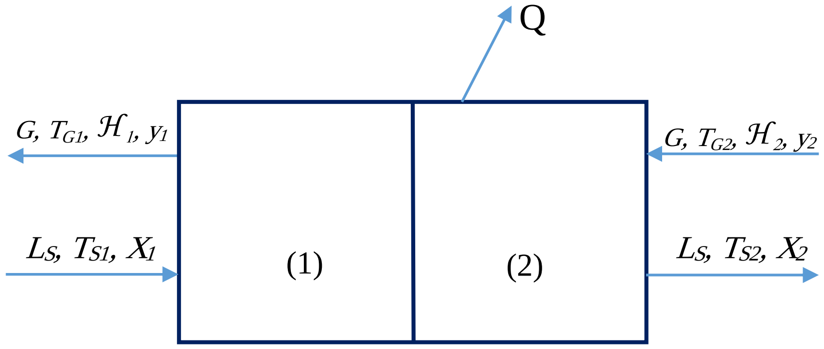
1.10 Material and heat balance for continuous dryers.

Figure below show a flow diagram for a continuous type dryer where the drying gas flows counter currently to the solids flow.



The solid enters at a rate of L_s $kg_{drysolid}/h$, having a free moisture content X_1 and a temperature T_{S1}. It leaves at X_2 and T_{S2}. The gas enters at a rate G kg_{dryair}/h, having a humidity $\mathcal{H}_2$ *kg water vapor/*kg_{dryair} and a temperature of T_{G2}. The gas leaves at T_{G1} and $\mathcal{H}_1$.

For **material balance** on the moisture:

$$G\mathcal{H}_2 + L_s X_1 = G\mathcal{H}_1 + L_s X_2 \quad \dots\dots\dots 32$$

For **heat balance**: the enthalpy of wet solid is composed of the enthalpy of the dry solid plus that of free liquid as free moisture. The heat of wetting is usually neglected.

The enthalpy of gas H_G in kJ/kg dry air is:

$$\mathcal{H}_G = S(T_G - T_o) + \boldsymbol{\lambda_o \mathcal{H}} \quad \dots\dots\dots 33$$

$$S = C_a + C_H\mathcal{H}\ , kJ/kg.k \quad \dots\dots\dots 34$$

where

λ_o: is the latent heat of vaporization of water (liquid) at reference temperature=2501 kJ/kg

S is the humid heat kJ/kg. K

C_a and C_H specific heat of gas and vapor kJ/kg. K

The enthalpy of wet solid H_s in kJ/kg dry solid is:

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$$\mathcal{H}_s = C_{ps}(T_s - T_o) + XC_{pA}(T_s - T_o) \ldots\ldots\ldots 35$$

where

C_{ps} Specific heat of dry solid kJ/kg$_{drysolid}$. k.

C_{pA} Specific heat of liquid moisture kJ/kg$_{water}$. k.

• The heat of wetting or adsorption is neglected .

So, the **heat balance** on the dryer is:

$$G\mathcal{H}_{G2} + L_s\mathcal{H}_{s1} = G\mathcal{H}_{G1} + L_s\mathcal{H}_{s2} + Q \ldots\ldots\ldots\ldots 36$$

Where Q is the heat loss in the dryer kJ/kg. For adiabatic process Q=0, and if heat is added Q is negative.

1.11 Rate of drying for continuous direct heat driers.

During high temperature drying, humidity of air has only minor effect on the rate of drying and calculations are generally based on rate of heat transfer. At low temperatures, mass transfer driving force is considered. These calculations, however, give only rough estimates and experiments should be conducted for obtaining reliable design data.

1.11.1 Drying at high temperature.

In continuous driers, where the solid moves from one end of the equipment to the other end as in rotary driers, the drying gas undergoes a more or less uniform change in temperature. In case of the solids, on the other hand, three different trends in temperature change can be recognized and accordingly the drier is divided into three distinct zones as shown in Figure (7).

