Revised 10/00

CHEMICAL ENGINEERING LABORATORY 3, CE 427

DRYING OF SOLIDS

Introduction

Material covered here pertains to Chapter 24 of M,S&H. Please read relevant sections of this chapter.

Drying involves the final removal of relatively small amounts of water, or in some cases solvent, from a material. Excluding the partial drying of a solid by mechanical means, for example, by squeezing, all drying operations depend upon the application of heat to vaporize the volatile constituents. All solid materials have a certain equilibrium moisture content when in contact with air at a particular temperature and humidity. If the temperature or humidity of the air is subsequently changed, then moisture is exchanged until the new equilibrium value is reached. Thus, the situation is analogous to a mercury thermometer. At 20°C, for example, the mercury level is at a certain point. If the temperature changes to, say 25°C, the mercury level changes to a new equilibrium value.

The moisture in a solid is retained in two forms as shown in Figure 1. These comprise:
(a) Bound moisture, which exerts an equilibrium vapor pressure less than that of free water at the same temperature. How this moisture is retained depends upon the nature of the solid; it may be retained in fine capillaries, or adsorbed onto surfaces, or within a cell or fibre walls, or in physical/chemical combination with the solid.

(b) Unbound moisture which exerts an equilibrium vapor pressure equal to that of water at the same temperature. This moisture is retained in the voids of the solid.

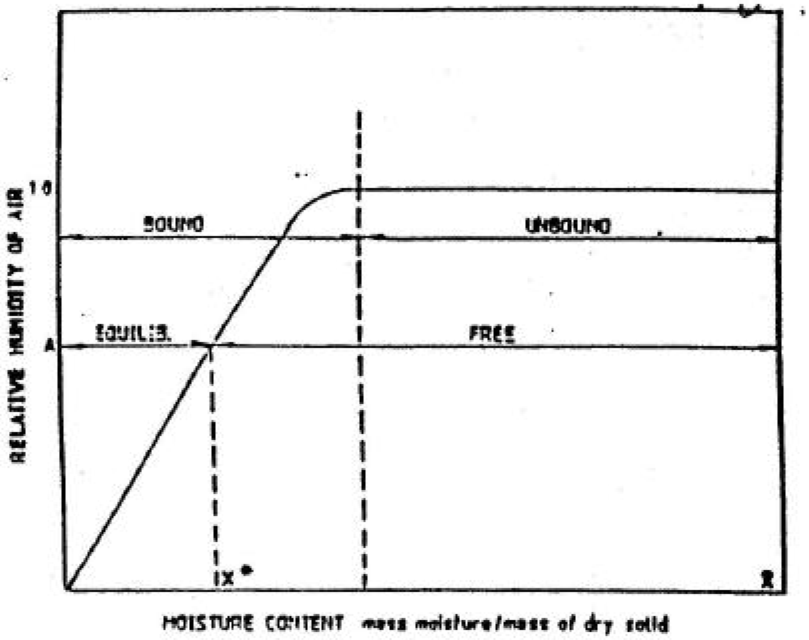
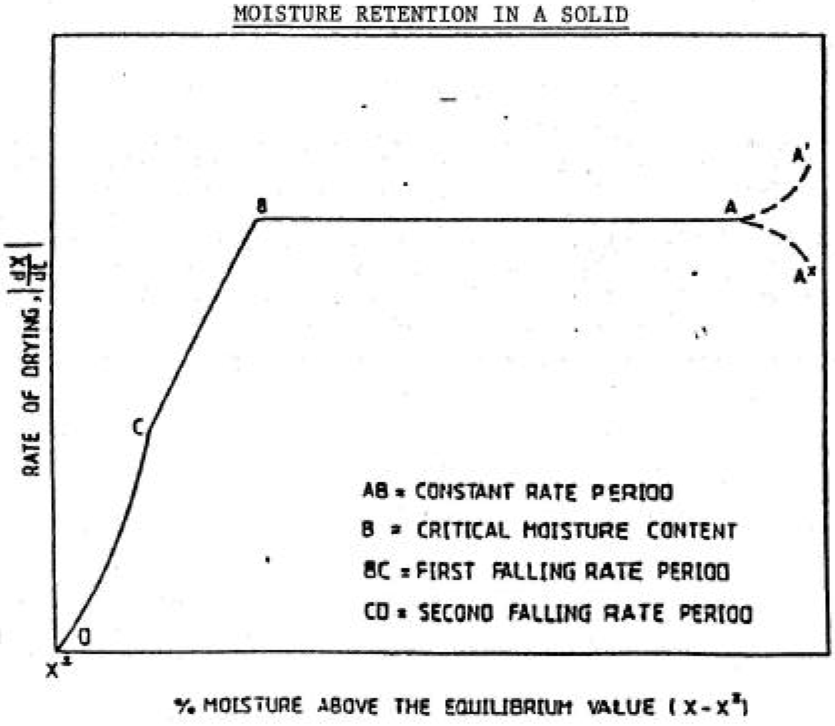


