

THE DRYING OF APPLES IN A LABORATORY TRAY DRIER

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The Chemical Engineering Laboratory is a senior-level course at Purdue University. Looking back, the need for the laboratory first emerged in the summer of 1935 when a required set of two unit operations laboratory courses was introduced by Prof. Clifton Lovell in the undergraduate chemical engineering curriculum. The laboratory was originally housed in Heavilon Hall, and moved to the old Chemical & Metallurgical Engineering section of Forney Hall in the summer of 1940. The two-course set evolved through the years, incorporating a historic change in the chemical engineering discipline for the experimental setups to include separation processes, transport phenomena, and reaction engineering. When the Fundamentals Laboratory was introduced into the curriculum in 2011, the senior unit operations laboratory was decreased to a single four-credit course.

The course requires students to work on three projects during a semester. One is a Measurement-Analysis Project, and two are design projects. In the Measurement-Analysis Project, students are introduced to the lab by measuring process variables in different experimental setups throughout the Unit Operations Laboratory (UOL). This requires students to complete two lab sessions before they report their measurement results. During these first two lab sessions, students work on the measurement of one or more of the significant variables, and results of statistical data analyses are reported in a memorandum. Next, students spend the remaining seven sessions on an Analysis Project, in which they conduct experiments to characterize their assigned processes. In the remaining sessions, students identify the dependent and independent variables, obtain model equations needed to characterize the operation, and perform experimental runs. The objective of the Measurement-Analysis Project is to have students apply chemical engineering fundamentals to measure process variables, design an experimental program, and analyze the results in order to characterize the process.

In the fall of 2011, Prof. Arvind Varma, the head of the School of Chemical Engineering, launched the renovation of the Unit Operations Laboratory. This upgrade was essential for chemical engineering students to gain experience using

laboratory equipment and experiments designed for today's industrial reality. The Allan H. Fox Unit Operations Laboratory now provides an industrial setting for seniors in chemical engineering to sharpen their skills and apply their theoretical training gained in the classroom. Advanced undergraduate students investigate open-ended chemical engineering design projects and engage in creative problem-solving and decision-making activities. In this laboratory, seniors develop their scale up, process design, experimental design, data analysis and testing skills, as well as experience working in diverse teams and reporting their results orally and in written form. The projects assigned in this laboratory course have involved working with a bench scale packed bed catalytic reactor, an immobilized enzyme reactor, and a soluble enzymatic reactor in which reaction kinetics and mass and heat transfer effects on reaction rates are investigated. A second set of projects has involved a variety of separations, such as gas-liquid absorption, sieve-tray fractional distillation, membrane oxygen separation from air, liquid-liquid extraction, and ion exchange recovery of salts from dilute solutions.^[1]

In planning for the renovation, feedback was gathered from both faculty and the school's Industrial Advisory Council members. It was first decided to eliminate obsolete experiments, and new experimental setups were added to supply

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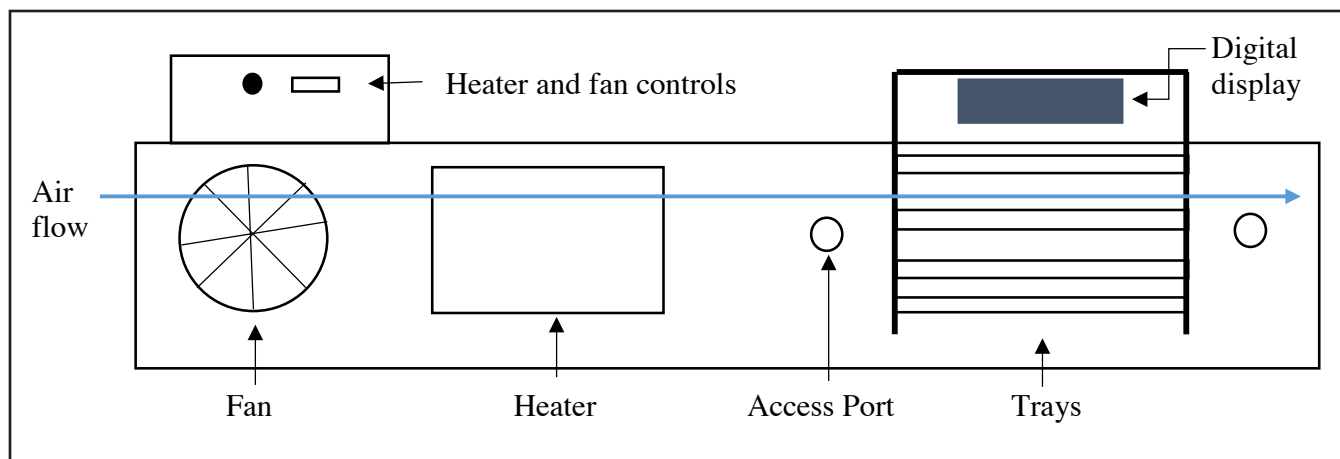


Figure 1. Schematic diagram of tray drier.^[7]

students with an even richer experience, including a process control system that can be independently operated, two water-cooling towers, three tray driers, and a flash vaporizer with a PID controller. In addition, two new design projects were developed and built in the laboratory and focused on crystallization and polymerization processes.

When the Tray Drier experiment was first used by students at Purdue, the material to dry was wet sand, like experiments used in other chemical engineering senior labs around the country. However, the wet solid was problematic for keeping a clean house whenever the driers were operated. We chose instead to dry apples, as they are much cleaner to handle and replicate a real industrial process, for which many monograph reports exist as well as research publications in the open literature.^[2-5] This provides a real-world application and allows students to find parameter values that they can compare against the ones obtained experimentally in the lab. Drying apples involves simultaneous heat and mass transfer processes.^[3] Therefore, the main objective of this study was to determine the performance of the drying process by analyzing the moisture content of the apple over time. For this purpose, a laboratory scale tray drier was used to determine the drying rate curves at different operating conditions.

