bulb is found to be 0.010 lb per pound of dry air. Therefore the moisture pickup is 0.022–0.010, or 0.012 lb per pound of dry air.

The amount of water evaporated in the dryer = 90.5 (2.28 – 0.32) = 177 lb per hr.

The weight of dry air, make-up and exhaust, required to remove the water of evaporation = $\frac{177}{0.012}$ = 14,750 lb of dry air per hour.

Step 2: Let x = percentage of recirculated air and 100 – x = percentage of make-up air.

Then $\frac{x}{100}$ (humidity ratio of exhaust and recirculated air) + $\frac{100 - x}{100}$ (humidity ratio of make-up air) = humidity ratio of supply air. Hence, $\frac{x}{100}$ (0.022) + $\frac{(100 - x)}{100}$ (0.010) = 0.018 at 120 F dry-bulb, 85 F wet-bulb, or x = 66.7 percent recirculated air and therefore the required make-up air = 33.3 percent.

DETERMINATION OF DRYING TIME

In most drying problems it is necessary to obtain the drying time of a particular material. Three methods are listed below in order of preference.

1. Conduct tests in a laboratory dryer simulating conditions in the commercial machine, or obtain performance data directly from the commercial machine.
2. If the specific material is not available, obtain drying data on similar material by either of the above methods. This is subject to the experience and judgment of the investigator.
3. Estimate drying time from the theoretical equations which have been considered under Mechanism of Drying.

In designing commercial equipment the usual procedure is to conduct tests in a laboratory dryer in which commercial operating conditions are simulated. A representative sample in the physical form of the material as used in the laboratory tests should be identical to that which will be encountered in commercial operation. Otherwise the test results may not be an accurate indication of the drying characteristics of the commercial material.

In many cases where it is impracticable to run laboratory tests, commercial drying data are derived from the experience of the equipment manufacturer. This should not be overlooked since it can be an important source of data which would otherwise have to be obtained by less reliable methods.

Method 3, estimating drying time from the theoretical equations, should be used only as a last resort because it yields only approximate values.

Commercial Drying Time

The first step in selecting a commercial dryer is to apply the estimated drying time to determine the size of the commercial machine necessary for a given capacity. If the drying time has been derived from laboratory tests it is necessary to consider the following factors:

1. *In a laboratory dryer considerable drying may have been* effected by radiation and conduction of heat to the material, whereas in a commercial dryer these factors are usually negligible.
2. Humidity conditions in a commercial dryer may be higher than in a laboratory dryer. For drying operations with controlled humidity, this factor can be eliminated by duplicating the commercial humidity condition in the laboratory dryer.
3. Operating conditions usually cannot be kept as uniform in a commercial dryer as in a laboratory dryer.
4. *Because of the relatively small sample* used, the test material may not be representative of the material handled commercially.

In consideration of the preceding factors 1 to 4, it should

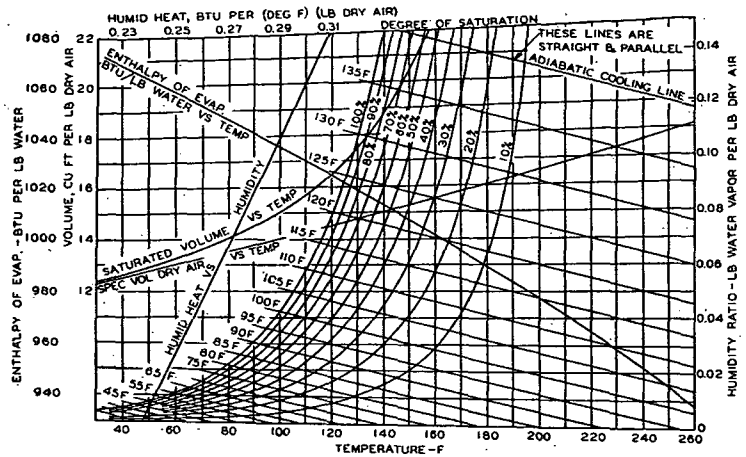

Fig. 5 .... Psychrometric Chart for Drying Calculations[5]

be stressed that the test drying time must be corrected to suit commercial conditions. This is a matter of experience and judgment on the part of the designer.

DRYER CALCULATIONS

To determine preliminary cost estimates for a commercial dryer it is usually necessary to make the following calculations:

Circulating air. The amount of circulating or supply air required is established by the optimum air velocity with reference to the material. This may be obtained from laboratory tests or previous experience, keeping in mind that there is also an optimum moisture pickup for the air, as explained in the section Application of Hygrometry to Drying.