Figure 1

The distinction between bound and unbound moisture is a property of the specific solid under consideration. If the solid represented in Figure 1 is dried in air of relative humidity 'A', then all of the unbound and part of the bound moisture can be removed. This will comprise the 'free' moisture above the equilibrium moisture content corresponding to the air condition. Hence the 'free' moisture = (X-X*). Note that the distinction between 'equilibrium' and 'free' moisture contents depends both upon the nature of the solid and the conditions. Also the bound moisture represents the equilibrium moisture content of the solid in contact with air that is saturated -- that is, air with a relative humidity of 1.0.

Drying Rate Behavior

A typical drying rate curve is shown in Figure 2. The rate of drying, dX/dt, is plotted as the ordinate against the % moisture above the equilibrium value, X-X*. Clearly, as drying proceeds, X decreases and dX/dt would be a negative number. Since you are interested in the rate at which drying is occurring, it makes more sense to plot , which is a positive number. As explained before, the equilibrium content, X*, is determined by the condition of the air being used to dry the solid.



GENERALISED RATE OF DRYING CURVE FOR A SOLID MATERIAL

The word, "typical," was used above because many types of wet solids would display this behavior. However, the materials that you dry may not exhibit all regions. If this is the case, this does not mean that your samples disagree with "theory." Rather it could mean: (1) that there are some features of your sample that are atypical of most materials; (2) that you didn't take sufficient data to resolve or discriminate a certain region or regions of the graph.

As shown in Figure 2, there are four basic regions of the typical drying rate curve. When the material is first placed in the dryer, it could be at any point on the 4-region curve, but if it is sufficiently wet, it will possibly be at either Point A' or A*. There will be a relatively short period of time during which the rate either rises or falls until a steady-state drying rate is reached at Point A. Obviously, if you want to "observe" this first region on your graph, you will need to take a number of data points early on in your run.

Section AB represents a constant drying rate. During this period drying takes place by evaporation of moisture from a saturated surface. This involves diffusion of the water vapor through a 'stationary' air film and into the bulk of the air.

The rate of evaporation is given by:

(1)

where K_g is the overall mass transfer coefficient for the gas film,
A is the area of solid available for drying,
p_s is the vapor pressure of water at the surface temperature, and
p_w is the partial pressure of water vapor in the air stream,

Clearly, p_s - p_w is not only the driving force for mass transfer, but is also a measure of the capacity of the air stream to take-up moisture. Under steady state conditions the rate of evaporation is related to the rate of heat transfer by forced convection so that,

(2)

where h is the heat transfer coefficient,
is the temperature driving force (i.e., difference between the air and surface temperature) and, under constant drying $T_{surface}$ equals the wet-bulb temperature of air.
is the latent heat.

Equation (1) is usually expressed in terms of the humidity difference:

(3)

where the symbol, #, stands for humidity and K' is the corresponding mass transfer coefficient. In this period therefore, the rate of drying is determined by h, A and T and is not influenced by conditions within the solid. The heat transfer coefficient depends upon the air velocity and the direction of flow, and may often be approximated by:

(4)

where G is the mass flowrate per unit area and C is a constant for the system and is a function of various conditions including the direction of air flow relative to the wet-surface. If air flow is parallel to the surface under the conditions listed in M,S&H (Re between 2600 and 22000), the heat transfer co-efficient may be a function of mass velocity, G, and the diameter of the flow channel, D_e as:

$$h \alpha G^{0.8}/D_e^{0.2} \qquad (5, \text{MS\&H } 24.13)$$

Under other conditions when the flow is perpendicular to the direction of flow and air velocity is between 0.9-4.5 m/s:

$$h \alpha G^{0.37} \qquad (6, \text{MS\&H } 24.14)$$

As a note, in situations where the gas temperature is high, for example with direct-fired driers, radiation heat transfer may be important.