In tray driers, a hot-air stream passes over the surface of the product, providing some of the heat of evaporation and acting as a medium by which water vapor is carried away from the solid. Drying occurs in three different periods, or phases. In the initial period, also referred to as warm-up period, sensible heat is transferred to the product and the contained moisture. During the second phase, or constant-rate drying period, free moisture persists on the surfaces and the rate of evaporation changes very little as the moisture content decreases. In the third phase, or falling-rate drying period, diffusion of moisture from the internal structure of the solid to the outer surface becomes the limiting factor that reduces the drying rate. The heat and mass transfer coefficients are determined during the constant-rate drying period.

APPARATUS

The tray drier used in this experiment is depicted schematically in Figure 1 (Hampden Model H-6180). The drier is a 60" long by 24" wide by 60" high unit with a uniform flow tunnel base support and control panel support. The uniform flow tunnel is a 10" square modular structure with air straighteners to insure a uniform flow and two psychrometer access ports. Mounted in front of the panel is an axial flow fan rated approximately 430 ft³/min at 1550 RPM with a variable DC motor drive. At the other end of the tunnel, in between the psychrometer access ports, is the drying compartment consisting of the balancing arm and rack assembly. The compartment is provided with a transparent access door that is opened and closed from a vice action latch.

The control panel is instrumented with a main AC circuit breaker and indicating pilot light for main power access to the panel. A separate fan switch and fan control, located adjacent to the main circuit breaker, are to control the air movement to the drying compartment. The temperature of the air can be controlled by the heater switch/variable control contained on the control panel.

For weighing the components in the drier, a digital scale capable of weighing up to 12 kilograms +/- 1 gram, is centrally located above the drier. The scale features a tare function where the user can zero the scale after putting on a load to see the load change effects. The trays with sample material to dry are placed in the rack assembly that features four compartments with a one-inch separation between trays.

Measurements were taken inside the tray drier through the access ports with a hygrometer that measures relative humidity and wet and dry bulb temperatures. An anemometer is used to measure the air speed. A peeler, apple slicer, and knife were all used prior to drying the apples to take off the skin and cut the apples into the desired amount and thickness of slices. The safety equipment used during this project included

Coefficient	Experimental Value	Literature Value Range (Reference)
Effective Diffusivity (m ² /s)	3.3 x 10 ⁻⁹ to 8.0 x 10 ⁻⁹	1.7 x 10 ⁻⁹ to 3.02 x 10 ⁻⁹ [13]
Heat Transfer (W/m ² C)	9.3 to 15.1	21.43 to 44.3 [8]
Mass Transfer (m/s)	7.0 x 10 ⁻⁸ to 4.4 x 10 ⁻⁷	5.38 x 10 ⁻⁸ to 8.39 x 10 ⁻⁸ [9] 3.7 x 10 ⁻¹⁰ to 7.4 x 10 ⁻⁹ [10]

Lab Session	No. of Slices	Height of Slice (in)	Length (in)	Radius (in)	Exposed Surface Area all slices (in ²)	Exposed Surface Area all slices (m ²)
1	8	1	3	1.375	511.0	0.330
2	16	0.5	2.75	1	635.4	0.410
3	16	0.5	2.625	1	607.4	0.392
4	24	0.25	2	0.75	497.7	0.321
5	32	0.25	2	0.75	663.6	0.428
6	32	0.25	2.25	0.875	860.3	0.555
7	32	0.25	2.75	0.875	1047.5	0.676
8	32	0.25	2.875	0.875	1094.4	0.706

safety goggles and thermal insulating gloves while handling anything at elevated temperatures.

PROCEDURE

The experiments began by slicing the apple into wedge-shaped apple slices using the apple slicer and zeroing the digital scale on the tray drier. The slices were laid on their sides and evenly distributed onto the four trays, to increase the surface area reached by air flow. The four trays were then placed upside down in the drier to prevent the lip of the tray from blocking air flow, and the weight was recorded. Controlled variables were the air temperature, the air speed, and the exposed surface area. Air temperature and speed were set using the heater set point and the fan controller. Eight experiments were conducted to perform a full factorial design, allowing students to test all levels of air temperature, air speed, and exposed surface area (see Table 1 for values tested).

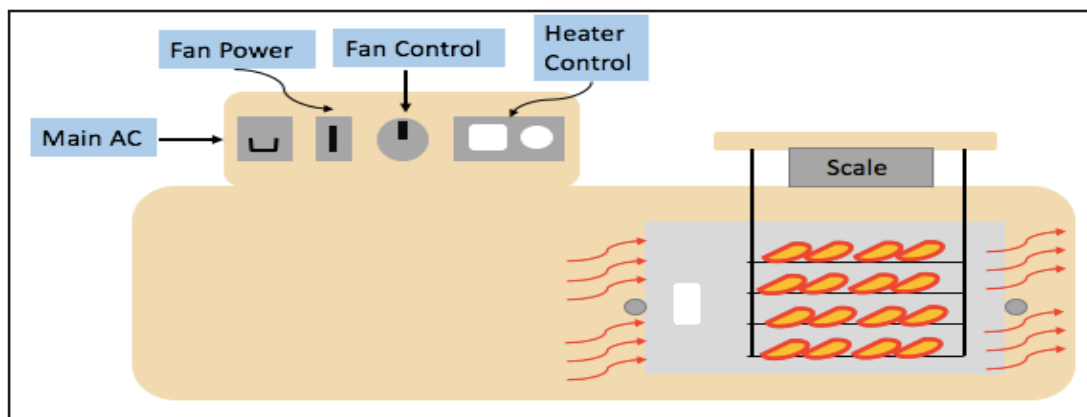
For the first experiment, the fan was turned onto the center of the range and the heater was set to the desired temperature set point. Measured variables were the relative humidity, wet bulb temperature, dry bulb temperature, and air flow rate. These variables were measured upstream and downstream of the trays using the sensors every two minutes for the first 10 minutes, and then at four-minute intervals. Even though the heater set point was 90°F, the air temperature only reached 84°F inside the drier during the initial experiments. The first experiment was set at a low air temperature and exposed

surface area with a high air speed. For the following experiments, the temperature was set by using the hygrometer inside the drier and increasing the set point on the heater until the desired temperature was reached.

