DEMONSTRATING SIMULTANEOUS HEAT AND MASS TRANSFER WITH MICROWAVE DRYING

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In a recent article, Nirdosh and Baird[1] emphasized the critical role that the laboratory plays in the undergraduate engineering experience. It is crucial that laboratory experiments provide practical reinforcement of the theoretical chemical engineering concepts developed in lecture courses, but due to budget constraints, it is often also necessary to develop inexpensive experiments or to make use of existing equipment. This paper describes an effective and inexpensive microwave drying experiment that can be used on a variety of levels. On the introductory level, the data analysis associated with this experiment illustrates the numerical approximation of derivatives from discrete data, while on the advanced level, the experiment develops an understanding of simultaneous heat and mass transfer.

BACKGROUND

Of all the chemical engineering unit operations, drying is one of the most widely used, with applications in various processing industries such as food processing, pulp and paper, pharmaceuticals, etc. Because of its widespread use and the fact that it may account for up to ten percent of industrial energy consumption,[2] it is therefore essential that the fundamentals of the drying process be encountered and understood by undergraduate chemical engineering students.

There are a variety of drying techniques, such as vacuum drying and spray drying,[3] each with its own operational characteristics. Conventional dryers include both direct and indirect methods of heat transfer.[4] Direct dryers (also called convection dryers) use contact between the wet solid and a hot gas to accomplish heat transfer, with the vaporized liquid being carried away by the drying gas. In indirect dryers, heat for drying is transferred through a wall that separates the wet solid and the heating medium, with the vaporized liquid being removed independently of the heating medium. Indirect dryers are also called conduction, or contact, dryers.

The driving force for heat transfer in both direct and indirect dryers is the temperature difference between the drying medium and the wet solid. In the case of microwave drying, a magnetron produces a pulsing electromagnetic field. Polar molecules such as water align with this field, and as the field direction changes, the molecules are forced to realign. These molecular oscillations create friction that generates heat, raising the temperature and causing liquid evaporation.[5] Thus, although supplied from an external source, the energy for microwave drying is often thought of as being generated *within* the wet solid.

Although the mechanism of delivering energy to the wet solid in microwave drying is different than in conventional drying, since microwave energy does not penetrate very far below the surface of the exposed material,[6] the transport processes occurring during microwave drying are very similar to those that occur during conventional drying. As liquid evaporates from the surface of the solid-liquid mixture, liq-

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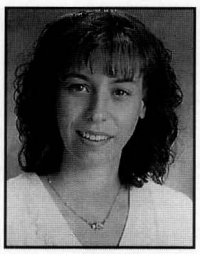

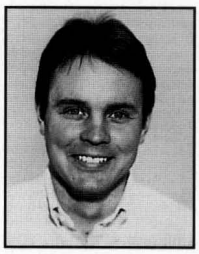

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uid from within the solid migrates to the surface because of concentration gradients. Thus, drying, either by conventional or microwave devices, inherently involves simultaneous heat and mass transfer.

The primary data obtained during a drying experiment are the moisture content as a function of time (on a dry basis the moisture content equals the liquid mass divided by the solid mass). Curve 1 in Figure 1 presents a typical moisture content curve. The moisture content data can be differentiated to yield the drying rate curve, Curve 2 in Figure 1.

$$\text{Drying Rate} = \left(\frac{-1}{m_s}\right)\left(\frac{dm}{dt}\right) \qquad (1)$$

Typically, drying rate curves for materials with a thoroughly wetted surface exhibit three periods.[7] The first stage is the warming-up period. This stage is characterized by increasing the material temperature to that of the evaporation temperature of the wetting liquid. Also, the drying rate increases as the liquid begins to vaporize. This is followed by a period of constant-rate drying where the surface moisture evaporates and moisture is steadily brought to the surface to maintain a continuous liquid film over the surface. The third, and last, period in the drying-rate curve, called the falling-rate period, is characterized by a nonlinear decrease of the drying rate due to the increasingly uneven moisture distribution over the surface. The constant-rate and falling-rate stages of the drying-rate curve are separated by the point of critical moisture content. This point marks the instant

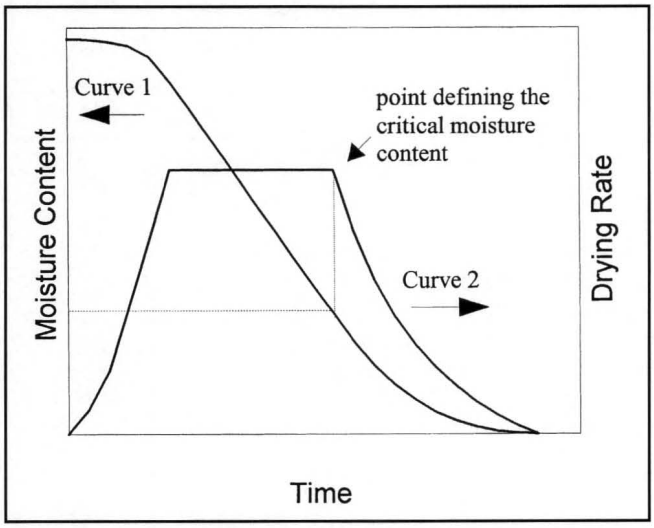

Figure 1. *Typical moisture content and drying-rate curves for a solid with a thoroughly wetted surface.*

when the liquid no longer forms a continuous film over the entire surface because the rate of moisture transport to the surface is less than the rate of evaporation from the surface. The critical moisture content is not a material property. It varies with drying rate, thickness of the material, particle size, and other factors that affect moisture movement. Critical moisture content is best determined by experiment.

APPARATUS

The equipment required for this experiment is inexpensive and easy to operate. Specifically, an off-the-shelf Frigidare MC-1100M microwave with ten power settings ranging from 72 W to 720 W was used. The power settings of the oven are in terms of percentage of the maximum power. This microwave oven is rather old, but a comparable current model could be purchased for less than $200. Other required items include a digital balance accurate to the nearest gram, a stopwatch (or the microwave timer), microwaveable trays or Pyrex glass beakers, and a thermocouple (specifically, a type T was used). Sand wetted with water was studied, with the nominal diameter of the sand particles being 600 microns.

METHOD

Wet sand in the ratio of approximately 1 kg of sand to 0.2 kg of water was used. This ratio provided the condition that all of the sand was completely wetted, but no standing pools of water were present. The sand and water were thoroughly mixed together. The mixture was weighed, spread into an even layer approximately 0.025 m deep in a 0.15x0.15x0.05 m tray that was placed in the center of the microwave oven. The microwave was started at a desired power level. The weight of the mixture was recorded every minute until the sample was dry. In addition, the surface temperature of the sand could also be monitored with a thermocouple when the sample was removed from the oven for weighing. The effect of removing the sample from the oven for weighing was examined by using various drying intervals, such as 30 seconds, 1 minute, 5 minutes, and 10 minutes. Only minor changes in the sample weight were observed for these different drying intervals. Appropriate safety precautions include wearing safety glasses and oven mitts when handling the hot tray.

RESULTS

Figure 2 presents experimental moisture content and drying rate data for the highest power setting of the microwave oven (720 W), while Figure 3 compares the drying rate

curves obtained at three power settings (720 W, 540 W, and 360 W). All of the experimental data are very similar to the idealized data of Figure 1, clearly illustrating the three stages of drying. Table 1 demonstrates the influence of power setting on the critical moisture content. Recall that the critical moisture content is not a material property; rather, it is dependent on operating conditions. The trend of increasing critical moisture content with increasing power setting is typical.[4] As the drying rate is increased (by increasing the power setting), it becomes progressively more difficult for the rate of moisture transport to the surface to remain as high as the rate of surface evaporation. Thus, the falling-rate period, which begins when the critical moisture content is reached, occurs at a higher moisture content.

During the constant-drying-rate period, a pseudo-steady state is achieved, with the power input going to the latent heat of evaporation of the liquid and energy losses. Table 2 presents the efficiency of the constant drying-rate period assuming a latent heat of evaporation of 2300 kJ/kg (corresponding to approximately 80°C). The efficiency is calculated as the energy required for water evaporation (equal to the evaporation rate, kg/s, times the latent heat of evaporation, kJ/kg) divided by the rate of energy input (kW = kJ/s). The observed efficiencies are rather high, ranging from 74% to 87%. Given the advanced age of our microwave oven, its power output is probably less than the nominal value (we accepted the nominal power outputs and did not actually measure the oven's power output). If this is true, the actual efficiencies are higher than those calculated here. The high efficiencies of microwave drying are partially due to the energy-transfer mechanism. Since energy is supplied directly to the wet solid, there is no large energy requirement for heating the drying medium as in conventional drying devices.

The efficiency decreases with increasing power level. Initially this was thought to be due to increased energy losses to the lower portions of the wet solid by conduction. At low power inputs, the temperature of the wet solid might be relatively uniform at the start of the constant-drying-rate period as conduction has had sufficient time to transport energy from the surface to the interior of the wet solid. At high power inputs, conduction may be unable to transport energy from the surface to the interior regions of the wet solid rapidly enough to achieve temperature uniformity at the start of the constant-drying-rate period. If this were the

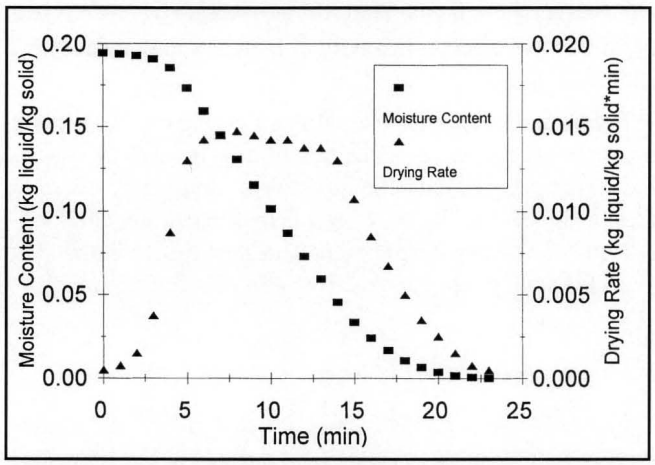

Figure 2. *Moisture content and drying-rate curves for a power level of 720 W.*

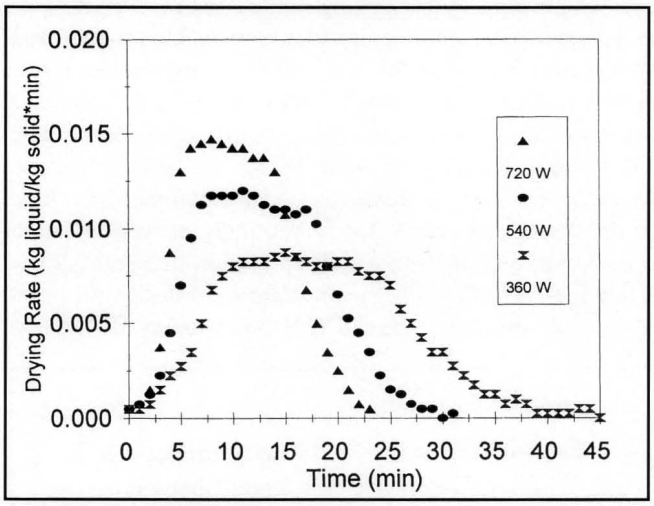

Figure 3. *Comparison of drying-rate curves for power levels of 720 W, 540 W, and 360 W.*

TABLE 1
Influence of Power Level on Critical Moisture Content for Drying Sand

Power Level	*Critical Moisture Content*
720 W	7.4%
540 W	7.1%
360 W	6.2%
144 W	5.7%
Literature value[4] (unknown power level)	5.9%

TABLE 2
Influence of Power Level on Constant Drying-Rate Period Efficiency
(from Figure 3 drying-rate curves)

Power Level (kW = kJ/s)	*Evaporation Rate (kg/s)*	*Evaporation Energy (kJ/s)*	*Efficiency*
0.360	1.36×10^{-4}	0.313	87%
0.540	1.90×10^{-4}	0.437	81%
0.720	2.33×10^{-4}	0.536	74%

case, conduction would still be removing some of the energy input from the surface to the interior during the constant-drying-rate period. This energy "loss" would lead to decreased efficiencies at high power levels. This explanation, however, loses its appeal when the energy inputs during the warming-up period are compared. These energy inputs are about 240 kJ, independent of power level. This constancy of energy input during the warming-up period indicates that energy losses due to conduction are likely to be the same for all power levels. The reason for decreasing efficiency with increasing power level requires another explanation that requires further investigation.

