bed Dryers

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Abstract - The main aim for this present work is to prove that higher efficiencies can be achieved when the allotted drying time is considered as a parameter of the drying cycle. The paper investigates how to theoretically calculate the most efficient drying parameters for wheat based on the ambient conditions and allotted drying time. Drying in the constant and falling rates is discussed through mathematical models developed for each drying period. Drying air temperatures between 290 and 370 Kelvin, and drying air velocities between 0.3 and 5.3 meters per second are explored. The wheat is dried from a moisture content of 0.22 kilograms of water per kilograms of dry basis to a moisture ratio of 0.05. Energy and exergy efficiencies are utilized as a determining factor for most efficient drying parameters. The results prove that the dryer is most efficient when the dryer runs at 370 Kelvin and 0.3 meters per second when the allotted drying time is less than 21.7 hours. An allotted drying time between 21.7 and 25.4 hours would require a drying air temperature between 290 and 293 Kelvin, and a drying air velocity of 0.3 meters per second. If the allotted drying time is greater than 25.4 hours, the ambient drying air temperature is most efficient due to no energy input. Results from mathematical models are compared to experimental results and it shows a good correlation with an average percent error of 5.9 percent.

Keywords: Wheat drying, Fluidized bed dryer, High efficiency drying parameter, Allotted drying time, Energy efficiency, Exergy efficiency, Mathematical model

1. Introduction

Drying is utilized to remove moisture from a moist solid by converting the moisture into a gaseous state. In most drying applications water is the liquid being removed and air is the drying medium that provides the heat transfer to the water. Drying is useful in many different applications throughout the world ranging from food to pharmaceutical. Currently the most common and best-known practical and theoretical way to dry a particle of solid is by using convection drying with a bed dryer. Compared to other drying methods, a fluidized bed dryer has many positive features. Intense mixing during the fluidization of drying particles causes a large amount of heat and mass transfer between the drying gas and the particles being dried. This results in shortening of the drying time and a very rapid equalization of the temperature of the gas in the whole volume of the dried product, to the extent that the process practically takes place in a gradient-free field of gas temperature (Jaros and Pabis, 2007). The paper is going to focus on fluidized bed dryers.

The drying of food has many benefits but it comes at a price. Industrial dryers consume on average about 12% of the total energy used in manufacturing processes. In manufacturing processes where drying is required, the cost of drying can approach 60– 70% of the total cost (Hamdullahpur et al., 2002). Thus, to increase efficiency with drying systems has been an important research area.

Due to the lack of theoretical design knowledge and large amount of variables, the dryer design is often completed experimentally and then scaled up from the results. Many difficulties associated with mathematically modeling a fluidized bed dryer exist. One difficulty is how to determine the fluidization velocity due to irregular or non-uniform material quality. Not only is material lost through the air stream due to material collision but also the turbulent flow creates non-uniform drying for all particles. Another difficulty is that the flow patterns of the solid and gas likely differ in larger dryers when scaling up. All these variations make choosing efficient running parameters difficult and in some cases impossible without experimental data (Kudra and Mujumajar, 2009).

Throughout the years many models have been developed in order to model drying curves, including the Page's model (Wilton et al., 2014). By utilizing experimental data the variables of the models can be determined so that the drying curve can best be represented. The American Society of Association Executives (ASAE) Grain and Feed Processing and Storage Committee developed a standard that defines the drying characteristics for many grains and crops. This standard is utilized in the paper to model the falling rate of drying curve for wheat.

Wheat grain is chosen as the material to be dried. The main goal is to determine the most efficient drying parameters based on the required drying time for wheat material. The paper focuses on wheat drying, but it also provides the knowledge to develop a model for other materials and parameters, so that it may be used as a starting point for drying efficiency evaluation of many materials. Parameters such as drying air velocity, drying air temperature, and moisture content are evaluated to determine the correlation with efficiency.