On Figure 2, Point B at the end of the constant rate period, is termed the "Critical Moisture Content." At this point the surface of the solid is no longer saturated and 'dry spots' begin to appear; the outside wet area, A, may therefore be reduced progressively and the rate of drying falls off. Point C represents a condition when the original surface film has evaporated completely. Beyond this point, the rate of drying is controlled by the rate of moisture movement through the solid.

The second falling rate period, C to D, represents conditions when the drying rate is largely independent of conditions outside the solid. For example, if moisture transfer from within the solid to the surface is by vapor diffusion, it is the forces which control this diffusion that determine the drying rate.

In practice, transfer may be by any combination of liquid diffusion (e.g., with solids such as soap which form single-phase solutions with moisture or when removing the last traces of bound moisture from wood), capillary movement (e.g., with porous solids like clays) and vapor diffusion. In any event, as moisture retreats further from the surface the rate of transfer falls further until the Equilibrium Moisture Content at Point D is reached, corresponding to the existing air conditions.

Because many materials are atypical, it is not practical to predict the shape of Figure 2 under given conditions. Therefore drying tests are necessary. This involves suspending a sample in a dryer or duct. For reasons which follow from the description of drying, the prerequisites for meaningful tests are:

i) The sample must not be too small and must be representative of the material to be dried in the plant.

ii) The experimental conditions in the test dryer must be similar to those that would prevail in the full-scale unit in the plant. Thus, the solid should be supported in the test to achieve the same ratio of exposed area to non-exposed area, and the particle geometry should be the same as that of the material to be dried in the plant. Other conditions as regards radiant heat transfer and the range of air temperatures, flow rates, and humidities should be the same as well.

Equipment

This experiment is carried out on a bench-scale batch drying unit consisting of a centrifugal fan, an electric 8-kw heater for preheating the air, and a balance for weighing the samples to be dried in the heated air stream as shown in Schematic below. The flow of air, which passes through a horizontal, cylindrical duct, can be regulated by means of a damper at the inlet to the fan. The duct is 1600 mm in diameter and 1350 mm long. Some of the samples to be dried are made of porous pumice stone and are suspended in the center of the duct by a support wire attached to the balance. Other sample materials may be available also.

B	Balance
D	Damper
F	Fan
H	Electric Heater
S	Sample
W	Water Bottle
T	Wet Bulb TC
Y	Dry Bulb TC

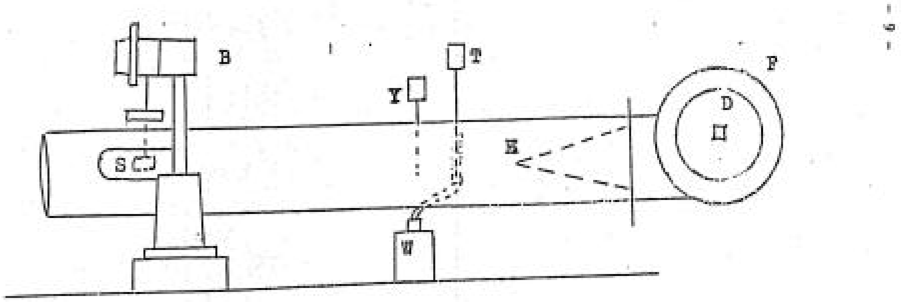


FIG. 3 BATCH DRYER

Operating Procedure

Experiments will be performed with the spherical and cubical objects only. The outside dimensions and surface areas will be provided to you by the laboratory instructor/ or are written on the sheet of paper next to the laboratory experiment. The dry weight measurements, W_o, for each sample are resolved down to 0.01 gram using the DIAL-O-GRAM balance. (Note: This is not the "bone dry weight," but simply the weight after the sample has been in contact with ambient air for an "infinite" length of time.) This balance has a vernier scale. In using the vernier, the vernier reading is made at the vernier line which most closely lines up with any of the other dial graduations.

The samples will be soaked in distilled water for two to three hours prior to your laboratory session.

When ready to proceed with the drying operation, plug in the batch dryer system (220 volts, 2-phase) and the digital temperature indicator (110 volts, 1-phase). This is usually already setup.

Turn the air blower on (turn pointer dial from O to I) and adjust the air flow damper to give an outlet air velocity of approximately 5 m/s (984 ft/min = 16.4 ft/s) using the rotating vane anemometer. Allow the vane to be in the air stream for about 15 seconds to enable it to reach steady speed and then press and hold down the switch plate for reading. The value read may vary with distance. Be careful how you hold the device and reproduce it 'identically' for all your runs.

With the air heater set in the MIN position, determine the humidity of the flowing air by injecting water onto the wet bulb slowly until the wet bulb temperature changes. When the wet bulb reaches a steady low temperature, record both the wet and dry bulb thermocouple readings. Then, to proceed with the drying experiment, increase the air heater setting to give a temperature of 29°C on the dry bulb thermocouple.

Remove one of the wet solid samples from the water and carefully remove adhering water from the surface by pressing it once on absorbent paper. Quickly suspend the sample from the hook connected to the balance via the open end of the duct. Start timing and record weight at time zero. **Be sure to switch off blower when taking weight readings**. Do this rapidly and return air flow as quickly as possible.

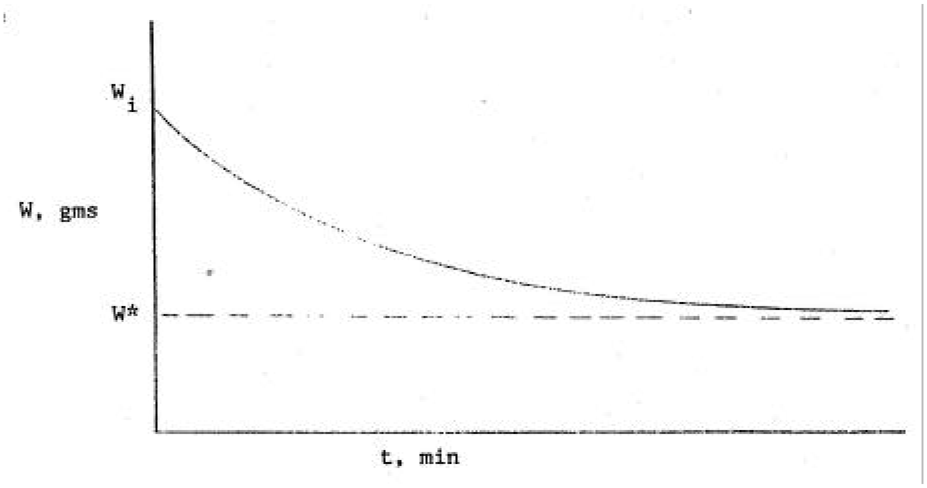
Take weight readings at short time intervals initially, for example, say every 15 seconds or so and gradually extend this period as the run continues, for example, 5 min. intervals after about 15 min. Continue the drying process as long as the weight continues to decrease. You must exercise some engineering judgment regarding the measuring intervals! If you don't take them often enough, you may miss some important detail in the drying curve. Typical W vs. time plot is shown below.

Repeat the weighing procedure for each of the samples to be dried.

List of experiments to perform:

Ensure that the WET-BULB is WET for all RUNS.

1. **RUN 1:** Set air flow rate to 5m/s. Perform COMPLETE drying experiment (all phases) with the round object that has been soaked in the water.
2. When work is completed with the round object soak it in water. Determine the approximate time required to get the dX/dt data for the constant drying rate phase.
3. **RUN 2:** Now with the air flow rate at the same rate, perform the COMPLETE drying experiment for the cubical object.
4. After step 3, soak the cube in water as well and determine the amount of time you need to do the experiment for in order to find the dX/dt information for the constant drying rate.



Beyond this point we will perform a series of runs in the constant drying rate phase only (experiments are of a shorter duration). The experiment is designed like this i) For the round object we will keep the air flow rate at 5m/s and perform experiments at 4 temperature values T_1, T_2, T_3, T_4 (**RUNS 3-5** since one of the temperature runs has already been done in RUN 1 above). Cover as wide a range of temperatures as possible. ii) For the cubical object, we will keep the temperature constant at ambient room temperature and perform experiments at 4 flow rates between 1-10m/s (G_1, G_2, G_3, G_4) (**RUNS 6-8** since one of the temperature runs has already been done in RUN 2 above). Since the objects need to be completely saturated with water before the run, soak the solids in water for at least 1/2 hour before each run. Proceed as follows:

5. Ensure that the round object has been soaked in water for 1/2 hour. Place object in flow at a given temperature, say T_i. Perform the drying experiment in the constant drying phase only.
6. Now soak the round object in water.
7. Do the experiment with the cube now at a fixed air flow rate, say G_i. Perform the drying experiment in the constant drying phase only.
8. Now soak the square object in water.
9. By this time the round object in step 6 must have soaked for ~1/2 hour. Change the temperature and flow rate so that we can do the experiment for the round object at the second temperature. In this fashion, stagger the experiments for the round and cubical object and repeat

steps 5-8 above till all the data has been collected (4 temperatures for the round object and 4 gas flow rates for the square object).

Treatment of Data

1. Tabulate the operating conditions for each run, as follows:

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**
Specimen (Data provided by TA)								
Material								
Dimensions								
Dry Mass, W_o, gm								
Surface Area, in^2								
Inlet Air Condition								
Dry Bulb Temperature, °C								
Dry Bulb Temperature, °F								
Wet Bulb Temperature, °C								
Wet Bulb Temperature, °F								
Hot Air Temperature, °C								
Hot Air Temperature, °F								
Air Flow Velocity, ft/min								

2. For each run, tabulate the specimen weight, W, versus time, t, and plot these data. Use a separate graph sheet for each run. Estimate the final equilibrium weight, signified as W*, for each specimen in RUNS 1 and 2. It should be evident from the graph what this weight is; in fact, it should even be evident from your data, assuming you took data for a sufficiently long time that the weight was not changing, or at least was changing very slowly with time.

3. For each weight, W, calculate X, the per cent change in weight from the equation:

where W = weight of the specimen.
W_o = initial weight of the dry specimen before soaking.

Thus, the final equilibrium moisture content is:

In principle, X* should be the same for each specimen of a given material, regardless of the shape. However, it would be different for different materials.

4. Prepare the following spreadsheet tabulation for each specimen in RUNS 1 and 2:

A	**B**	**C**	**D**	**E**
Time, Min.	W, Grams	X%		X - X*

The drying rate, , is approximated by the numerical estimate, . Thus:

For each specimen, plot versus X - X*, as shown in Figure 1. What region or regions of the typical drying curve are exhibited?

5. No doubt you will find considerable scatter in your plots. Go back to your original plots of Part 2 above. Draw smooth curves through the data as best you can. For each specimen, **using some judgment**, pick off about 20 points of W versus t_i. Set up a spreadsheet tabulation as in Part 4. Then prepare a drying curve plot for each specimen based on the smoothed data. Again, Try to identify the various regions of the typical drying curve. Alternatively, use a fitting routine to draw a smooth curve (splines) through the data and then use the derivative of the curve to get the drying rate.

ANALYSIS OF DATA WITH VARYING GAS FLOW RATE AND TEMPERATURE in the constant drying region for runs 1-8:

6. For each of the runs use the experimental data to find the mass transfer flux, N . Then apply Eq. 2 to determine the heat transfer co-efficient, h, as a function of either the gas flow rate, G, or temperature, T. Make plots of h vs. G and T for the sphere and cube. Determine the exponent n or come up with a description of the dependences.

Address the following questions in your report:

i) What is the effect of shape on mass transfer and on the estimated heat transfer co-efficient, h? Why?

ii) What is the effect of gas flow rate on the estimated heat transfer co-efficient, h? Why?

iii) What is the effect of air temperature on the estimated heat transfer co-efficient, h? Why?