Make-up and Exhaust. The amount of make-up and exhaust air required to maintain steady-state conditions within the dryer is discussed under the section Application of Hygrometry to Drying. In any continuously operating dryer, the relation between moisture content of the material and quantity of make-up air is given by Equation 6

$$G_T(W_2 - W_1) = M(w_1 - w_2) \text{ where } W_2 \text{ is constant.} \quad (6)$$

where

G_T = dry air supplied as make-up air to the dryer, pounds per hour.
M = stock dried in a continuous dryer, pounds per hour.
W_1 = humidity ratio of entering air, pounds of water vapor per pound of dry air.
W_2 = humidity ratio of leaving air, pounds of water vapor per pound of dry air.
w_1 = moisture content of entering material dry basis, pounds of water per pound.
w_2 = moisture content of leaving material dry basis, pounds of water per pound.

In batch type dryers, the drying operation is given by Equation 7

$$G(W_2 - W_1) = M_1 \frac{dw}{d\theta} \quad (7)$$

where

M_1 = weight of material charged in a discontinuous dryer, pounds per batch.
$\frac{dw}{d\theta}$ = the instantaneous rate of evaporation corresponding to w. W_2 is a variable during a portion of the cycle.

In actual practice the quantity of make-up air supplied is kept constant and is based on the average evaporation rate. Equation 7 then becomes identical with Equation 6 where $M = \frac{M_1}{\theta}$. Under this condition the humidity in the batch dryer will vary from a maximum to a minimum during the drying cycle; whereas, in the continuous dryer the humidity at any given point is constant with constant load.

Heat Balance. In order to estimate the fuel requirements of a dryer it is usually necessary to make a heat balance, consisting of the following:

1. Radiation and convection losses from dryer.
2. Heating of the commercial dry material to the leaving temperature (usually estimated).
3. Vaporization of the water being removed from the material (usually considered to take place at the wet-bulb temperature).
4. Heating of the vapor from the wet-bulb temperature in the dryer to the exhaust temperature.
5. Heating of the total water in the material from the entering temperature to the wet-bulb temperature in the dryer.
6. Heating of the make-up air from its initial temperature to the exhaust temperature.

The energy absorbed by items 1 to 6 must be supplied by the fuel. The proper selection and design of the heating equipment is an important part of the overall design of the dryer.

DRYING METHODS AND EQUIPMENT

Drying systems are sometimes classified according to the method of heat transfer that is employed, since the entire problem of drying resolves itself into individual problems of heat transfer and the thermodynamics of air and water vapor. The methods of heat transfer are radiation, conduction, and convection. Many types of dryers have been built on these principles for different purposes.

Drying systems can also be classified, according to the method of product handling, as batch operation, semi-continuous, and continuous.

The method of supporting or transporting the material to be dried, efficiency of operation, cost of investment, and the method of applying heat to the material are to be considered in selecting the equipment. Usually the final selection is a compromise between mechanical design, heat efficiency, quality, and product loss.

A systematic procedure is often justified when selecting a dryer for a given process. A general procedure will consist of:

1. Survey of suitable dryers
2. Preliminary cost estimates of various types
   a. Initial investment
   b. Operating cost
3. Drying tests should be conducted in prototype or laboratory units of the most promising equipment available. Sometimes a pilot plant is justified.
4. Summary of tests to evaluate quality and samples of the dried products.

Some items may overshadow the operating cost, or the investment cost, such as:

1. Product quality, which should not be sacrificed.
2. Dusting, solvent, or other product losses.
3. Space limitation.
4. Bulk density of product which may affect packaging cost.

A comprehensive bibliography for special reading will be found in the article by S. J. Friedman.[6]

Radiant Drying

In artificial systems, radiating surfaces heated by steam, electricity, or other means, afford a good method of heat distribution and control. Radiant heating sets up convection currents, and consequently, in low temperature dryers, only about one-third to one-half of the total heat for evaporation is actually supplied to the material by radiation. At high temperatures the radiation output increases rapidly, according to the *fourth-power law*. The total radiation may be computed by the equations and tables given in Chapter 5. In general, fins and irregular surfaces do not increase radiation, hence, the area to be used in calculations is the area of a smooth-surface envelope enclosing the radiating elements.

A certain amount of air circulation is required through a radiant dryer in order to carry off the vapor.

Radiant heat from infra-red lamps has been accepted by