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CBE 140A: Tray Dryer

## 1 Introduction

As the name implies, tray dryers are used to remove moisture from varied products on trays through forced convection of a heated gas, usually air. As one of the most common unit operations in the chemical process industries, applications can range from foods (potato and fruit chips, gelatin, table salt), pharmaceuticals (removing solvent from drugs, often at moderate or low temperatures to minimize chemical decomposition), textiles (leather, wool), and more. For any granular or powdered solid produced, a dryer is likely one of the final unit operations employed.

## 2 Objective

This experiment will focus on characterizing the typical drying process and investigate how it varies with the type of product being dried and the operating conditions. The basic principles of heat, mass, and momentum transfer, surface chemistry, and solid structure all impact a sample's drying behavior. A range of different diameter sands, as well as varied porosity of filter paper, are available to be dried. Variable conditions include air velocity, inlet temperature, and sample position and orientation in the tray dryer.

## 3 Theory

Before we begin, a quick note: while many volatile liquids can be removed from a solid using a tray dryer, the following sections will assume water is being removed. Regardless, the same principles apply when evaporating other liquids.

First, a few definitions: The moisture content,  $X$ , of a sample is the weight of absorbed water divided by the dry weight of the sample. Denoting mass as  $m$ ,

$$X = \frac{m_{\text{wet sample}} - m_{\text{dry sample}}}{m_{\text{dry sample}}} \quad (1)$$

The drying rate, denoted here as  $R$ , of a sample is the instantaneous rate of reduction in weight of absorbed water per unit time and per unit area exposed to air, denoted  $A$ . Absolute values are included to ensure a positive drying rate, since moisture content is decreasing:

$$R = \frac{1}{A} \left| \frac{dm_{\text{water}}}{dt} \right| = \frac{m_{\text{dry sample}}}{A} \left| \frac{dX}{dt} \right| \quad (2)$$

The moisture content of air in particular is well-studied, particularly at atmospheric total pressure. The normally measured temperature of such a mixture is referred to as its dry bulb temperature. If the bulb of a thermometer is saturated in a soaked wick prior to use, the resulting

measurement is the sample's wet-bulb temperature. The mass of water vapor per unit mass of dry air is defined as the absolute humidity. The partial pressure of the water, taken as a ratio with the vapor pressure of water at the dry bulb temperature, is defined as the relative humidity. Considering the wetted air being cooled, the dew point at which water vapor first condenses is referred to as the saturation temperature. A sample's wet-bulb temperature approaches the saturation temperature, particularly when radiative heat transfer is negligible. Several types of psychrometric charts plot the relationship between absolute and relative humidity, dry and wet-bulb temperature, and enthalpy. See the Grosvenor and Mollier charts in [1] in Figures 12-1, and 12-3, respectively.

Now discussing the drying process: When a fully wetted solid contacts heated air, water will immediately begin to vaporize in an attempt to reach thermodynamic equilibrium (provided the gas is not already fully humidified). Since the heat of vaporization of water is large, the temperature of the solid will decrease through the process of evaporative cooling. The flowing gas, which develops a boundary layer over the solid, will experience diffusion of water vapor through this layer while being swept away with the bulk flow. Simultaneous to this mass transfer, heat will be transferring from the hot air, through the boundary layer, into the solid and absorbed water. The rates of mass and heat transfer can be described by boundary layer theory and Newton's law of cooling, respectively, which are provided below in Equations 3 and 4.

After some time (referred to as an induction period), the solid's temperature will become stable at or near the wet bulb temperature, a property of only the air stream. The drying rate will become constant and, depending on the operating conditions, limited by either the rate of heat transfer to the solid or the rate of mass transfer of water vapor away from the sample. During this constant drying rate period, the sample surface remains wetted.

As the water content drops, eventually the sample surface is no longer saturated. Drying further, water must now diffuse through the solid to its surface prior to diffusing into the air. This additional resistance slows the rate of drying as the moisture content approaches zero. This is referred to as the falling rate period, following the constant drying rate period, the transition occurring at the substance's critical moisture content. Upon further drying, eventually an equilibrium moisture content will be reached when the drying rate falls to zero.

These characteristic periods of the drying process are displayed in Figure 1. Typical patterns are displayed for moisture content over time, drying rate over time, and drying rate as a function of moisture content in inserts A, B, and C, respectively.

The effect of variations in air temperature, inlet humidity, and velocity can be predicted through its impact on the governing heat and mass transfer equations. For convective systems, as is the case here, the relevant flux equations are as follows. When a system can be assumed to be at a pseudo-steady state, the ratio of  $q$  and  $N$  is constant and equal to the latent heat of evaporation.

$$q = h(T_{\text{bulk}} - T_{\text{surface}}) \quad (3)$$

where  $q$  = heat flux, in units of energy per time per area,

$T_{\text{bulk}}$  = the bulk air temperature, and

$T_{\text{surface}}$  = the surface temperature of the solid, and

$$N = k(y_{\text{bulk}} - y_{\text{surface}}) \quad (4)$$

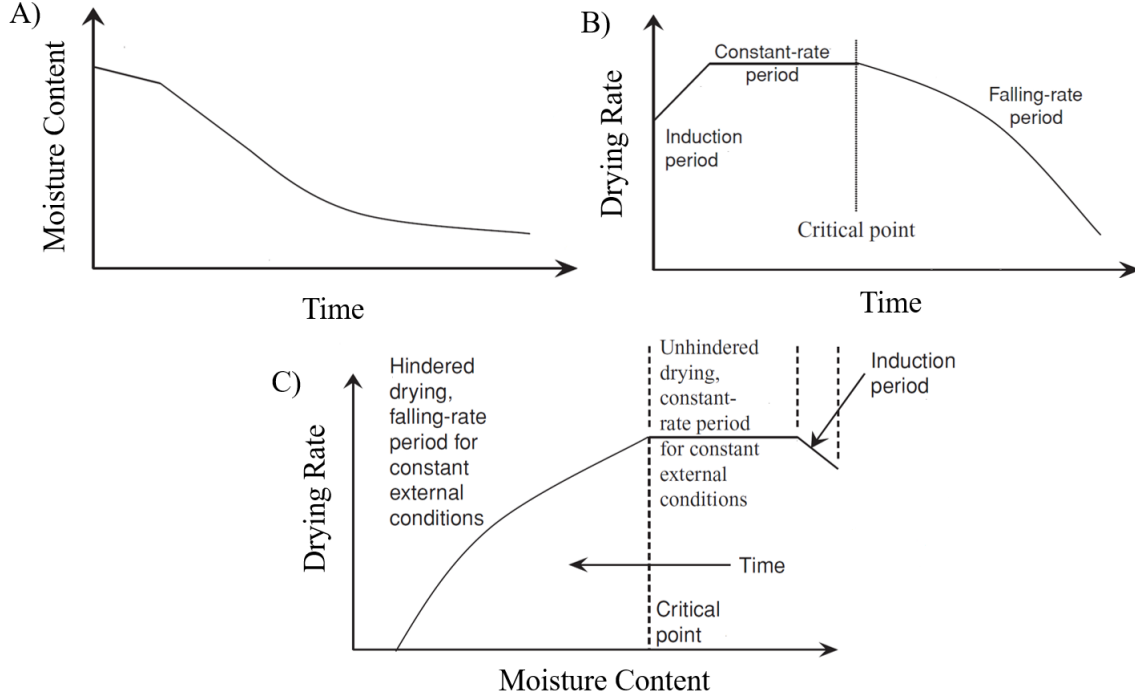


Figure 1: Typical results for drying of a saturated substance plotted in three ways. Adapted from Figure 12-13 in [1].

where  $N$  = water molar flux, in units of moles per time per area,

$y_{\text{bulk}}$  = the mole fraction of water in the bulk, and

$y_{\text{surface}}$  = the mole fraction of water at the solid surface.

Empirical studies have shown the effect of velocity on convective heat and mass transfer can be predicted using dimensionless analysis. Many correlations exist, depending on the geometry, flow type, surface conditions, etc., and are well documented in the corresponding textbooks. For example, fully-developed laminar flow over a constant-temperature plate yields the following (derived in [2, 352]), relating the Nusselt number (which, once known, allows determination of the convective heat transfer coefficient,  $h$ ) to a function of the Prandtl and Reynolds numbers:

$$Nu = 0.664Pr^{\frac{1}{3}}\sqrt{Re} \quad (5)$$

Similar correlations are available for determination of the convective mass transfer coefficient,  $k$ , typically phrased in terms of the Sherwood, Reynolds, and Schmidt numbers. From these correlations, a direct relationship between air velocity and the rate of heat and mass transfer can be determined.

When a sample is dried beyond its critical moisture content, the mass transfer of water vapor to the solid surface begins to limit the drying rate. Relevant mechanisms for mass transfer within the solid might include diffusion, convection, and capillary action, in the case of a porous sample. Depending on the diameter of solid pores, bulk or Knudsen diffusion models will be more appropriate [1, 5-58].

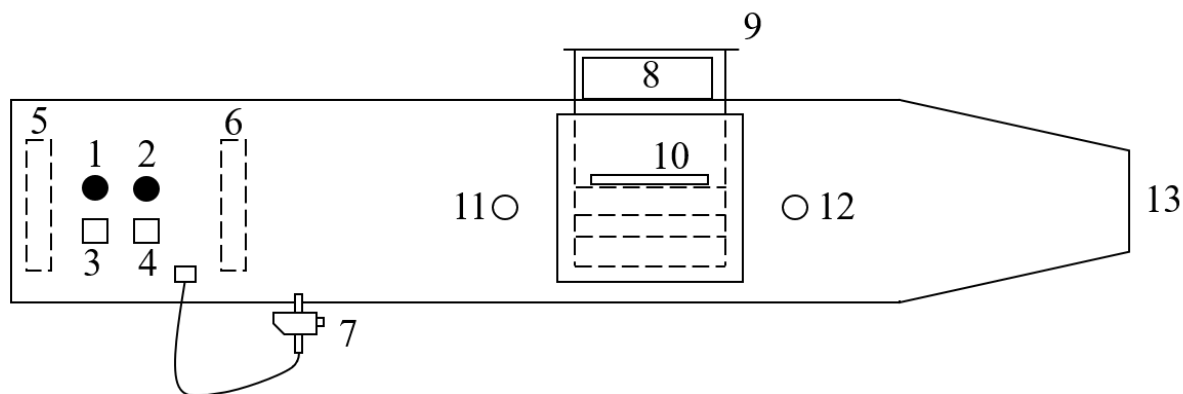


Figure 2: Experiment 3: tray dryer apparatus.

## 4 Experimental Apparatus

To begin, Figure 2 illustrates a side view of the apparatus. A square duct takes in air through its left-hand side opening, forced by a fan (5), across a sample (10) suspended by hanging trays (9), and out the tapered right-hand side opening (13). Parts within the duct are drawn with dashed lines. The fan has a power switch (3) and a speed control knob (1). An electric heating element (6) also has a power switch (4) and a variable power control knob (2). Note that this knob controls the power directed through the heating element, not the air temperature. The maximum air temperature is dependent on the fan setting—at  $0.5 \text{ m}\cdot\text{s}^{-1}$ , do not expect to exceed  $80^\circ\text{C}$ , while at  $1.5 \text{ m}\cdot\text{s}^{-1}$ , expect a maximum air temperature of  $40^\circ\text{C}$ . (Be careful not to apply too much torque to these knobs as the wiring is delicate.)