2. Mathematical Models

2. 1. Assumptions and Properties

In order to perform drying calculations on wheat, material assumptions, material properties, and drying conditions must be determined. The wheat is assumed to be spherical with a diameter of 3.66mm. A particle density of 1215 kg/m^3 is used and a total weight of 1kg is dried. The initial moisture content of the wheat is set at 0.22 kg moisture/kg dry basis, similar to the freshly harvested wheat. Before drying, the wheat is assumed to have been equalized with ambient air temperature and to have uniform moisture diffusion to the surface. For the simplification of the calculations, the drying air is determined to have a relative humidity (RH) of 0%. Due to the fact that wheat does not naturally undergo a constant drying rate period unless it is harvested prematurely, all water is assumed to be bound below the moisture content of 0.22kg H_2O/kg dry solid and any greater moisture content is treated as unbound water. The unbound water has not been dissolved into the wheat and thus it is at the surface. A situation where this might occur is when the wheat is washed and then dried directly.

The ASAE S448 DEC98 standard states that the bed shall not exceed 3 layers of particles and the airflow should be at least 0.3 meters per second (ASAE Standards, 1998). The drying area is set to be 0.1246 square meters. The dryer wall is set to be adiabatic. The temperature range of the dryer may vary from 290 Kelvin to 370 Kelvin. Temperatures above 370 Kevin are not explored due to possible damage to the wheat grain. The ambient air temperature shall be constant and equal to 290 Kelvin. A stepwise transition phase is assumed instead of a continuous transition although the transition phase between the constant rate period and the falling rate period is far more complex than that shown in the calculations. The mathematical model does not take into account the kinetic or potential energy of the wheat or drying air at any given time.

2. 2. Models for Constant Rate and Falling Rate

Drying in the constant rate period requires the material that is being dried to have free or unbound moisture. Due to the fact that unbound moisture requires less energy to remove than the bound moisture, drying a material at a faster rate may be beneficial. This is true in a case where the material is at risk of absorbing more moisture such as after a washing process. One benefit of having the air velocity above the minimum fluidization velocity is to prevent the material from sticking together. Most importantly, once the material is fluidized the entire surface area of the material is exposed to the drying air. During the constant rate drying period the exposed surface area is directly proportional to the efficiency. Processes that are limited with time also benefit from using a velocity that is at or greater than the minimum fluidization velocity due to the fact that drying time is reduced.

In order to calculate the drying rate during the constant rate drying period, the drying time must be determined. The equation provided by Christie (2003) is used, that is, the time of drying as the material is dried from the initial moisture content X_1 to the final moisture content X_2 in the constant drying rate as:

$$t = \frac{L_s h_{fg}(X_1 - X_2)}{Ah(T - T_W)} \tag{1}$$

where, h = Heat transfer coefficient (W/m^2*K); h_{fg}= Enthalpy of vaporization (kJ/kg); T= Temperature of the gas (K); T_w= Surface temperature of the solid (K); A = Exposed surface area of material (m^2); L_s = Weight of the dry solid (kg);X_1= Initial free moisture content (kg free water/ kg dry solid); X_2= Final free moisture content (kg free water/ kg dry solid); t= Drying time (hr.).

Once the material enters the falling rate drying period, the material properties start to affect the moisture removal rate. The standard adopted by ASAE (ASAE Standards, 1998) provides a unified procedure for determining and presenting the drying characteristics of grains and crops. Bu be valid below 373 Kelvin, the equation for modeling the drying of wheat during the falling rate period is:

$$MR = e^{-139.3e^{\frac{-4426}{T}}t} \tag{2}$$

Where, MR = Moisture ratio (kg/kg), T = Air Temperature (K), t = Drying time (s).

2. 3. Energy and Exergy Efficiencies

The energy efficiency is defined as the energy used for moisture evaporation divided by the energy incorporated into the drying air for the length of the drying time. The definition focuses solely on the moisture removal and it excludes the temperature of the material. This is due to the fact that we are only concerned with the amount of moisture removed rather than the material temperature. The energy efficiency during this drying process is expressed as (Dincer, 2003):

$$\eta_e = \frac{W_d[h_{fg}(M_{p1} - M_{p2})]}{\dot{m}_{da}(h_1 - h_0)\Delta t} \tag{3}$$

where, W_d= Weight of dry material (kg), h_{fg}= Latent heat of vaporization of water (kJ/kg water), M_{p1}= Initial particle moisture content, dry basis (kg water/kg solid), M_{p2}= Final particle moisture content, dry basis (kg water/kg solid), $\dot{m}_{da}$= Mass flow rate of the drying air (kg/s), h_1= Initial specific enthalpy (kJ/kg), h_2= Final specific enthalpy (kJ/kg), Δt= Change in time (sec).