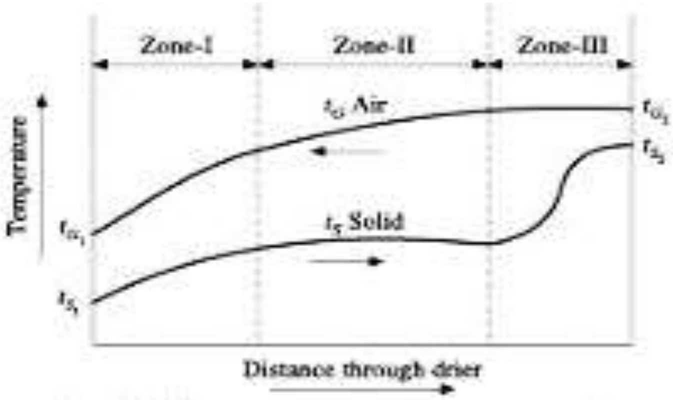

Figure (7) Three zones in a continuous high temperature drier.

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Zone-I is the pre-heat zone where the solid is heated by sensible heat transfer from the gas until there is a dynamic balance between the heat required for evaporation and that supplied by the gas. Very little evaporation takes place here.

Zone-II, surface moisture and unbound moisture are removed and the temperature of the solid remains more or less constant.

Zone-III, unsaturated surface drying and evaporation of bound moisture take place. The temperature of the solid increases considerably in this zone and it leaves the drier at a temperature very close to that of inlet gas. This zone constitutes the major part of many driers.

Considering heat transfer only between gas and solid, an enthalpy balance for a differential length d_z of the drier can be written as:-

$$d_{qG} = d_q + d_Q \dots\dots\dots\dots 37$$

Where,

qG = heat lost by the gas.

q = heat actually transferred to the solid.

Q = heat loss to the surrounding.

Rearranging equation (37) obtains

$$d_q = d_{qG} - d_Q = Ud_s(T_G - T_w) = Ua(T_G - T_w)d_z \dots\dots\dots\dots 38$$

Where,

U = overall heat transfer coefficient between gas and solid.

(TG- Tw) = temperature difference for heat transfer.

S = interfacial surface per unit drier cross section.

A = interfacial area per unit drier volume.

Equation (38) may therefore be written as

$$d_q = GC_s d_{TG} = Ua(T_G - T_w)d_z \dots\dots\dots\dots 39$$

Where

d_{TG} is the temperature drop in the gas due to heat transfer to the solid alone.

C_S is the humid heat of the gas.

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$$dN_{toG} = \frac{dT_G}{(T_G - T_w)_m} = \left(\frac{Ua\,dz}{GC_s}\right) \ldots\ldots\ldots\ldots 40$$

If the heat transfer is constant,

$$N_{toG} = \frac{z}{\mathcal{H}_{toG}} = \frac{dT_G}{(T_G - T_w)} \ldots\ldots\ldots\ldots 41$$

$$H_{toG} = \frac{GC_s}{Ua} \ldots\ldots\ldots\ldots 42$$

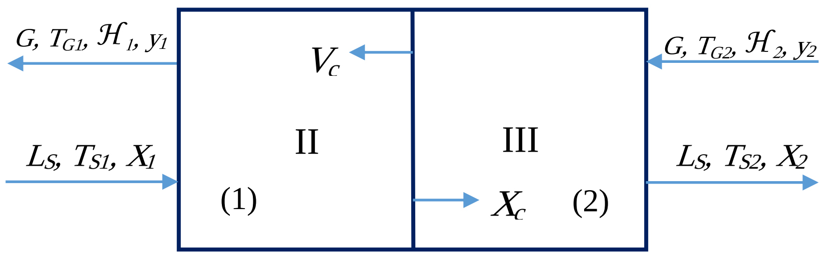
N_{toG} and H_{toG}= the overall number and length of heat transfer units $(T_G - T_w)_m$= change in gas temperature due to heat transfer to solid only dT_G= approximate average temperature difference between gas and solid.

Assuming the temperature profile to be straight line for each of the three zones separately, $(T_G - T_w)_m$ becomes the logarithmic mean of the terminal temperature differences for each zone and N_{toG} becomes the corresponding number of transfer units.

The approximate average temperature differences in the three zones, particularly in Zone-II are the average wet-bulb depressions in the respective zones since the surface of the solid is at the wet-bulb temperature of the drying gas.

1.11.2 Drying at low temperature.

Since the drying takes place at low temperature the preheating of solid is not a major factor. The preheating zone merges with zone II. In zone II unbound and surface moisture constant, X_c as in drying at high temperature. The unsaturated surface drying and evaporation of bound moisture occurs in zone III. The humidity of incoming gas increases from y_2 to y_c as it leaves zone III.



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The retention time can be calculated as:

$$t = t_{II} + t_{III}$$

$$t = \frac{L_s}{A}\left[\int_{X_c}^{X_1} \frac{dX}{R} + \int_{X_2}^{X_c} \frac{dX}{R}\right] \ldots\ldots\ldots\ldots 43$$

In zone II,

$X > Xc$, the rate of drying $R = Rc$ (is given by equation 14a,14b and 16):

$$t_{II} = \frac{L_s}{A}\left[\int_{X_c}^{X_1} \frac{dX}{R}\right] \ldots\ldots\ldots\ldots 44a$$

$$t_{II} = \frac{L_s}{A}\left[\int_{X_c}^{X_1} \frac{dX}{k_{ymB}(\mathcal{H}_w - \mathcal{H})}\right] \ldots\ldots\ldots\ldots 44b$$

Make material balance:

$$G = d\mathcal{H} = L_s dX \ldots\ldots\ldots\ldots 45$$

Sub for dX in equation 44 from equation 45,

$$t_{II} = \frac{L_s}{A} \cdot \frac{G}{L_s}\left[\int_{H_1}^{H_c} \frac{d\mathcal{H}}{k_{yMB}(\mathcal{H}_w - \mathcal{H})}\right] \ldots\ldots\ldots\ldots 46$$

Assuming yw to be constant (which will correspond to saturation humidity at the wet bulb temperature of incoming air and there is no heat loss).

$$t_{II} = \left(\frac{L_s}{A}\right) \cdot \left(\frac{G}{L_s}\right) \cdot \left(\frac{1}{k_{yMB}}\right) ln\left[\frac{\mathcal{H}_w - \mathcal{H}_c}{\mathcal{H}_w - \mathcal{H}_1}\right] \ldots\ldots\ldots\ldots 47$$

In zone III,

$X < Xc$, the rate of drying R give from linear proportional ($R = a\,A + b$) as:

In a specific case of drying from Xc to X^* ,

1- $Rc = a\,Xc + b$
2- $R^* = 0 = a\,X^* + b$

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Rc= a (Xc-X),*

R = a (X-X)*, then

$$R = \frac{[R_c(X - X^*)]}{(X_c - X^*)} \dots\dots\dots\dots 48$$

Applying $Rc=ky\ (y_w - y)$ sub. in equation 48

$$R = \frac{[k_{yMB}(\mathcal{H}_w - \mathcal{H})\ (X - X^*)]}{(X_c - X^*)} \dots\dots\dots\dots 49$$

From equation 43 time of drying in zone III,

$$t_{III} = \frac{L_s}{A}\left[\int_{X_2}^{X_c} \frac{dX}{R}\right] \dots\dots\dots\dots 50a$$

$$t_{III} = \frac{L_s(X_c - X^*)}{A\ k_{yMB}}\left[\int_{X_c}^{X_1} \frac{dX}{(\mathcal{H}_w - \mathcal{H})(X - X^*)}\right] \dots\dots\dots\dots 50b$$

$$G(\mathcal{H} - \mathcal{H}_2) = L_s - (X - X_2) \dots\dots\dots\dots 51$$

$$\mathcal{H} = \mathcal{H}_2 + (X - X_2)\left[\frac{L_s}{G}\right] \dots\dots\dots\dots 52$$

Differentiating equation 51,

$$G d\mathcal{H} = L_s dX \dots\dots\dots\dots 53$$

Sub equation 52 and 53, X*=0 in equation 50b

$$t_{III} = \frac{L_s}{A} \cdot \frac{X_c}{k_{yMB}} \cdot \frac{G}{L_s}\left[\int_{\mathcal{H}_c}^{\mathcal{H}_2} \frac{d\boldsymbol{\mathcal{H}}}{(\mathcal{H}_w - \boldsymbol{\mathcal{H}})\left((\boldsymbol{\mathcal{H}} - \boldsymbol{\mathcal{H}}_2).\left(\frac{G}{L_s}\right) + X_2\right)}\right] \dots\dots 54$$

$$t_{III} = \frac{L_s}{A} \cdot \frac{X_c}{k_{yMB}} \cdot \frac{G}{L_s} \cdot \frac{1}{\left((\boldsymbol{\mathcal{H}} - \boldsymbol{\mathcal{H}}_2).\left(\frac{G}{L_s}\right) + X_2\right)}\ ln\left[\frac{X_c(\mathcal{H}_w - \mathcal{H}_2)}{X_2(\mathcal{H}_w - \mathcal{H}_c)}\right] \dots\dots 55$$

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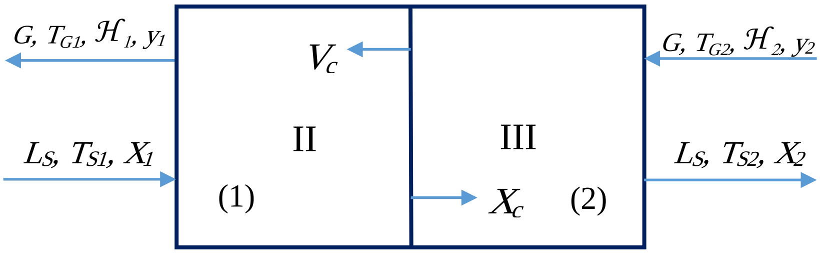
Note: equation 55 cannot be applied for rate of drying controlled by internal diffusion

◉ In case of parallel flow of driers,



$$t_{II} = \left(\frac{L_s}{A}\right).\left(\frac{G}{L_s}\right).\left(\frac{1}{k_{yMB}}\right)\ ln\left[\frac{\mathcal{H}_w - \mathcal{H}_1}{\mathcal{H}_w - \mathcal{H}_c}\right] \ldots\ldots\ldots 56$$

$$t_{III} = \left(\frac{L_s}{A}\right).\left(\frac{X_c}{k_{yMB}}\right).\left(\frac{G}{L_s}\right).\frac{1}{\left((\mathcal{H} - \mathcal{H}_2).\left(\frac{G}{L_s}\right) - X_2\right)}\ ln\left[\frac{X_c(\mathcal{H}_w - \mathcal{H}_2)}{X_2(\mathcal{H}_w - \mathcal{H}_c)}\right] \ldots\ldots 57$$

1.12 Drying Equipment.

Some dryers are continues, and some operate batch wise, some agitate the solids, and some are essentially un-agitated. Operation under vacuum may be used to reduce the drying temperature. Some dryers can handle almost any kind of material, while others are severally limited in the type of feed they can be accept.

A major division may be made between:

1. Dryers in which the solid is directly exposed to a hot gas.
2. Dryers in which heat is transferred to the solid from an externa medium such as condensing steam, usually through a metal surface with which the solid is not in contact.

Dryers which exposed the solids to a hot gas are called direct dryers; those in which heat is transferred from an external medium are known indirect dryers.

Solids handling in dryers, most industrial dryer handle particulate solids during part or all of the drying cycle, in adiabatic dryers the solids are exposed to the gas in the following ways:

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1. Gas is blown through a bed of coarse granular solids which are supported on a screen. This is known as through – circulation drying. As in cross-circulation drying the gas velocity is kept low to avoid any entrainment of solid particles.

2. Solids are showered downward through a slowly moving gas stream, often with some undesired entrainment of fine particles in the gas.

3. Gas is blown across the surface of the bed or slab of solids, or across one or both faces of a continuous sheet or film. This process is called cross-circulation drying.

4. Gas passes through the solids at a velocity sufficient to fluidize the bed.

5. The solids are all entrained in a high-velocity gas stream and are pneumatically conveyed from a mixing device to a mechanical separator.

In indirect dryers heating the only gas to be removed is the vaporized water or solvent, although sometimes a small amount of "sweep gas" often air or nitrogen is passed through the unit.

1. Solids are spread over a stationary or slowly moving horizontal surface and cooked until dry. The surface may b heated electrically or by a heat transfer fluid such as steam or hot water.

2. Solids are moved over a heated surface, usually cylindrical by an agitator or a screw or paddle conveyor.

3. Solids slides by a gravity over an inclined heated surface or are carried upward with the surface for a time and then slides to a new location "Rotary dryer".

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