Since the apple only lost 13% of its weight in the first experiment, the second experiment increased the exposed surface area by cutting all the apple slices in half so that there were 16 slices. The second experiment was set at a high air temperature and air speed with a low exposed surface area.

For the third experiment, the desired temperature was 110°F. Because this temperature was not reached inside the drier even with the heater set to the maximum set point, the fan speed was decreased until the desired temperature was observed inside the drier. The third experiment was set at a low air temperature, air speed, and exposed surface area. In the fourth experiment, the exposed surface area was increased further by cutting the apple into 24 slices. The fourth experiment was set at a high air temperature with a low air speed and exposed surface area. The fifth experiment was set at a high air temperature and exposed surface area with a low air speed. The exposed surface area was increased by cutting the apple into 32 slices and peeling the apple to remove the skin. The sixth experiment was set at a low air temperature with a high air speed and exposed surface area. The seventh experiment was set at a high air temperature, air speed, and exposed surface area. The eighth experiment was set at a low air temperature and air speed with a high exposed surface area. Table 2

Figure 2. Schematic of the apple slices positioning.^[5]



shows the details of the apple slices geometry and size, as well as the surface area available for drying. For further clarification, Figure 2 shows a schematic of how the apple slices were placed on the trays.

METHODOLOGY AND DATA ANALYSIS

In the apple drying process, heat and mass transfer occur simultaneously. Heat transfer occurs through conduction, convection, and radiation. For this experiment, negligible radiation was assumed given the relatively low temperatures used. During the initial warm-up period, the warm circulating air caused the apple slice to be heated by conduction from the outside surface to the inside of the slice, until the surface temperature of the apple was equal to the wet bulb temperature of the air, as air above the surface of the apple was saturated.^[7] The flow of warm air towards the drying trays heated the apple by convection, while mass transfer occurred across the liquid film surrounding the apple slice. When the temperature of the liquid in the apple was below its boiling point, water transport happened through liquid diffusion.^[3]

To determine the heat and mass transfer coefficients and characterize the drying process performance, we analyzed the effects of exposed surface area, air temperature, and air speed. These variables have a direct effect on the drying rate, the apple moisture content, and the air humidity. Figure

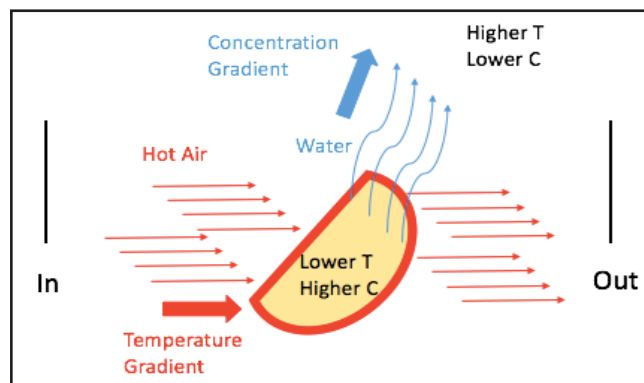


Figure 3. Schematic of one apple slice exposed to air flow.^[5]

3 shows a schematic of the shape of the apple slices and the macroscopic drying process around one slice.

A typical experimental run took anywhere from 135 to 150 minutes; therefore, students normally spent a full lab session (170 minutes) taking data from the tray drier with all three team members involved in measuring variables and registering their results in official data sheets, which they later transferred to Excel workbooks for calculations. All teams working with the tray driers reported some fluctuations in air flow rate and temperatures brought about by fluctuations in ambient air temperature and humidity. These fluctuations were not very large, but required students to smooth out their weight loss and moisture versus time curves.

To calculate the drying rate of the apple slices at different operating conditions, the weight of dry solids was experimentally determined and a total water content of 83% was obtained for the red delicious apples. This was done by drying a sliced full apple in a convective oven, at 70°C, until a constant weight was measured. Once the weight of dry solids was evaluated, the moisture content at any time was found by utilizing the following equation:

$$X_t = \frac{W - W_s}{W_s} \quad (1)$$

where

X_t = moisture content at time t [kg water/kg dry solid]

W = total product weight at time t [kg]

W_s = dry solid weight [kg]

A plot of moisture content versus time was used to determine the equilibrium moisture content, X_e . Once the equilibrium moisture content was determined, the free moisture content was found by using the following equation:

$$X = X_t - X_e \quad (2)$$

where

X = free moisture content [kg water/kg dry solid]

X_t = moisture content at time t [kg water/kg dry solid]

X_e = equilibrium moisture content [kg water/kg dry solid]

A plot of free moisture content versus time was used to determine the drying rate of the apples slices at various values of free moisture content. The drying rate was then plotted versus the free moisture content. The sections of constant-rate drying were used to determine the heat and mass transfer coefficients.

To determine the heat transfer coefficient, the Nusselt number was used as follows^[8]:

$$Nu = \frac{h_c x}{K_v} \quad (3)$$

where

Nu = Nusselt number

h_c = convective heat transfer coefficient [W/m².°C]

x = characteristic dimension [m]

K_v = thermal conductivity of humid air [W/m.°C]

An empirical correlation is used to relate the Nusselt number with the Reynolds and Prandtl numbers as follows^[8]:

$$Nu = C(RePr)^n \quad (4)$$

where

Nu = Nusselt number

C = constant

Re = Reynolds number

Pr = Prandtl number

n = constant

The rate of heat transfer utilized to evaporate moisture from the apple slices surface, during the constant drying rate period, is calculated by the following equation^[8]:

$$Q_c = 0.016h_c \{P(T_s) - \gamma P(T_e)\} \quad (5)$$

where

Q_c = rate of heat utilized to evaporate moisture [J/ m².s]

h_c = convective heat transfer coefficient [W/m².°C]

$P(T)$ = partial vapor pressure at temperature T [N/m²]

T_s = apple surface temperature [°C]

γ = relative humidity [%]

T_e = exit air temperature [°C]

Substituting for the convective heat transfer coefficient equation in Eq. (5) and dividing by the latent heat of vaporization of water and multiplying by the area of the exposed apple slices and the time interval gives:

$$m_{ev} = \frac{Q_c}{\lambda} A_t t \quad (6)$$

where

m_{ev} = moisture evaporated [kg]

λ = latent heat of vaporization [J/kg]

A_t = area of exposed apple slices [m²]

t = time [s]

where Q_c is a function of the Re and Pr numbers, as well as the empirical constants C and n and the vapor pressures at

T_s and T_e . This equation can be rearranged and linearized to determine C and n by linear regression with the data from the drying experiments. Once the constants are evaluated, the Nusselt number is used to calculate the convective heat transfer coefficient.