The energy efficiency is another tool to evaluate the drying parameters throughout all the drying periods. The exergy efficiency is commonly less than the energy efficiency due to entropy, but it follows a similar curve. The exergy efficiency can be calculated as (Dincer, 2003):

$$\eta_E = \frac{\dot{E}_{evap}}{\dot{E}_{da1}} \tag{4}$$

Where, $\dot{E}_{evap}$= Rate of exergy evaporation (kJ/s), $\dot{E}_{da1}$= Exergy of drying air entering the dryer (kJ/s).

3. Results and Discussion

3. 1. Efficiency at Falling Rate

Two of the main operating parameters on a bed dryer, which also greatly affect the energy and exergy efficiencies, are the drying air velocity and the drying air temperature. Due to the fact that wheat drying does not go through a constant rate drying period, the results are revealed only at falling rate.

Fig. 1 shows the energy efficiency in variation with the drying air velocity and temperature under the condition that wheat being the material is dried from 0.22 kg/kg moisture content down to a moisture ratio of 0.05. The energy efficiency starts out high at temperatures near ambient, but it exponentially decrease until the drying air temperature reaches 310 Kelvin, where the energy efficiency starts to increase to the maximum plotted temperature of 370 Kelvin. At the drying air temperature of 370 kelvin and 0.3 meters per second the energy efficiency reaches 4.8%. This efficiency is roughly equivalent to operating at 0.3 meters per second and 293 Kelvin with the difference of drying time. No benefit is seen when increasing the drying air velocity as expected. This is due to the fact that the drying air velocity is no longer an influence when the drying time is being determined during the falling rate period.

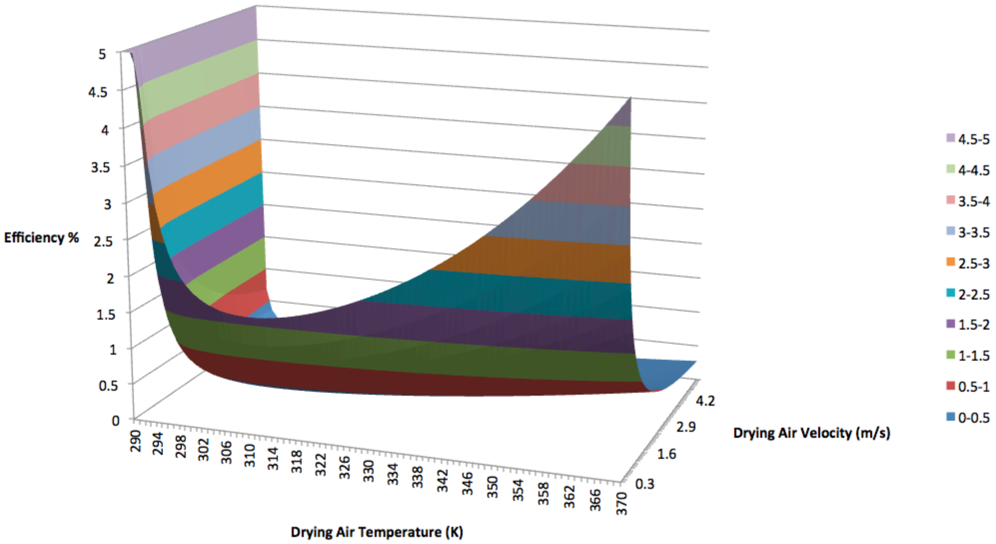

Fig. 1. Energy efficiency as a function of air temperature and velocity during the falling rate period

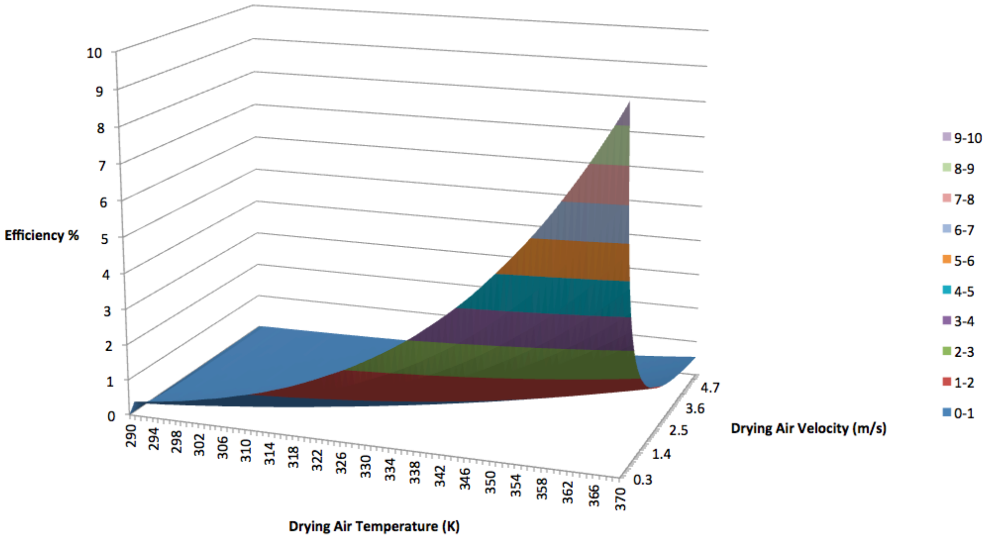

Fig. 2. Exergy efficiency as a function of air temperature and velocity during the falling rate period

The exergy efficiency plot as shown in
Fig. 2 above does not produce any negative efficiencies because the temperature of the material is no longer the wet bulb temperature. The exergy efficiency is low at drying temperatures near ambient

because the temperature of the material upon which vaporization is occurring is close to ambient. As the drying temperature is increased the exergy efficiency is also increased exponentially. At a drying air temperature of 370 Kelvin and velocity of 0.3 meters per second the exergy efficiency reaches a high value of 9.6%. This efficiency is higher than the energy efficiency because of the modifications made to the energy efficiency equations. The portion of the energy equation which accounts for the temperature increase of the material is omitted out for the purpose of this paper.

To demonstrate how energy efficiency is affected over time when the drying air temperature is held constant,

Fig. 3 as shown below is produced. In this plot the drying air velocity is set at 0.3 meters per second. As expected the efficiency starts high, but then it decreases exponentially as the moisture available at the surface diminishes and the moisture diffusion is decreased. At lower drying temperatures the efficiency remains higher because the available moisture is still high. At higher drying temperatures the energy efficiency reduces quickly because the available moisture is being reduced much faster.

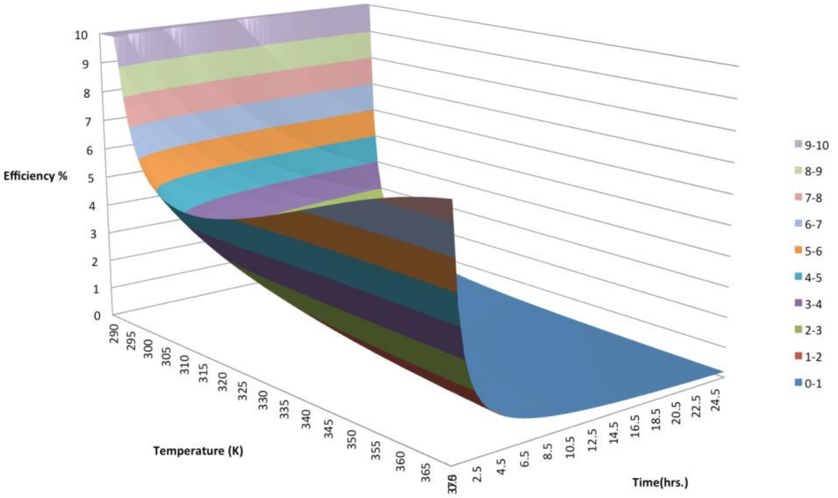

Fig. 3. Energy efficiency as a function of time and temperature during the falling rate period

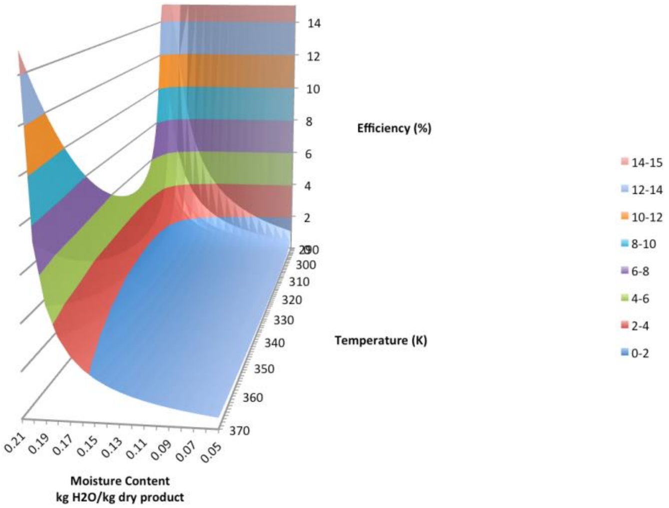

Fig. **Error! No text of specified style in document.**. Energy efficiency as a function of temperature and moisture ratio during the falling rate period

In the falling rate drying period, air velocity no longer has a significant effect on the drying rate. In

Fig. **Error! No text of specified style in document.**. above the energy efficiency is plotted as a function of the moisture ratio and drying air temperature. The drying air velocity is assumed to be constant at 0.3 meters per second for the plot. It clearly demonstrates the direct correlation with moisture ratio and efficiency. A higher moisture ratio indicates a greater moisture diffusion value to the surface at a constant temperature.

The amount of time required to reach a desired moisture ratio is dependent upon the drying air temperature. In order to show this relationship, a three dimensional plot as shown in Fig. 5 below is utilized when the drying air velocity is held constant at 0.3 meters per second. The plot demonstrates how the moisture is removed more rapid at higher drying air temperatures than that at lower drying air temperatures. The horizontal time axis starts the first data point at 1 hour and then it proceeds to the 26-hour point. A maximum of 26 hours is used because this is roughly the amount of time required to reach a moisture ratio of 0.05 at the lowest drying air temperature.

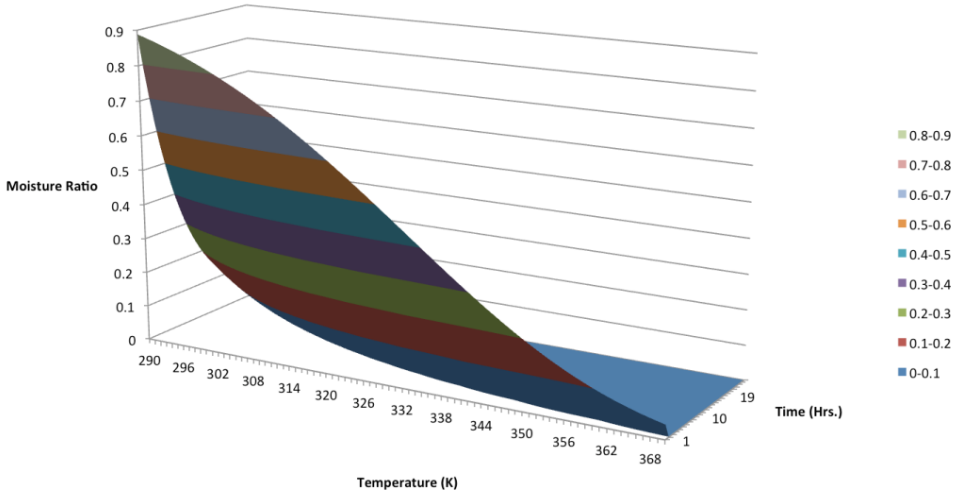

Fig. 5. Moisture ratio as a function of time and temperature during the falling rate period

