Comparative study of mathematical and experimental models of coffee bean drying rate in a solar dryer simulator

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Abstract. The drying process of coffee beans requires heat energy to evaporate the moisture content in the material to be dried. Arabica coffee is dried at controlled temperatures (50°C, 60°C and 70°C) and wind speeds (0.4 m/s, 0.8 m/s and 1 m/s). The initial moisture content of the coffee bean test of 70% was dried to a moisture content of 11%. The drying air temperature is important for drying at high temperatures using a solar dryer simulator, which results in rapid moisture removal and reduced drying time. Drying was carried out to obtain the rate of reduction of moisture content experimentally compared to theoretically on mathematical models of drying agricultural products (Newton, Modified Henderson and Pabis and Modified Midilli). Drying parameters are related to mass loss, temperature and humidity. From the results of the calculation of the experimental water content reduction rate with 3 formulas, the closest equation is Modified Midilli.

1. Introduction

Green coffee that has a high moisture content (more than 12 % wet basis) can be damaged by bacteria, mould, or yeast, especially if the beans are dead [1]. When the relative humidity is around 70 %, the coffee beans will gradually balance their moisture. If coffee is dried with very low moisture content, the beans will shrink and become deformed, which results in low-quality coffee [2-4]. The drying in this study was carried out to obtain a moisture content of 11 %. [6]

Drying was carried out for arabica coffee beans with controlled temperature (50°C, 60°C, 70°C) and relative humidity (10%-30%). Nine dryer models were used in the study (Newton, Page, Henderson and Pabis, Logarithmic, two-term, modified Henderson and Pabis, two-term exponential, approximation diffusion, and modified Midilli). The best model is modified Midilli, which can be used to design an optimal dryer. [14,15]

From the above considerations, it is found that the mathematical model for calculating the rate of water content reduction is still being developed. So, the author conducted a study using a convective drying simulator with temperature control (50 °C, 60 °C, 70 °C) and wind speed (0.4 m / s, 0.8 m / s and 1 m / s) to analyse the effect of dryer temperature variations on the evaporation rate and time required experimentally and compare the rate of decrease in water content of the Newton equation, Modified Henderson and Pabis and Modified Midilli with experimental on the product used is coffee beans.

2. Method

2.1 Tools and Materials

The research was conducted at the Sustainable Energy Research Centre of the University of North Sumatra. This research was carried out starting from March 2023. The tools used in this research are laptop, load cell sensor, DHT21 sensor and Arduino UNO sensor. The laptop is used to store and process data that has been obtained from the HX711 Weighing Sensor and the DHT21 Am2301 sensor. Load cell sensor is a transducer (electronic component that can measure physical quantities into electrical signals) that can convert pressure by load into electrical signals. Load cell sensors are used to measure the mass or load of coffee bean specimens. The DHT21 sensor gathers digital signal data and generates output in the form of calibrated data signals to detect humidity and air temperature. When the sensor detects temperature and humidity conditions, the detected data will be matched according to the calibration coefficient value contained in the memory. Arduino UNO is an open-source electronic prototyping platform that is flexible and easy to use in creating an interactive object or environment. The Arduino UNO is an open-source

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microcontroller board designed by Arduino that is based on the Microchip ATmega32BP microprocessor. The board comes with a set of digital and analogue input/output pins that can be connected to various expansion boards and other circuits. The test material used in the forced convection dryer with Heater is arabica coffee beans. Arabica coffee beans are obtained from the Sidikalang area.

2.2 Experiment Procedure
In the implementation of the drying test, air is used to dry. Where the air contained in the drying machine is blown from the Heater, so that the air temperature will rise and flow into the open air after passing the test sample.