A dual-thermometer sensor with a built-in fan (7) can simultaneously measure dry and wet-bulb temperature when applied to either port in the duct before or after the sample, at (11) or (12). For accurate wet-bulb temperature measurement, ensure its bottom reservoir contains deionized water and the wick is submerged. Alternatively, two Vernier  $\text{CO}_2$  gas sensors can be used to record temperature and humidity at both ports. Air velocity can be measured with an anemometer (not shown) at either the duct's inlet or outlet.

Wetted samples should be placed on a tray (10) prior to handling through a sample door (not shown) onto the hanging support (9). The top of this support can be placed on a mass balance (8) for instantaneous weight measurement. For low-weight samples, the wind disturbance to the balance will cause too much variability—instead, remove the tray and sample periodically for measurement outside the air duct. Take note this will improve mass precision but will disturb the thermal state of the sample as it dries.

Samples available for drying include the following: multi-fold paper towels, 541 and 542 Whatman filter papers (having the ability to filter particles larger than  $22$  and  $2.7 \mu\text{m}$ , respectively), and sand. The sand can be processed through a series of sieves to obtain different samples, each having a narrow range of particle size.

## 5 Safety

The major hazards associated with this experiment are the following: The tray dryer, powered from an electrical outlet, introduces the risk of injury from electric shock. Avoid by ensuring the power cord does not become submerged and is not touched when in operation. Through accumulation of

biological contaminants in the water, there is also a risk of infection. If water is spilled on the floor, there are risks of slips and falls. Avoid this by carefully handling water when wetting samples. This list is only a starting point and not intended to be fully comprehensive—please keep the safety of yourself and others in mind throughout the laboratory sessions.

## 6 Experimental Procedure

When first operating this apparatus, set the heating power at its maximum setting and the fan speed to a moderate position. Be careful not to alter these settings until a trial has completed. Allow the duct to reach equilibrium, with the sample door closed, while preparing the towel to be dried.

Measure the weight and dimensions of a dry, multi-fold paper towel, in its triple-folded orientation, as well as the weight of an empty tray. Soak the towel in water on the tray before draining off excess water. Record the weight of the wetted paper towel.

When the duct has reached steady state, begin drying the paper towel by placing it on a tray onto the hanging support and closing the sample door. Record the combined weight of the towel and the tray, the air velocity with an anemometer, and the air dry and wet-bulb temperature and humidity at ports 11 and 12 at regular intervals. If there is substantial change at port 11 before the sample, this might be the result of heating and humidification of the room air—evidence for this can also be tracked by measurement of the room air’s physical properties over the course of the laboratory session. Continue collecting data until an equilibrium moisture content has been observed.

Conduct additional trials at identical fan speed and heating power with: ten stacked 541 Whatman filter papers, then with ten stacked 542 Whatman filter papers, then with varied samples of sieved sand (taking note of the range of particle sizes for each sample).

Conduct additional trials for a particular type of sample for multiple fan speeds at constant inlet air temperature. Repeat the process at a constant fan speed and sample type while varying the inlet air temperature.

## 7 Data Analysis

For each trial, process the data and generate figures for moisture content and drying rate vs. time and drying rate vs. moisture content. Analyze the mass balance for each trial, determining if the rate of moisture loss as observed from the mass balance agrees with the moisture gained by the air stream, as observed from humidity measurements. Plot the temperature-humidity data of the room air, at port 11, and at port 12 on a psychrometric chart. Comment how well these figures compare to expected results and describe what might have caused any discrepancies.

Illustrate how drying behavior (constant drying rate, critical moisture content, equilibrium moisture content) is impacted by the sample type (e.g., porosity or particle size), air speed, air inlet temperature, and any other independent variables investigated. Note this is a combinatorial analysis with many possible pairings of variables to study. For each pairing of controlled and observed variables, compare the empirical results to predicted trends, comment on their agreement, and describe what might have caused any discrepancies.

## References

- [1] Don W. Green, editor. *Perry's chemical engineers' handbook*. McGraw-Hill, eighth edition, 2008.
- [2] Julian Smith, Warren McCabe, and Peter Harriott. *Unit operations of chemical engineering*. McGraw-Hill, seventh edition, October 2005.