3. 2. Efficient Operating Parameters Based on Allotted Drying Time

Food including wheat is commonly dried to prevent spoiling and to allow for longer storage time. If the wheat is not dried quickly enough, bacteria could spoil the grain and it would be unusable. The amount of time upon which the material must be dried could also be dependent upon the throughput requirements for the dryer, energy available or dryer limitations. In order to analyze the most efficient operating parameters based on the allotted drying time, a plot of drying air temperature versus energy used and time has been produced in Fig. 6. below. This plot is showing the amount of time and the energy that are required to dry wheat from a moisture content of 0.22 kg/kg down to a moisture ratio of 0.05. A drying air velocity of 0.3 meters per second is used because no benefit is seen with an increased drying air velocity as shown in Fig. 11. The amount of energy required when using a drying air temperature of 370 Kelvin is 9676 kilojoules. At this same drying air temperature the drying time to reach a moisture ratio of 0.05 is roughly 56 minutes. In order to dry the material to the same moisture ratio with less energy, a drying air temperature less than 293 Kelvin must be used. At a drying air temperature of 293 Kelvin, the drying time is roughly 21.7 hours. For this specific example, a drying temperature of 370 Kelvin would be used unless the allotted drying time is greater than 21.7 hours. This concept can be applied to many materials and dryers in order to determine the most efficient drying parameters.

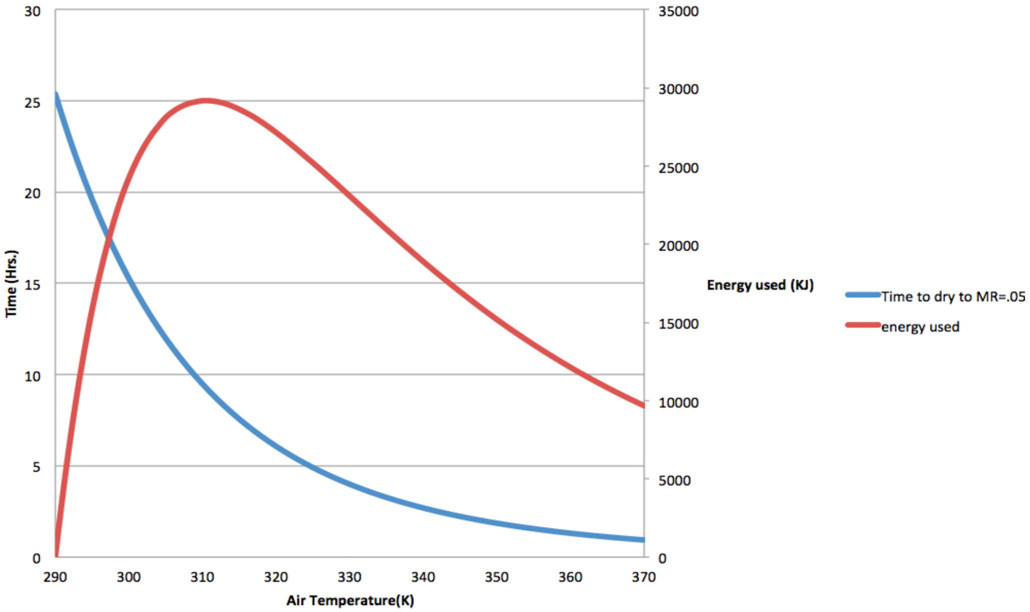

Fig. 6. Time and energy required to reach a moisture ratio of .05 during the falling rate period

3. 3. Experimental Versus Model Comparison

In order to validate the mathematical models used in the paper, a plot is produced to allow comparison between actual experimental data and the models.

Fig. 7. shows the experimental results taken from Hamdullahpur and Hajidavalloo (2000) on the same plot as the data produced from the mathematical models used in this paper. Three experimental runs at three different drying air temperatures are conducted over a 75-minute time frame. Over the 75 minute time frame the material is weighed every 5-10 minutes in order to determine the instantaneous moisture ratio. The same numbers are produced using the model and they seem to have similar results.