To determine the effective diffusivity, Fick's second law was utilized during the falling rate period, which occurs when the final moisture content is approached.^[3] The solution of Fick's second law of diffusion in transient conditions can be approximated by the following^[9]:

$$MR = \frac{W - W_s}{W_o - W_s} = \frac{6}{\pi} \exp\left[-\frac{D_e \pi^2 t}{r^2}\right] \quad (7)$$

where

MR = moisture ratio

W = total product weight at time t [kg]

W_s = dry solid weight [kg]

W_o = initial total product weight [kg]

D_e = effective diffusivity [m²/s]

t = time [s]

r = half thickness of the apple slices [m]

Taking the natural log of both sides and plotting $\ln(MR)$

versus time gives a slope equal to $\left[-\frac{D_e \pi^2}{r^2}\right]$, from which the effective diffusivity can be calculated. Furthermore, the thin-layer drying model^[8] proposes an equation in terms of drying parameters to characterize the changes of mean moisture content of food products during drying. These parameters account for the combined effect of various transport phenomena in the drying process and are shown in the following equation:

$$MR = k_o \exp(-kt) \quad (8)$$

where

MR = moisture ratio

k_o = lag factor

k = drying constant [1/s]

t = time [s]

Combining Eqs. (7) and (8) we can solve for the lag factor and the drying constant. The drying constant can then be utilized in the definition of the Dincer number as follows^[9]:

$$Di = \frac{u}{kr} \quad (9)$$

where

Di = Dincer number

u = flow velocity of drying air [m/s]

k = drying constant [1/s]

r = half thickness of the apple slices [m]

Dincer and Hussain^[10] developed a new Biot number and a correlation between the Dincer number and this Biot number that has proven to be a very useful tool for practical drying

applications:

$$Bi_m = \frac{24.848}{Di^{0.375}} \quad (10)$$

where

Bi_m = Biot number for mass transfer

Di = Dincer number

This correlation can be used to solve for the Biot number. The definition of the Biot number^[9] is

$$Bi_m = \frac{h_m r}{D_e} \quad (11)$$

where

Bi_m = Biot number for mass transfer

h_m = mass transfer coefficient

r = half thickness of the apple slices [m]

D_e = effective diffusivity [m²/s]

This definition can then be utilized to solve for the mass transfer coefficient.

SAMPLE CALCULATIONS

The sample calculations begin with the calculation of the moisture content, followed by the drying rate, the Diffusion coefficient, and finally the heat and mass transfer coefficients for experimental trial 5. As mentioned above, the apple moisture content was found to be 83%. For analysis of trial 5, determine the dry weight of the apple by the following equation:

$$\text{Dry Weight} = (1 - \text{initial moisture content}) * \text{Starting weight} \quad (12)$$

$$\text{Dry Weight}_{\text{Trial 5}} = (1 - 0.83) * 90 \text{ grams} = 15.3 \text{ grams}$$

From this we can calculate the moisture content from Eq. (1).

$$X_t = \frac{W - W_s}{W_s} = \frac{90 - 15.3}{15.3} = 4.882 \frac{\text{kg water}}{\text{kg dry solid}} \quad (12a)$$

As we graph this versus time for all points we are able to obtain the equilibrium moisture content (X_e) for this trial, the value of 0.0265 was determined. Using Eq. (2), the free moisture content is calculated.

$$X = X_t - X_e = 4.882 - 0.0265 = 4.856 \frac{\text{kg water}}{\text{kg dry solid}} \quad (12b)$$

Once the free moisture content is determined for all times, plot the results as shown in Figure 4.

From here, the drying rate can be calculated using:

$$\text{Drying Rate} = \frac{\Delta X}{\Delta \text{time}} = \frac{4.856 - 4.790}{2 - 0 \text{ min}} \frac{\text{kg water}}{\text{kg dry solid} * \text{min}} = 0.033 \frac{\text{kg water}}{\text{kg dry solid} * \text{min}} \quad (13)$$

Once this is calculated for all times, the rate values can be plotted to obtain Figure 5.

Following, the Moisture Ratio is calculated using Eq. (7) as shown for the first time interval:

$$MR = \frac{W - W_s}{W_o - W_s} = \frac{90 - 15.3}{90 - 15.3} = 1 \quad (13a)$$

After obtaining these values for all time intervals, the natural log of MR is plotted as a function of time. The slope of this line will be used to calculate the effective diffusivity. This procedure was developed by Guiné, et al.^[8] For Trial 5 the slope was

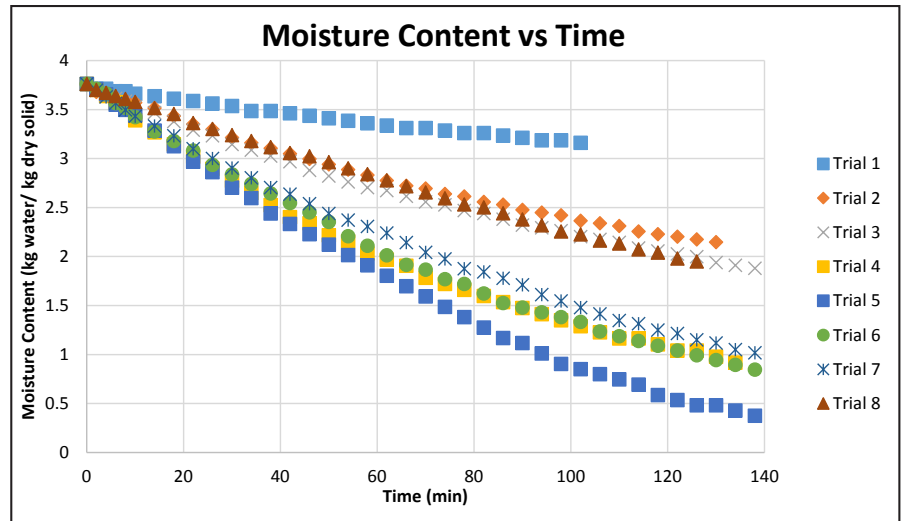


Figure 4. Moisture content as a function of time.

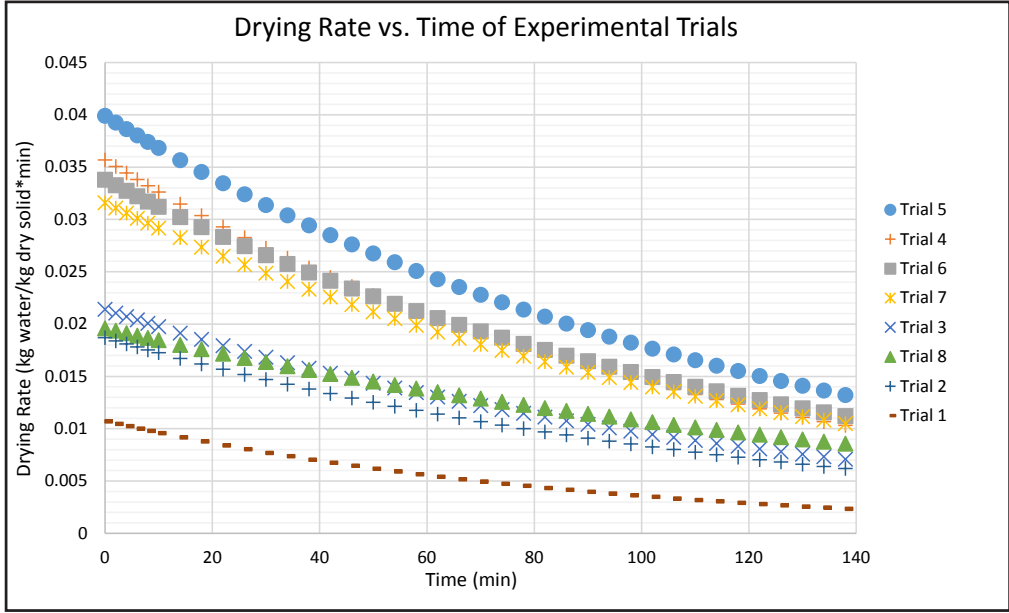


Figure 5. Drying rate as a function of time.

found to be -0.0219 and the diffusivity is calculated from:

$$\text{slope} = -\frac{D_e \pi^2}{r^2} \tag{14}$$

$$D_e = -\frac{\text{slope} * r^2}{\pi^2} = \frac{0.0127}{60(\text{sec}^{-1})} * 0.01905^2 (\text{m}^2) \tag{15}$$

Next, use Eq. (9) to calculate the Dincer number:

$$Di = \frac{u}{kr} = \frac{0.2 \left(\frac{\text{m}}{\text{s}}\right)}{0.0127 / 60(\text{sec}^{-1}) * 0.01905} = 13.66 \tag{15a}$$

and the Biot number for mass transfer can be obtained using Eq. (10)^[9]:

$$Bi_m = \frac{24.848}{Di^{0.375}} = \frac{24.848}{13.66^{0.375}} = 9.32 \tag{15b}$$

This can then be used with the definition of the Biot number, Eq. (11), to obtain the mass transfer coefficient h_m :

$$h_m = \frac{Bi_m * D_e}{r} = \frac{9.32 * 7.83E-09 \frac{\text{m}^2}{\text{s}}}{0.01905(\text{m})} = 3.83E-06 \left(\frac{\text{m}}{\text{s}}\right) \tag{16}$$

To calculate the heat transfer coefficient, a procedure developed by Anwar, et al. was used,^[7] first the average temperature of the apple slice and humid air is calculated. The apple slice is assumed to be at the wet bulb temperature.

$$T_i = \frac{T_{\text{wetbulb}} + T_{\text{air}}}{2} = \frac{17.67^\circ\text{C} + 40.06^\circ\text{C}}{2} = 28.9^\circ\text{C} \tag{17}$$

The physical properties of humid air were calculated using correlations proposed by Tiwari^[12]; the density is calculated as follows:

$$\rho_v = \frac{353.44}{T_i + 273.15} = \frac{353.44}{28.9 + 273.15} = 1.17 \frac{\text{kg}}{\text{m}^3} \tag{18}$$

The thermal conductivity of the humid air can then be calculated by the following correlation:

$$K_v = 0.0244 + 0.6773 * 10^{-4} * T_i = 0.0244 + 0.6773 * 10^{-4} * 28.9 = 1.17 \frac{W}{m * ^\circ C} \quad (19)$$

The specific heat capacity of humid air can then be calculated by:

$$C_v = 999.2 + 0.1434 * T_i + 1.101 * 10^{-4} * T_i^2 - 6.7581 * 10^{-8} * T_i^3 = 1003.4 \frac{J}{kg * ^\circ C} \quad (20)$$

The dynamic viscosity of the humid air is calculated by:

$$\mu_v = 1.718 * 10^{-5} + 4.62 * 10^{-8} * T_i = 1.718 * 10^{-5} + 4.62 * 10^{-8} * 28.9 = 1.85 * 10^{-5} \frac{kg}{m * s} \quad (21)$$

The vapor pressures at the apple surface ($T_{wet\ bulb}$) and in the air (T_{air}) are then calculated:

$$P_{apple} = EXP\left(\frac{25.317 - 5144}{T_{wet\ bulb} + 273.15}\right) = EXP\left(\frac{25.317 - 5144}{17.67 + 273.15}\right) = 2057\text{ Pa} \quad (22)$$