The following is the test procedure for drying coffee beans:

1. Ensure the machine can start by connecting to the stabilizer. And turn on the blower and heater and set the air controller value as desired.
2. Each sensor is connected to the laptop and ensures that the sensor can read the conditions so that it can generate data.
3. Preparing 100 grams of coffee beans as test material, where the coffee beans have been cleaned, peeled from the skin or have been ground.
4. The forced convection drying machine is switched on
5. If the specimen has reached a decrease in moisture content to 11% then the test is said to be complete

2.3 Observation Parameters
The research was conducted starting in March 2023. Tests were carried out with 3 variations in temperature and wind speed. Where measurements are taken every second.

So that the discussion of this final project does not widen and is directed, the discussion is limited to: Comparing the moisture content equation in Newton’s formula, Modified Henderson and Pabis, Modified Midilli with experimental results, the material dried was coffee beans with a mass of 200 grams per each test with an initial moisture content of 70%, the final moisture content of coffee beans achieved was 11%, and temperature variations (50℃, 60℃ and 70℃).

Some of the variables used in this study: Independent Variable: Mass of Coffee beans 200gram, Control Variables: Temperature of the heater, Humid and Speed, and Dependent variables: Moisture content reduction rate, diffusivity, moisture ratio and temperature in the drying chamber.

2.4 Data Analysis
Controlled mass loss, humidity and temperature data obtained from the program and measured every second were used for the calculation of moisture content loss and diffusivity in the drying model.

1. Moisture content
The moisture content contained in the product is expressed in two ways, namely wet basis and dry basis. Wet basis moisture content can be defined as the ratio of the mass of water in the product to the total mass of the product. Mathematically, the wet basis moisture content is written as follows:

\[ M_{wb} = \frac{M_0 - M_d}{M_0} \]  

(1)

Dry basis moisture content is the mass of water in the product per unit dry mass of the product, expressed by the equation:

\[ M_{db} = \frac{M_0 - M_d}{M_0} \]  

(2)

2. Diffusivity
Variation of moisture diffusivity of parchment coffee as an inverse function of absolute drying air temperature. The effective diffusivity of parchment coffee for drying air temperatures ranging from 50℃ to 70℃ and different of relative humidities 10% to 30% is temperature dependent and can be calculated as a function of temperature:

\[ D_{parchment coffee} = 8,0 \times 10^{-7} e^{-2179,9/T_{ab}} e \]  

using an Arrhenius-type equation as given in equation:

For RH=10%

\[ D_{parchment coffee} = 8,0 \times 10^{-7} e^{-2179,9/T_{ab}} \]  

(3)

\[ r^2=0,997 \]

For RH=20%
To get the value of each constant in the 3 mathematical models, the value of the constant can be used in the figure below, namely the drying condition parameter table.

### 2.5 Experimental Setup

In testing forced convection drying machines with heaters using testing tools and materials that have been described in figure 1 (a) and figure 1 (b). Data is taken automatically (sample weight, drying room temperature and drying room humidity) where the sensor is connected directly to the laptop.

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### Table 2.1 A mathematical model used to predict the drying of agricultural products.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D = 5.0 \times 10^{-9} e^{-542.28/T}$</td>
<td>Newton</td>
<td>Mujumdar, 1987</td>
</tr>
<tr>
<td>$D = 4.0 \times 10^{-9} e^{-546.25/T}$</td>
<td>Modified</td>
<td>Karathanos, 1999</td>
</tr>
<tr>
<td>$D = 4.0 \times 10^{-9} e^{-546.25/T}$</td>
<td>Modified</td>
<td>EmamiTabil Panigrahi, Ghosh, &amp; Venkatachalapathy, 2014</td>
</tr>
</tbody>
</table>

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**Figure 1 (a).** Experimental Set-up 1
3. Results and Discussions

3.1 Water Content Decrease Pattern
After conducting nine experimental drying studies of coffee beans at different temperatures (50°C, 60°C and 70°C) and wind speeds (0.4 m/s, 0.8 m/s and 1 m/s) for drying, the rate of decrease in moisture content is presented in the figure.
Figure 3. Experiment at 50°C and 1.0 m/s and tests at 60°C and 0.4 m/s

Figure 4. Experiment at 60°C and 0.8 m/s and tests at 60°C and 1.0 m/s.
Figure 5 shown the rate of decrease in water content from the first to the ninth test has a decreasing process during drying, this shows that the higher the drying temperature, the faster the decrease in the mass of coffee beans. The fastest drying time at 70°C with a wind speed of 1.0 m/s is 47.25 hours and the longest test at 50°C with a wind speed of 0.4 m/s is 69.5 hours.

To find out the number of per cent that approximates the experimental rate of decrease in moisture content from the theoretical one, we can use the equation

\[
\text{Percent Close} = \frac{\text{moisture content Theory} - \text{Experimental}}{\text{moisture content Theory}}
\]

From the results of the calculation of the experimental water content reduction rate with the Newton, Modified Henderson and Pabis and Modified Midili formulas, the closest equation to the test results is the Modified Midili formula in six tests with the smallest percent close to 3.92352612%, Modified Henderson and Pabis in two tests with the closest percent of 4.10429145% and Newton in one test with a percent of 24.4228245%.

3.2 Analysis of the Effect of Temperature Variation on the Rate of Reduction of Water Content

Figure 5. Experiment at 70°C and 0.4 m/s and tests at 70°C, 0.8 m/s, and 1 m/s
Figure 6. Effect of temperature variation with velocities of 0.4m/s, 0.8m/s and 1m/s

From figure 6, it can be seen that the drying air temperature of 70℃ shows the fastest time to reach the desired moisture content of 11%, followed by the drying temperature of 60℃ and the longest drying time occurs at 50℃.

3.3 Coffee diffusivity calculation

To calculate the diffusivity of coffee at 50℃, 60℃ and 70℃, the equation can be used:

When $T=50℃$

\[
D_{\text{parchmet coffee}} = 8,0 \times 10^{-7} e^{(-2179.9/T_o)}
\]

\[
= 8,0 \times 10^{-7} e^{(-2179.9/323.15)}
\]

\[
= 8,8 \times 10^{-10} \text{ m}^2 / \text{s}
\]

When $T=60℃$

\[
D_{\text{parchmet coffee}} = 8,0 \times 10^{-7} e^{(-2179.9/T_o)}
\]

\[
= 8,0 \times 10^{-7} e^{(-2179.9/333.15)}
\]

\[
= 1,152 \times 10^{-9} \text{ m}^2 / \text{s}
\]

When $T=70℃$

\[
D_{\text{parchmet coffee}} = 8,0 \times 10^{-7} e^{(-2179.9/T_o)}
\]

\[
= 8,0 \times 10^{-7} e^{(-2179.9/343.15)}
\]

\[
= 1,36 \times 10^{-9} \text{ m}^2 / \text{s}
\]

4. Conclusion

With an increase in temperature, the rate of decrease in water content is faster and the drying time required is shorter. This is because with an increase in the temperature of the drying air, the greater the heat energy is given to the coffee being dried and results in a difference between the heating medium and the coffee, so as to bring more water contained in the coffee. This is what encourages the drying time to be shorter. This is evidenced by the drying air temperature of 70℃ showing the fastest time to reach the desired moisture content of 11%, followed by a drying
temperature of 60℃ and the longest drying time occurs at 50℃. The maximum effective moisture diffusivity value of 70℃ drying temperature and 10% relative humidity is \(1.36 \times 10^{-9} \text{m}^2/\text{s}\). From the results of the calculation of the experimental water content reduction rate with the Newton, Modified Henderson and Pabis and Modified Midili formulas, the closest equation is obtained, namely the Modified Midili formula in six tests with the smallest percent close to 3.923526145%, Modified Henderson and Pabis in two tests with the closest percent of 4.104529145% and Newton in one test with a percent of 24.4228245%.

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**References**


[6]. *Engineer’s Notebook*. Measuring Coffee Bean Moisture Content