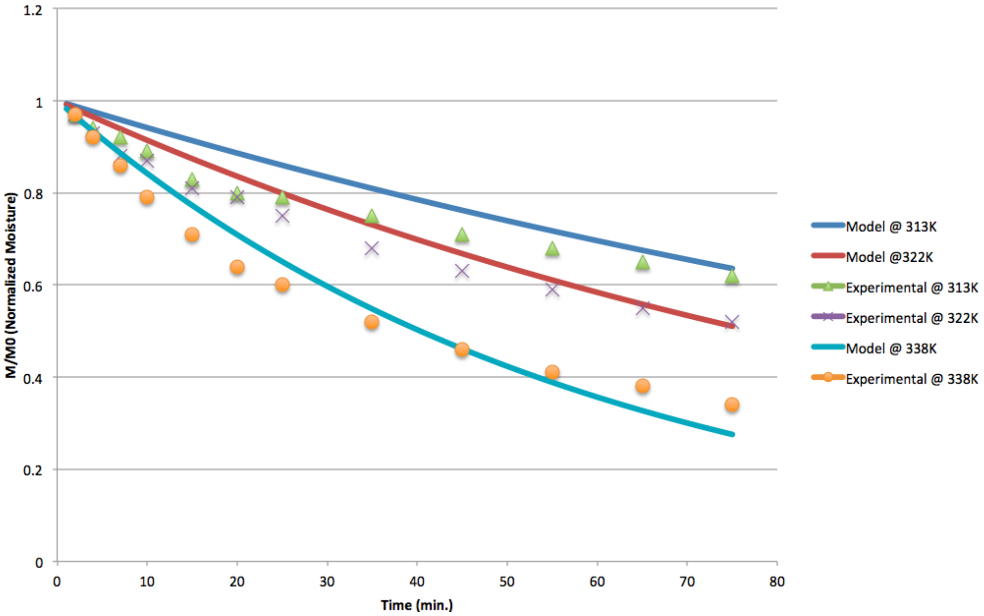

Fig. 7. Comparison of experimental and numerical results for wheat drying

The experimental results seem to decrease quicker than the model, but they return closer near the end of the 75 minutes drying period. The average percent error for the drying air temperatures of 313 Kelvin, 322 Kelvin, and 338 Kelvin are 6.04, 4.78, and 6.95 respectively. A maximum percent error of 18.9% occurs when it is being dried at an air temperature of 338 Kelvin after 75 minutes. The average combined error is 0.04 kg/kg, which equates to 5.9 percent error. These differences that can be explained are due to the variance with different wheat grains and chemical composition. The wheat size, age, growing conditions, harvesting conditions, soil type, and many others all play a factor in the diffusion coefficient. Due to the fact that the diffusion coefficient varies naturally with wheat, the theoretical model is mainly used for correlations and predictions.

4. Conclusion

Comparison of the results with the mathematical model provides the verification that the model can predict the drying rate of wheat in a bed dryer. Although the model had an average percent error of 5.9 percent, the correlation between drying air temperature and drying rate is understood. With this understanding, the most efficient drying parameters can be determined. In the case where the allotted time is less than 21.7 hours, the most efficient drying temperature would be 370 Kelvin and a drying air velocity of 0.3 meters per second. If a drying time that is greater than 21.7 hours, but less than 25.4 hours, is allotted, the drying air temperature will then vary between 290 and 293 kelvin as shown in Fig. 6.. In the case where the allotted drying time is greater than 25.4 hours, the ambient air temperature of 290 Kelvins can then be used for the drying temperature parameter. A benefit of the developed model includes being able to adapt it to many other materials and drying parameters. The allotted drying time is often not considered when the efficient drying parameters are needed to be determined and thus it is a waste of energy that otherwise could be saved.

Due to the lack of available experimental data, it would be beneficial to develop an experimental dryer to further confirm the mathematical model. This would also help determine drying air temperature and velocity limits as well as verification with other materials. Other variables as size, shape, shrinkage and bed depth that may affect the drying rate could also be explored with an experimental setup. Many areas exist in the drying of materials for further research and experiments to increase the efficiency of a dryer and to provide many benefits around the world.

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