Drying Processes

Consider first evaporation from a droplet of pure liquid (e.g., a water droplet) or pure solid (e.g., ice crystal).

\[ m = \text{mass of droplet} \]
\[ N_W = \text{flux of water vapor at droplet surface} \]
\[ Q = \text{Conductive heat flux at droplet surface} \]

Mass balance on droplet:

\[ \frac{dm}{dt} = \dot{f} \left( H_d - H_s \right) a = N_W \cdot a \]

where \( H = \text{humidity} = \frac{\text{mass of water}}{\text{mass of air}} \)

\( S = \text{droplet surface} \)

Generally, heat transfer inside droplet is rapid so entire droplet is at \( T_s \).

Energy balance:

\[ T_s C_p L \frac{dm}{dt} = a Q + N_W \left( \lambda + C_p L T_s \right) a \]

Conductive part

\( \lambda \) = heat of evaporation of liquid at \( T_s \)

Convective part

Heat flux at droplet surface

Combining yields \( Q = \dot{a} \frac{dm}{dt} \)

Q is also given by the heat transfer coefficient:

\[ Q = \dot{a} \left( T_{bulk} - T_s \right) \]
h can be determined using standard correlations for heat transfer in the absence of mass transfer, although a correction factor for a mass flux (similar to the flux correction factors for mass transfer coefficients) may need to be applied. Example 18.5-1 of BSL gives a derivation for the film model. More specifically,

\[ Q = -k(\nabla T)_s = h(T_{\text{bulk}} - T_s) \]

where

\[ Q = \text{energy flux at surface (since } \gamma^* = 0 \text{ due to no slip condition)} \]

Example 18.4-6 of BSL

\[ \mathcal{E}_s = -k(\nabla T)_s + \sum (N_i \mathcal{H}_i)_s \]

conducting

pert, i.e., Q pert

Using the film model, we get for a single species diffusing

\[ h = h^0 \frac{\sum N_i C_{PA}/\rho_s}{1 - \exp \left( \frac{\sum N_i C_{PA}/\rho_s}{h^0} \right)} \]

heat transfer coefficient in the absence of mass transfer
Combining equations from above:

\[ H_s - H_{bulk} = \frac{h}{2k} (T_{bulk} - T_s) \]

Define \( H_{bulk} \), \( T_{bulk} \), and the function \( H_s(T_s) \) (i.e., the saturation humidity as a function of temperature \( T_s \)) and \( T_s \) can be solved for. \( T_s \) is termed the "wet bulb" temperature.

Consider next the adiabatic saturation of water.

\[
\begin{array}{c|c|c|c|c}
\text{Tin} & \text{Q-0} & \text{Out} & \text{Tout} = T_{sat} & \text{Hout} = H_{sat} \\
\hline
\text{Hin} & \text{m} & \text{q} & \text{m} \text{ mixed liquid of sat} & \text{sat} \\
\text{inlet} & \text{enthalpy per unit mass of air} & \text{intermediate location where equilibrium is achieved, i.e., air is saturated.} \\
\end{array}
\]

Mass balance: mass flow of air

\[
\frac{dm}{dt} = G (H_{in} - H_{sat})
\]

Enthalpy balance:

\[
T_s \ \text{C}_{p,i} \ \frac{dm}{dt} = G (H_{in} - H_{sat})
\]
This leads to

\[
\frac{h_{in} - h_{sat}}{H_{in} - H_{sat}} = C_p L T_{sat}
\]

This can be rewritten as follows:

\[
C_p \text{air} T_{in} + h_{in} \left( \lambda_0 + C_{p,v} \right) T_{in}
\]

dehumidification at reference temperature, assumed to be \( T=0 \). Thus temperatures in some equation can be considered to be \( T-T_{ref} \) with \( T_{in} \) in °C.

\[
= C_p L T_{sat} \left( h_{in} - h_{sat} \right)
\]

Rearranging:

\[
\left( C_p + h_{in} \right) \left( T_{in} - T_{sat} \right) = \left( \lambda_0 - \left( C_p L - C_{p,v} T_{sat} \right) \right) \left( h_{sat} - h_{in} \right)
\]