The drying-rate curves of Figures 2 and 3 were generated from the moisture-content curves through numerical differentiation using a central-difference method. The central-difference method is best used in cases involving large time intervals[8] as is the case with this experiment. Assuming evenly spaced data, at some time, t_i, the central difference approximation to the drying rate is

$$\text{Drying Rate} = \left[\left(\frac{-1}{m_s}\right)\left(\frac{dm}{dt}\right)\right]_{t_i} \cong -\frac{1}{m_s}\left[\frac{(m_{i+1} - m_{i-1})}{2(t_{i+1} - t_i)}\right] \quad (2)$$

The drying rates at the first and last points were generated using related forward and backward difference approximations as shown in the following equations:

First Point:

$$\text{Drying Rate} = \left[\left(\frac{-1}{m_s}\right)\left(\frac{dm}{dt}\right)\right]_{t_0} \cong -\frac{1}{m_s}\left[\frac{(-m_2 + 4m_1 - 3m_0)}{2(t_1 - t_0)}\right] \quad (3a)$$

Last Point:

$$\text{Drying Rate} = \left[\left(\frac{-1}{m_s}\right)\left(\frac{dm}{dt}\right)\right]_{t_n} \cong -\frac{1}{m_s}\left[\frac{(m_{n-2} - 4m_{n-1} + 3m_n)}{2(t_n - t_{n-1})}\right] \quad (3b)$$

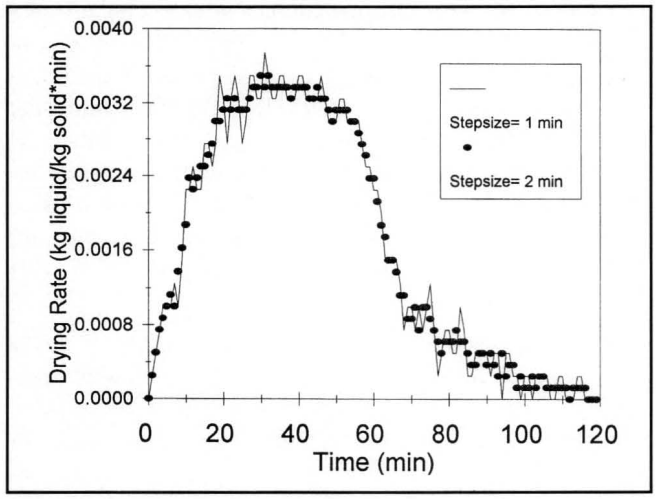

Figure 4. *Effect of step size on numerical differentiation at a power level of 144W.*

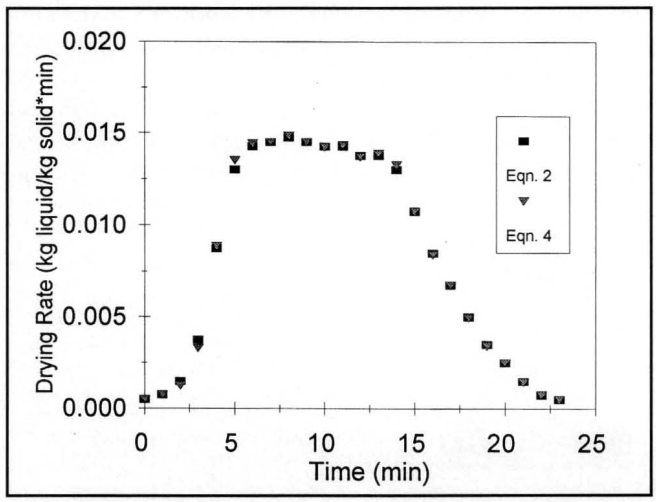

Figure 5. *Effect of truncation on numerical differentiation at a power level of 720 W.*

Figure 4 illustrates the importance of sampling interval on the numerical differentiation process. These data were taken at a low power setting (144 W), and the drying-rate curve was generated using step sizes of both one and two minutes. The drying-rate curve obtained using a step size of two minutes is relatively smooth, while the drying-rate curve obtained using a step size of one minute fluctuates, particularly during the constant-rate drying period and as the drying rate falls to zero. At this low power setting, the amount of water evaporated in a one-minute interval was approaching the accuracy of the scale, introducing significant round-off error into the calculations.

Figure 5 examines the effect of truncation error on numerical differentiation of the data. This figure compares the central difference approximation of Eq. (2) to the following, more accurate, central-difference approximation:

$$\text{Drying Rate} = \left[\left(\frac{-1}{m_s}\right)\left(\frac{dm}{dt}\right)\right]_{t_i} \cong -\frac{1}{m_s}\left[\frac{(-m_{i+2} + 8m_{i+1} - 8m_{i-1} + m_{i-2})}{12(t_{i+1} - t_i)}\right] \quad (4)$$

The minimal difference between the derivatives generated by the two differentiation formulas is indicative that truncation error is not significant in this instance and the numerical differentiation formula of Eq. (2) is sufficiently accurate.

EXTENSIONS

This experiment offers great flexibility and can be extended to examine other concepts, including temperature profiles, particle size and geometry effects, and drying characteristics of different materials.

- Temperature profiles of the solid surface can be produced by recording the surface temperature with a thermocouple when the sample is removed for weighing. Surface

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temperatures show trends similar to the drying-rate curves (see Figure 6). The temperature profiles demonstrate the warming-up period, a constant- temperature period, as well as a rapid falling-off period. Due to the difficult nature of temperature measurement in microwave drying, these data are applicable only for representing trends in the temperature profile. It should be noted that the surface-temperature values of Figure 6 did not reach 100°C, the boiling point of water at atmospheric pressure. This can be accounted for by the effect of surface evaporation[5] and by the measurement technique that allowed for some cooling of the sample upon removal from the microwave. In general, during microwave drying, the surface temperature falls between the wet-bulb temperature in the oven and the boiling temperature.[4] Our microwave oven was not equipped with a carousel, and given the uneven nature of the energy field in a microwave oven, the temperature probably varied with position. We did not study this phenomenon, however, and only measured the surface temperature near the middle of the sample.

- Students can be asked to design an experiment that illustrates that mass transport effects are responsible for the falling-rate period. Evaporation of water with no solid present can be used to do this. In this instance, the falling-rate period is eliminated, with the constant-drying-rate period ending abruptly as the last of the water is evaporated.
- Particle-size effects can be examined by using sand that has been sifted into different particle sizes. Critical moisture content increases with decreasing particle size since smaller particles pack closer together, slowing the movement of moisture to the surface.[4]
- Datta[5] states that geometry plays a role in microwave processing. This effect can be explored by changing the shapes of the containers and the thickness of the bed height while maintaining a constant mass.
- The analysis presented here does not yield detailed information about the fundamental mechanisms of heat and mass transfer during the drying process, It is possible, however, to estimate interphase heat and mass transfer coefficients and effective liquid diffusivities using methods presented in the literature.[4] Also, complex mathematical models of the drying process have been developed.[9]
- Drying characteristics of different materials can be compared. Various materials have been used in our laboratory, including calcium carbonate, sponges, bread, and fruit.

CONCLUSIONS

This experiment demonstrates the drying process effectively. It is an extremely flexible, safe, and inexpensive experiment that can be incorporated into the undergraduate laboratory curriculum. The experiment is easy to set up and run. Typically, meaningful experimental data for higher power settings can be collected in about thirty minutes. This experiment also involves data analysis that introduces students to the various methods of treating data and the errors associated with each method.

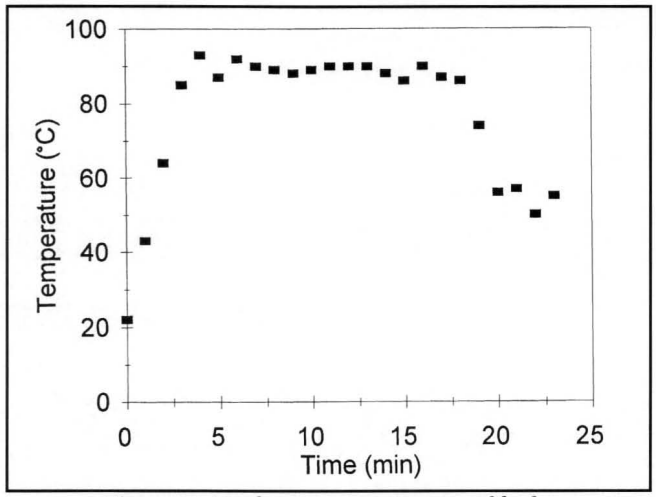

Figure 6. *Surface temperature profile for a power level of 720 W.*

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NOMENCLATURE

i	index for numerical differentiation (unitless)
m	mass of liquid (kilograms)
m_s	mass of solid (kilograms)
t	time (minutes)
t_0	time of first data point (minutes)
t_n	time of last data point (minutes)

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