The Reynolds number of the air flow can then be calculated:

$$Re = \frac{\rho_v * v * d}{\mu_v} = \frac{1.17 \frac{kg}{m^3} * 0.2 \frac{m}{s} * 0.127\text{ m}}{1.85 * 10^{-5} \frac{kg}{m * s}} = 1599 \quad (23)$$

Although this airflow is not turbulent all other experimental trials were in the turbulent regime. The Prandtl number can also be calculated as follows:

$$Pr = \frac{\mu_v * C_v}{K_v} = \frac{1.85 * 10^{-5} \frac{kg}{m * s} * 1003.4 \frac{J}{kg * ^\circ C}}{1.17 \frac{W}{m * ^\circ C}} = 0.705 \quad (24)$$

The moisture evaporated at each time interval (m_{ev}) is then calculated between each time interval. It is obtained from the following parameter:

$$Y = \ln\left[\frac{m_{ev}}{0.016 \frac{K_v}{x * \lambda} (P_{apple} - \gamma * P_{air}) * A * \text{time}}\right] = \ln\left[\frac{0.001\text{ kg}}{0.016 \frac{1.17 \frac{W}{m * ^\circ C}}{0.01905\text{ m} * 225700 \frac{J}{kg}} (2056.7\text{ Pa} - 0.075 * 7282.9\text{ Pa}) * 0.1945\text{ m}^2 * 120\text{ sec}}\right] = 5.02 \quad (25)$$

Taking the natural log of the product ($Re * Pr$) and performing a linear regression analysis on the two obtained values for all time points of the trial leads to the values for the constants n and C in Eq. (4). For Trial 5, n was found to be equal to 0.6 and C equal to 0.144. These are used in the Nusselt number equation for calculation of the heat transfer coefficient:

$$h_c = \frac{K_v}{x} * C * (Re * Pr)^n = \frac{1.17 \frac{W}{m * ^\circ C}}{0.01905\text{ m}} * 0.144 * (1599 * 0.705)^{0.6} = 13.5 \frac{W}{m^2 * ^\circ C} \quad (26)$$

The calculations for each of the mass and heat transfer parameters are shown in Tables 3 and 4. Note that the denomination of Eq. (25) is listed as Z in Table 4.

RESULTS

Students are required to apply statistical analysis to their data for each project in order to determine the error bounds and statistical significance of the independent variables. In this case, the independent variables that were manipulated in the experiment—air velocity, temperature, and slice area exposed—were statistically analyzed to determine their effect on the drying performance. This allows students to determine which variables have significant effects on their experiments. Results for each of the eight experimental trials are shown in Table 5.

TABLE 3
Calculation table for mass transfer coefficient

Trial	Slope of ln(MR) vs. Time	Effective Diffusivity (m ² /s)	k_0	k (s ⁻¹)	Di	Bi	Mass Transfer Coefficient (m/s)
1	-1.58E-03	3.25E-09	0.61	1.58E-03	11400	0.75	6.96E-08
2	-4.25E-03	4.63E-09	0.61	4.25E-03	5530	0.98	1.79E-07
3	-4.88E-03	5.32E-09	0.61	4.88E-03	3905	1.12	2.34E-07
4	-9.72E-03	5.96E-09	0.61	9.72E-03	2051	1.42	4.45E-07
5	-1.28E-02	7.83E-09	0.61	7.67E-01	14	9.32	3.83E-06
6	-9.59E-03	8.02E-09	0.61	9.59E-03	4032	1.10	3.98E-07
7	-8.23E-03	6.88E-09	0.61	8.23E-03	3093	1.22	3.77E-07
8	-4.76E-03	3.98E-09	0.61	4.76E-03	2933	1.24	2.23E-07

TABLE 4
Calculation table for heat transfer coefficient

Trial	1	2	3	4	5	6	7	8
Ti (°C)	20.67	24.55	27.35	29.70	33.02	25.82	26.79	22.44
Density (kg/m ³)	1.20	1.19	1.18	1.17	1.15	1.18	1.18	1.20
K_v (W/mC)	0.02580	0.02606	0.02625	0.02641	0.02664	0.02615	0.02621	0.02592
Cv (J/kgC)	1002	1003	1003	1004	1004	1003	1003	1002
Viscosity (kg/ms)	1.81E-05	1.83E-05	1.84E-05	1.86E-05	1.87E-05	1.84E-05	1.84E-05	1.82E-05
$P_{(Te)}$ (Pa)	1636	1638	1869	2048	2335	2040	1818	1569
$P_{(Te)}$ (Pa)	3653	5730	6836	7977	10076	5425	6516	4621
Re	9114	6591	5196	3028	1561	8112	5576	3169
Pr	0.704	0.705	0.705	0.705	0.705	0.705	0.705	0.705
m_{ev}	1.03E-03	1.76E-03	1.83E-03	1.38E-03	1.90E-03	1.72E-03	2.38E-03	1.72E-03
Z	1.17E-04	1.87E-04	1.87E-04	1.49E-04	1.68E-04	1.18E-04	1.84E-04	1.52E-04
ln(mev/Z)	2.53	2.60	2.62	2.54	2.76	2.96	2.88	2.74
ln(RePr)	8.77	8.44	8.21	7.67	7.00	8.65	8.28	7.71
Heat Transfer Coefficient (W/m ² °K)	9.25	9.79	9.38	13.06	13.45	15.05	13.29	13.76

TABLE 5
Summary of results

Experimental Trial Number	Temperature (°C)	Wind Speed (m/s)	Number of Slices	Heat Transfer Coefficient (W/m ² °C)	Mass Transfer Coefficient (m/s) x 10 ⁸	Effective Diffusivity (m ² /s) x 10 ⁹
1	27.8	0.63	8	9.25	6.96	3.25
2	38.3	0.60	16	9.79	17.9	4.63
3	40	0.48	16	9.38	23.4	5.32
4	42.8	0.38	24	13.06	44.5	5.96
5	48.3	0.20	32	13.45	38.3	7.83
6	36.1	0.86	32	15.05	39.8	8.02
7	39.4	0.57	32	13.29	37.7	6.88
8	32.2	0.31	32	13.76	22.3	3.98

All three variables tested displayed significant effect on the drying rate, as seen in Figure 6 (a), (b), and (c). The air temperature exhibited the most significant effect on the drying rate, followed closely by the velocity of the air passing across the surface of the apple.

Once the variables were determined to have an effect on the drying performance, a model of the effect of the variables on the drying rate was performed. Figure 6 (d) shows the actual data obtained from the experimental procedure compared to the model prediction, and Figure 7 shows the normal quantile plot of the residuals within the model. For the specified experimental region, the drying rate was modeled by the following equation:

$$\text{Drying Rate} \left(\frac{\text{kg water}}{\text{kg dry solid} * \text{min}} \right) = 0.00267 * \left[\frac{\text{Wind Speed} \left(\frac{\text{m}}{\text{s}} \right)}{0.33} \right] + 0.00845 * \left[\frac{\text{Temp} (\text{°F})}{18.75} \right] + 0.00499 \left[\frac{\# \text{ of slices}}{12} \right] - 0.04035 \quad (27)$$

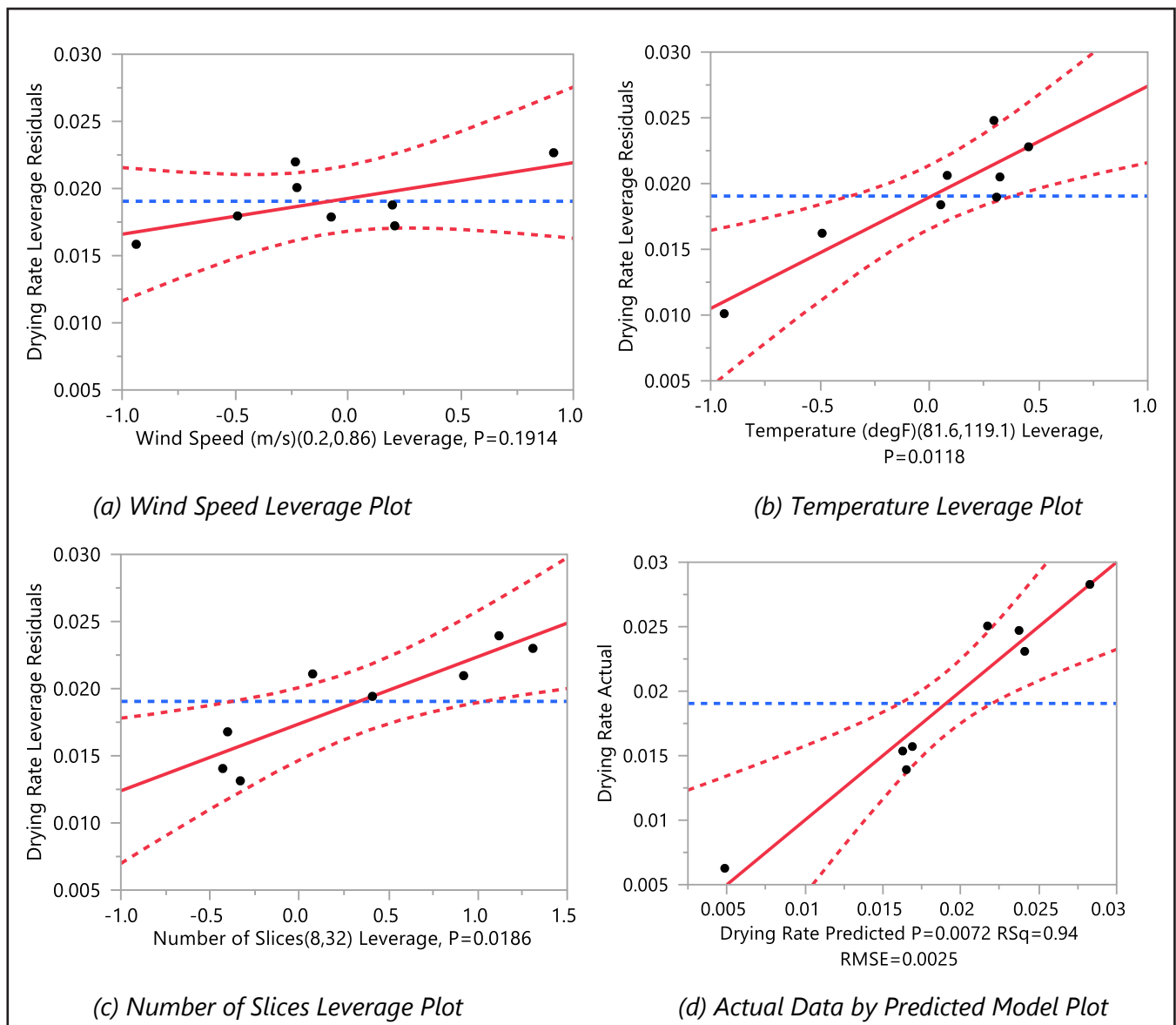


Figure 6. Leverage Plots for (a) Wind Speed, (b) Temperature, and (c) Number of Slices; (d) Model Accuracy.

The adjusted coefficient of determination of the model was found to be 89%. Possible explanations for error and model improvement are examined in the Discussion section.

DISCUSSION

Students are required to compare their experimental results with those published in recent literature when available; in this case, several publications were found with values for the diffusivity and the heat and mass transfer coefficients for apple drying. Table 1 shows a summary of the results from this work compared to those recently published by several authors. The effective diffusivity was within the range of values found by Velic, et al.^[13] while the heat transfer coefficient values from the same publication were slightly higher than the ones found by the students in this lab experiment. A notable difference between the study by Velic, et al.^[13] and the present study was the investigation of effect of air flow rate at a fixed temperature (60°C), compared to a range of temperatures (28 to 48°C). Both studies were carried out in a laboratory tray drier but the air speed range covered by Velic, et al.^[13] was larger (0.5 to 2.8 m/s) compared to the range in this study (0.2 to 0.86 m/s). This difference may explain the higher values for the heat transfer coefficients in the Velic, et al.^[13] study.

For the mass transfer coefficient, fewer past studies have published values obtained for drying apples in a similar tray drier. Guiné, et al.^[10] examined a temperature range from 30 to 60°C, and the air flow velocities varied from 0.5 to 2 m/s in a tunnel drier with much smaller dimensions than the one used in the current study. An additional study that is worth comparing against was published by Guiné and Barroca for the drying of Joaquina Pears^[9] whose results for the mass transfer coefficient are in excellent agreement with those obtained by the Purdue University students.

From the experiment, three variables were determined to have an effect on the drying rate of the apples. Upon analysis of the P Values shown in Table A1 in the Appendix, it was determined that the air speed did not have a significant effect on the drying rate of the apples from the data obtained. Although not within a 95% confidence interval, the air speed does appear to have a significant effect on the drying rate. For this reason, it was included in an empirical model. Further experimental work should be performed to fully assess the significance of this variable.

Table A2 in the Appendix shows that the other two controlled variables were relevant in the drying rate of the apples. Temperature of surrounding air had the strongest effect on the drying performance.

Although this is promising, the range of temperatures tested was only from 80 to 120°F. At some point, there will be a diminishing return from the air temperature. This could occur from either a shriveling effect on the apple slices or the apple baking instead of drying. Unfortunately, the drier used for the experiments did not allow for temperature in excess of 120°F and these limits were not obtained. The other significant effect on the drying rate was the number of apple slices obtained from an

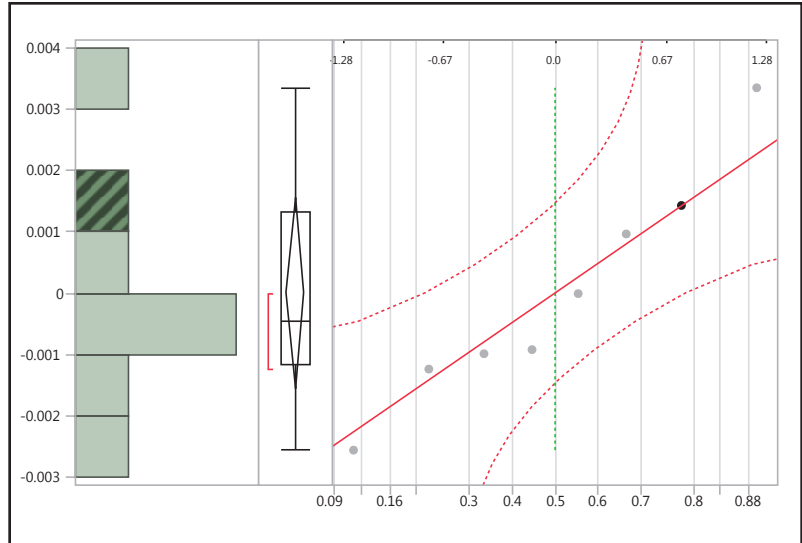


Figure 7. Residual plot distribution.

Table A1: ANOVA of the Fitted Model

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.00035999	0.000120	19.9177
Error	4	0.00002410	6.025e-6	Prob > F
C. Total	7	0.00038409		0.0072*

Table A2: Parameter Estimates and Error Analysis

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.0175015	0.000974	17.96	<.0001*
Air Speed (m/s)(0.2,0.9)	0.0026654	0.001697	1.57	0.1914
Temperature (°F)(81,119)	0.0084536	0.001927	4.39	0.0118*
Number of Slices(8,32)	0.0049941	0.001303	3.83	0.0186*

Appendix.

individual apple. This directly correlates to the exposed surface area of the apple slices and indirectly to the thickness of the apple slice. An increase in the exposed area showed a positive effect due to the extra surface area available for mass and heat transfer. The model obtained had an adjusted coefficient of determination that was lower than desired. However, this was most likely due to the uncontrollable environment in the lab. Analyzing the effect of room air humidity on the drying rate could potentially increase the accuracy of the model.

The lab in which the experiment was conducted has three driers, and we placed them next to each other in a section of the building that is well-ventilated with plenty of room for the three-student teams working on each drier. This causes some problems of fluctuations in ambient air temperature and humidity that influence the measurements inside the driers to a certain extent but not significantly. On the other hand, the proximity of three different teams to each other while working in the experiment promotes constructive discussions and exchange of ideas among students that lead to improvements in conducting the measurements and analyzing the data. One such improvement brought about through the lab student interaction was students' decision to turn the trays upside down to provide a better exposure of the apple slices to the flowing air, as opposed to what can be achieved with the normal position where the tray edge interferes with the flow of air.

Through the Measurement-Analysis Project, students learn to measure variables, determine their significance, and characterize the process. Students design and conduct an experimental program to determine the significant variables and develop a basic model for the process. Students apply chemical engineering fundamentals to determine the necessary performance data required to characterize the behavior of a pilot size equipment. Students in the Chemical Engineering Laboratory are encouraged to develop the methodology, select the theory applicable to their project, and work effectively in a team to solve open-ended project assignments. The instructor performs the role of a consultant giving advice to help the students stay on the right track, encouraging them to search the published literature to find the latest concepts and results that they can compare against their experimental findings.

CONCLUSION

The apple drying experiment has provided students at Purdue the opportunity to work on an industrially relevant application, taking extensive experimental data, with simple measuring devices that can be analyzed to generate relevant heat and mass transfer parameters. Educational objectives of this experiment were applying previous knowledge from heat, mass, and mo-

mentum transfer to the analysis of the performance of a tray drier, working under strict safety rules, performing mass and energy balances and statistical analysis of the data to obtain parameters that are compared against published heat and mass transfer coefficients, and communicating the results both in an oral progress report and in a written report that is graded both by a communications specialist and by the course instructor for the quality of presentation, writing, and technical content. Students gained a rounded experience by applying their knowledge of chemical engineering principles to an authentic context, and received constructive feedback to improve their technical and communications skills for the two subsequent design projects in the Chemical Engineering Laboratory course.

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