\( \lambda_0 \) heat of vaporization at \( T_{sat} \)

also \( C_p \text{humid air, in} = C_p \text{air} + \left( h_{in} \right) \text{"humid heat"} \)

\[
\therefore \quad T_{inlet} - T_{sat} = \frac{\lambda}{C_p \text{humid air, in}} \left( h_{sat} - h_{in} \right)
\]
Generally, $h$ is termed the psychrometric ratio ($P$). Employing the Chilton-Colburn $j$ factors for heat and mass transfer, we get

$$P = \frac{j + j_h}{j} \cdot \left( \frac{P_c}{S_c} \right)^{\frac{2}{3}}$$

for an air-water system. Since the Lewis number $\approx 1$, and $j_h \approx j$, we have $P = 1$ so the adiabatic saturation temperature and wet bulb temperature are the same.

Note that the above energy and mass balances apply for adiabatic saturation. If the outlet is located at plane "3", where the air is only partially saturated, in which case we replace $H_{out}$ and $T_{sat}$ with $H_{out}$ and $T_{out}$. This defines the adiabatic saturation curve $H_{out}(T_{out})$. 
Psychometric Chart

Drying Rates

When drying porous solids or liquid solutions of high molecular weight solute (e.g., wood or milk solution) then capillarity or the fact that the mole fraction of water remains near unity even if a large fraction of water is evaporated, means that for a significant period the material dries as if it was pure water.

Drying Rate

Temperature

T = Wet bulb

Time

Constant rate period

Falling rate period

During this period, either surface dews off or liquid water

occurs.
In general, for a tunnel dryer:

- **Hot dry air** → **Material to be dried** → **Cooled moist air**

- Humidify driving force for moist to air

- Of air: saturation appreciably during drying, then local conditions in dryer air along adiabatic saturation line, and need to integrate over length of dryer to determine overall drying rate.

- Temperatures driving done for heat transfer

- **Hot, Dry Air** → **Particles in plug flow**

- Air is well mixed → **Dried Particles + Moist Air**

- Well mixed air in drying chamber

- Driving forces
Freeze Drying (also termed "lyophilization" from the Greek "Solvent loving" due to the fact that freeze-dried material is highly porous and easy to re-dissolve in a solvent) generally consists of two steps: freezing and sublimation.

**Freezing**

When glass-forming materials are added, such as maltose, sucrose, or PVP, concentrated solution in glassy state.

Primary drying (sublimation of ice)

Secondary drying (desorption from concentrated solution)
Freezing and Drying Processes

Temperature

Room Temp

Solute concentration

Liquids curve

Eutectic temp

Glass transition temp

Secondary drying

glass forms producing further ice crystal growth

Phase diagram

Critical point

Solid

Liquid

Triple point

Vacuum

0.1 psi

T & P are in this range so that ice sublimes

Small contact rate per unit area

As ice decreases due to extra heat resistance transfer ratio higher but ratio constant so T constant

Temperature

Drying rate

time
Design of a typical freeze dryer

Condenser (at low T, ~ -40°C)

Pumping gas (e.g. N₂)

(To facilitate convection)

P = 10-100 Pa

Vacuum pump

Heating platen (heat supplied by both conduction and convection)

Samples to be dried (~ -20°C)

References:


MODEL FD600 - FD1000 STANDARD COMMERCIAL DRYERS

The Cuddon Freeze Dryer was designed after consideration of the factors necessary for pharmaceutical and health food freeze-drying techniques.

METHOD
Four steps are used to carry out the basic principle of drying biologicals by sublimation of ice in vacuum. Although each product may demand different handling techniques, the four conditions are necessary and must be met in the following order.

1. The product must be solidly frozen below its eutectic point.
2. A condensing surface of low temperature must be provided.
3. The system must be capable of evacuation to low pressures in a reasonable time.
4. A controlled source of heat input to the product must be employed to drive the water from the solid to the vapour state.

From beginning to end, a constantly changing state of difference must exist between the product ice temperature and the system pressure/temperature. The migration of water vapour from the product ice occurs only if this differential exists. This is achieved by controlling the energy absorbed by the product during sublimation.

Freeze drying equipment is designed to create a controlled set of conditions which maintain the optimum temperature pressure difference for a given product and thereby allowing the transfer of moisture in an efficient manner.

DESCRIPTION

CHAMBER:
Chamber construction can be offered in stainless steel or mild steel. The standard mild steel model interior is shot blasted and primed, then coated with four coats of epoxy chemical resistant paint. This specification is similar for the chamber doors that are double hinged for correct alignment. Two viewing ports each 200mm in diameter are provided in the doors, one each, for observation of the ice vapour condenser, and the other at shelf level. Cuddon Freeze Dryers are approved by the New Zealand Ministry of Agriculture and Fisheries. The chamber is fitted with stainless steel pneumatically operated valves that isolate the vacuum line connection, drain, water defrost and vacuum release. The exterior can be painted in your choice of colour.

MODULAR SHELF HEATING PLATES:
The plates are fabricated from type 304 stainless steel, with flat upper sides and embossed lower sides to provide a heating fluid passage. The shelves are assembled in banks for ease
of manufacture and to reduce weight when handling. Each bank is fitted with wheels that run in a stainless steel track located directly above the vapour condenser. Two sets of type 316 stainless steel product trays are provided. These trays feature rounded corners for easy cleaning.

**SHELF REMOVAL:**
The heating system is connected to each shelf module by two type 316 stainless steel flexible hoses and quick release couplings. Each shelf module is removable from the drying chamber by rolling onto a trolley.

**TROLLEYS:**
Two trolleys are provided that have self centring and locking pins so that they may be positioned in front of the chamber. Each module trolley has a continuation of the chamber rail and allows the complete assembly to be rolled out onto this trolley for maintenance or cleaning.

**HEATING SYSTEMS:**
A thyristor controlled electric boiler that is connected in series with the plates provides heating. A centrifugal pump circulates the heat medium. The temperature of the plates is electronically controlled as required by the drying pattern selected at the control panel. A cooling heat exchanger is provided in the circuit for reducing the temperature of the plates when necessary either by water, or refrigerant if the shelf freezing option is desired. Safety devices are provided in the event of the circulating pump failing or if the fluid in the plates reaches critical low temperatures. A balance tank is fitted to a high point of the system to contain the thermal expansion when heating the fluid from low temperature.

**VACUUM SYSTEMS:**
The rotary piston vacuum pump is connected to the chamber by heavy duty PVC lines and pneumatic isolating valve. The exhaust of the pump is vented to the exterior of the building. The pump is equipped with a gas ballast facility.

**VAPOUR CONDENSER:**
The ice vapour condenser is manufactured from type 316 stainless steel tube in parallel circuits to form a direct expansion refrigerated coil. The assembly is fitted beneath the heating shelves and forms a permanent fixture. Defrosting the accumulated ice from the coil is by water. Hot water is recommended if a quick defrost time is desired. Heat recovery from the refrigeration system can be selected as an optional extra that will provide hot water for this purpose.

**MOTOR CONTROL CENTRE:**
The plant is provided with a motor control panel housing a mains isolator, circuit breakers, motor starters, overload protection, thermistor modules, relays, and hours run meter. This board is pre-wired at our factory. A separate operators control panel houses a vacuum gauge, chart recorder, programmable temperature controller and function switches that interface to a PLC, this runs the auxiliary equipment and monitors drying conditions. Audible alarm functions alert the operator to irregular occurrences.

**SPECIFICATIONS**

**MODEL FD600 STANDARD COMMERCIAL FREEZE DRYERS :**
<table>
<thead>
<tr>
<th>Specification</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Chamber</td>
<td>Stainless or Carbon Steel</td>
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<tr>
<td>Overall length</td>
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<tr>
<td>Overall Width</td>
<td>1840mm</td>
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<tr>
<td>Overall height</td>
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<td>Shelf heating</td>
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MODEL FD1000 STANDARD COMMERCIAL FREEZE DRYERS: