DRYING PYRETHRUM

by

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ABSTRACT

Drying technology is being more and more used in chemical industry, food industry, processing agricultural products, and fibber industry. In the majority of processing industries, drying is carried out for one or more reasons:

1)To offer ease dealing in further processing. For example; drying sweet chrysanthemum in order to increase sweet agents. It can be instead of the cane sugar. The sweet taste is nearly 200 times of that of the cane sugar. Generally, after picking up the fresh leaves of the sweet chrysanthemum, it is necessary to send them to drying equipment at the temperature about 80 C° ---100 C°. With the help of the drying their fresh leaves, their volume will be reduced to one of seventh or one of eighth of fresh leaves volume. Then it is through chemical processing them to get sweet ingredients. Finally, these sweet ingredients are dried at the temperature nearly 140 C° to get the final white products.

2) To supply the final product with satisfactory moisture, such as tea, tobacco. The moisture of fresh tea leaves is about 70%. After drying the final moisture of tea is about 6 %.

3) To preserve the products during storage. For example, drying rice, corn, and other agricultural products are to impede the enzyme to oxidation of these agricultural products, because the final lower moisture of the dried agricultural can limit the enzyme to grow.

4) To avoid the presence of the moisture which may lead to corrosion as in drying some metal products.

The drying process includes moisture migration and evaporation. The heat and mass transfer are always key controls for any drying processes in designing the dryer. The drying energy efficiency and drying cost should be considered firstly. Currently high

density industrial drying technology is developing quickly based on a deeper understanding of the drying process and the character of wet objects.

The purpose of the paper is to analyse the drying process, including heat and mass transfer, moisture movement and moisture evaporation, and the air flow situation in the drying chamber through discussing the practical drying pyrethrum.

A moisture moving model in capillaries is set up to study the moisture movement inside the pyrethrum, which will influence the drying rate because the moisture in the wet pyrethrum exists mainly in the capillaries.

A mathematical model of Heat and Mass transfer has been developed to explaining the drying principle and to design a suitable dryer for drying pyrethrum. Psychrometric chart and other charts are introduced to understand the change of warm air conditions during drying pyrethrum.

The drying curve predicts the moisture changes in the wet materials and the characteristics of the dryer.

Analysis of the air flow patterns in the air duct leads to improvement in the air velocity distribution in the drying chamber.

After studying the whole drying theory, the forced convection multiple continuous dryer is recommended for drying pyrethrum. In this dryer, the heat energy necessary for moisture evaporation is supplied through the convection of warm air. The vapour is carried away by the warm air. The continuous drying will result in higher drying efficiency. This dryer offers some outstanding features as follows:

(1) This dryer offers a larger output for a given floor area.
(2) The drying conditions can be easily controlled.
(3) Higher heat efficiency can be obtained in this dryer due to the continuous drying process.
(4) Automatic loading and discharging save some labour costs.
(5) Compared with other dryers, lower operation costs and lower manufacture costs are obtained in selecting this dryer.

High density drying should produce the top quality dried products at the lowest cost. In drying plants or agricultural products, the top drying quality has some specification as follows.

(1) The final moisture contents of the dried products should be in equilibrium with that of the air in which it is to be stored so that further changes in moisture are small. This conditions is called the equilibrium moisture content. For most organic plants, the EMC is in the ranges 9-15% of oven dry weight.

(2) The oxidation of ingredients should be lower than 15% by weight.

(3) The broken volume should be lower than 15% by the total volume.

(4) Odour and colour should be maintained. For example drying tobacco, the colour should be the golden yellow. For drying some vegetables, the natural green colour should be kept during the drying process.

It is hoped that this study may lead to improved drying technology in drying Chinese tea, tobacco, vegetables, mushrooms, agricultural products and food.

Chapter 1

Introduction

1.1)Final moisture contents

In the pyrethrum industry, drying is necessary to remove the extra moisture. The drying process is very energy consuming so that it is necessary to consider the drying efficiency with respect to both energy and time.

Evaporation of moisture in the drying process is the cheapest and most convenient method used by industry. The purpose of drying pyrethrum is to concentrate the chemical ingredients in pyrethrum for making pesticide by removing a lot of extra moisture.

Based on the drying purpose, the final moisture in the dried products can be obtained. Usually it is about 12% by weight of dried products. The final moisture is the important parameter in the drying process. The lower the final moisture, the higher the drying cost. On the other hand if the final moisture is too high, it may induce oxidation or rotting. Usually in industry drying it is hoped to get lower final moisture, but at the reasonable drying cost. How to decide the final moisture of being dried plants in industry fields are the key factor.

The final moisture is the equilibrium moisture with the relative humidity of ambient air at a given temperature for a long time. Because when any objects are put into the ambient, the absorption or desorption is always take place automatically in order to get the moisture equilibrium state. If the final moisture of dried materials is lower than this equilibrium moisture at the certain temperature, the dried materials will absorb moisture from the atmosphere. In drying fields, it should avoid this absorption of moisture from ambient. For any drying process, it is necessary to pay attention on the final moisture of dried materials.

In order to decide the final moisture, the HENDERSON equation is used to calculate the final moisture.

$$1 - \phi = e^{-cTw_g^n} \quad ...(1.1)$$

Here ϕ = the equilibrium relative humidity.

   W_g = the equilibrium moisture within the solids by dried bone.

   T= the equilibrium temperature (k).

   c,n = the constant determined by the characters of solids.

Table 1 gives some final moisture of agricultural products.(These values are from the book ' Hand Book of Industrial drying ' P559)

Table 1 The recommendation for final moisture in drying grain

	ear corn	wheat	oats	Barley	sorghum	Soybeans	Rice	peanuts
grain								
Final maximum moisture content of crop for safe storage	13%	13% (12% for seed)	13% (12% for seed)	13%	12%	11%	12%	13%

1.2)Classification of wet materials and property of wet materials

A few of methods are used in the classification of wet plants. To assist drying, it is expected that this classification will be of benefit by explaining the moisture movement inside the wet materials. So, the wet materials can normally be divided into three categories as follows:

(1.2.1) Non hygroscopic capillary-porous
The defining criteria are three features :
a)There is clearly recognisable pore space. The pore space is filled with moisture as it is saturated. When it is dried, the air will occupy the pore space. The moisture in these spaces is free moisture.
b) There is a little bound moisture that is the physical moisture, and this can be neglected during drying this non hygroscopic capillary-porous materials.
c) During the drying process there is no shrinkage. Sand belongs to this category.

(1.2.2)Hygroscopic-porous
Most plants and timber belong in this category. The defining criteria are as follows:
a) There is a clearly recognisable pore space, which is full with free moisture.
b) There is a large amount of bound moisture.
c) Shrinkage often occurs during drying.

(1.2. 3) Colloidal

Soap and glue belong to this category. The defining criteria are as follows:

a) There is no pore space (evaporation can take place only at the surface). No air can move through this wet material.

b) All moisture is bound moisture.

When wet materials are classified, they should be homogeneous, because only homogeneous materials can be considered as having a mass and transfer process in them that is a continuous process.

Pyrethrum is a typical hygroscopic-porous material. The solid skeleton consists of a series of capillaries. The moisture which can be evaporated is trapped in the capillaries. It should be noted that the cell walls act as semi-permeable membranes for the effusion of moisture.

In this category of colloidal, the moisture exists mostly as free moisture or physical-bound moisture. Drying is very useful in removing the free moisture and physical-bound moisture due to smaller combining force in physical bound-moisture than that in chemical-bound moisture.

The process of the moisture changing can be expressed as follows:

Bound moisture→Unbound Moisture→Free moisture→Vapour

1.3)Some parameters represent the characters of wet materials.
1.3.1) Porosity

The porosity is a measure of the ratio of the total void space volume to the total body volume. When the void space volume increase, the porosity increase too.

$$\varepsilon = \frac{V}{V_m}...(1.2)$$

Here: ε : the porosity.

V: the total void spaces volume.(m³)

Vm: the total body volume.(m³)

1.3.2)Tortuosity

Tortuosity means the ratio of body dimension in a given direction to the distance of the path traverse by the moisture in the diffusion process.

$$\ell = L / L_d \ldots(1.3)$$

ℓ :the tortuosity.

L: the body dimension in a given direction.(m)

L_d: the length traversed by the moisture in the diffusion process.(m)

1.3.3) pore shape factor

ς is the pore shape factor that characterises the deviation of the diffusion channel shape from that of the standard cylinder.

In drying practice, the function of the pore or capillaries distribution in relation to the radius of the capillary will give great influence to the distribution of moisture in wet materials. Because these porous distribution situations determines the mass of the moisture in capillaries.

Function(1.4) is introduced to compute the total pore volume

$$\varepsilon_{max} = \int_{r_{min}}^{r_{max}} \frac{d\varepsilon}{dr} dr \ldots(1.4)$$

$$\frac{d\varepsilon}{dr} = f_v(r) \ldots\ldots(1.5)$$

$$\varepsilon_{max} = \int_{r_{min}}^{r_{max}} f(r) dr \ldots(1.6) \ldots.. (1.6)$$

Here ε_{max} = the largest porosity.

r= the radius of the capillary.(μm).

f_v is the differential equation of the volumetric pore characteristic that reflects the pore distribution.

From equation (1.6), the maximum porosity can be determined . Then the moisture mass can also be determined , moisture mass can be calculated as the product of liquid density and porosity. Fig(1.1) is introduced to explain the pore distributions situation .

$$\frac{d\varepsilon}{dr}$$

f(r)

r(min)   r(max)
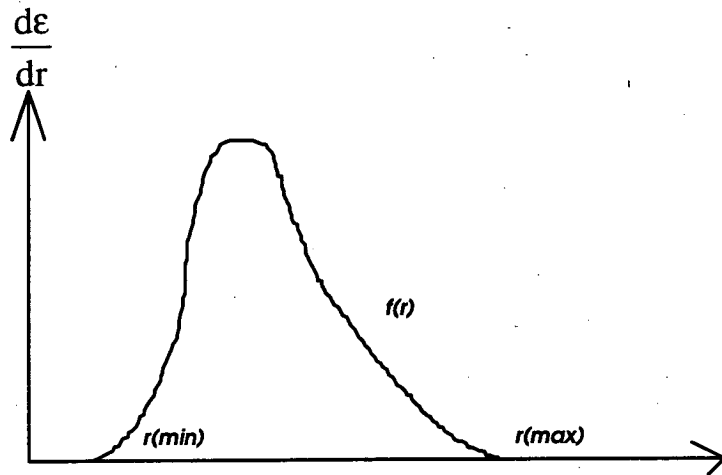
Fig(1) Differential curve of pore distribution

1.4)The categories of moisture existing in the wet materials

In order to study the heat and mass transfer during drying process, it is necessary to understand the different existing types of moisture in wet materials, because the category of the moisture present decides the moisture diffusion mechanism.

A) Surface moisture.

This is the water on the surface of the material due to surface tension force.

B) Free, or capillary moisture.

This moisture exists in the pores or capillaries of wet materials. Free moisture is the moisture in excess of the equilibrium moisture and consists of unbound and some bound moisture. It should be noted that only the free moisture can be evaporated at the temperature usually used.

C) Bound moisture.

This bound moisture can be subdivided into three kinds based on the different bonds.

a) chemical moisture bonding

b)physical--chemical moisture bonding.

c)physical mechanical moisture bonding

D) The equilibrium moisture.

The equilibrium moisture is the lowest moisture content of the wet solids, when the moisture pressure of the wet solids is equal to the vapour pressure of moisture in the ambient air under a given temperature and humidity.

Usually, if wet porous material is kept in contact with warm air at a constant temperature and humidity, moisture transfer will take place until equilibrium is reached. Under the given conditions, the final moisture content is termed the equilibrium moisture.

When the vapour pressure on the wet surface is higher than that within the mixing air, desorption takes place. Some moisture will move from the wet surface to the ambient air until the vapour pressures of both them become equal. To remove much more moisture from the wet surface, it is through reducing the relative humidity within the moist air. As a result, a lower vapour pressure in the air will be produced. So, the larger gap of pressure between the air and wet solids will be obtained. Much more moisture will move from the wet solids to the air further. The new equilibrium at the lower moisture can be got.

Absorption and desorption isotherms curve are reported in the book' Hand Book of Industry Drying' . A lot of them have a characteristic shape as illustrated in Fig(1.2).

percentage gas humidity

sorption   desorption

moisture content (dry basis) kg/kg
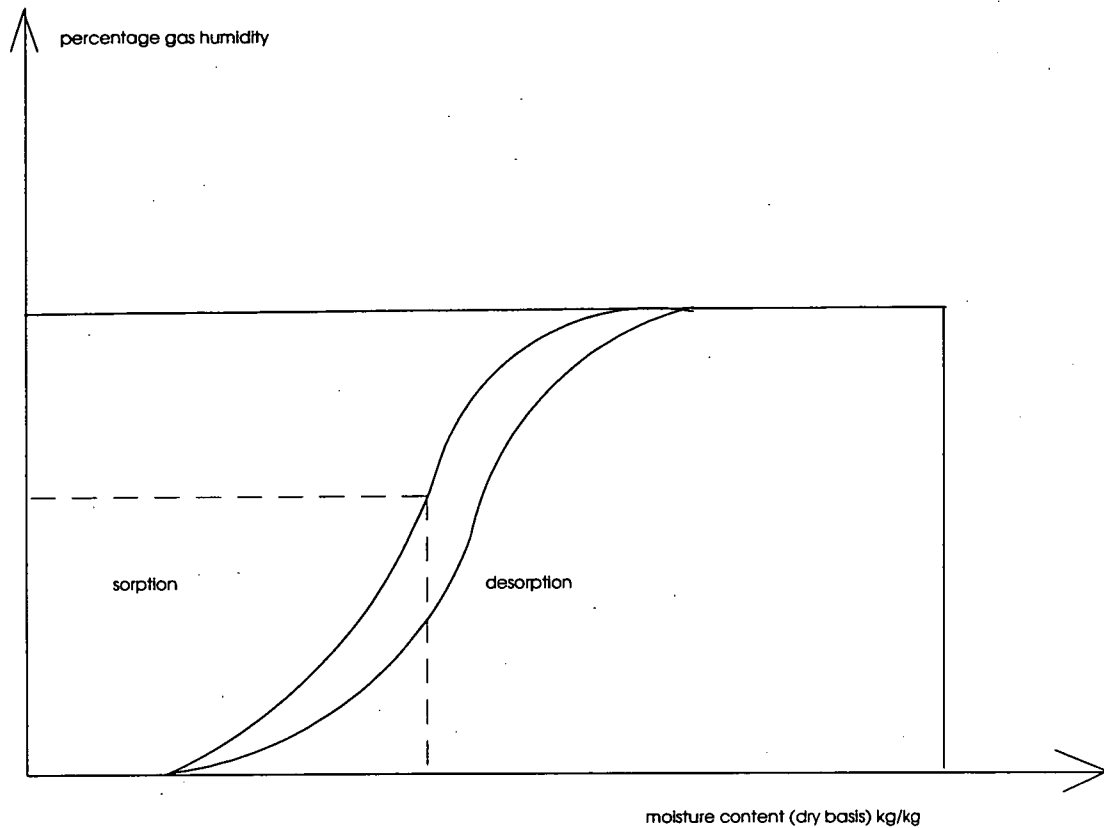
sorption and desorption isotherms
fig(1.2)

1.5)The model of moisture movement in capillaries

There are four stages of moisture movement. At the initially stage, the capillaries are filled with moisture. And the moisture moving is in the liquid phase under an hydraulic gradient. It should be noted that moisture in small pores will be in the less pressure than that of a body of liquid at the same temperature. The Kelvin equation expresses this phenomenon.

$$\ln \phi = \frac{-2\sigma}{r} * \frac{M}{\rho RT} ...(1.7)$$

Here ϕ =the relative humidity.

σ =surface tension, N/m.

ρ = the density of the vapour moisture , kg/m³.

R= the gas constant, J/(mol K).

M= moisture molar mass, kg/k mol.

r= the radius of the pore, μm.

During the second stage, as water leaves the capillaries, warm air moves in to take its place. Within the capillaries there are formed thin curved interfaces between the air and liquid water until eventually, the capillaries are free of liquid water. Due to warm air migrating into the capillary, the liquid bridge is built up between the air ball and the wall of the capillary. The moisture can migrate either by creeping along the capillary wall or by successive evaporation and condensation along the moisture bridge.

At the third stage, the air ball in the capillaries will become larger and larger due to the moisture subsequently moving out. These liquid bridges evaporate entirely leaving only absorbed moisture that is moving in the vapour, because the absorbed force is too strong for moisture to move as liquid.

At the fourth stage, the surface is saturated due to migration of the from moisture inside the wet products. The saturation equilibrium will be built up between the wet surface and the environment around the surface. So, the moisture is moving as vapour.

Fig (1.3) is introduced to describe this model.

moistur moving
in a capillary

1

2

evaporation

3

vapour moving
in a capillary

4
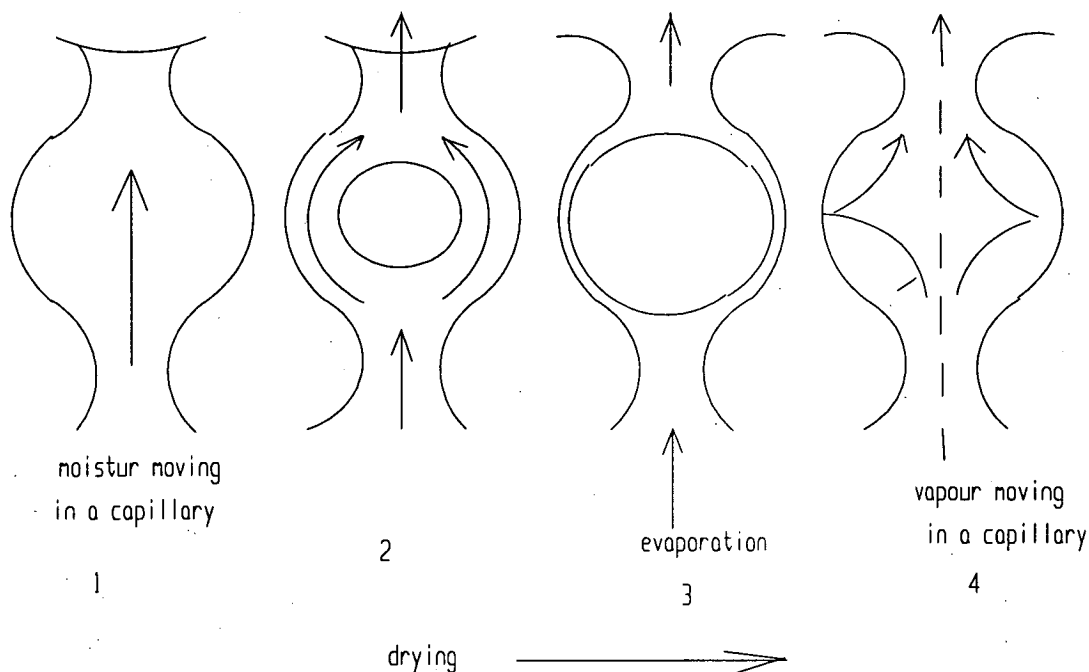
drying ⟶

fig(1.3) drying model

1.6)Drying methods

There is no manufactured dryer that satisfies all drying processes, because wet products are different from each other in their chemical and physical properties. Also the purpose of drying these wet products involves removal of different masses and different forms of the moisture from within the wet products. Various dryers are employed in different drying processes. For industrial drying, as well as the ability to remove water efficiently, it is necessary to consider other factors. For example, some dryers work best at drying hygroscopic materials; but other work very well at the drying non hygroscopic solids. Some offer the higher heat efficiency at reasonable operation cost. The first task for designing the dryer is to select the appropriate type of dryer. The most commonly used methods of drying agricultural products are convection, conduction, convection, conduction combined and the radiation dryers.

1.6.1)Convection drying

Convection drying is broadly employed in drying agricultural products. Usually in convection dryer, warm air or waste air with temperature above 60 C° is used as heat agent. Warm air flowing under the certain force or naturally passes through the wet materials to supply heat energy and to remove the evaporated moisture and carry it out from the drying chamber. Some times to save energy, partial recycle of warm air occurs when the temperature of exhausted warm air is relative higher. Normally it is nearly above 60 C°.

In the convection drying method, the dryers can be divided into four kinds as follows:

A) Batch dryer.
B) Recirculate dryer.
C) Vibration dryer.
D) Continuous dryer.

A) Batch dryer

In this dryer, the wet materials are put on the trolleys or large dishes. During the drying process, the warm air is forced past these dishes. The wet materials are in a static state.

Compared with other convection dryers, the manufacturing cost of the batch dryer is lower than other dryer. From operation cost view, batch dryer needs a lot of labour to load and discharge the products. This limits its application to drying small quantities of wet products or these needing a long drying period.

In practice, the warm air distribution profile isn't uniform at each section of the drying chamber. The drying uniform in drying agricultural products is lower than that in the continuous dryer. In order to improve this shortcoming, an air baffle is usually employed to change the air flow direction automatically based on the different drying stages. In a batch dryer the moisture contents of dried materials aren't uniform. In some designs of batch dryer, air diffusers are employed further to improve the air distribution. Ideal difference in the temperature at the different places of the drying chamber should be lower than 5 °C In some accurate batch dryer of small size, the temperature variation of the drying chamber is nearly 1 °C. As a result of introducing the air diffusers the pressure loss of air flow in the dryer will increase .

The Fig(1.4) is introduced to explain the constructer of the batch dryer.

Fig(1.4) batch dryer

1. air heater
2. air fan
3. drying trolley.
4. air dumper
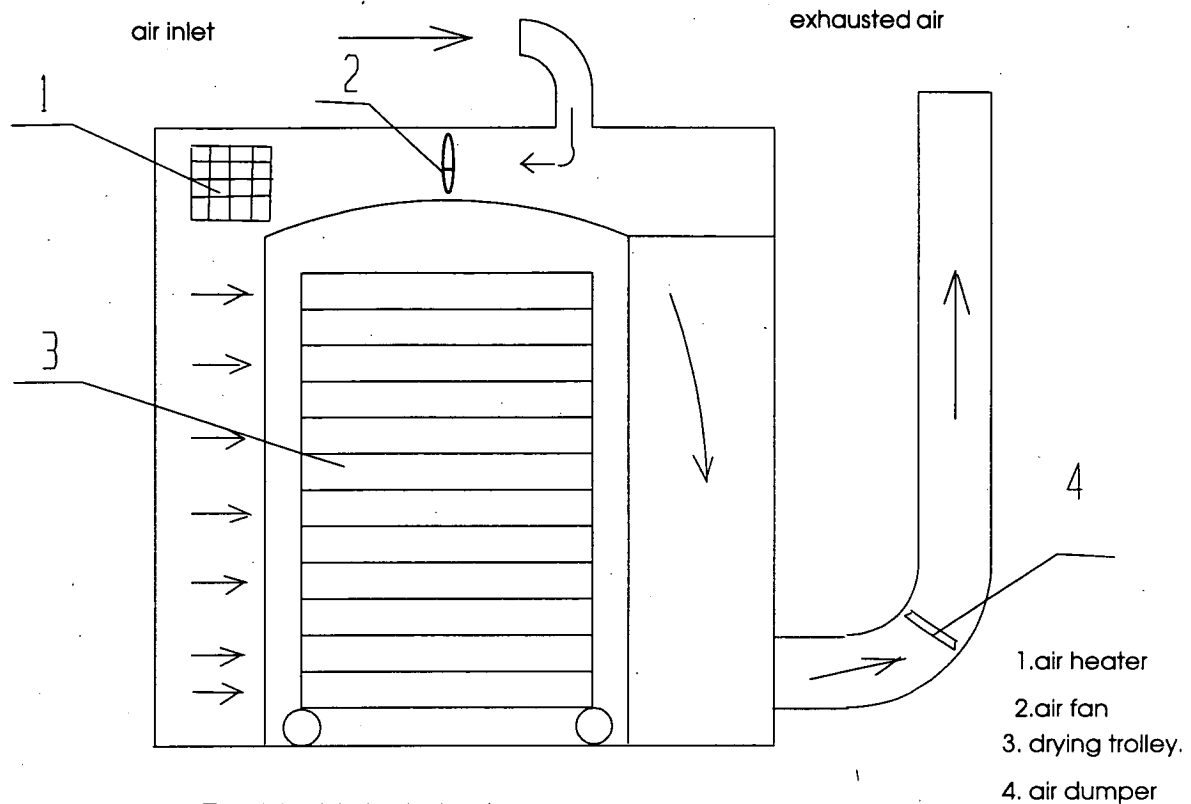
air inlet   exhausted air

B) Recycle dryer

In convection drying method, recycle air is often used to improve the energy efficiency. The partial exhaust air is collected from the exhaust air duct of the drying chamber, then sent to the drying chamber again. Usually in a recycle dryer the drying chamber is divided two parts. The first one is supplied with the exhaust air at the drying initial drying stage. The second one is supplied with the fresh warm air.

At the initial drying stage, due to not enough moisture moving to the surface to keep the surface saturated, the shrinkage occurs during drying plants. In order to decrease the shrinkage, the warm air at the low temperature with higher relative humidity is suppled to the drying chamber. Sometimes exhaust air that has a temperature above 60 °C with relative humidity nearly 50%--65% can satisfy the requirement .
The Fig(1.5) is introduced to explaining the recycle dryer system, which ia supplied with mixed warm air.

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air out

1   2   3

1 trolley   exhausted air

2 air heater

3 air fan
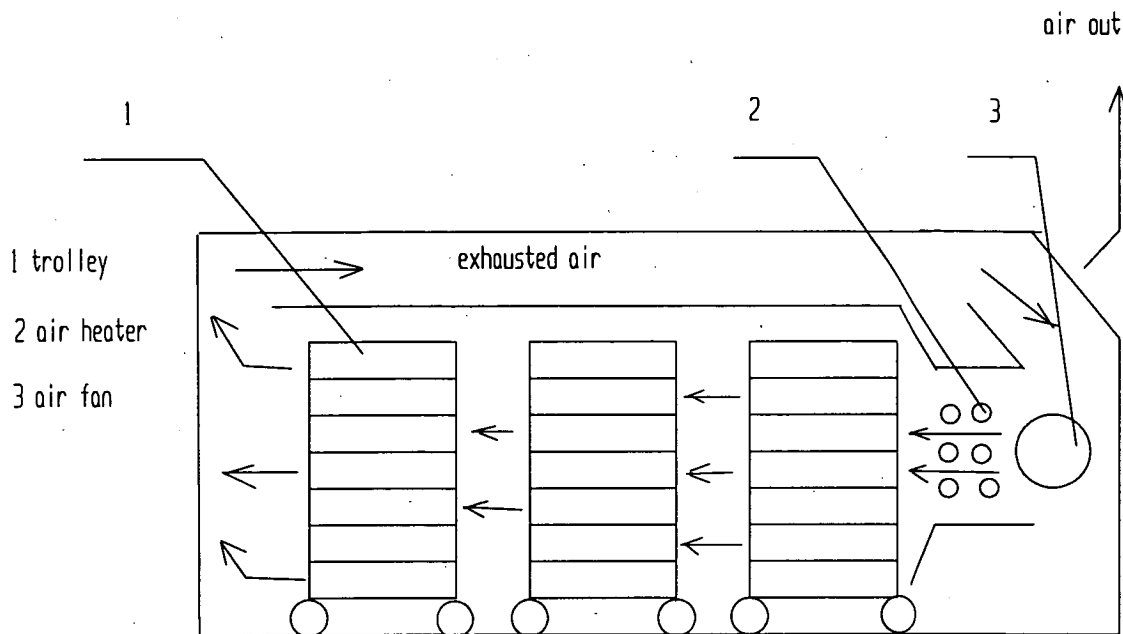
fig(1.5) recycle dryer

C) Vibration dryer

In convection drying methods, a vibration dryer is widely used. The wet materials are moved by vibration of the transporting belts. The basically principle is that the transporting belt is moving forward slowly, then moving backwards quickly through the special cam and spring. Although the speed of transporting belt is changing continuously, the materials is keeping moving by their inertia.

Usually there are a few transporting belts in the dryer. When the wet materials have moved to the end of the first transporting belt, they are dropped down to the second transporting belt. So, the transporting process is a succession process. A vibration transporting dryer can produce higher drying uniformity plus the gentle transporting process can reduce the breakage of dried materials.

Compared with other convection dryers, the manufacturing cost of the vibration dryer is higher than that of other convection dryers. Fig(1.6) represents the constructor of the vibration.
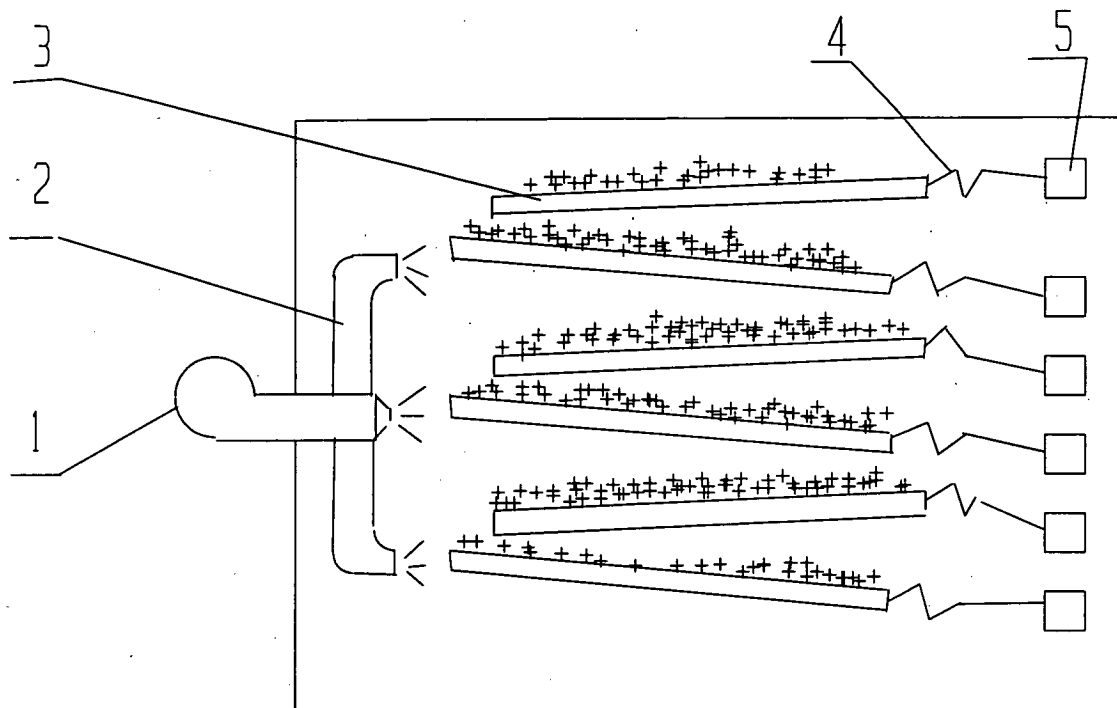
1) fun   2) Air diffuser   3)vibration bed   4) spring   5) can element

fig(1.6)

vibration dryer

D) Continuous dryer

This dryer is widely used in drying agricultural products. In this dryer, wet materials are continuously loaded and discharged. According to the direction of movement of the wet materials, this dryer can be subdivided into three kinds.

a) Vertical continuous dryer.
b) Horizontal continuous dryer.
c) Inclining continuous dryer.

Vertical continuous dryer

In this dryer, the wet materials are transported from the top of the drying chamber to the bottom of the dryer. Normally the drying chamber in this dryer is a large cylinder. The transporting equipment consists of a series of circle plates with two different radii. On these circle plates the wet materials are put, The warm air is forced past these circle plates where the wet materials are put .

At the initial drying stage, the wet materials drop down from the loading transporting belt to the first plate which has the smaller radii. When these plates are rotated, the wet materials are pushed towards the outer edges of this plate by means of one group of the harrows. These harrows whose teeth on these harrows govern the moving direction of the wet materials are driven on the same axis of these circle plates. When the wet materials have moved to the outer edges of the smaller plate, they will drop down to the second larger plate. On the second plate, the direction of the harrows teeth is different from the first plate harrows, and these harrows teeth will pull the wet materials to the centre of the second plate. When the wet materials reach to the centre of the second plate with large radius, they will drop down to the third plate which has the same radius as the first one. The forced warm air is blown between two plates through the wall of the drying chamber. So, the wet materials on the different plates can get heat energy from the warm air. This dryer is employed in lower mass moisture of wet materials that is easy to rotate. For example, during drying corn, rice, some beans, this vertical dryer is employed.

Horizontal continuous dryer

In this dryer, the wet materials are carried on the transporting belts that are moving horizontally. The direction of the air moving is parallel, or against, the direction of the wet materials. The transporting belts can be single or numerous depended on the mass of drying products.

The construction of the single transporting belt is very simple. At the inlet the wet materials are loading by loading machine or humans. The wet materials are transported through the drying chamber to evaporate the moisture. Finally, the same transporting belt will move the dried materials out of drying chamber. The single horizontal continuous dryer is used for wet materials with initial moisture content 35%.

The horizontal multiple transporting belts are used widely in drying plants with moisture contents of about 70% ~90%. The manufacturing cost of multiple transporting belts is obviously higher than that in single transporting belt, but high density drying and lower per unit operation costs make up for this disadvantage.

Inclining Continuous dryer

In this dryer, the transporting belts are installed at an angle to the direction of air movement. There is an acute angle between air movement direction and wet materials movement. This dryer utilises the advantages of both the vertical dryer and the

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horizontal dryer. If the volume of the drying chamber is the same, the largest area for heat and mass transfer between warm air and wet materials is obtained in an incline continuous dryer. The heat efficiency will be higher than that in the other two kinds of continuous dryers, but the manufacturing cost is more expensive than that of other two kinds of dryers.

1.6.2)Conduction drying

Compared with convection drying, conduction drying has the higher heat transporting efficiency. The drum dryer is the typical conduction dryer. In conducting drying the heat agent is warm air or steam. In conduction drying, there are four factors that govern the drying process as follows:

a) The temperature of the heat agent.

b) The thickness of the wet materials.

c) The feeding speed of the wet materials.

d) The condition of the wet materials.

Conduction drying is usually used for drying stick materials which are directly put on the conduction equipment. So, the thickness of wet materials is very important factor during drying process. The feeding speed decides the mass of wet materials and decides the requirements of warm air mass. The condition of the wet materials should include the initial conditions of wet materials, such as temperature, initial moisture. The picture (1.7) shows the drum dryer constructor. When the high drying temperature is needed, for example temperature is over the 200 °C, the conduction dryer is employed. Normally some relative moving between the wet materials and the wall of conduction dryer is used to improve the drying uniformity and avoid burning.

wet material in

drying

hot drum

drying

hot drum

dry material out

dry material out
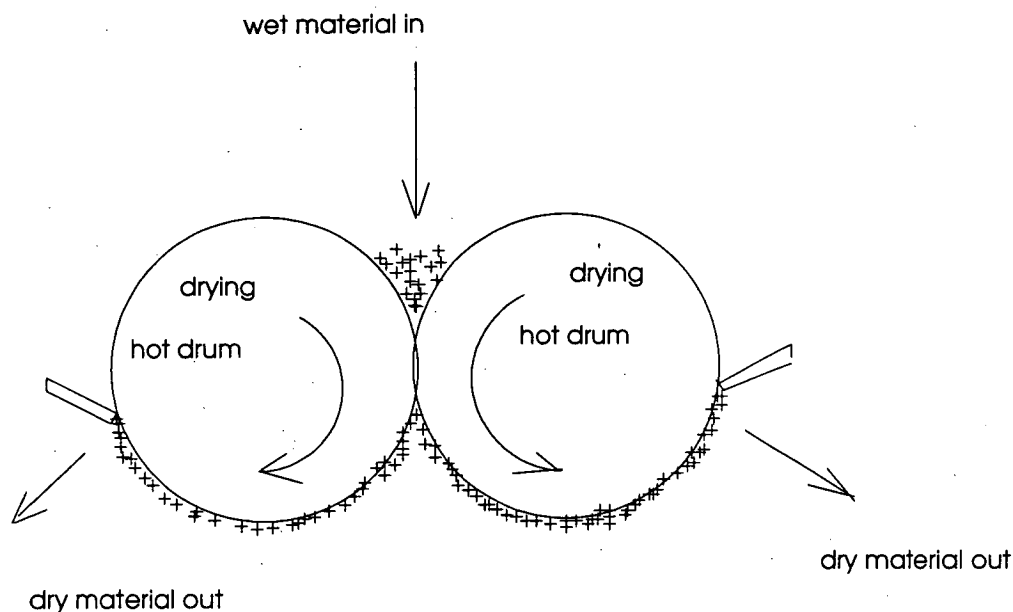
Fig(1.7) drum dryer

Another typical conduction dryers are called as cylinder dryer, where the drying chamber is a cylinder. The wet solids is automatically loaded into this cylinder. The outside of this cylinder is surrounded by steam, warm air, or smoking with high temperature. When this cylinder is rotated, the wet solids continuously contact with the hot wall of this cylinder. Heat transfer takes place between the wall of the drying chamber and wet solids. A lot of moisture is evaporated in the air inside this cylinder. So the mass transfer takes place between the air and wet solids.

1.6.3) Combing conduction with convection drying ---Fluid Bed Dryer

In industrial drying, combining conduction and convection in the heat transfer process is sometimes employed in order to get higher heat transfer efficiency. The fluid Bed Dryer is the typical drying equipment of this kind. In drying various starches, this Fluid Bed Dryer is often used. The particles of wet starch are blown through a long curved pipe which is surround by steam or warm air with temperature over 130 °C The wet starch particles get heat energy through contacting with the warm wall of this

pipe and the warm air inside this pipe, which is heated by heat conduction through the wall of this pipe.

1.6.4)Radiation drying

Electromagnetic radiation with the wavelength band 0.76--400 μm is employed in radiation drying. The principle used is that the radiation from this waveband penetrates the surface area of the wet materials and causes vibration of the molecules. This vibration produces a thermal effect in wet materials.

Compared with other drying methods, the radiation drying operation cost is higher, but the drying uniformity is better than the convection drying and conduction drying. The Fig(1.8) is described the radiation drying.
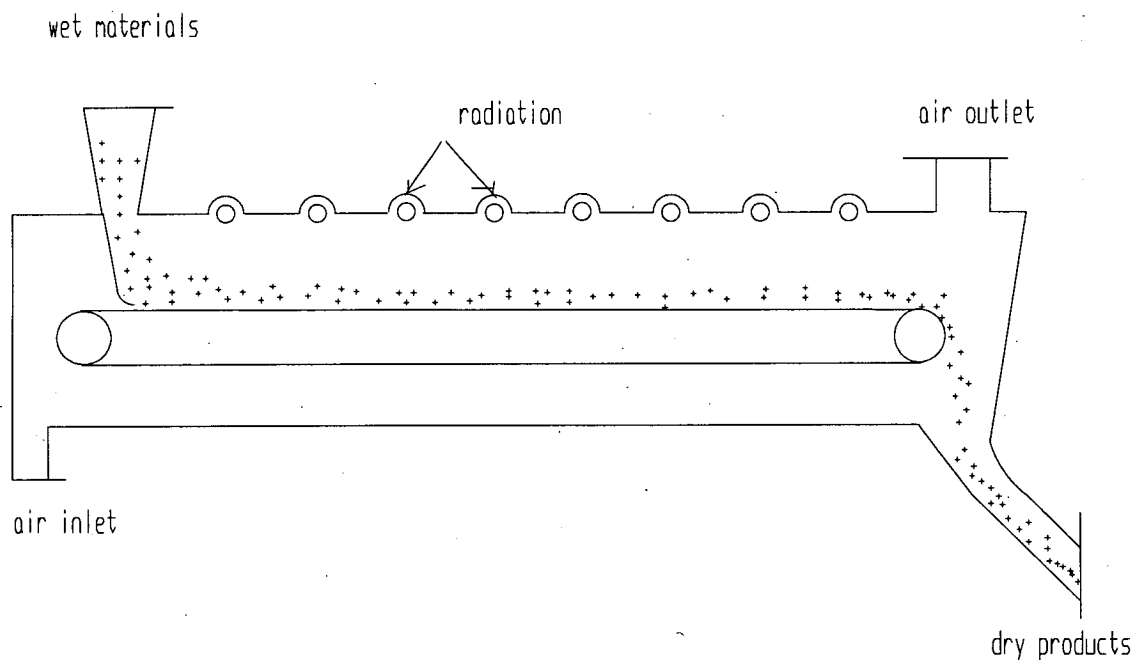
wet materials

Fig(1.8) Radiation dryer

1.6.5)Modern microwave and dielectric drying

The basic principle for modern microwave and dielectric drying is that microwaves and dielectrics are not forms of heat, but will cause materials to heat themselves due to quick changes in the direction of the electromagnetic field.

In this drying method, the amount of free moisture in wet materials greatly affects its dielectric constant, because moisture has a high dielectric constant. The thermal effect of electromagnetic energy absorption is proportional to the dielectric constant.

These five drying methods are often used in drying plants or agricultural products. Besides them, there are other drying methods such as freeze drying, vacuums drying, displacement drying, superheated steam drying.... More and more drying technology is developing to meet the requirements of high density industrial drying.

1.7)Reference to Chapter 1

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Chapter 2

Model development in mass transfer

2.1)Introduction

Pyrethrum is a typical hygroscopic porous material. Its drying is more complicated than that of non hygroscopic porous materials. Mass transfer takes place on the surface and inside the plants in liquid or vapour. The mass transfer model is to set up to understand the mass transfer mechanism during drying pyrethrum.

Drying is the removal of moisture by evaporation from the surface of wet materials. Both warm air factors and wet materials factors give the great influence on evaporation process. So, it is necessary to investigate the external and internal conditions of the drying process.

2.2)External condition

In any drying process, the external conditions are the temperature, humidity, rate and direction of warm air flow; the moisture mass within the wet solids and the volume of the wet materials that is offered to contact with warm air in unit time.

During the drying process, mass transfer includes moisture migration from the surface of the solid to the warm air and moisture moving within plants. During the initial drying, mass transfer takes place between the surface of the solid and air flow. External conditions govern the drying process at the drying initial stage. Because the mass transfer resistance of the air boundary around the wet products is greater than the internal moisture migration resistance.

2.2)Internal condition

The internal conditions are considered as moisture concentration and gradients of the moisture within the wet solids, the porous distribution situation, and the moisture moving path inside wet solids.

The Kirpichev number which explains some factors of drying process is introduced to understand the internal and external how to control the drying process. In book ' Drying: principles, applications and design ', on p52, the equation (2.1) is given to explain the Kirpichev number.

$$K_{iH} = \{h*(Tg-Tgw)b\}/\Delta H * \rho s * D * (x_1 - x_{eg})...(2.1)$$

Here K_{iH}: the Kirpichev number.

h:surface heat transfer coefficient (W/m² K).

Tg: dry bulb temperature of the warm air (C°).

Tgw: wet bulb temperature of the warm air(C°).

b: the thickness of the wet materials(m).

ΔH: the latent heat of the air flow (KJ/kg)

ρs: the moisture density of the surface of the wet substance(kg/m³).

D: diffusivity of the moisture (m²/s).

X_1: moisture of wet substance(kg/kg).

X_{eg}: the equilibrium moisture(kg/kg).

or using the equation of wet-bulb temperature

$$K_{iM} = \frac{k * (Y_w - Y_g) * b}{\rho_s * D * (X_1 - X_{eg})} ...(2.2)$$

Here: K_{iM} :the Kirpichev number.

Y_w the humidity of wet bulb.

Y_g: the gas humidity.

b: the thickness of the wet materials. (m).

ρ_s: the moisture density of the surface of the wet substance (kg/m³).

D: diffusivity of the moisture (m²/s).

X_1: moisture of wet substance (kg/kg).

X_{eg}: the equilibrium moisture (kg/kg).

Two Kirpichev numbers are introduced, but they are used in different situations. K_{iH} is used to describe heat transfer process while K_{iM} describes mass transfer process.

When the dry bulb temperature is equals to the wet bulb temperature in air flow around the wet substances, the Kirpicherv number tends to zero. It means that the surface is saturated. The internal transfer rate will be faster than the external transfer. The drying process is limited by the external conditions.

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When the moisture of the wet substances tends to the equilibrium moisture, the Kirpicherv number tends to infinity. The internal mass transfer will be much slower than the external transfer. The drying process is controlled by internal transfer.

if $k_i < 0.5$ or $B_i < 0.2$ external conditions control the drying process.

if $k_i > 20$ or $B_i > 50$ internal conditions control the drying process.

if $0.5 < k_i < 20$ or $o.2 < B_i < 50$ both conditions are important for the drying process.

These magnitudes are obtained from P53 in book 'Drying: principles, Applications and Design ' by Czeslaw Strumillo and Tadeusz Kudra .

Here B_i is called as Biot number which is introduced to describe heat and mass transfer.

2.3)Analysis of the influence of internal and external conditions of pyrethrum during drying process

Pyrethrum is one of the Hygroscopic plants. Normally hygroscopic substances have two kinds of moisture. One is free moisture. Another is the bound moisture. At the drying initial stage, the free moisture in capillaries is evaporated first. The initial moisture in wet materials must be greater than the equilibrium moisture at the drying temperature. From the equation (2.2) and (2.1), it can be seen that the Kirpichev number has the smaller value due to the large gap between X_1 and X_g. The drying process is controlled by the external conditions, such as the warm air flow, the drying temperature. The surface of wet pyrethrum is keeping saturated and the drying rate is the constant. When the drying process is developing eventually, the free moisture is dried up.

At this stage, the trends of wet pyrethrum will express the internal resistance to moisture moving, because the moisture mass within the wet pyrethrum is reduced by evaporation. The moisture contents of pyrethrum is approaching the equilibrium moisture. The difference between X_1 and X_{eg} become smaller and smaller. As a result, the value of Kirpichev will become larger and larger. The internal conditions will control the drying process. At this stage, it can be understood that the moisture moving is limited by the internal resistance within pyrethrum. The surface of pyrethrum isn't saturated enough. So, the evaporation rate is greater the rate of the moisture diffusion within the wet pyrethrum. The falling drying stage commence.

It is obviously that the internal resistance is mainly depends on the property of the wet solids such as their initial moisture mass, porosity distribution within the wet materials, and the radius of the porosity of the wet materials. These properties of wet products are variable with time during the drying process. The moisture distribution and moisture mass within wet plants is a function of the drying time and temperature.

2.4)Drying stage

The drying process of hygroscopic plants can be divided into three stages: the preheating stage, the constant-rate stage and the falling rate stage.

2.4.1) Preheating stage

The preheating stage takes place at the initial period of drying. When wet plants contact with warm air, their temperature is increased by heat convection. The increased temperature gives moisture molecules in wet substances the more momentum energy. With the increase momentum energy, moisture molecules have a great trend to migration. At the same time, the vapour pressure within the wet plants will be increased too.

2.4.2)The constant--rate stage

At this stage the moisture moving equilibrium is built up between the wet substance and the air flow around it. The rate of moisture migration to the surface of wet substance is equal to the rate of moisture evaporation to the air flow. At the constant-- rate stage, the surface moisture and some free moisture is dried up. At this drying stage, the external drying condition controls the whole drying process. During the drying initial period, vaporisation takes place on the wet surface. The drying rate is controlled by the diffusion of the moisture vapour across the air--moisture boundary. At the end of the constant rate period of drying, moisture is subsequently transported from inside wet solids to the surface by capillary forces. The drying rate can be still a constant.

When drying process is eventually developing, the moisture on the boundary has been reduced by evaporation further. No enough moisture is supplied to diffuse from inside plants to outside. A few dry spots will appear on the boundary, which means the drying rate will drop down due to the amount of the moisture decreasing. The falling rate period commences.

In fact the constant rate stage is very short in drying hygroscopic plants.

The constant rate drying period is described by the equation (2.3)

$$\frac{dw}{dt} = K_m * A * (X_w - X_a)......(2.3)$$

$\frac{dw}{dt}$ = drying rate.(kg/s)

K_m coefficients that describe the heat transfer and moisture transfer condition at the surface.(kgm²/s)

A=the surface area.(m²)

X_w = the amount of the moisture on the surface.(kg/kg)

X_a =the humidity in the warm air.(kg/kg)

2.4.3)The falling rate period

As drying process is developing, the saturated film on the wet surface eventually becomes completely evaporated. The evaporation process begins at the ends of capillaries. Because the mass of moisture is reduced and the resistance of moisture migration is increased, the drying rate will be reduced. The drying rate is determined by the total surface area for evaporation and the amount of the moisture on the surface. Here, some scholars considered the total areas for evaporation will be the constant during drying process. Others considers the areas for evaporation will increased for evaporation at the ends of capillaries. Whether the areas for evaporation is the constant or increasing, the drying rate will be reduced by reducing the amount of the moisture due to continuous evaporation. the temperature of the wet materials surface will gradually increase to the temperature of the warm air. As drying proceeds the moisture diffusion rate inside the wet solid will control the drying rate. The moisture concentration gradient between the surface and the centre of wet materials will have a great influence on the inside moisture diffusion rate.

At the same time the heat transfer is towards the deeper part of the wet materials by conduction. Moisture diffusion can be as in liquid or vapour. But the parameters of wet materials will produce high resistance to moisture diffusion within wet solids. As the rate of internal moisture moving is reduced, the drying rate reducing more rapidly.

The equation (2.4) is introduced to describe the falling rate drying periods.

$$\frac{dw}{dt} = -K * A * \frac{dp}{dx}......(2.4)$$

here: $\frac{dw}{dt}$ = the drying rate.(kg/s)

K= the moisture diffusion coefficient within wet materials.(kgm^2/ m^2s)

A= the surface area.(m²)

$\frac{dp}{dx}$= the drying force for the moisture movement in terms of water vapour pressure.(kg/m^2)

Fig(2.1) is introduced to explaining the drying stages.

$\frac{dw}{dt}$
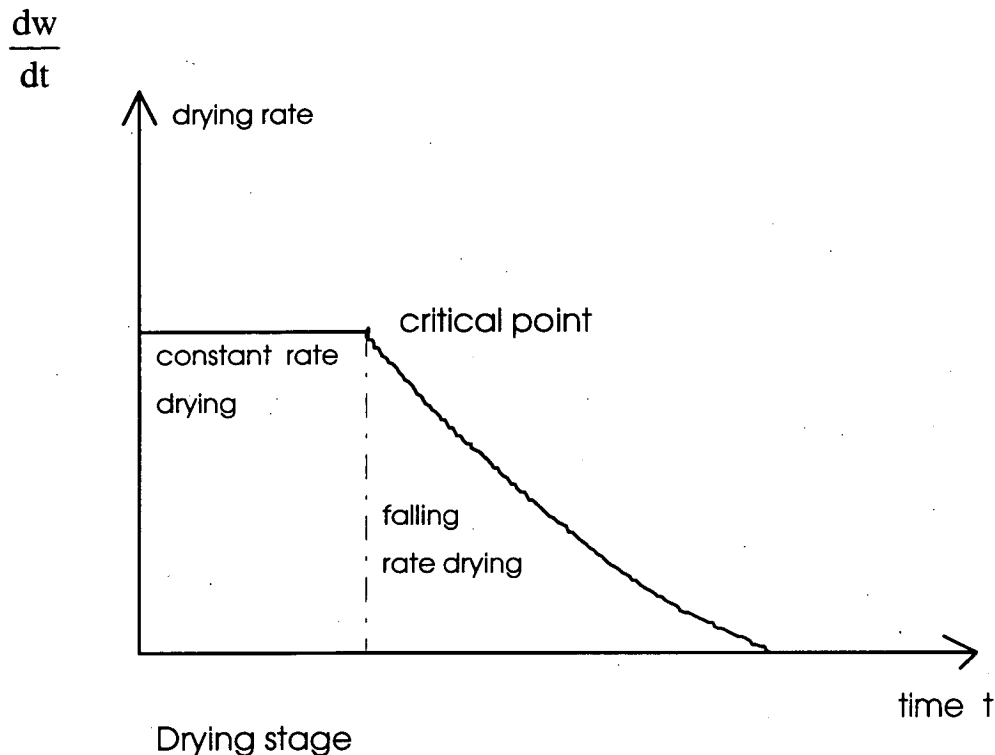
Fig (2.1)

2.5)Drying process and humidity chart

In drying engineering, warm air is widely employed as the heating agent. Warm air is a vapour -gas mixture, which must not be saturated during the drying process. The humidity within the mixing air is continuously changing. The dry air and vapour exert a certain pressure upon each other when they are mixed. This pressure of each component is called the partial pressure. From the drying view, it should be noted the difference between the partial pressure of moisture vapour in the warm air and the pressure of the moisture in the wet materials. This difference is defined as the driving forces. In designing a dryer, when selecting the parameters of the warm air, it is

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necessary to maintain sufficient pressure difference between the vapour in the warm air and moisture pressure within the wet plants.

Humidity charts show the drying process and the changes of the mixing air humidity. In drying engineering, humidity charts are very useful to calculate any drying process.

2.6) Psychrometric chart

The psychrometric chart represents the properties of the mixture of air and moisture vapour. This chart gives the mixture properties as follows:

2.6.1) Dry bulb temperature.

Dry bulb temperature is the air temperature. It is given on the horizontal axis of the psychrometric chart.

2.6.2) Absolute humidity

Absolute humidity is the ratio of the weight of moisture vapour to the weight of the dry air. The absolute humidity is on the vertical axis of the psychrometric chart.

2.6.3) Relative humidity

The ratio of vapour pressure to saturation vapour pressure is known as relative humidity. Relative humidity gives a measure of the maximum moisture that exhausted air can hold at given temperature because relative humidity can never be greater that 1.0.

2.6.4) Dew point.

At the dew point temperature, the state of the air mixture is the equilibrium state between saturation and condensation. The temperature of the wet bulb at saturation is equal to that of the dry bulb .

2.6.5) Wet bulb temperature

Wet bulb temperature is the temperature measured by the thermometer whose bulb is covered by a wet cloth and exposed to the moving air. The wet bulb temperature measures the latent heat within moisture air, because unsaturated air is passed over a wetted thermometer bulb, water evaporates from the wetted surface, the latent heat absorbed by the vaporising water results in a lowering of temperature of wetted surface.

2.6.6) Enthalpy

Fig (2) drying process on the psychrometric.
chart
I – II heating air
II – III Warm air saturation process
in the drying chamber
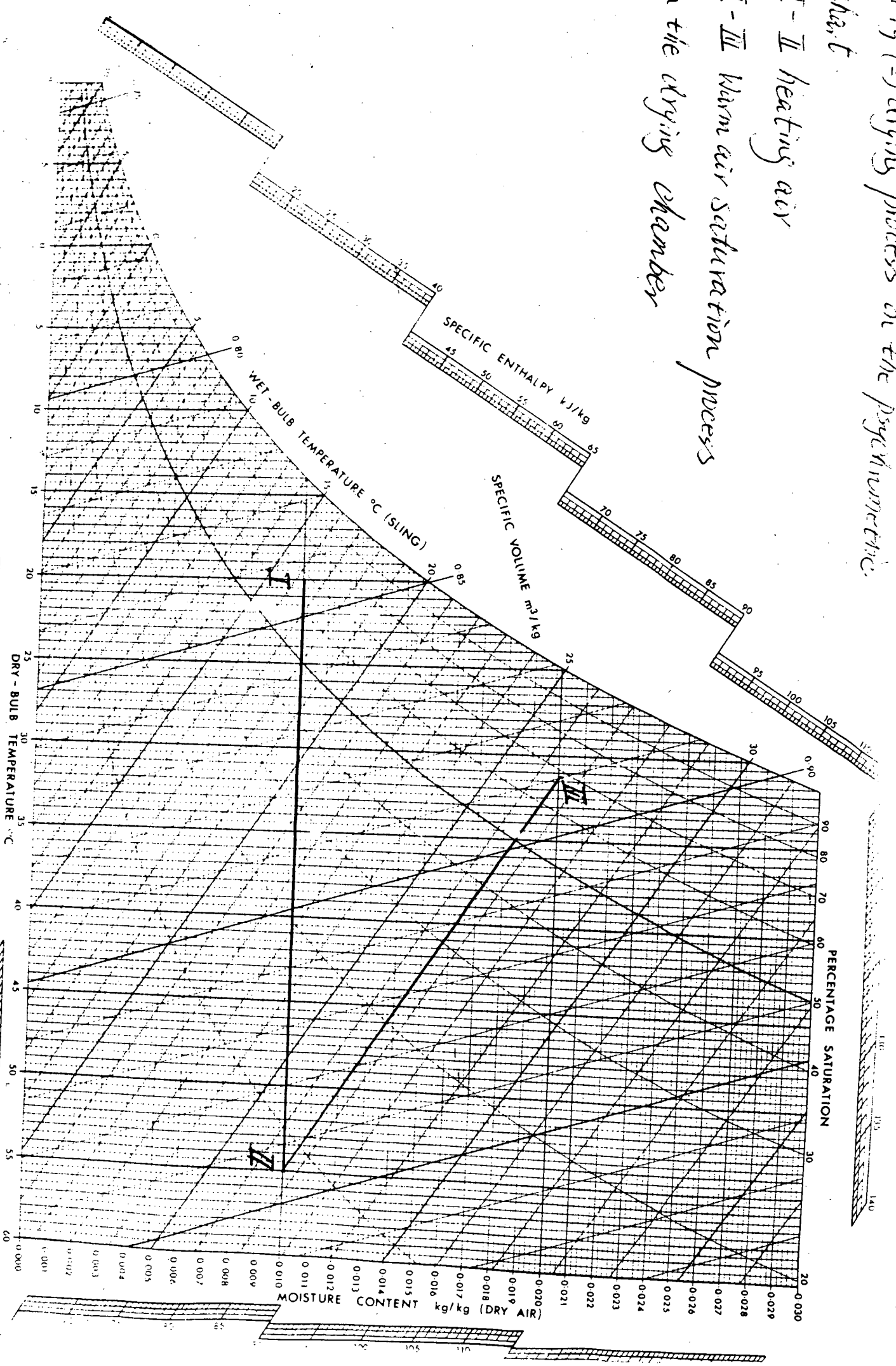
Enthalpy is the total heat content of the moist air.

2.6.7) Specific volume.

The specific volume is the volume of each unit weight of the moist air.

2.7) Drying process on the psychrometric chart

The drying process on the psychrometric chart is represented by the change of warm air conditions. The convection drying process is consists of two stages:

One is to heat the air. This process is known as sensible heating process. During this process, the temperature of the air rises. But the mass of the air, the mass of the humidity within the air mixture doesn't change. This process is represented by a horizontal line on the psychrometric chart.

Another is to saturating the warm air in the drying chamber. When warm air is contact with the wet surface of the plants, as a result of that the vapour pressure of the moisture within the warm air is below that of the moisture on the wet surface, the evaporation takes place. More and more moisture diffuse to the warm air. Heat is moving from air to the wet surface. So, the temperature of the warm air drops down while the mass of the moisture is going up. But the wet bulb temperature will be the constant, which means the total enthalpy should be the same during saturation process in the drying chamber. This process is represented by the line that is parallel to the wet bulb temperature line. Before the warm air is sent to the drying chamber, firstly it goes to the air heater to get enough heat energy. The heating air process is represented by the horizontal line which is parallel to the dry bulb temperature line. These two lines on the psychrometric chart will be intercepted. This interface point represent the air condition at the entrance of the drying chamber.

The Fig (2.2) represents the drying process on the psychrometric chart.

2.8)Psychrometric ratio

The relation of heat to mass transfer coefficient for the water evaporation process is called as Psychrometric ration in some literature.

$$\frac{h}{k_g} = C_H \ ...(2.4)$$

here $\dfrac{h}{k_g}$ = psychrometric ratio.

h= heat transfer coefficient,(kJ/m² s)

k_g=mass transfer coefficient,(kg/m² s).

C_H = the humidity heat that is defined as the specific heat of a mixture of 1 kg of the dry air and y kg of moisture vapour.(kJ/kg)

$$C_H = C_B + C_{Av} * Y ....(2.5)$$

C_B= the dry air heat capacity at constant pressure(kJ/kg K).

C_{Av}= the vapour moisture heat capacity at the constant pressure (J/kg K).

Y= the humidity within the dry air(kg/kg).

2.9) Mollier chart

This chart is convenient for thermal drying calculation. In this chart, the enthalpy is expressed on the vertical axis. The absolute humidity is expressed on the horizontal axis. Usually this chart is known as the I-Y chart. The isenthalpic lines (I_g constant) are inclined to the horizontal axis of an angle of 135°.The Fig(2.3) shows the drying process on the Mollier Chart.
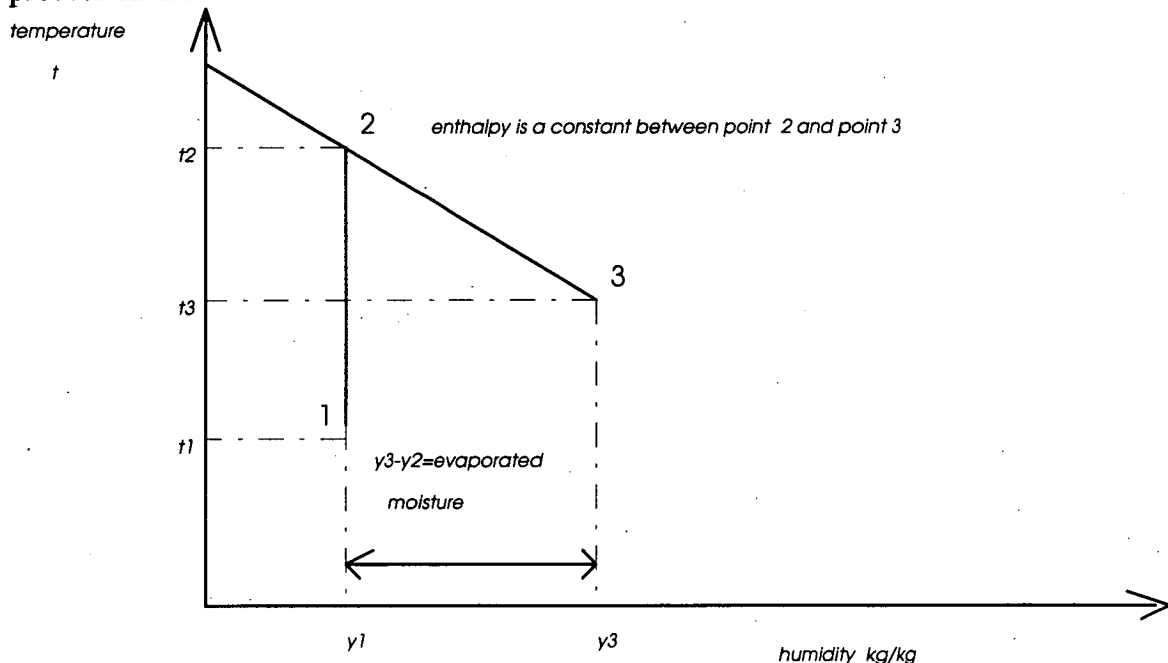
Fig(2.3) drying process on the Mollier Chart

The drying process is represented on this chart by two lines. One is 1-2, that is a vertical line that reflects the air is through the heater to increase the heat emerge. So, the total enthalpy is increased too. This is the air heating process. Another line is 2-3, that represents the evaporation process. If it is assumed that no heat loss exists during the drying process, the moisture increase should follow the line of constant enthalpy.

The value between point 1 and point 2 is the amount of heat energy required for drying process. The segment 1-3 reflects the warm air humidification. The difference between point Y_3 and Y_1 decides the mass of the moisture evaporated per kg of dry air.

2.10)Moisture diffusion in hygroscopic plants

Moisture moving in drying process is pure mechanism motions that includes the moisture moving on the surface and moisture moving in the capillaries. The rate of moisture moving determines the rate of the whole drying process.

2.10.1)Liquid diffusion

As explaining above, there are two methods of moisture moving. One is in liquid. Another is in vapour. At the drying constant rate, the moisture moving is in liquid. The liquid diffusion was introduced by Lewis. The equation (2.6) describes the moisture diffusion in liquid.

$$W_\ell = -D * \{\frac{d(x_\rho)}{dx}\} .....(2.6)$$

Here; W_ℓ = the liquid moisture transfer rate(kg/m² s).

   D= the moisture transfer co-efficient in liquid(kg m/m² s).

   $\frac{dx_\rho}{dx}$ =the moisture gradient concentration in wet substance(kg/kg m)

From this equation, it can be understood that the liquid moisture transfer rate is proportional to the gradient of moisture concentration. But the direction is reversed.

2.10.2)Vapour diffusion

In drying hygroscopic plants, the vapour diffusion is the main mechanism moving. Vapour diffusion take place inside the plants. It is controlled by the parameters of the wet plants. The effect of this transfer can be described by an equation of the Fick type.

$$M = -D_{ef} \frac{\partial C}{\partial X}$$

$$D_{eff} = D_e * D_{AB} \text{......(2.7)}$$

Here: D_{eff} = the effective diffusion coefficient in capillaries.(m^2/s)

D_e = the equivalent coefficient of diffusion in the capillary materials.(m)

D_{AB} = kinematic diffusion coefficient. (m/s)

$$D_e = \frac{\varepsilon \delta}{\varepsilon_{\varepsilon}} \text{......(2.8)}$$

Here: ε = the porosity that means the ratio of the total void spaces volume to the total plant volume.

ε_e = the equivalent porosity.

δ = the boundary layer thickness. (m)

From the equation (2.7) and equation(2.8), It is clear that the effective diffusion coefficient in capillaries is proportional to the porosity of the porous plant and the thickness of the boundary layer. These parameters control the vapour moisture migration.

2.11) Moisture Diffusion in the bulk

In the drying chamber, the hygroscopic plant is supported by transporting belts in the bulk form. The vapour from the wet materials needs to go through the bulk   of the wet pyrethrum before migration to the warm air. The bulk, the thickness of the bulk and the configuration of the wet solids will give some influence on the moisture migration. This moisture diffusion is a special feature in the drying hygroscopic plants in the bulk form.

$$\frac{dW_b}{dt} = (k * v) / (b * f) \text{....(2.9)}$$

$\frac{dw_b}{dt}$: the moisture diffusivity rate in the wet bulk.(kg/s)

k: the constant depends on the different plants (kg/m s)

V: the warm air speed in the drying chamber.(m/s)

b: the thickness of bulk on the transporting belts.(m)

f: the ratio of the total surface area of the one piece pyrethrum to the thickness of the one piece of pyrethrum.(1/m)

$$f = b_s / A_s \ldots (2.10)$$

A_s: the total surface area of the one piece pyrethrum.(m^2)

b_s: the thickness of one piece pyrethrum.(m)

When moisture is come out from the wet pyrethrum, the external drying conditions and the properties of the bulk will govern the rate of the migration of the moisture. For practical purpose, manufactures choose an appropriate thickness of the bulk to get the higher bulk moisture diffusivity.

2.12) Moisture Diffusion by Capillary Force

In hygroscopic plants there are a lot of capillaries with different radii. During the drying process, moisture diffusion takes place between these capillaries due to the capillary suction.

The two-pore system model can be introduced to explaining this phenomena by Mr.P.V.Danckwerts in his book' Drying principles and practice ' on P179. It is assumed that at the drying initial stage, these capillaries are full with moisture. When the drying process develops further, the moisture is moving out from the capillaries. But the moving rate is different from each other in the different capillaries. It is obvious that the level of the moisture in the wide pore will falls faster than it in the narrow pore due to small absorption forces. So, moisture diffusion from one pore to another pore produces until the rate migration of the moisture get the same in both capillaries. It is known as diffusion by capillary force. In plants, different capillaries are connected by wall of cells. The moisture can go through the walles of cells.

The diffusion of moisture under the capillary force is one of the features of moisture moving in hygroscopic plants.

2.13)Moisture effusion

This phenomena will take place when the radius of a capillary is lower than 10^{-7} m. The moisture diffusion is in vapour. The mass vapour rate is determined by the equation (2.11).

$$W_{AE} = D_{E_{eff}} * (\frac{\partial C_A}{\partial x}) \ldots \ldots (2.11)$$

Here: W_{AE} = the mass vapour rate.(kg/s)

$D_{E_{eff}}$ = an effective effusion coefficient.(Kg m/kg s)

$\frac{\partial C_A}{\partial x}$ = moisture concentrate gradient.(kg/m)

$$D_{E_{eff}} = \frac{\varepsilon * \varepsilon}{\sqrt{3}} D_E \ldots \ldots (2.12)$$

Here: ε = the porosity of the capillary plant

D_E = the effusion diffusivity (kg m/kg s).

From equation(2.11) and (2.12), it can be seen that in the mass vapour rate is proportional to the characters of this wet solids capillary and moisture concentration.

As result as the moisture mechanism explained above, there are other moisture transporting methods in hygroscopic plants, such as diffusion by pressure gradient inside plants, the diffusion caused by shrinkage and diffusion due to gravity.

2.14)Drying rate

The drying rate is defined as the amount of moisture removed from the dried material in unit time per unit area of drying surface.

2.14.1) Critical drying rate

The critical drying rate is a special term that is widely used in drying plants. It means the largest rate of the drying process limited by different characters of wet plants. If the drying rate exceeds the critical drying rate, a lot of shrinkage, cracking or hard surface will be produced. It is clear that for different drying temperature, there are different critical drying rates. Usually the critical drying rate is determined by experiment. The mathematical relationship between critical drying rate and wet plants characters is not well reported in the literature.

2.14.2) Drying rate equation

The drying rate is determined by the amount of the moisture within the wet materials, the drying surface areas and drying time.

$$W_d = \frac{-M_w}{A_m} * \frac{dw}{dt} \ldots (2.13)$$

here Wd= the drying rate.(kg/m² s)

dw/dt= the moisture evaporating rate.(kg/ s)

M_w = moisture mass.(kg/kg)

A_m = the area for moisture transferred.(m²)

From the equation(2.13), it can be concluded that the drying rate is controlled by the moisture evaporating rate, the moisture mass and the areas for mass transfer. In the drying process, usually the moisture mass of wet materials and the mass transfer area in the drying chamber are the drying initial conditions which are decided by the characters of wet materials and drying method. But the evaporation rate is determined by a few important factors. Normally the moisture evaporation rate is limited by the resistance to mass transfer, external conditions and the boundary condition,

2.15)Drying Curve

2.15.1) Three Basic Co-ordinates used in Drying curves

The drying curve represents the whole drying process, which is determined by the external and internal conditions. There are three especial co-ordinates to describe the drying process as follows:

A) The mass of the moisture in wet solids and drying time. It is called the drying curve.

In this curve coordinate system, the moisture content is on the vertical axis while the horizontal axis represents the drying time. The Fig(2.4) represents the ordinary drying curve. From the drying curve, when the final moisture is decided , the drying time is easily obtained.
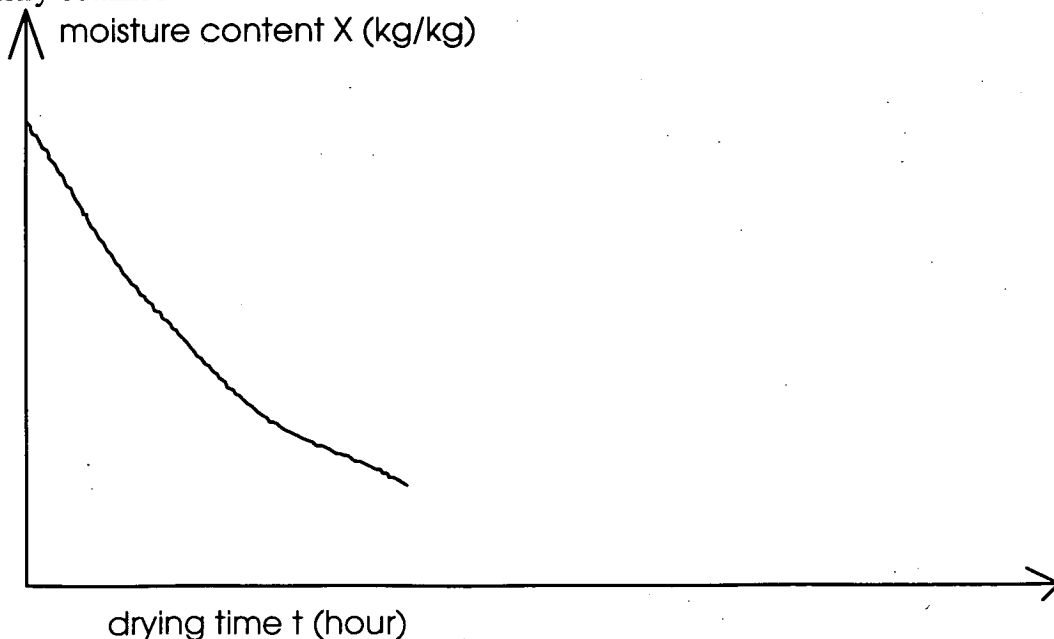
Fig(2.4) Drying curve

B) The drying rate and moisture content in wet solids. This is called the drying rate curve.

In this coordinate system, the value of the vertical axis is the drying rate while the horizontal axis means the material moisture contents. The Fig(2.5) is introduced to explain the drying rate curve.
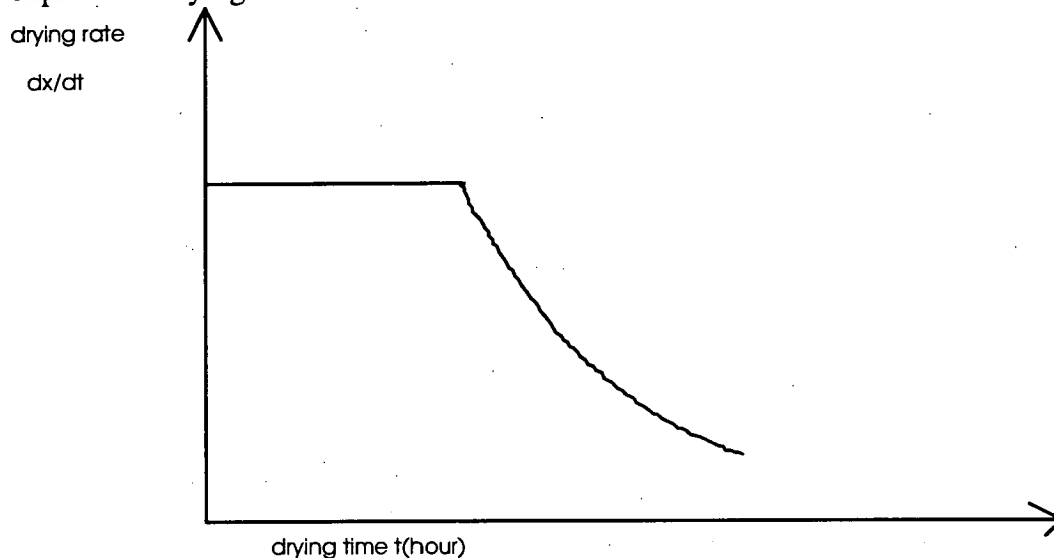
Fig(2.5) Drying rate curve

C) The temperature of the wet materials and moisture contents in wet solids, which is called the temperature curve.

This curve represents the relationship between the drying temperature and moisture contents within the wet materials. From the temperature curve, the appropriate drying temperature can be selected for a given drying process. The Fig (2.6) represents this temperature curve.

moisture content X (kg/kg)

drying temperature
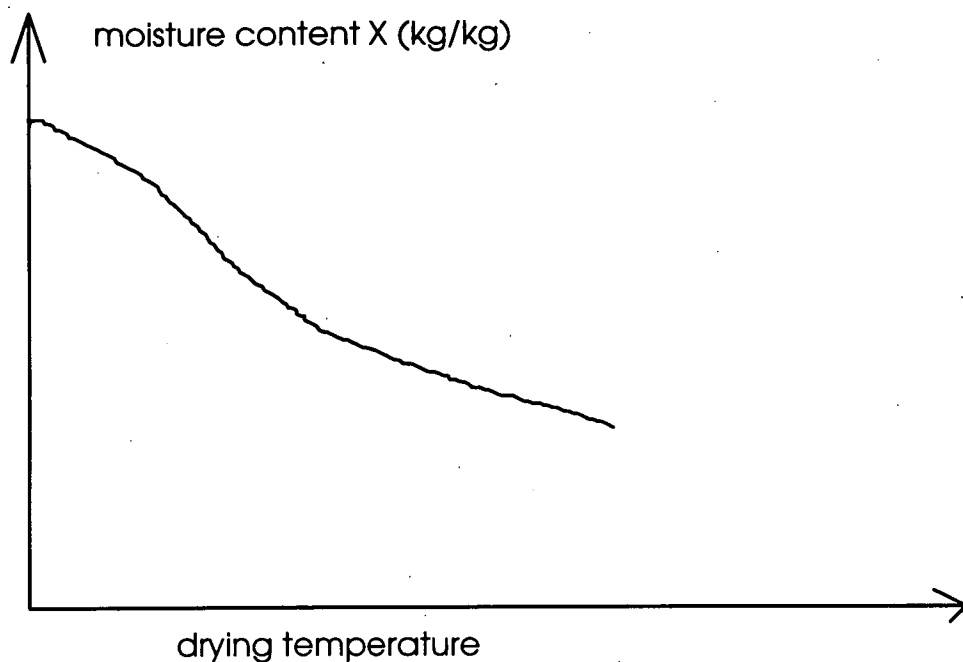
Fig(2.6) Drying Temperature Curve

2.15.2) Discussion about these three drying curves

These three drying curves are used in different situations. The type (A) and type (B) are used as the basically data for design the dryer. The type (C) is employed to analyse the influence of the temperature in drying process, and developing faster drying process. Because the temperature of the wet materials is equals to the temperature of the wet bulb in warm air flow. So sometimes the higher temperature with lower relative humidity of air flow is taken to developing the high density faster drying technology. For example, during spring collecting wet tea, there are a lot of wet tea to wait for drying. The higher drying temperature is selected in order to improve the drying rate. The temperature is nearly 140 °C ---180 °C. Of course, under this drying temperature, the drying time is relative shorter.

In industrial drying, drawing different curve to represent the various drying process is very important.

When the drying conditions are given, the different materials show the different drying character, which means under the same external conditions, the drying process will be totally different due to different internal conditions. On the other corner, from the drying curve the materials characteristic can be recognised too.

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2.16) The drying curve of non-hygroscopic capillary--porous materials

The feature of this drying curve is one critical point that will occur. When the moisture at the surface tends to zero, the drying rate will drop down obviously. Because in non-hygroscopic capillary --porous materials the moisture is in form of free moisture. When the surface moisture trends to zero, it means the moisture mass trends to zero too. So, the drying rate is dropped down very quickly and just one critical point exists in the drying curve.

The Fig(2.7) represents the drying curve of non-hygroscopic capillary--porous materials.
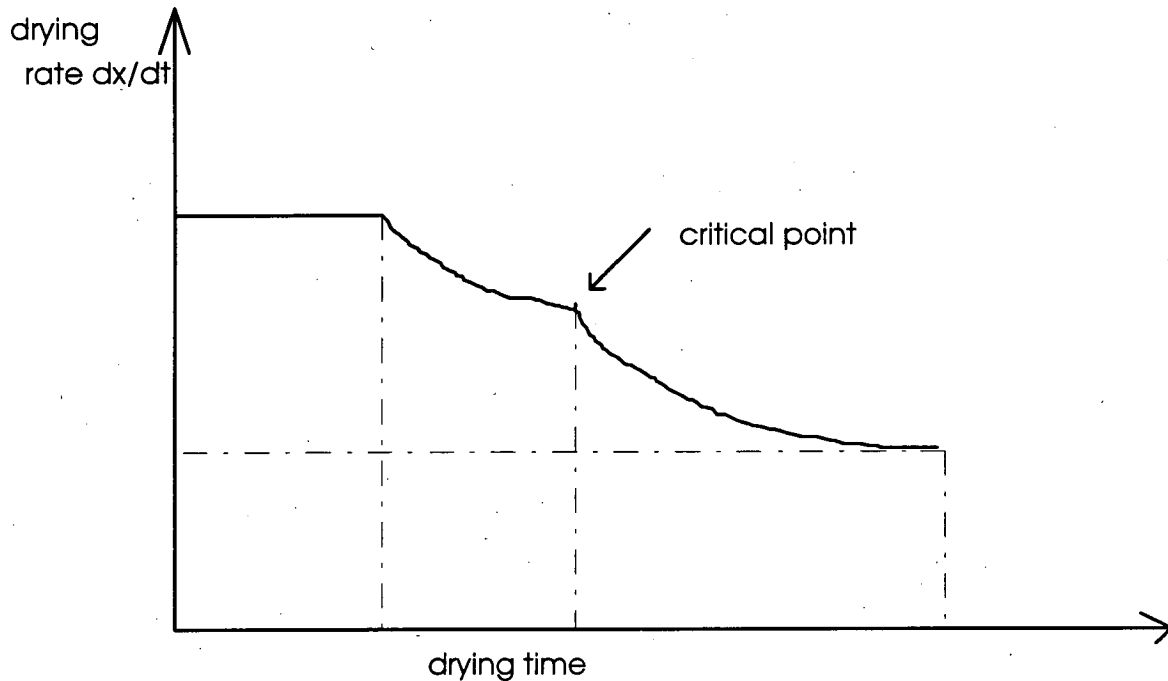
Fig(2.7) Drying curve for non hy-hygroscopic capillary--porous materials

2.17)The drying curve of hygroscopic--porous materials

There are two critical points in the drying curve of hygroscopic--porous materials, which is different from the drying curve of non-hygroscopic capillary--porous materials. The constant drying rate is finished when the free moisture is dried up. The first critical point comes out. The first critical point represents the point at which the drying rate falls. This is the rate of the moisture evaporation is greater the rate of the moisture moving out from the wet solids. The internal conditions controls the drying process. The second critical points means the drying stage is controlled by the moisture diffusion within wet materials. The drying rate falls more rapidly than before second critical points. In fact, when the second critical points appear, usually there are

a lot of absolute moisture existed in some hygroscopic plants. It should be noticed in design the dryer for some hygroscopic plants.

After the second critical drying curve, the drying rate is very slow. The Fig (2.8) represents this drying curve.

drying rate

1st critical point

2nd critical point

drying time
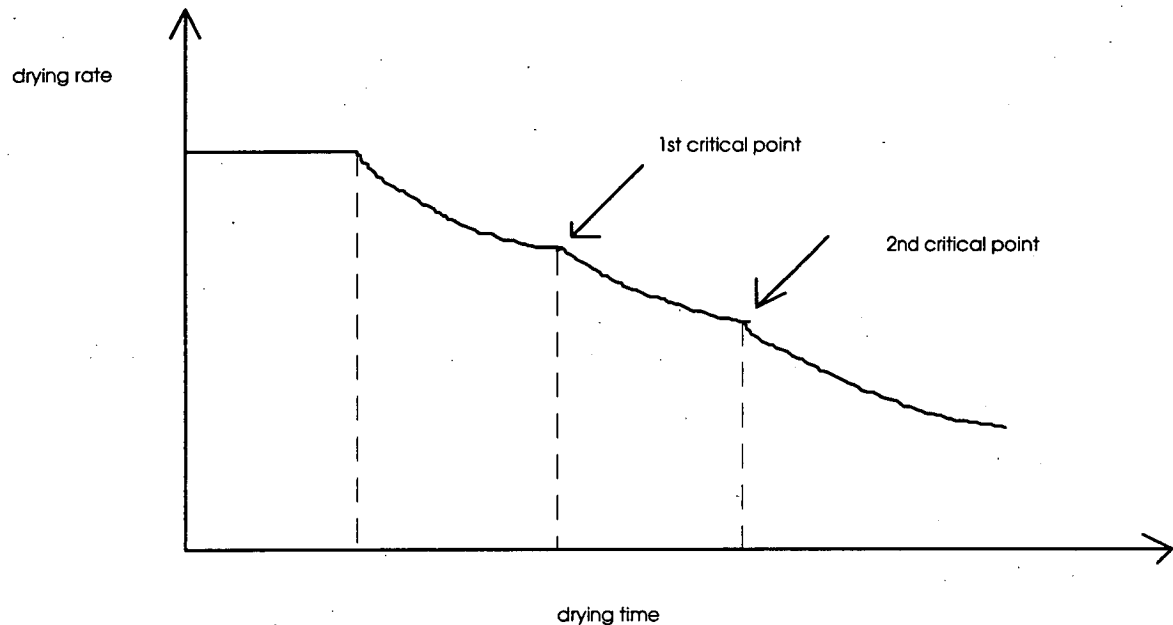
Fig(2.8) Drying curve for hygroscopic-- porous materials

2.18)Colloidal bodies drying curve

For this materials, no critical points appear on the drying curve. Because the moisture can be considered as through 'dissolved' in wet materials, for example, like glue. The moisture moving is under moisture diminishing concentration gradient. So there isn't critical points to come out. the fig(2.9) is introduced to explain this drying curve.

drying time t
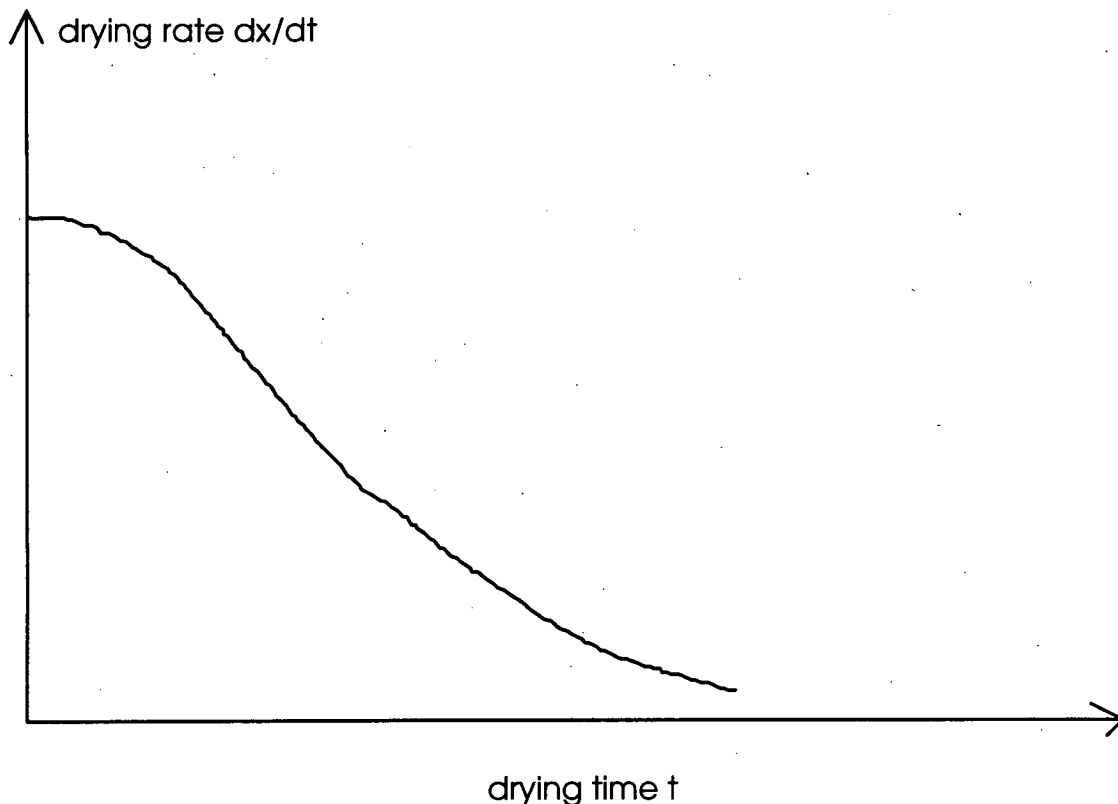
Fig(2.9) Drying curve for colloidal bodies

It can be understood that the typical drying curves represent the internal characteristics of the different materials on the moisture moving. From the different drying curves, the wet materials can be recognised too.

2.19) Shrinkage, surface hardening and oxidation

Shrinkage, hard surface and oxidation are typical drying problems which will influence the quantity of the dried materials.

2.19.1) Shrinkage

Shrinkage takes place for porous hygroscopic plants in any drying method. In general, if the initial drying rate is too high, the outer surface of the wet porous solids will become rigid. At the same time, their final volume is fixed early in drying process. As drying process is developing progressively, the tissues split and rupture within the wet solids. Internally open structure is forming. It can be understood that when the initial drying rate is lower, the wet solids will shrink with little change in shape.

Due to shrinkage and a rigid surface, some pressure gradients within the wet materials will be set up. This pressure will impede the moisture diffusion from inside wet solids towards the surface. In any drying technology, in order to avoid much shrinkage of porous plants, a lower initial drying rate is employed.

2.19.2)Surface Hardening

A hard surface will result in decreased permeability which lowers the moisture diffusion. In general, a hard surface is formed under the initial high drying temperature, and is usually accompanied with the shrinkage. The formation of hard surface is a result of complex physical and chemical changes.

2.19.3)Oxidation

Oxidation in drying plants usually is induced by some enzymes on the plants. Sometimes, a low drying temperature is benefit for enzymes growth. The oxidation is a bio-chemical phenomena.

The oxidation will influence the taste, smell and colour. According to different drying purposes, sometimes it is necessary to impede the oxidation of plants, and sometimes it is necessary to enhance the oxidation.

It is clear that the drying temperature will control the oxidation, hard surface and shrinkage. So, when it selects the drying temperature, it should be consider the influence of drying temperature on these three special phenomena.

Further study the relationship between the drying temperature and these three phenomena will improve the drying technology applied on the drying porous plants.

2.20)Reference to Chapter 2

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5) Harris , 1983, Modern air conditioning practice. P89.

Chapter 3

Heat transfer Model

Introduction

Heat transfer occurs through heat conduction, heat radiation and heat convection. According to the second low of thermodynamics, when a difference temperature exists, the heat transfer always take places to reach the equilibrium of the temperature. During any drying process, the heat transfer and mass transfer occur simultaneously. The heat transfer greatly influence the drying thermal efficiency. In order to select the right heat transfer method, it is necessary to study the different heat transfer processes.

3.1)Heat conduction

Heat conduction is a heat transfer process, where heat flows from a place of high temperature to another place with lower temperature within a solid medium or between different solids in direct physical contact.

Temperature is a measurement of the internal energy in an object. The temperature is determined by the velocity and relative position of the molecules, the more rapidly the molecules are moving, the greater the temperature will be. When the temperature of an object is higher than the environment, it can be said that the molecules in this object have the greater kinetic energy. Molecules with greater kinetic energy will tend to transfer part of their energy to the molecules with a lower temperature.

In heat conduction, the elastic impact or diffusion of faster--moving molecules from a place with higher temperature to regions with lower temperature often take place. The basic equation for heat transfer by conduction was proposed by the French Scientist -- J.B.Fourier in 1822.

$$q_k = -K * A * \frac{dT}{dx} .....(3.1)$$

This equation is applied to one dimensional conduction in the steady state of heat flow.

Here: q_k = the rate of heat transfer by conduction.(W)

k = the thermal conductivity of the material.(w/m °C)

A= the area for heat conductive. (m²)

$\dfrac{dT}{dx}$=the temperature gradient at the section where the heat conduction occur.

It is specified that the direction of heat flow is positive, when heat flow's direction is the same as the direction of increasing the distance from the heat transfer surface to a distance x.

3.2)Heat radiation

Radiation can be transported through a transparent radium or through a space, even through a vacuum, which is a heat transfer process too.

It is known that all bodies can emit radiant heat continuously. This radiant heat is determined by the temperature and property of the bodies surface. Usually, radiant heat is transferred in the form of finite batches of energy. As a result of increasing temperature of the object, the radiant heat increases. The principle of heat radiation is similar to the light transfer by wave form.

$$q_{r=\varepsilon * A * T^4} \dots (3.2)$$

$q_{r=}$the quantity of heat energy as a result of radiant heat.(w)

A= the surface area for heat radiation.(m²)

T= the surface temperature.(°C)

ε = the dimensional constant. It is called as Stefan--Boltzmann constant.(w/m² °C)

This equation means that any black body surface with a temperature over absolute zero will radiate heat at a rate proportional to the fourth power of the absolute temperature.

Thermal radiation occurs within a wavelength band between 0.2 μm and 800 μm. When thermal radiation is falling on the any surface, the absorption, reflection or transmission will produce on the surface. An equation is introduced to describe these three physical phenomena.

$$\alpha + \beta + \tau = 1 \dots (3.3)$$

Here: α = the absorptive.

β = the reflectivity.

$$\tau = \text{the transmisivity.}$$

Normally, for most solids, τ is equal to zero. When the object absorbs all radiation that falls on it, it is known as a black body. When the object reflects all radiation that falls on it, it is called a white body.

3.3)Heat convection

Heat convection, heat conduction and heat radiation are three essential forms of the heat supplied during any drying processes. In drying pyrethrum, heat transfer in drying chamber is by forced heat convection. The heat is transferred between the surface of the solids and the surrounding medium. It is known as heat convection transfer, which is caused by molecules in motion. Heat convection equation defined simply this physical phenomenon.

Convection always take place between a solid surface and a liquid or a gas flow, when a difference of temperature exists.

When the temperature of the fluids is above that of a solid, firstly, heat will be transferred by conduction from the adjacent particles of fluid to the cooler surface of the solid. So, the particle on the edge of the flow will become cooler than those in the centre of the flow.

The centre particles of the fluid will move to the edge due to difference of the temperature between centre and edges in the same flow. During this movement, the centre particle and edge particle will mix with each other and the heat energy will be transferred again between the central particles and the edge particles. In heat convection, heat energy is transfered as the result of the fluid particles motion.

Convection transfer occurs in the direction of the temperature gradient .

$$q = A * h_c * (T_s - T_\infty)...(3.4)$$

Here: q = the rate of the heat flow from the heat medium to the solid.(kJ/s)

A = the area for heat convection.(m²)

h_c = heat transfer co-efficiency.(kJ/m² s °C)

T_s = the temperature of the solids.(°C)

T_∞ = the temperature of the warm air flow.(°C)

The convection heat transfer equation shows that when the temperatures between solids and surrounding medium are different to each other, heat convection takes

place. Hot, dry substances always lose the heat and simultaneously cold substances gain the heat by particle movement.

The rate of the heat convection transfer is proportional to the difference in temperature between the substance's surface and the surrounding air. The coefficient of this rate is known as convection heat transfer co-efficient h_c. The convection heat transfer co-efficient is determined by the thermal properties of the air flow , the configuration of the drying chamber and the thermal property of the wet materials. In fact, convection heat transfer is divided into two types; free convection and forced convection. The heat flow in convection process is divided into steady heat flow or transient heat flow. When the temperature of the fluid at any point doesn't change with time, this heat flow is called as steady heat flow. Transient heat flow means that the temperature at various points in the system change with time.

3.3.1)Free convection

When a solid is put in a fluid (liquid or gas) with a different temperature then the solid, heat flows from the high temperature place to the low temperature place automatically. The particles of the fluid is moving as a result of density difference caused by the temperature gradient. This heat mechanism moving is called free or natural heat convection.

This heat flow will change the density of the fluid boundary conditions near the solids. The lighter density fluid moves upward and higher density fluid moves downward. This motion depends on the temperature gradient in fluids. This is the basically principle of free convection heat transfer.
The equation (3.5) summaries the free convection heat transfer.

$$dq = h_c * (T_s - T_\infty) * dA ...(3.5)$$

Here: dq = the heat transfer rate (kJ/s)

h_c = the free convection heat transfer coefficent.(kJ/s m² C°)

dA = the unite area for heat transfer.(m²)

T_s = the temperature of the solids. (C°)

T_∞ = the temperature of the warm air.(C°)

In fact, the heat transfer coefficient isn't uniform over the surface of the solids. So, in the free convection process, the differential equation is employed. In free convection the heat transfer coefficient is low and is difficulty to get accurately by calculation.

3.3.2)Forced convection heat transfer

In drying processes, forced convection is more common than free convection due to better heat transfer efficiency. Under an external force, such as a pump or blower, the mixing movement among the particles at different temperature in the fluid is done during heat transfer process, it is called as forced convection.

In forced convection heat transfer, the air flow can be divided into two kinds: lamina air flow and turbulent flow.

3.3.2.1)Laminar air flow and turbulent air flow

In laminar warm air flow, the air moves in layers. The air particles are moving in a certain order. The velocity of the air flow at any point is the same. In laminar flow, heat transfer occurs only by molecular conduction. There are no turbulent mixing currents. In laminar air flow heat transfer is by molecular motion on a submicroscopic scale between layers of the air flow.

In turbulent flow, the movement of the different particles in the air flow is irregular. Although the whole movement of the total air flow is regular. In turbulent flow, the heat convection is improved due to increased mixing of the moving particles which leads to an increased the rate of heat transfer.

In drying process, in order to aid the heat transfer efficiency, it is expected to increase the turbulence of the warm air under the state base through some mechanism.

3.3.2.2)Forced convection in laminar flow past a flat plate

In drying chamber, forced convection in laminar flow is usually used due to easily control the air flow conditions. It can be understood that there are two regions in the warm air flow; One is the temperature boundary layer where the temperature of the air flow varies from the free air flow temperature T_s to the temperature T_p of the plate in the drying chamber. Another one is outside the boundary layer, where the temperature is considered to be everywhere equal to the free air flow temperature T_s. It is clear that there is a temperature gradient in the warm air flow. The heat transfer

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between temperature boundary of the air flow and the plate in the drying chamber is by conduction , not by transport of fluid. Rogers and Mayhew in their book' Engineering Thermodynamics Work and Heat Transfer' on P516 introduced an equation (3.6) to explaining the heat transfer of forced convection in laminar flow.

$$q = -k_f * (\frac{dt}{dy})_0 ...(3.6)$$

Here q= the rate of heat transfer.

k_f =the thermal conductivity of the fluid.

y= a polynomial. If the temperature of the air flow at any section is expressed by t, t may be expressed as a polynomial in y. ($t=t_w + ay + by^2 + cy^3$; a , b , and c are dependent on the boundary conditions. At the intersection between air flow and plate in the drying chamber, y=0).

t= the temperature of air flow at any section.

3.4)Boundary layer

Heat transfer and mass transfer between solids and gases always occur in the boundary layers.

The concept of boundary conditions was introduced by the German scientist, Prandtl, in 1904. The intersect surface between air flow and wet materials is called as boundary layer. These boundary layers can be different for different types of drying process.

3.4.1) A few assumptions.

In order to define the boundary layer during drying pyrethrum, some assumptions are made as follows. Because boundary layer in drying pyrethrum should suit with the certain drying process.

1) When drying pyrethrum, there is one dimension heat and mass transfer process, which occurs normal to the direction of the transporting belts. The direction of the boundary is parallel to the transporting belt.

2) The warm air flow is uniform steady laminar flow .

3) The mixing movement of the air particle always takes place in the normal direction to the boundary. The longitudinal mixing of moving particles in the warm air is neglected.

4) The residual time in the drying chamber for all air particles during the same drying period is the same.

5) The wet bulk of the pyrethrum is homogeneous.

3.4.2) The initial condition of the boundary layer

The boundary initial conditions for heat transfer and mass transfer are expressed in terms of the temperature, moisture mass along the vertical direction to the boundary layer.

$y=0$, $T_y = T_s$, $U(y)=C_1$ $t=0$.

Here: $y=$ the variable distance vertical to the boundary, when $y=0$, it means that this place is at the interface between the air flow and wet solids surface.

$T_y =$ the temperature within the boundary.

$T_s =$ the temperature of the surface of the wet solids.

$U(y)=$ the moisture within the boundary.

$t=$ time.

$C_1 =$ the constant that is the mass of the moisture on the saturated surface

$y=H$, $T_y = T_a$ $U(y)= C_2$.

When $y=H$, it means that this place is at the boundary outside edges.

$T_a =$ the air flow temperature.

$C_2 =$ the constant that is the mass of the moisture within the air flow.

The boundary layer for drying pyrethrum is defined as a close layer around the wet pyrethrum. This boundary layer can be divided into two. One is a thin layer covering the surface of the wet materials called as close layer. Another is a region outside of this layer. It is called as outside layer. In the close layer, the velocity gradient of the air flow is greater due to air velocity reducing down to zero at the wet solids surface. But the viscous force of the air flow can be considered larger due to contact with solid surface. In the outside layer, the velocity of the air particles is equal to the free stream value and the viscosity is negligible.

During drying pyrethrum, the initial temperature at the start of drying is assumed to be equal to the wet bulb temperature of the surrounding air flow. the temperature should the constant across the thickness of the bulk of the wet pyrethrum.

3.4.3)The thickness of the boundary layer

The thickness of the boundary layer is defined as the distance from the surface at which the local velocity reaches 99 percent of the external velocity u_∞.

3.4.4)The velocity of the air fluid on the boundary

In the close layer, at the intersection with the wet material surface, the air velocity falls to zero. Heat transfer from the air flow to the wet solids face is through conduction.

But in the outside layer of the boundary condition, the air velocity reaches at the nearly the external velocity and heat transfers is by convection.

3.4.5)The temperature of the wet materials at the intersection with the boundary layer

At the intersection with the close boundary, the temperature of the wet material at its surface is always equal to the temperature of the air in contact with it.

3.5)The moisture diffusion within the boundary layers

Moisture diffusion on the surface of the wet objects or on the boundary layer is always as vapour. Firstly free moisture diffusion from the wet surface to the close boundary layer take place. Secondly the moisture within the wet porous capillaries is continuously diffusing to the surface. Then the moisture on the surface is vaporised into the warm air.

According to the Fick's diffusion law, the moisture gradient determines the rate of the moisture diffusion in an homogeneous system, which is induced by the difference of moisture amount between the close layer and outside layer of the boundary. The Fick's law mathematical formation as follows:

$$dm_w = -K * A * \frac{\partial U}{\partial y} * dt ...(3.6)$$

Here dm_w = the amount of moisture diffusion within the time t.(kg/s)

K= the diffusion co-efficient.$(\text{kg}^{-1}\text{s}^{-1}\text{m}^2\text{kgm})$

A= the plane of area at the right angle to the diffusion direction.(m^2)

$\dfrac{\partial U}{\partial y}$ = moisture gradient within the boundary.(kg/m)

From the Fick's law, it is clearly that the moisture gradient is the controlling factor for moisture diffusion. This law suggest that a lower relative humidity of the air flow will increase the rate of the moisture diffusion from the wet solids to the air flow. Increase the area for the moisture diffusion will produce the same results.

3.6)Heat transfer in the boundary layer

When an air flow contacts with a wet solid heat transfer takes place. This phenomena is expressed by the equation (3.7).

If u is the velocity of the air flow over the boundary, the heat transfer at any point of the close boundary layer is explained by the equation (3.7)as follows:

$$u * \frac{\partial u}{\partial x} = k_\ell * \frac{\partial^2 T}{\partial y^2}...(3.7)$$

Here: u= the lengthwise velocity over the boundary.

$\quad$ k_ℓ = the thermal diffusion along the boundary.

$\dfrac{\partial T}{\partial y}$ =the temperature gradient normal to the boundary condition.

On the boundary, the air velocity over the boundary will greatly influence the heat transfer.

3.7)Evaporation in the boundary layer

Investigation of the effect of the evaporation on the boundary layer of the air fluid is necessary, because the evaporation and diffusion of the moisture are controlling the drying process.

The evaporation process is the phase changing process from the liquid to the vapour. When warm air is contacting with the wet surface of the solids, because the vapour

pressure of moisture within the warm air is below that of the moisture on the wet surface, evaporation takes place. The difference in the moisture vapour between the wet surface of the solids and the warm air is considered to be the evaporation force or driving force.

The evaporation process is limited by the many factors. Air pressure, temperature of the air fluid, velocity of the air flow, and impurities contained in the liquid are among them. The most important factors are the temperature and the velocity of the air flow. The temperature of the air will control the pressure, especially the air saturation pressure.

3.8)The equilibrium moisture content

Some authors have discussed the equilibrium moisture amount. A few equations are developing to describe this value. The simplest equation for equilibrium moisture content is that suggested by Smith (1974). (Journal of Food Engineering 1992 Vol 16 P241)

$$W_e = W_b - C * \ln(1 - rh)...(3.8)$$

Here W_e = the equilibrium moisture mass.

W_b = the boundary moisture mass.

C= the constant.

rh= the relative humidity within the air flow.

Nellist (1974) developed the Smith equation for dynamic equilibrium moisture content of rye grass seeds in the following form. (In the magazine 'Food engineering' of dated the fourth in 1992 on P241 at the title ' Thin Layer Drying Models for Malt by Mr.J. L.Woods at the Department of Agricultural and Environmental Science of University of Newcastle.)

$$W_e = a - b \ln T_a - C \ln(1 - rh)...(3.9)$$

Here: T_a = the temperature of the air.

a,b,C : the constants.

These two equations describe the same equilibrium moisture mass in the different terms and obtain different mathematical relationships. The equation (3.8) is mainly focussed on the air relative humidity while the equation (3.9) pays more attention to the influence of the temperature of the air.

Comparing these two equations, it can be concluded that Nellist equation gives weaker correlations than those given by the Smith. From this equation, the equilibrium moisture mass is mainly depended upon the air temperature.

From these two equations, it is obvious that the equilibrium moisture content varies with relative humidity within the air and air temperature.

At the equilibrium state, desorption or absorption will take place at the same moisture contents. Which one take place is based on the equilibrium moisture content.

3.9)Air moisture content

As a result of air passing over the wet surface, its moisture content will increase from value W_a to $W_a + \Delta W$ due to moisture evaporation from the wet products. The moisture balance will be set up for the warm air fluid.

Outlet moisture mass = inlet moisture mass + moisture gained by air from evaporation process.

The equation (3.10) is introduced to explain the change of the air moisture content during drying process. This equation is appeared in the book 'Drying : principles, applications and design'.

$$\frac{dW_a}{dw_w} = -\frac{\rho_s * (1 - \varepsilon)}{(1 + x) * V_a * \rho_a}(\frac{dw_a}{dt})...(3.10)$$

Here W_a = air moisture content at time t kg/kg.

   W_w = wet product moisture content at time t kg/kg.

   ρ_s = Density of wet products kg/m³.

   ρ_a = Density of humidity air kg/m³.

   ε = the porosity of wet products.

   x= the initial moisture content in the wet materials.

From this equation, it can be found that the densities of air and wet materials exert different influences on air moisture. The density of the air and the density of the wet materials are determined separately by the mass of the moisture content in both of them. The porosity situation of the wet materials decides the mass of the moisture of wet material, so, it will influence the air moisture contents due to its influence on the moisture content of wet materials.

3.10)The equilibrium vapour pressure

When the liquid and vapour moisture is in the equilibrium state, the vapour pressure is called as equilibrium pressure. When temperature is constant, the equilibrium pressure is constant too. If the pressures between vapour on the wet surface and vapour within the air flow are in equilibrium, no evaporation takes place.

The saturation vapour pressure is the vapour pressure at which a change in phase can occur at a constant temperature.

On the boundary conditions, it is understood that when the temperature of the liquid is the same as the that of the vapour, an amount δm_w of the moisture will pass isothermally from the liquid to the vapour state. That moisture moving will lead to a total volume change and internal energy change . When liquid and vapour are in the equilibrium, the pressure and the densities is decided by the temperature. The Clausius-Clapeyron equation is introduced to explain the equilibrium pressure.

$$\frac{dP*}{dT} = \frac{\Delta H_e}{T(\alpha_v - \alpha_\ell)} \quad ...(3.11)$$

(book, P 123 W.H.Brutsaert-Evaporation into the Atmosphere)

Here $P*$ = the equilibrium pressure.

T= temperature.

ΔH = the heat is needed for per unit mass of phase change is the latent heat of vaporisation.

α_v the specific volume of the vapour.

α_ℓ = the specific volume of the liquid.

$$\delta V = [\alpha_v(T) - \alpha_\ell(T)] * \delta M ...(3.12)$$

δM =the mass of the moisture evaporation.

δV = the volume of the moisture evaporated.

α_v = the specific volume of the vapour.

α_ℓ = the specific volume of the liquid.

This equation is expressed by the differentiation form, because the evaporation volume and mass is vary with temperature and time.

By definition, the heat energy for per unit mass of phase change is the latent heat of vaporisation.

$$H_\ell = \frac{\delta H}{\delta M} ...(3.13)$$

Here $\delta H = \delta U + P * \delta V$

δU = the change of the internal energy of the system.

P= the pressure on the boundary.

δV = the volume change.

The equation reflects that heat supplied into the system equals to the sum of the change in internal energy and the work done by the system. If the form is changed a little, another equation can be obtained as follows;

Here U_v = the internal energy within the vapour.

U_ℓ = the internal energy within the liquid.

P= the pressure on the boundary.

From this equation, during evaporation, the latent heat within the air will increase and the moisture mass is increased too. The value of the latent heat increase is equal to the internal energy change plus the work done by the system.

3.11)The evaporation developing model within the boundary layer

The moisture evaporation on the boundary layer will control the drying rate. Evaporation within the drying process is different from the evaporation that takes place between the liquid and gas. This is because evaporation within the drying process is related to moisture diffusion inside of the wet solids, moisture diffusion on the wet surface and moisture diffusion within the air flow.

The dry air pressure, the vapour pressure, temperature gradient vertical to the boundary face and the moisture gradient within the boundary are main factors which control the evaporation rate on the boundary. But at different place, these factors will have different effects. According to the evaporation development on the boundary, the

$$H_\ell = U_v - U_\ell + P * (\alpha_v - \alpha_\ell)...(3.14)$$

boundary can be segregated into three zones as follows:

3.11.1) First region

This region is the interface between the air boundary layer and wet material face. When the warm air contacts with the wet surface, the heat transfer occurs due to the difference in the temperature between them. The heat fluid will move from the warm air to the cooler wet surface. As result of the heat transfer, the liquid molecules on the wet surface get more and more heat energy. According to thermal first law, this heat

energy will increase the internal energy of the liquid molecules. Due to this increase in the internal energy, the speed and kinetic energy of the molecules will increase too.

3.11.2) Second region

This region is within the boundary near the first region. As the heat fluid is continuously moves to the cooler wet surface, the liquid molecules move faster and faster and overcome the surface tension force of the wet face. The distance among the liquid molecules will become larger and larger. As a result of the kinetic energy increase, the liquid molecules become the vapour molecules, so, this second region is know as the evaporation region.

3.11.3) The third region.

This region which is remote from the interface of the boundary is where the vapour molecules continuously to get heat from the warm air, and mix with the warm air. The mixing rate is determined by the vapour mass and dry air mass.

$$R_\gamma = \frac{m_v}{m_a} ...(3.15)$$

here R_γ = the mixing ratio between the vapour and the dry air within the boundary layer.

m_v = the mass of the vapour contained in the third region of warm air boundary.(kg)

m_a = the mass of the dry air contained in the third region of the warm air boundary.(kg)

This mixing ratio can be expressed by the vapour pressure and total pressure of the gas.

$$R_\gamma = \frac{m_v}{m_a} = (\frac{M_v}{M_a}) * P_v / (P - P_v) ...(3.16)$$

here M_v = molecular weight of the vapour.

M_a = the molecular weight of the dry air.

P_v = the vapour pressure within the air flow.

P= the total pressure of the air flow.

At the evaporation region, mixing takes place too, but the mixing ratio will less than that within the mixing region due to less vapour pressure. A vapour gradient will be set up within the boundary condition. This vapour gradient can be understood as one component of the diffusion force acting on the vapour molecules within the air flow.

In fact, especially in the batch dryer, the evaporation zone can be observed within the bulk of wet materials. A thin dried zone exists. But the thickness of the dried zone is smaller than the whole zone of the wet bulk at the drying initial stage. With drying progressively developing, the dried zone is developing too.

3.12)The surface effects on evaporation

Some authors noted that the smoothness of the surface of the wet solids will have some influence on moisture diffusion to the surface.

Paper (1986) discussed the difference in structure and texture, then he indicted that the smoother product surface has the greater resistance to moisture diffusion. Because the smooth surface has the uniform surface tension forces while at the non-smooth surface, some difference of the surface tension force exists on the surface, which will benefit for the moisture escaping or diffusion from the surface.

3.13)Evaporation rate on the surface of wet plants

The evaporation rate is determined by the drying force. The equation is as follows:

$$N_A = K * [\frac{\ln(1+B)}{B}] * \Delta C_A ...(3.17)$$

N_A = the evaporation rate.

K= the mass transfer co efficient.

B= the drying force.

ΔC_A = the finite moisture concentration.

The drying force B is expressed by the equation (3.18).

$$B = \frac{C_{pG} * (t_z - t_0)}{\Delta H_v} ...(3.18)$$

Here C_{pG} = dry air heat capacity.

ΔH_v= the difference in enthalpy on vapour between the saturated--liquid and saturated --vapour states.

t_z= the temperature at the certain distance from the wet surface.

t_0= temperature at the boundary free surface.

From this equation, it is obvious that the drying force is mainly determined by the temperature gradation vertical to the boundary direction.

In fact, the evaporation rate is controlled by some factors as follows, especially in drying wet porous plant leaves, flowers, seeds, fruits, vegetables.

a) The dimension of the wet solids.

b) Types of moisture transfer mechanism, whether it is diffusion or capillary mechanism controlling.

c)Wet bulk uniformity.

d)Physical characters of the wet and dry solid objects.

e)Heat and mass transfer rate between warm air and wet solids.

f) The section areas of the dryer.

g) The characteristic drying rate curve of the wet materials.

h) The character of the dryer.

So, if it is hoped to improve the evaporating rate, improving the drying characters, and heat and mass transfer rate should be considered.

3.14)Evaporation under the surface of the wet porous capillary materials

For porous capillary plants, evaporation not only takes place on the surface of the wet solids, but also takes place in the capillaries under the surface. When the drying process is developing progressively, the evaporation rate on the surface will be greater than the rate of the moisture effusion to the surface, therefore evaporation will develop towards the centre of the capillaries

3.15)Friction resistance among the three phases

In any drying process, the evaporation always takes place on or within the wet surface of the solids. That means the evaporation takes place not only at the interface of the liquid and vapour, but also among the solids, liquid, and vapour. Friction among the phases will cause some resistance to the evaporation.

On the boundary layer, as well as the resistance from the viscosity of the air flow and liquid, the properties of the porous-capillary wet materials will influence the evaporation.

On the surface, evaporation is the physical process of changing from the liquid phase to the vaporific. When evaporation takes place, the sensible heat energy is changing into the latent heat energy.

3.16)The transition of laminar air flow in the boundary during drying pyrethrum

According to the assumption about the boundary condition, the air flow in the drying chamber is a laminar flow. In fact , any laminar flow always has some small disturbance and waves, but due to the large viscous forces, these small disturbance and waves will prevented from growing. During drying pyrethrum, in a drying chamber, the boundary layers are moving due to transporting belts moving at the constant speed. Further, the wet pyrethrum will be turned over a few times in the drying chamber. This mechanical motion of the wet pyrethrum will induce the transition of air laminar flow to turbulent flow.

It can be explained that due to the wet pyrethrum's moving, the ratio of viscous forces to inertia forces decrease and eventually, a point is reached at which disturbances will no longer decay, but will grow .

This transition in warm air flow will increase the heat convection transfer co-efficient and will improve the heat transfer efficiency during the drying process because in turbulent flow, heat transfer is through the particles mixing with the moving air flow. Heat transfer will be faster in turbulent flow than in lamina flow where the heat transfer is carried on by the molecular conduction. When designing dryers of convection heat transfer, some mechanical methods are often introduced to increase the turbulent portion of the laminar warm air flow.

3.17)The Nusselt modulus and heat convection coefficients

On the boundary layer, the heat transfer is governed by the mixing movement of the particles in the air flow. An increase in the velocity of air flow will aid the mixing between warmer particles and colder particles.

At the interface of the boundary, heat transfer take place between warm air and cold solid through conduction. The rate of heat flow can be obtained mathematically as follows:

$$q_{fluid-surface} = -K_f * A * \frac{\partial T}{\partial y}\Big|_{y=0} ...(3.19)$$

$q_{fluid--surface}$ = the rate of heat transfer between warm air and wet pyrethrum by conduction.(KJ/s)

$-K_f$ = The thermal conductivity at the boundary.(KJ m/m² C° s)

A= the area for heat transfer by conduction.(m²)

$\frac{\partial T}{\partial y}$ = the temperature gradient in the vertical direction to the boundary layer.(C°/m)

For heat convection, the mixing of the moving particles in the air flow and the convection heat transfer coefficient govern the heat transfer due to the temperature gradient in the warm air flow. So, the rate of heat transfer by convection should be equal to the rate of heat transfer by mixing moving of the air particles.

$$q_{fluid--surface} = -K_f * A * \frac{\partial T}{\partial y}\Big|_{y=0} = h_c * A * (T_s - T_\infty)...(3.20)$$

That the magnitude of the temperature gradient in the air flow should be the same one expressed by different equations. So the equation (3.21) is obtained.

$$\partial t = \partial(T_s - T_\infty)...(3.21)$$

If the value of the system length of the object is introduced , another equation is obtained .

$$\frac{h_c * L}{K_f} = \frac{-\frac{\partial T}{\partial y}\Big|_{y=0}}{\frac{(T_s - T_\infty)}{L}} = \frac{\partial(\frac{T_s - T}{T_s - T_\infty})}{\partial(\frac{y}{L})}\Big|_{y=0}...(3.22)$$

The value of the combination of the convective--heat --transfer coefficient h_c, the significant length L and the thermal conductivity K_f in the term $\dfrac{h_c * L}{K_f}$ that is known as the Nusselt number.

$$N_u = \frac{h_c * L}{K_f} ...(3.23)$$

Here: Nu= the Nusselt number.

L=the thickness.

K=the thermal conductivity.

The physical meaning of the Nusselt number can be considered as the ratio of the temperature gradient in the air flow in contact with the surface to a temperature gradient along the system geometry. Once the Nusselt number is determined, the convective--heat --transfer coefficient can be calculated.

$$h_c = \frac{N_u * K_f}{L} ...(3.24)$$

From this equation , reducing the value of the length L will increase the heat transfer coefficient in heat convection process.

The Nusselt number has an important relationship with property of the air flow for a particular geometry.

$$N_u = 0.32 * R_e^{0.5} * P_r^{1/3} ...(3.25)$$

In this equation, P_r called as Prandtl number that is the ratio of viscous effects to conduction effects. The P_r is a dimensionless parameter. It is composed entirely of fluid property. It has the strong influence on the fluid convection in heat transfer through influence on the Nusselt number.

$$P_r = \frac{C_p * \mu}{K} ...(3.26)$$

Here C_p= specific heat in the fluid.(KJ/kg C°)

μ= fluid viscosity.(Kg/m²)

K= fluid conductivity.(W/m² C°)

*Fluid	P_r
liquid	0.004--0.003
Gases	0.7---1.0
water	1.7---13.7
light organic liquids	5---50
oils	50---10,000
Glycerin	2000--85,000

These magnitudes are obtained from < heat transfer> by FRANK M. WHITE.

R_e, Reynolds number, is probably less then about 2000 in laminar flow. It is determined by the dynamic properties of air flow.

$$R_e = \frac{v * l * \rho}{\mu} \quad .....(3.27)$$

Here : v= the velocity of the fluid.(m/s)

l = the length of the fluid in drying chamber or in duct.(m)

ρ= the density of the fluid.(kg/m³)

μ=the viscosity of the fluid.(p_a*s)

From the equation (3.26) and the equation (3.27), it is very clear that an increase in the velocity of the air flow, or the length, or a decrease the thickness of the wet materials will improve the convection heat transfer co efficient. In fact, increasing the velocity of the warm air often leads to increasing the heat energy. Therefore it will cause higher energy costs. But increasing the length of the air flow, and reducing the thickness of the wet materials are always employed in designing the dryer.

3.24)Reference to Chapter 3

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Chapter 4
Heat and Mass Transfer in the Bulk of Wet Pyrethrum

Heat and mass transfer within the wet bulk of plants are less frequently reported in the technical literature than that of solids. Deeper study of this problem has great significance. This heat and mass transfer can be an important design parameters of transporting belts construction and design of the drying chamber. Here some problems with drying process of pyrethrum are investigated.

Introduction

In any drying method, the wet materials are always put on the transporting belts or trolleys in the bulk form. It is impossible to dry pyrethrum in a single layer. So, discussing the heat and mass transfer in the bulk of wet pyrethrum is an important supplement to heat and mass transfer on the boundary condition.

Firstly, a few assumptions is need to be introduced.
a) The whole bulk of wet pyrethrum on the transporting belts is homogeneous. The whole bulk is symmetric with the centre line of the depth of the bulk.

b) No external pressure is exerted on the bulk, except its gravity. The bulk is formed on the transporting belts by naturally dropping drown with help of gravity.

c) The porosity and the thickness of the bulk is naturally variable with the average value of the moisture in the bulk.

d) The porosity will become larger during the drying process. Because the shrinkage of wet pyrethrum volume will take place due to loss the moisture.

Some properties of the whole bulk of wet pyrethrum are similar with that of non capillary--porous materials such as sand. But a large difference between the sand and the wet bulk of the pyrethrum is shrinkage. No shrinkage takes place during drying sand while shrinkage always takes place within wet bulk of pyrethrum during drying process. A large volume shrinkage whin the bulk of pyrethrum will take place. Here this shrinkage isn't just on the surface of every piece of pyrethrum, but also on the whole bulk volume. Another difference is that there isn't the liquid moisture moving within the wet pyrethrum. But during drying the sand liquid and vapour moisture diffusion occur at the same time.

The third difference is about pore pressure. Within sand, the pore pressure will influence the liquid moisture moving or vapour moving. But within wet bulk of pyrethrum, the pressure of the pore can be neglected due to large radius of the pores.

Heat and mass transfer characteristics of the bulk wet pyrethrum in the drying chamber were studied. It was found that at the steady-state conditions of the warm air flow, the thermal properties vary with depth within the wet bulk. The heat transfer equation and mass transfer equation are introduced as follows:

$$[\frac{dQ}{dt}]_c = h_c * A * [T_a - T_s] \quad ...(4.1)$$

here: $[\frac{dQ}{dt}]_c$ = the rate of heat transfer on the boundary.(KJ/s)

   h_c = the heat transfer co-efficient.(kJ/m² s C°)

   A= the heat transfer areas on the boundary condition.(m²)

   T_a = the temperature of the warm air.(C°)

   T_s = the temperature of wet solids.(C°)

If it is assumed that no shrinkage takes place during the drying process, the rate of the mass transfer is expressed as follows:

$$[\frac{dW}{dt}]_c = -k_g * A * (P_s - P_a)...(4.2)$$

Here: $[\frac{dW}{dt}]_c$ =the rate of mass transfer(Kg/s).

   K_g = mass transfer co-efficient.(Kg/s m² pa).

   A= the area of mass transfer.(m²)

   P_s = the moisture pressure of the boundary surface.(Pa)

   P_a =the moisture pressure within the warm air.(Pa)

It is clear that heat and mass transfer processes take place simultaneously. It can be considered that the heat energy from heat transfer is used to evaporated a certain moisture as mass transfer. The equation (4.3) expresses this relationship.

$$[\frac{dW}{dt}]_c * q_L = -[\frac{dQ}{dt}]_c...(4.3)$$

here: q_L = the latent heat of evaporation in unite mass of moisture at the temperature °C.

It is known that :

$$-[\frac{dQ}{dt}]_c = h_c * A * [T_a - T_s]$$

So, $$[\frac{dW}{dt}]_c = -\frac{h_c * A * [T_a - T_s]}{q_L} ....(4.4)$$

From this formula, it is understood that the heat transfer rate depends on the heat transfer efficiency under the given drying conditions. Within the bulk, the term of bulk density and the depth of the bulk are employed to describe mass and heat transfer.

The equation(4.4) is changed into the equation (4.5).

$$[\frac{dW}{dt}]_c = -\frac{h_c * M * [T_a - T_s]}{q_L * D_b * \rho_b} ...(4.5)$$

Here: D_b = the depth of the bulk.(m)

ρ_b = the density of the bulk.(kg/m³)

M = the mass of moisture (kg)

From this equation , it can be understood that the mass transfer speed is in inverse proportion to the depth of the bulk and the density of the bulk. In practical dryer designing , usually the reasonable smaller value of bulk depth is selected to increase the mass transfer rate within the bulk.

4.2) Heat transfer models of the wet bulk of pyrethrum

There are three different heat transfer regions from the centre to the bottom or to the top within the wet bulk according to the change of heat transfer process within the wet bulk of pyrethrum. During drying pyrethrum the warm air is blown over the both sides of transporting belts. On the top or at the bottom, the temperature is the highest within the bulk. At the centre of the bulk, the temperature is the lowest.

1) Top region.
Vapour convection and solid conduction dominates the heat transfer at the top of the wet bulk due to contact with warm air on the boundary condition.
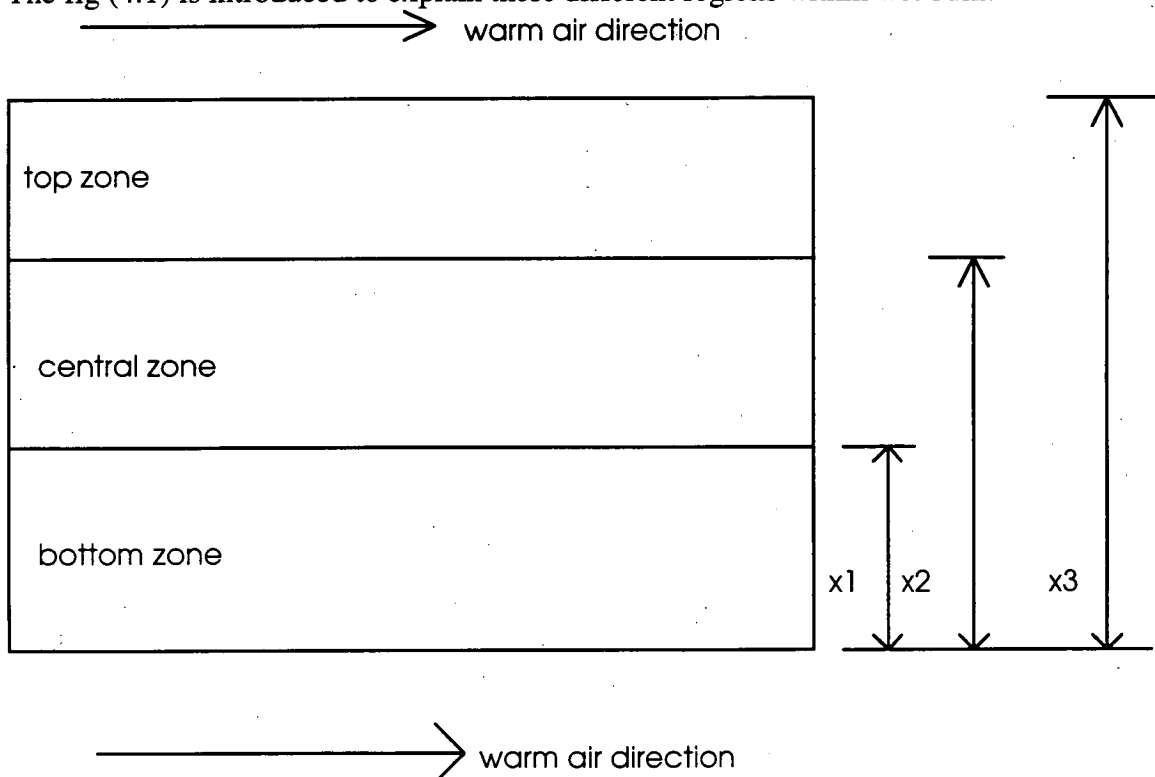
2)Bottom region.

There are two situations in this region. The first situation occurs when the warm air is blown over the top surface of the wet bulk. As a result, at the bottom the warm air temperature is the lowest due to heat transfer from temperature boundary of the warm air to the top, then to the centre zones firstly. At last, warm air just arrive to the bottom. The moisture diffusion rate is very low and is just in liquid form. The second situation is as the same as the top regions when the warm air is blown over the bottom of the wet bulk simultaneously.

3) Central region.

This third region depends on the directions of the movement of the warm air. It is situated at the centre of the bulk. Due to the air flow moving from top and bottom, the temperature is lower at the centre than that at the top or at the bottom. Liquid moisture conduction within the wet pyrethrum and solids conduction within the bulk of wet pyrethrum is controlled the heat transfer at the centre zone. Just a little vapour moisture exists at the centre zone, because of the lower temperature than on the top and on the bottom.

The fig (4.1) is introduced to explain these different regions within wet bulk.

———————————————> warm air direction

———————————————> warm air direction

Fig(4.1) different regions within the wet bulk

4.2.1)Discussion

In a dryer for drying pyrethrum, the warm air is supplied from both sides of the transporting belts. So, at the top zone and bottom zone heat transfer is governed by the vapour convection and solids conduction.

As the drying process progressively is developing, the amount of the moisture vapour density from the wet pyrethrum will be reduced. The viscosity of the moisture will be reduced too.

These two phenomena will lead to a decrease in the heat convection co-efficient. On the other hand, as the drying is further developing, the surface temperature will be continuously going up. The heat conductivity of the solids will increase too.

It can be concluded that at the top zone of the wet bulk of wet pyrethrum, heat transfer is governed by the vapour convection and conduction within the solids. With the drying developing, some factors charge and the effects of vapour convection will be weaker while the effect of solids conduction will be stronger.

When drying pyrethrum, the top zone and bottom zone will have the same situation about heat transfer.

At the centre zone of the wet pyrethrum heat transfer is different, because the temperature of the centre zone is lower than that at the top or bottom zone. The moisture exists in the liquid form and in vapour. Heat transfer is determined by the three factors as follows;

1) Vapour heat conductivity and warm air molecules convection and conduction.
It can be understood that at the temperature boundary of the air the heat transfer is controlled by the moisture vapour heat conductivity and air molecules convection conduction, which decide the temperature of temperature boundary of the air flow. Within the air flow some moisture is in liquid form, but a much less mass compared with vapour mass, so liquid heat conductivity influence is very weak.

2) Liquid heat conductivity.
Liquid heat conductivity decides mainly the heat transfer on the surface of wet pyrethrum, because some moisture in liquid form are on the surface of wet pyrethrum due to moisture mechanism. When heat transfer progressively towards inside of wet

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pyrethrum, heat transfer is controlled by liquid heat conductivity and solid heat conductivity.

3) Solid heat conductivity.

Solid heat conductivity has two situations; one is the heat conductivity from one pyrethrum to another pyrethrum within the same bulk, another means the cell constructer heat conductivity within the same of wet pyrethrum.

When the drying process keeps going, the amount of the moisture vapour will be increased. So, the heat convection by vapour will exert more and more influence on the heat transfer. The heat convection by vapour will reach a maximum, then drop down due to the wet bulk becoming dried up and the moisture vapour's mass decrease.

There are a lot of the pores within the wet bulk. These pores are full of warm air. When the warm air is in contact with the wet pyrethrum, heat transfer takes place by warm air convection. At the initial drying stage, it is a similar process to heat transfer on the boundary layer. As the drying process develops progressively, the radius of the pores within the bulk will become larger and larger due to shrinkage of wet materials. More and more warm air enters the bulk. The heat transfer convection by warm air molecules will more and more control the heat and mass transfer process.

4.2.2)Conclusion

Within the wet bulk of pyrethrum, the heat transfer is controlled by air convection , vapour convection co-efficient, liquid conductivity, and solids conductivity at the different zones. At the different drying stages, these factors will be variable with drying time due to moisture lost within the wet bulk.

4.3)Temperature profile and temperature histories within wet bulk of pyrethrum

In order to describe the temperature within the bulk of wet pyrethrum, the temperature profile and temperature histories are introduced.

4.3.1) Temperature profile

For the temperature profile, in coordinate system, horizontal axis is the symbol of the distance from the top of the bulk to the bottom or from the bottom of the bulk to the top, which is depended on the direction of heat transfer. The vertical axis indicates the temperature within the bulk.

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In drying chamber for pyrethrum, the warm air movement direction is parrel to the transporting belts. Warm air flows over wet pyrethrum from both sides of the transporting belts. So, the temperature profile shape should be like fig(4.2).

temperature (C)

distance from top (mm)
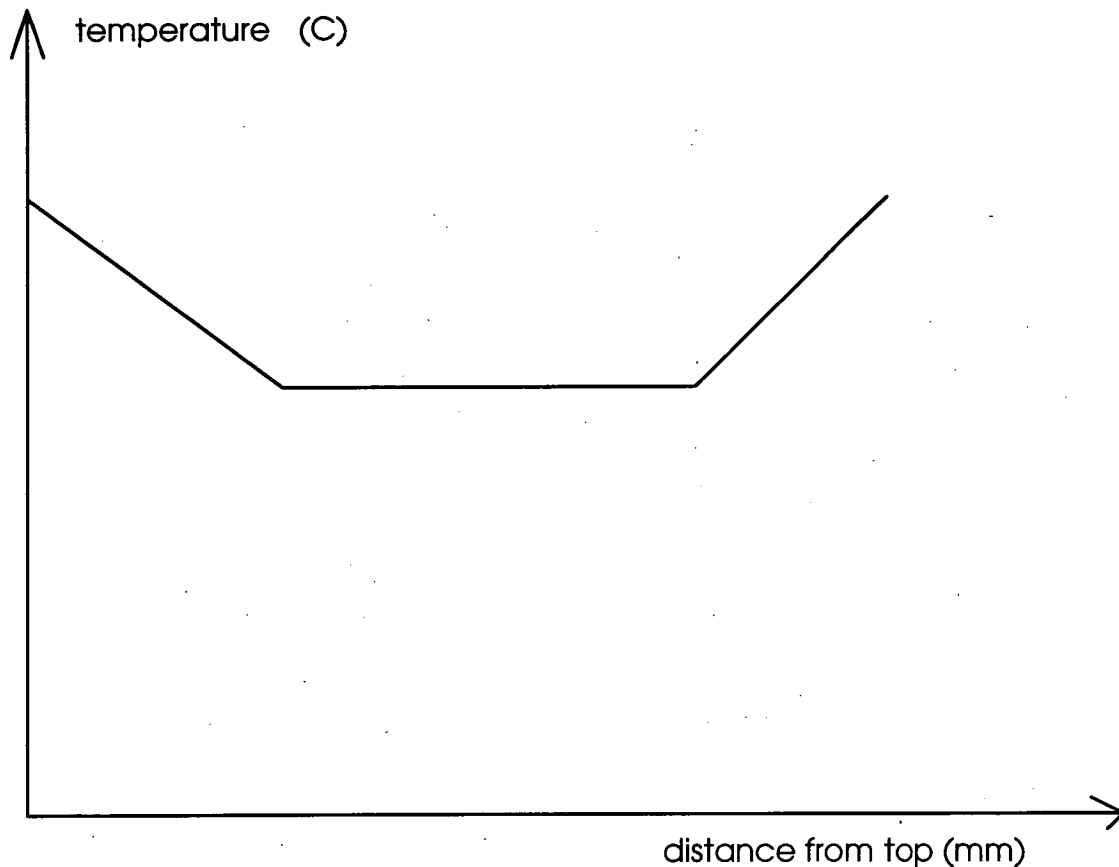
Fig(4.2) temperature profile

From this temperature profile, it can be seen that there are three different heat transfer regions within the bulk of wet materials. Usually in the first region and the third region, the temperature within the wet bulk is the function of the distance from the top or from the bottom of the bulk. The tangent of the temperature linear at the first and the third region represents the average conductivity coefficient within bulk of wet objects. The trend of the slope of temperature linear is gentle when the value of the average conductivity co-efficiency is smaller. The trend of the temperature linear is too steep, when the value of the average conductivity coefficient within the bulk will be larger. As a result, the heat transfer will be better. At the second region, the temperature is a constant which doesn't change with the distance of heat transfer. Actually, this second region is very thin.

Here the term of average heat conductivity within the bulk of wet materials is introduced in order to conveniently evaluate the thermal property of the bulk of the

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wet materials. It must be understood that the average heat conductivity of the bulk of wet materials is different from that of the wet materials itself.

The value of the average heat conductivity within the bulk is determined by the cubic shape of the wet materials, the thickness of the bulk, the density of the bulk, the velocity of the warm air and the thermal conductivity of wet materials.

At the different regions of the wet bulk, the average heat conductivity of the bulk will change due to the different heat transfer process in the different region within the bulk.

4.3.2)Temperature histories curve

If some temperature sensors are put at the various depth of the bulk of the wet materials, the variation of the temperature within wet bulk will be recorded at a certain period of the drying process. In coordinate, the vertical axis symbolises of the temperature and the horizontal axis means the time. The temperature history curve within the wet bulk will be obtained. This curve reflects the rate of the temperature rise at the different regions within wet bulk. The typical shape of this curve is like fig(4.3), which can be segregated into three proportions. The shape of the temperature historic at the different regions is similar, but the slope of the line will be different.
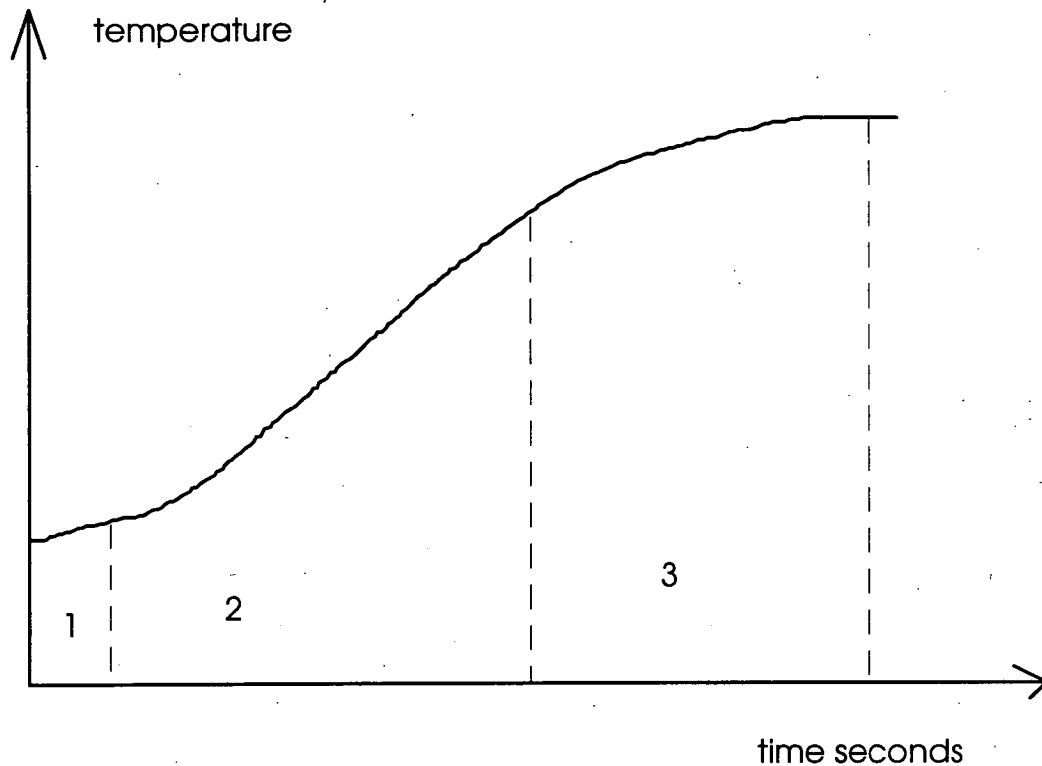
fig(4.3) temperature history curve

1) At the initial period, the temperature rise slowly.

2) During drying process developing, the temperature rising is faster than before.

3) As the drying process further develops, the temperature rising is more and more gentle to approach the maximum value that is close to the wet bulb temperature of the warm air , but always below that temperature.

4.4)Mass transfer within the wet bulk

One-dimensional diffusion process in the wet bulk with two open boundaries is the feature of the mass transfer in the wet bulk, because from the top or the bottom of the wet bulk, the moisture can diffuse to the air flow. It can be considered that the bulk system is the symmetric system for the moisture diffusion.

As discussed above, there are three regions within the wet bulk. Temperature and the moisture amount at the top and the bottom regions are assumed to be nearly the same. At the top and bottom, the largest moisture mass is in vapour. At the central region, the moisture mass is the smaller at the same time due to low temperature.

The central zone is called as cold zone. Under the different of the vapour pressure moisture moving will be moving from the centre to the top or bottom in vapour.

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In order to investigate the moisture moving within the wet bulk, some assumptions are introduced here.

1) A vapour phase pressure gradient exist, which is along the vertical direction of the wet bulk. That the maximum value of vapour phase should be the surface of the bulk.

2) The pore pressure within the wet bulk can be neglected due to the larger radius.

At a given time, when the top or bottom zone is dried, the phase change plane will move inward to the centre zone. The central moisture will move out through the pores of the already dried bulk to leave the wet materials. At the same time the warm air is continuously to the moving in to the centre zone through the dried pores.

The mechanism of moisture movement within the wet bulk is mainly moisture diffusion. The permeability of the warmer and moisture decide the mechanism of the vapour moisture moving within the wet bulk.

$$V_v = \frac{-K * K_{rv}}{\mu_v} * \frac{\partial P_v}{\partial x} ...(4.6)$$

Here : V_v = the velocity of the moisture vapour moving.

  K= the warm air permeability.

  K_{rv} = the vapour relative permeability.

  μ_v = the viscosity of the vapour fluid within the wet bulk.

  $\dfrac{\partial P_v}{\partial x}$ the change of the vapour pressure along the depth of the wet bulk.

Analysis of this equation shows that the warm air permeability and the vapour permeability into the wet bulk will be the greatest influence on the moisture moving within the wet bulk. A stronger warm air permeability will produce the larger warm air mass into the wet bulk and thus more hot energy will be obtained at the central cold zone. Usually the warm air permeability depends on the air speed over the wet bulk, the drying temperature, the porosity of the wet bulk, and the bulk depth.

$$K = \gamma * \frac{V * (T_d - T_w)}{D} * \varepsilon ...(4.7)$$

Here γ = empirical constant.

  V=the warm air speed.

  T_d = the dry bulb temperature of the warm air.

  T_w = the wet bulb temperature of the warm air.

  D= the thickness of the wet bulk.

ε = the porosity of the wet bulk

4.5) The permeability of the warm air and vapour within the wet bulk.

The warm air permeability describes the warm air moving through the wet bulk while the vapour permeability explains the moisture moving out from the wet bulk. The vapour permeability is decided by the vapour pressure gradient within the wet bulk, the porosity and the temperature gradient along the depth of the bulk. When a pressure gradient exists across a porous material, air fluid at the high pressure will move through the pores towards lower pressure. The permeability of the bulk is determined by the pressure gradient. If it is assumed that the whole bulk is uniform. The smaller the pore is, the lower the permeability.

$$K_{rv} = \gamma_{rv} * \frac{dP}{dy} * \frac{dT}{dy} ...(4.8)$$

here γ_{rv} = the constant of the texture of the wet materials.

V = the velocity of the warm air.

D = the depth of the wet bulk

$\dfrac{dT}{dy}$ = the temperature gradient along the depth of the wet bulk.

$\dfrac{dp}{dy}$ = the vapour pressure along the depth of the wet bulk.

It should be noted that these two permeability are changing with drying stages. Within the bulk , the pores are always with several constricted entrances. But the permeability of the bulk is mainly controlled by constriction in the direction of the air flow.

These two permeability through the wet bulk from the different directions are the control factors for moisture vapour moving out from the wet bulk. How to improve these two permeability is one way for increase the drying rate.

Some authors give the another equation to describe the moisture mechanism within the bulk of wet solids.(This equation is from 'Heat transfer in porous madia')

$$D_a = \frac{D_{vG}}{\mu_D} ...(4.9)$$

Here

D_a= the effective diffusivity coefficient.

D_{vG}= the continuous diffusivity of the vapour in the air flow.

μ_D= the resistance coefficient due to moisture diffusion.

The moisture diffusion rate is described by the equation

$$R_d = K_g * (P_{v\epsilon} - P_{vg})...(4.10)$$

here R_d= the rate of the moisture moving within the wet bulk.

K_g= overall mass transfer coefficient

$P_{v\epsilon}$= the vapour pressure at the evaporation plane.

P_{vg}= the partial pressure of vapour of the bulk gas phase

The moisture moving rate within the wet bulk is determined by the gap between vapour pressure and gas pressure. Or it can be say that the mass gap between gas and vapour will decide the moisture moving rate.

In practical design, turning the whole bulk of wet materials is expected to improve these two permeability. During turning over the wet bulk, the relative velocity of the air flow will be increased, the porosity of the wet bulk will increase and the total area exposed to the warm air will be increased too. The last result is to increase the moisture permeability within the wet bulk.

It can be concluded that mass transfer in the wet bulk will depended on the moisture mechanisms :

1) movement of moisture internally within the wet materials which will be a function of the internal physical properties of the wet pyrethrum and absolute moisture content;

2) the movement of moisture vapour from within bulk to the bulk surface under the external condition such as the temperature of the warm air, air humidity, the boundary surface area exposed to the warm air.

In industrial drying of pyrethrum, the drying rate should be get at nearly 250kg/hour. This drying rate will decide the thickness of the wet bulk which should be greater than 50mm on the transporting belts. Under these drying conditions, the rate of

moisture moving from within the wet bulk to the surface must be the controlling factor for the drying rate.

When heat transfer takes place on the surface of the wet bulk, the temperature gradient develops progressively from the heated surface of the wet bulk inwards while evaporation occurs at the surface simultaneously. The moisture migration from within the wet bulk to surface will occur by vapour diffusion within wet bulk. Due to the temperature gradient within the wet bulk, the moisture vapour gradient is formed too. This vapour gradient will drive the moisture moving out.

At the surface zone of the wet bulk, when the vapour is moving to the boundary layer and dried up, the vapour moisture will continuously move to replace the place of the dried up vapour. So, within the wet bulk vapour moisture diffusion are set up,

During drying pyrethrum, the drying rate on the surface is always greater than that at the centre zone due to higher temperature. It is easy to induce shrinkage on the surface of the wet bulk. Further, higher temperature will produce excessive surface evaporation and a higher moisture gradient from the interior towards the surface. Some times cracks or warping occurs. In order to impede these phenomena, turn over the wet bulk to improve the permeability of warm air and vapour.

When the bulk of wet pyrethrum is gently turning over during drying pyrethrum, the boundary zone and the centre zone will change each other. The whole area exposed to the warm air will be increased, which should produce better heat transfer on the boundary condition. The porosity of the wet bulk will be increased too. As a result of increasing the porosity of the wet bulk , more warm air is going into the wet bulk, which will improve the heat transfer inside of the wet bulk. The moisture diffusion rate in liquid or in vapour will be increased due to the permeability of the moisture increased.

It can be said that with the help of turning over the wet bulk in the drying changer, the moisture gradient within the wet bulk will be tend to be gentle. The moisture distribution situation within the wet bulk will become more uniform.

4.6)Reference to Chapter 4

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Chapter 5
Air flow in the drying chamber
Introduction

In forced convection drying process, air is blown from the fan, duct, heater, drying chamber, and chimney that consist into the air path. Under the forced convection drying, in the drying chamber air condition belongs to the external condition that controls the drying process at the initial drying stage and give the great influence on the heat transfer and mass transfer. The heat transfer and moisture transfer between air and wet pyrethrum are the most important key factors in drying pyrethrum. Before the design work, studying the air flow dynamics will help us to understand better the drying process.

5.1)Air ordinary property
A) air density

During the drying process, as the moisture increases, the air density will decrease , because the density of moisture is lighter than that of oxygen and nitrogen.

2) air viscosity

During the drying process, the air viscosity can be considered constant. The air viscosity will influence the air velocity distribution.

$$\tau = \mu * \frac{dv}{dy} ...(5.1)$$

From equation (5.1), the air dynamic viscosity is obtained.

$$\mu = \frac{dv}{dy} / \tau ...(5.2)$$

Here μ=the dynamic viscosity.(kg/m s)

τ= shear stress.(kg/m)

$\frac{dv}{dy}$= the air velocity gradient vertical to the boundary layer.(m/s m)

3) the vapour pressure

The vapour pressure within the air flow will vary with the moisture content and the temperature.

5.2)A few assumptions

In order to investigate the heat and mass transfer over the wet materials, a study of the air flow is needed. The air flow pattern will be set up in the air flow system. Some

assumption about this pattern will be introduced to conveniently describe this air pattern.

1) the air flow is assumed to be two--dimensional steady flow.
2) the boundary layers are developing on each side of the wet bulk of pyrethrum.
3) the air flow is incompressible.
4) when the air flow is moving through the air system, the air is uniform.
5) within the air system, there isn't any loss of the air mass.

5.3)The flow mass

When the flow is through different components of the drying system, the whole mass of the air flux across the section of the different component is the same. This mass is determined by the equation (5.2).

$$M = \int_0^D \rho U dy ...(5.2)$$

here M= the total air mass(kg/s)

ρ = the density of the air flow.(kg/m³)

D= the depth of the air flow.(m)

U= the air flow mean velocity.(m²/s)

5.3)The basic principle:

When warm air is blown from the fan to the air duct, some dynamic properties of the air flow will change due to some section areas changing. Investigation about the dynamics of air flow in the air path are necessary for designing a suitable air system for the drier.

In order to describe the conservation of mass in the system through which the air flow, the continuity equation is introduced for incompressible flow. This concept was first announced by Leonardo Davinci (1452-1519).

For incompressible, steady air flow, one dimension flow, if the whole air path is consider as control volume that means both the mass and the density of the air flow are enclosed by the control volume.

The rate of accumulation of mass is expressed in terms of the rate of change density as

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$$\frac{\partial}{\partial t}(dM_i) = \frac{\partial \rho}{\partial t}dv...(5.3)$$

Here dM_i = the mass change at the i th component of air path.

dv = the air velocity change at the i th component of air path.

$\frac{\partial \rho}{\partial t}$ = the air density change with time due to moisture diffusion from wet solid
to the air.

In drying chamber, the air density is changing due to moisture increasing. Through the other components of air path, the density of the warm air will be the constant, because the ingredients of warm air are not changing. So, another equation is introduced to take into account that no air will be introduced or removed in the air path.

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial}{\partial x_i}(\rho_i V_i) = 0...(5.4)$$

ρ_i = air density at the i th component.(kg/m³)

X_i = the length of the i component. (m)

V_i = the velocity at the i th component.(m/s)

For the incompressible flow, $\frac{\partial \rho_i}{\partial t}$ = 0. ρ_i is considered as the constant. For the steady

flow, at the i th component, the section areas of the component should be not

changed. So, $\frac{\partial v_i}{\partial x_i} = 0$. When air density and air flow speed are the constant, as a

result , it can be concluded that no air mass change take place through the air path.

5.4)The conservation of momentum

The velocity of the air flow will be a function of the time due to different components changing. The air momentum is changing too. For one dimensional air flow, the rate

of accumulation of momentum may be expressed in terms of air velocity, air density and air mass change with time.

The equation(5.6)is introduced to show the conservation of momentum.

$$m = \rho_i * A_i * V_i = \rho_j * A_j * V_j ...(5.6)$$

Here m= the mass of air flow (kg/s)

ρ_i= the air density at the i component (kg/m³)

V_i=the air velocity through the i component (m/s)

A_i= the area of the i the component section (m²)

ρ_j=the air density at the j component (kg/m³)

A_j= the area of the j component (m²)

V_j= the air velocity through the j component (m/s)

5.5)The conservation of energy

According to the conservation law, energy will be the constant through the whole air system under all conditions, if considering the losses within the whole system. The Bernolli function express the energy conservation for flow. For the warm air in the drying process, the energy may have been obtained from the air heater to get heat energy, and from the elevation above the some point, from static energy, and from the its moving. Some dynamic energy will be changed into the thermal energy due to the friction in the air flow.

The energy equation can be expressed as

$$E + Q = g * z + \frac{p}{\rho} + \frac{V^2}{2} - \Delta q ...(5.7)$$

where E= the dynamic energy in the air flow.(kJ)

Q= the heat energy within the air flow.(kJ)

g= the acceleration due to gravity.(m/s²)

z= the relative elevation above some datum. (m)

p= the static pressure of the air flow.(kg/m²)

V= the air velocity.(m/s)

Δq= the lost energy due to friction. (kJ)

5.6)The velocity distribution of air flow in air duct

When the flow is through the air duct, the velocity of the air flow is developing. The air velocity of the layer adjacent to a rigid surface of the duct will be brought to rest due to viscosity. With increasing distance from a duct surface, the velocity of the air flow is less and less influenced by viscosity or by the duct surface. So, three different velocity developing regions can be obtained at the air duct according to the different velocity situations.

1) First region

It is nearly to the inlet of the duct. In this region, if air flow is laminar flow, some transition will be produced. It means some turbulent flow will be formed from the laminar flow due to the effect of shear stress.

2) Second region

It is assumed that at the second region the ratio of duct distance to the diameter of the duct is nearly 30. The boundary layers merge at the centre of the duct. At the central line the air velocity is usually a little larger than the mean velocity.

3) Third region

At the third region, the air velocity will reduce to the mean velocity. This region is at the back of the air duct.

The picture will explain these three regions.

The picture (5.1) will explain some situation about the three regions.

region 1   region 2   region 3

transition   boundary layer   nearly constant total
laminar   -- core interface   pressure in core
to turbulent
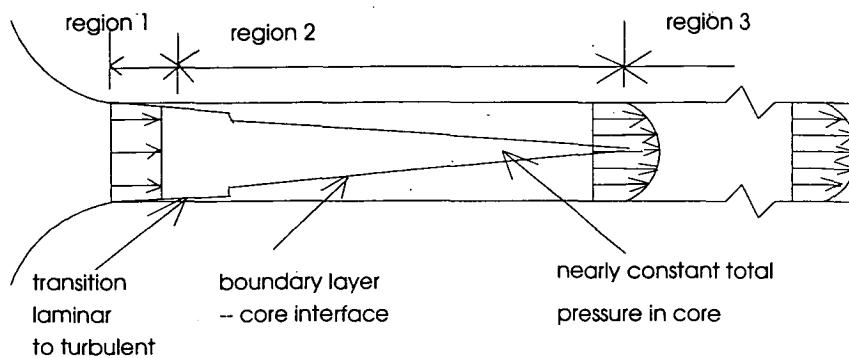
Fig(5.1)

5.7)The air diffuser applied in the dryer

In general, the air velocity in the duct doesn't satisfied with the requirements of the drying wet plants. So, some air diffusers are applied in the dryer. It is expected that the diffuser can improve the distribution of air flow in the drying chamber. In designing the air system of the dryer, the drying chamber is usually considered as the largest air duct. Different shapes of the air diffusers are employed in the drying chamber or outside the drying chamber to divide the air flow and reduce its velocity.

Since the maximum air velocity is at the centre of the air duct, the wet materials placed at the central zone of the drying chamber will get more warm air mass and more heat energy than other wet solids on the edges of the drying chamber. Thus results in the non-uniformity of the drying rate. This situation is more typical in the batch dryer than in other dryers. Some times the wet solids at the central zone of the air flow will be over dried.

An air diffuser is introduced to overcome this poor air velocity profile. Air diffusers are devices used for changing velocity pressure to static pressure and for reducing the velocity of the air flow or to change the air flow direction and to segregate the air mass. Sometimes the air diffuser is employed for center the air mass. Its application in the drying various process is very popular. In drying pyrethrum, the air speed at delivery from a fan is too high for use in a bed of pyrethrum flowers. The air speed is lowered using a diffuser by increasing the air flow areas.

The air diffuser is the simple mechanical equipment. Like other machines, its performance is related to its efficiency known as a performance parameter and loss coefficient.

The efficiency is defined as that is expressed by equation(5.8)

$$\eta = \frac{C_p}{C_{pi}} \ldots(5.8)$$

where C_p= the actual static pressure recovery.(Pa)

C_{pi}= the ideal static pressure recovery.(Pa)

$$C_p = (\rho \frac{V_1^2}{2}) \ldots(5.8)$$

Here ρ= the air density.(kg/m³)

V_1= the air velocity at the diffuser entrance of the air flow.(m³/s)

$$C_{pi} = 1 - (\frac{A_1}{A_2})^2 \ldots(5.9)$$

here A_1 =the area of the diffuser at the entrance

A_2 =the area of the diffuser at the exit.

As the air flow is through the air diffuser, some energy is lost due to the velocity change and the increase the friction area between the air flow and the wall of the diffuser. If the drying chamber is considered as the control volume, the energy lost by friction will be changed into the internal thermal energy. So, the temperature of the air will rise a little after passing through the air diffuser.

The value of the loss coefficient is vary with the shape of the diffuser. The equation shows the loss coefficient of the diffuser.

$$K_d = 1 - C_p \ldots(5.10)$$

Here K_d= the loss co-efficient in diffuser

$$K_d = \frac{\Delta H_d}{\frac{V^2}{2g}} = \frac{\Delta P_d}{\frac{V^2}{2}} \ldots(5.11)$$

ΔH_d= the head loss in the diffuser.(m)

g= gravity acceleration.(m/s²)

$\Delta P_d =$ the pressure loss in there diffuser.(P_a)

V= the mean velocity of the air flow in the diffuser.(m/s)

$C_p =$ actual static pressure recovery(P_a)

In fact, head loss or pressure loss exists within the whole air system due to friction or turbulence. The head loss or pressure loss is defined as the difference of the head between any two points within the air flow. In the drying process, the head loss is usually considered to change dynamic energy into thermal energy that will enhance the heat transfer between warm air and wet solid.

For a diffuser with a constant area section at the outlet, the loss efficiency is as follows:

$$K_d = C_{pi} - C_p ...(5.12)$$

The head loss or the pressure loss in the diffuser is given by the equation

$$\Delta H = (h_1 + \frac{V_1^2}{2g}) - (h_2 + \frac{V_2^2}{2g}) = f \frac{L}{D} * \frac{V^2}{2g} ...(5.13)$$

$\Delta H =$ the head loss in the diffuser. (m)

$h_1 =$ the head in the inlet of the diffuser.(m)

$V_1 =$ the air velocity at the inlet of the diffuser.(m/s)

$V_2 =$ the air velocity at the outlet of the air diffuser.(m/s)

$h_2 =$ the head in the outlet of the diffuser.(m)

f= the loss coefficients in the diffuser.

L= the length of the diffuser.(m)

V= the mean velocity in the diffuser.(m/s)

g=the gravity acceleration.(m/s²)

D= the diffuser average diameter.(m)

It is necessary to understand that the friction coefficient in the diffuser depends on the Reynolds number, on the relative roughness of the surface and on the cross-section of

shape, because the diameter of the diffuser changes in some diffusers, the average value of the diameter is employed in this equation.

5.8)Air velocity distribution in air diffuser

Investigation of the air velocity distribution in an air diffuser is necessary in design the air diffuser. It is similar with that in the air duct. The picture (5.2) explains this situation.

total pressue at (1) is nearly equal
to total pressure at (2)
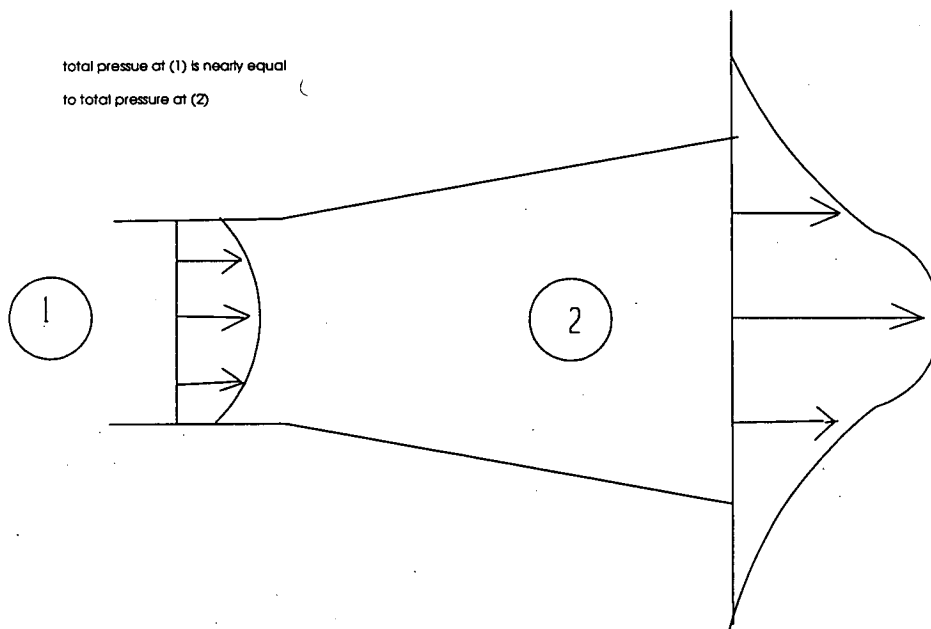
Fig(5.2) velocity profile change

At the entrance of a diffuser, the velocity of the air flow near the wall varies rapidly because the section become larger. The rapid decrease in velocity will results in high shear stress. This high shear stresses will enhance the turbulence of the air flow. At the outlet of the diffuser, the peak of the air velocity will be at the centre of the diffuser. Infusion of the air flow exists in the air diffuser.

Insufficient diffusion is a shortcoming for drying chamber. When the peak of the warm air is at the centre zone of the air flow, the temperature of the boundary layer will be reduced and not enough air mass will pass over the boundary layer. As a result of poor diffusion of the air flow, heat and mass transfer on the boundary layer will become weaker. The drying rate and energy efficiency is decreased.

5.9)The relationship between the performance of the air diffuser and inlet condition of the diffuser

The performance of the diffuser is based on the inlet condition of this diffuser, because the inlet conditions decide the energy distribution. In practical design, normally it is necessary to pay more attention to the shape of the inlet than that on the outlet.

The different shape at the inlet decide the diffuser performance. the picture (5.3) can be explaining some shape effecting to the performance of the diffuser.

sepration

mixing zone
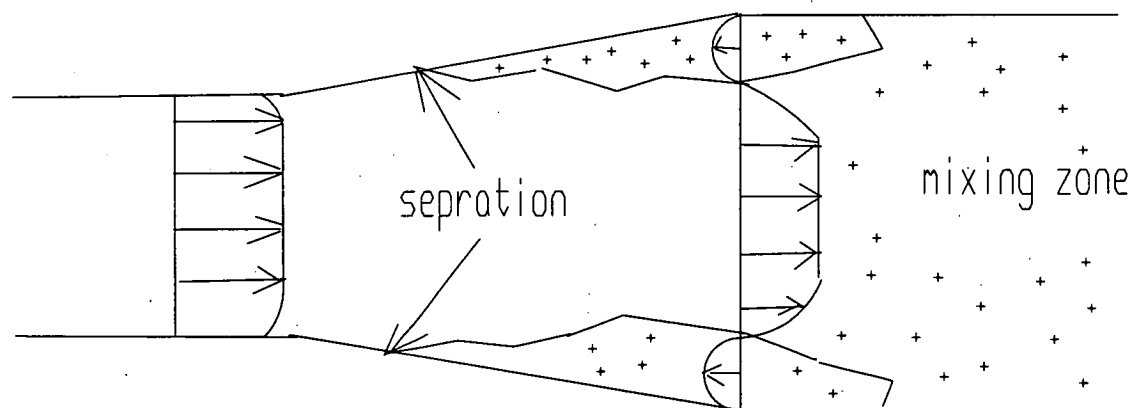
diffuser with outlet section

fig(5.3)

A straight duct is connected with the diffuser inlet will improve some diffusion. This straight duct is known as the mixing section region.

The angle of the diffuser is kept small, because a larger angle will results in rapid diffusion at the inlet of the diffuser.

In practice, there are some methods to improve the diffusion of the diffuser. A typical Method is to install a vortex generator at the centre of the diffuser to impede increase of the value of the centre velocity within the diffuser. Sometimes on the wall of the diffuser some holes are opened to remove low energy fluid or to blow in some new air flow to enhance the boundary conditions on the wall .

The picture(5.4) explains some improvements in construction of an air diffuser.
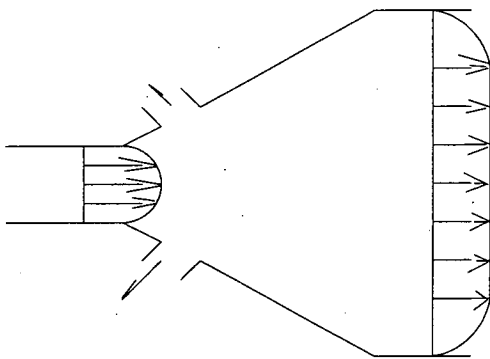
improvement constructor of air duct

and air velosity distribution
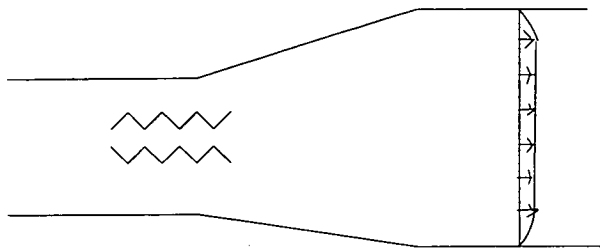
Fig(5.4) a vortex generator at the center of the diffuser c·

5.10)The loss of the air system in the drying chamber

During drying pyrethrum, there are multiple belts on the drying chamber. The gap between two transporting belts is considered as the air duct. It is expected to enhance the heat transfer in the drying chamber. As it is the laminar flow, the heat loss in the air duct is expressed in the equation (5.14)

$$\Delta H = f \frac{L}{D} \frac{V^2}{2g} ...(5.14)$$

ΔH = the heat loss (m).

f= the friction coefficient in the drying chamber.

L= the length of the air path in the drying chamber.(m)

V= the mean velocity in the drying chamber.(m/s)

D= the diameter of the air duct or the hydraulic diameter(m)

g= the gravity acceleration (m/s^2)

The friction coefficient f is determined by the Reynolds number, relative roughness and the duct shape. In the drying chamber, the relative roughness is an important key, but it is difficulty to decide the roughness of the drying chamber. Usually the experience of similar systems is the best guide to decide the roughness value in the duct.

For laminar flow, the friction coefficients can be expressed as

$$f = C_f / R ...(5.15)$$

f= the friction coefficient

C_f= the laminar flow coefficients and is the constant. When the cross section is circular, the C_f= 64. When the cross section is the square, the C_f= 56. When the cross section is an infinitely wide two-dimensional passage C_f = 96.

5.11)The head loss of warm air through the wet materials

When air is blown into the drying chamber, some head loss is produced through some components of the air path. In the drying process, head loss of the warm air blown through the wet solids must be considered. This loss is hard to estimate accurately. Usually, an empirical equation or experiment is employed to explain the relationship between the air velocity, characters of wet materials and head lost of the warm air.

For the case of through flow in drying grain , the equation(5.16) is applied. (This equation appears on p 49 of the book ' Drying Technology' edited by Hu Jing Zhuang and Shin Jing Lin)

$$\Delta H = \lambda * S * V_a^n...(5.16)$$

Here ΔH = the head loss within the wet materials (P_a).

λ and n are the constants that relate with the shape, size of the grain and the bulk density within the drying chamber.

S= the thickness of the grain in the drying chamber(m).

V_a= the air velocity through the grain.(m/s)

Some values of λ and n are obtained by experiments. Here some values that are used in China are introduced by the table (5.1). Note these values are obtained at the air velocity nearly 0.4m/s.(This table is obtained on P 50 from the book ' Drying technology edited by Hu Jing Zhuang and Sheng Jing Lin)

Table (5.1)

	wheat	barely	rice	corn	soya bean	pea
λ	13.83	14.12	17.26	6.57	2.65	8.04
n	1.42	1.43	1.41	1.55	1.60	1.51

For drying tea, another empirical formula is obtained from the same book ' Drying Technology' P 50.

$$\Delta H = a * G^{1.5} * S^{0.9} ...(5.17)$$

$\Delta H =$ the head lost within tea bulk (P_a).

a= the constant relates with tea bulk density. $a=9.3 * 10^{-16} * \rho^{4.2} (kg/m^3)$

$\rho =$ the bulk density of tea.(kg/m^3).

G= the mass of the air flow through the bulk of tea $(kg/h.m^2)$.

S= the thickness of the tea bulk(mm).

In fact, some experiments are needed to determine the deferent values of head lost of some grains under various air velocity .

5.12)The chimney

In the drying chamber, chimneys must be installed to expel the exhausted air. These chimneys can be considered as air vertical air duct with a bend. Between the section of the drying chamber and the section of the chimney there is a constriction of the section areas.

So, the velocity distribution is totally different from that in the drying chamber. According to the continuity equation, the velocity within the chimney is higher than that in the drying chamber. Due to velocity change and section change, some dynamic loss will be produced at the inlet of the chimney. As well as the loss within the drying chamber, the loss within the chimney must be considered.

The size and the place of the chimneys play a very important role in the drying process.

1) chimney sizing

Chimney sizing means the determination of the height and the cross section. The height decides the velocity within the chimney. The higher the chimney, the faster velocity and the more loss within the chimney.

The total area of the chimney should be larger than the area of the inlet of the warm air.

$$Ac = \beta * Ai ...(5.18)$$

Here Ac= the total area for the chimney.

Ai= the total area of the inlet of the warm air.

β=the constant usually the value of the β is selected as 1.3 to 1.5. Sometimes when very wet plants with moisture about 90% by weight is drying, the value of the section of the chimney will be larger then the section of the inlet of the warm air. because it is necessary to expel wasted air with high relative humidity on time. It is obviously that the larger section of the chimney will reduce the loss, and shorten the residency time of the warm air in the drying chamber.

2) The right place of the chimney

The installed place for the chimney is very important. The position of the chimney will determine the air moving direction due to the suction within the chimney. Sometimes after the position of the chimney is decided, in order to improve the air moving direction, some valves are introduced into the chimneys. These valves can adjust the section of the chimneys. So the velocity within the chimney will be changed. Due to the velocity change, the contraction of the chimney will be changed too.

5.12)The contraction within the chimney

When the velocity is increased within the chimney, the pressure decreases and so contraction for the exhausted air is set up. This contraction is the expelling force for the exhausted air. This contraction is the control factor for the direction of air movement. With the help of the valves in the chimney, contraction of the chimney can be adjusted.

At the initial drying period, in order to warm up the wet solids, the valves are partly closed some, the warm air residence time will be attenuated. More heat will transported into the wet solids. At different drying period, different contraction and different air moving direction can be obtained.

5.13)Selection of the fan in the air system

In designing the air system, the last task is to select the fan. Selecting the fan means to decide the type of the fan and the power of the fan. The power of the fan is expressed by the equation (5.19).

$$Power(w) = \frac{Q * P}{\eta} \ldots(5.19)$$

Here Q=The air flow volume m³/s.

$$Q = V_a * A_d \ldots(5.20)$$

V_a = the air velocity though the air duct. (m/s)

A_d = the section area of the air duct. (m²)

P= the pressure loss overall the whole air system due to pressure difference across system. (kg/m²).

η = the mechanic efficiency of the fan.

It should be noted that the pressure loss over the whole air system is consists of a summary of the pressure lost in every components in the air system.

The fan is divided in to two categories One is centrifugal fan, another is Axial Fan. The different fans are the consequence of the desire to meet some service conditions most appropriately. Each type has certain structure or functional features which offer it especially adaptable to some particular use.

In the forced convection dryer, usually the centrifugal fun is employed to below the warm air. Because in convection forced dryer, the fan duty is characterised by low head and large capacity.

5.14) Reference for Chapter 5

1) R.Allan. Wallis, 1983, Axial flow fans and ducts. P6, P11.

2) Hu Jing Zhuang, Shen Jing Lin, 1988, Drying technology.P49, P 50.

3) Robert P.Benedict, 1980, Fundamentals of pipe flow.P8-P12.

4) D.S. Miller, 1978, Internal flow system. P52-P65.

Chapter 6
Design the dryer

Introduction

When designing the dryer, it is necessary to discuss heat and mass transfer. Including calculations of the thermal heat balance and the requirement for the heater power, residual time for wet materials in the drying chamber, and the transporting belts to load and discharge the dried materials. Before designing the dryer, some small-scale tests are needed to determine drying characters about the wet materials required to predict the approach method where the wet materials would be in the real unit.

In the dryer, the heat and mass balance should exist over through the dryer. Here three equations are usually introduced to calculate the dryer. For an ideal dryer, there isn't heat or mass loss within the direct heat supply from incoming gas.

In this designing the heat and mass balance equations are employed.

Heat balance equation.

Mass balance equation.

Residual time equation.

6.1)Heat balance equation for the dryer

Heat balance for a continuous dryer is based on unit time (kJ/s).

At the steady -state drying process, the heat balance equation is used in calculating heat energy required by the drying process.

$$Q = Q_1 + Q_2 + Q_3 + Q_4 - Q_5 ...(6.1)$$

Q = the heat required for drying process. (kJ)

Q_1 = The heat required to evaporate the moisture. (kJ)

$$Q_1 = M_w * \lambda ...(6.2)$$

M_w = the mass of moisture evaporated during drying process. (kg/s)

λ = the evaporating heat at the drying temperature.(kw/kg s)

Q_2 = the heat used for the wet solids heating.

$$Q_2 = M_p * (C_{m2} * T_{m2} - C_{m1} * T_{m1})$$
...(6.3)

Here:

M_p = the loading mass of wet pyrethrum. (kg/s)

C_{m2} = the specific heat of pyrethrum at the outlet of the drying chamber. (Kw/kg °C)

T_{m2} = the temperature of dried pyrethrum at the outlet. (°C)

C_{m1} = the specific heat of wet Pyrethrum at the inlet. (kw/kg °C)

T_{m2} = the temperature of wet pyrethrum at the inlet.(°C)

Q_3 = the heat required for heating the transporting equipment.

$$Q_3 = M_t * C_t * (T_{t2} - T_{t1})...(6.4)$$

M_t = the mass of the transporting belts. (kg/s)

C_t = the specific heat of transporting belt. (kw/kg °C)

T_{t2} = the temperature of the transporting belt at the outlet. (°C)

T_{t1} = the temperature of the transporting belt at the inlet. (°C)

Q_4 = the heat introduced to the dryer by the moisture within the wet pyrethrum.(kJ)

Q_5 = the heat lost in the drying chamber through the dryer surface. (kJ)

6.2)Mass balance for the dryer.

During the steady-state drying process, the mass of moisture introduced into the dryer is equal to the moisture loss out of the dryer.

Moisture into the dryer should include two parts. One is moisture in the wet materials. Another is moisture in the fresh warm air.

Moisture out of dryer should content two parts too. One is within the dried pyrethrum. Another is in the exhausted air.

An equation is relating to explain the mass balance in the dryer. Follows:

$$M_a W_{a1} + M_{w1} W_1 = M_a W_{a2} + M_{w2} W_2$$
...(6.5)

here: M_a = the warm air mass through the dryer. It is the constant. (kg/s)

W_{a1} = the warm air humidity at the inlet. (kg/kg)

W_{a2} = the warm air humidity at the outlet. (kg/kg)

M_{w1} = the mass of wet materials at the inlet.(kg/s)

M_{w2} = the mass of dried materials at the outlet. (kg/s)

W_1 = the moisture content in the pyrethrum at the inlet.(kg/kg)

W_2 = the moisture content in the pyrethrum at the outlet.(kg/kg)

From the mass balance equation, the final moisture in the exhausted air can be calculated.

The heat and mass balance equations are the basic functions for calculate the drying processes, and are depend on the conservation theory.

6.3)The initial designing data

6.3.1)Average initial moisture of the wet pyrethrum and density

W_1 = 70% by weight. ρ_y = 370 kg/m³.

6.3.2) Last moisture of the dried pyrethrum

W_2 = 12% by weight.

6.3.3) The commercial asking for loading speed to drying chamber

M_p = 350 kg/hour.

6.3.4) The drying temperature

The drying temperature is limited by some factors as follows:

a) The highest temperature that should be accepted by the wet solids.

b) The initial mass of the moisture within the wet solids. If the initial moisture is higher, a longer time for heating the wet solids is required.

c) The characters of wet materials. For example, when the rice or corn is drying, the drying temperature and drying rate should prevent cracking on the surface of the grain.

d) The drying purpose.

In fact the drying temperature is selected mainly by experiment. For most porous plants, the free moisture is usually evaporated under the 80 °C. For some plants sensible to temperature, the drying temperature should be carefully decided. For example, in the mushroom whose initial moisture is about 90%, if the drying temperature is over 60 °C , the colour, taste, smell will be damaged. The drying temperature for mushrooms is about 40 °C. For pyrethrum, when the drying temperature is over 80 °C, oxidation develops fast within the wet pyrethrum. As a result of oxidation, the effective ingredients will be reduced too much. So, the 80 °C is selected for drying temperature.

For drying green plants, the drying process is divided into three groupies, according to drying temperature.

i) low temperature drying.

The drying temperature is between 40 °C--60 °C. For drying some vegetables, mushrooms, a low drying temperature is employed.

i i) Middle temperature drying.

The drying temperature is between 60 °C--80 °C. Middle temperature drying can supply enough time for moisture moving out from inside wet materials.

i i i) The high temperature drying.

The drying temperature is over 80 °C. In drying tea on the convection drying chamber the high drying temperature is used, which is nearly 120 °C --160 °C.

The table 2 gives some reference drying temperature for some agricultural products

Table (6.1)   Drying Temperature (this table is obtained from the book ' Industry Drying Hand Book')

Grain	Ear corn	wheat	oats	Barley	Sorghum	Soybeans	rice	peanuts
drying temperature for seed	43 °C	43 °C	43 °C	41 °C	43 °C	43 °C	43 °C	32 °C
drying temperature for commercial use	54 °C	60 °C	60 °C	41 °C	60 °C	49 °C	43 °C	32 °C
drying temperature for animal feed	82 °C	82 °C	82 °C	82 °C	82 °C			

6.3.5) The air velocity

For drying some small size solids, the critical air velocity concept must be introduced. The critical air velocity means the largest velocity that can not blow over the wet solids in the drying chamber. The critical air velocity for different wet solids is obtained by experiment. The air velocity in drying chambers should be less than this critical velocity.

The air velocity should offer enough air mass for heat and mass transfer to occur during drying process.

Combing these two issues pluses empirical data, the air velocity is obtained. In the drying chamber, the air velocity is about 0.3--0.5m/s. In the air duct before the drying chamber the air velocity is about 1.5m/s. The air velocity in the air duct is limited by the heat transfer rate between the air heater and air. If the air velocity is too fast, not enough heat energy can be obtained through the air heater.

6.3.6) The area for air duct

The area of air duct and air velocity decide the air mass. The area of air duct is controlled by the whole dimension of the drying chamber and the air diffusers within the air duct.

Here the area for air duct $A_d = 2.4m^2$

6.3.7) The mass of wet pyrethrum feed into the drying chamber

According to commercial requirements and practical possibility, the loading rate of wet pyrethrum $M_p = 350kg/hour$

6.3.8) The ambient temperature

$T_1 = 20\ ^\circ c$

6.3.9) Ambient air moisture content

$W_a = 0.01kg/kg$

6.4)Thermal calculations
6.4.1) the mass evaporated in the drying chamber

$$M_w = M_p \frac{(W_1 - W_2)}{(1 - W_2)} ...(6.8)$$

Here M_w = the moisture evaporated in the drying chamber.

M_p = the loading rate of the pyrethrum. M_p = 350 kg/hour.

W_1 = the initial moisture within the wet pyrethrum. $W_1 = 0.75.(kg/kg)$

W_2 = the last moisture within the dried pyrethrum. $W_2 = 0.12.(kg/kg)$

$$M_w = 350 \frac{(75\% - 12\%)}{(1 - 12\%)}$$

=250.5 kg/hour.

100

6.4.2) Air volume before air heater

$$M_{av} = V_a * A_d ...(6.9)$$

V_a = the air velocity. V_a =1.5m/s.

A_d =2.4m²

M_{av} =1.5*2.4(m³/s)

=3.6m³

6.4.3) Air mass within the air path

During the drying process, the mass of warm air will be the constant in the whole air path. From the psychrometric chart Fig(6.1), the specific volume for air V= 0.843m³/kg at 20 c°, The moisture amount is that W_a is 0.01kg/kg.

$$M_a = \frac{L}{V} ...(6.10)$$

$$= \frac{3.6m^3 / s}{0.843m^3 / kg}$$

=4.27kg/s

6.4.4) The enthalpy at T_1= 20 C°; W_a=0.01kg/kg

From the psychrometric chart, the enthalpy H_1 =45 kJ/kg

6.4.5) After the heater, the temperature of the warm air

T_2=80 c°

6.4.6) The enthalpy at T_2=80 c°; W_a=0.01kg/kg

When the air is through the air heater, this process is sensible heating. So, the mass of moisture within the air is the constant. From the psychrometric chart, the enthalpy of the warm air is obtained. H_2= 120kJ/kg.

6.4.7) Calculating the heat power

It is assumed that in the drying chamber there is no heat loss through the air heater. So, the theory heat power is computed as following:

$$Power=M_a (H_2 - H_1))...(6.11)$$

Power =4.27*(120-45) (KW)

=320.25 (KW)

6.4.8) Thermal efficiency

$$\eta = \frac{M_w C_w}{M_a (H_2 - H_1)} ...(6.12)$$

here: C_w = the requited heat energy for evaporated per kg water at 80 C°.

C_w = 2350kJ/kg.

$$\eta = \frac{250 * 2350 / 3600}{4.27 * (120 - 45)}$$

= 50.95%

In the drying chamber, the thermal efficiency is limited by the temperature of the exhausted air, the fresh air temperature and the heat loss from the dried materials, from the transporting belts and from the drying chamber.

Reducing the temperature of exhausted air can lead to increased thermal efficiency, but will also reduce the capacity of exhausted air to carry the moisture because at lower temperature, air is saturated more quietly.

Increasing the temperature of the fresh air at the inlet of the drying chamber will lead to increased thermal efficiency, but for drying agricultural products, too high drying temperature will damage some ingredients within the products.

Usually, increasing the mass of wet products and reducing the heat loss within the drying chamber are employed to increase thermal efficiency.

6.5) Calculation about the wet pyrethrum
6.5.1) The whole volume of the wet pyrethrum

In order to decide the dimension of the drying chamber, first it is necessary to consider the whole volume of wet solids and the depth of wet materials on the transporting belts.

$$V_w = \frac{M_w}{\rho_w} ...(6.16)$$

Here: M_w = the mass of wet pyrethrum determined by the commercial constraints.

M_w = 350kg/hour

ρ_w = the average density of wet pyrethrum.

ρ_w = 370kg/m³ (with the moisture 75%)

V_w = 0.945m³.

6.5.2) The depth of wet pyrethrum on the transporting belts

$$D_w = \frac{V_w}{N_t * L_t} \quad ...(6.17)$$

here V_w = the whole volume of wet pyrethrum.

N_t = the number of transporting belts, N_t = 6.

L_t = the length of the transporting belts in the drying chamber. L_t = 3m.

$$D_w = \frac{0.945}{6*3}$$

$$= 0.052m$$

6.6) The dimension of the drying chamber

6.6.1) The volume of the drying chamber

The smaller the dimensions of the drying chamber for a given loading, the lower the manufacture cost. In practical design, the dimensions of the drying chamber are considered from some factors as follows:

a) It should offer enough area for heat and mass transfer.

b) It should offer enough room for installing the transporting equipment.

c) It should supply an appropriate volume for air path and air diffusers.

d) It should meet the commercial requirements for production efficiency.

In 'Drying : Principles, Applications and Design ', the author introduced a formula to calculate the drying chamber volume.

$$V = \frac{A}{a} \quad ...(6.13)$$

Here: V = the volume of the drying chamber m³

A = the cross section of the drying chamber m².

a = interfacial area per unit volume m²/m³.

$$a = \frac{6\phi(1-\varepsilon)}{d_e} \quad ...(6.14)$$

here: ϕ = material shape factor.

ε = porosity.

d_e denotes the equivalent particle diameter.

$$d_e = 1.24 * \sqrt[3]{V_p} \quad ...(6.15)$$

V_p = volume of the particle.

This function is based on the cross section of the drying chamber and the dimension of the wet solids. For batch drying, the solution from this function will be more accurate than that for multiply convection drying .

6.6.2) The height of the drying chamber

The equation is used to calculate the height of the drying chamber.

$$H_c=(N-1)*\Delta H_c+2*H_t...(6.18)$$

here H_c=the height of the drying chamber.

N= the numbers of transporting belts.N=6.

ΔH_c=the centre distance of two transporting pulleys.

$$\Delta H_c = D_p + D_W + d + 2 * D_b...(6.19)$$

D_p= the diameter of the pulley. D_p= 0.18m.

D D_W = the depth of the wet pyrethrum. D_W = 0.052m.

d = the dissidence between two belts. d=0.15m.

H_t= the distance between the bottom transporting belt and floor, or the distance between the top transporting belt and ceiling of drying chamber.

H_t= 0.22m.

H_c=5*(0.18+0.052+0.15+0.003*2)+2*0.22

=2.38m

6.6.3) The width of drying chamber

The width of the drying chamber is depends on the feed volume of the wet pyrethrum and the constructer of the transporting belts.

$$B = \frac{M_w}{\rho_y * L_t * N * D_w}...(6.20)$$

D_w= the depth of wet pyrethrum on the transporting belt.

N= the number of the transporting belts.

M_w= The feeding mass of pyrethrum.M_w= 350kg.

ρ_y= the density of wet pyrethrum. ρ_y= 370 kg/m³.

L_t= the length of transporting belt. L_t=3m.

$$B = \frac{350}{370 * 3 * 6 * 0.052}(m)$$

=1.01m.

6.6.4) The length of the drying chamber

The length of the drying chamber is depended on the length of the transporting belts.

$L_t = 3$ m , this is the length of transporting belts.

$L_c = 3.5$m.

$$L_c = L_t + L_g + s...(6.21)$$

Here L_g = the diameter of the driving gear.(m)

s= the space for adjusting the chain.(m)

6.7)The air inlet duct and outlet duct dimension

In the drying chamber, the air inlet duct area should meet the requirement from air volume and should suit the construction of the drying chamber. In order to meet the requirements of air flow uniformity in drying chamber, the area of the outlet duct should be equal to that of air inlet duct from a theoretical view, but in practice the area of the outlet duct usually varies with the developing drying process.

At the initial drying stage, the outlet is closed to make the temperature rise in the drying chamber. As the drying process is developing, the relative humidity within warm air is increasing. The outlet duct should be opened larger. When drying plants, usually the outlet areas are adjusted at any time. In the continuous dryer, the materials outlet is the part of the air outlet. In this design the total area of outlet air duct should be smaller than that of inlet air duct.

Air volume L=3.6m³.

Air duct inlet total areas A_d=2.4m², due to air velocity V_a= 1.5 m/s.

Air duct outlet total areas A_{od}= 1.5--2m².

6.8) The place of air inlet duct and outlet duct.
6.8.1) The place of air inlet

In this design, the air inlet duct is placed between top three pairs of transporting belts.

The figs (6.1) are introduced to explaining the place of air duct inlet.

air moving direction → wet pyretrum moving direction ←
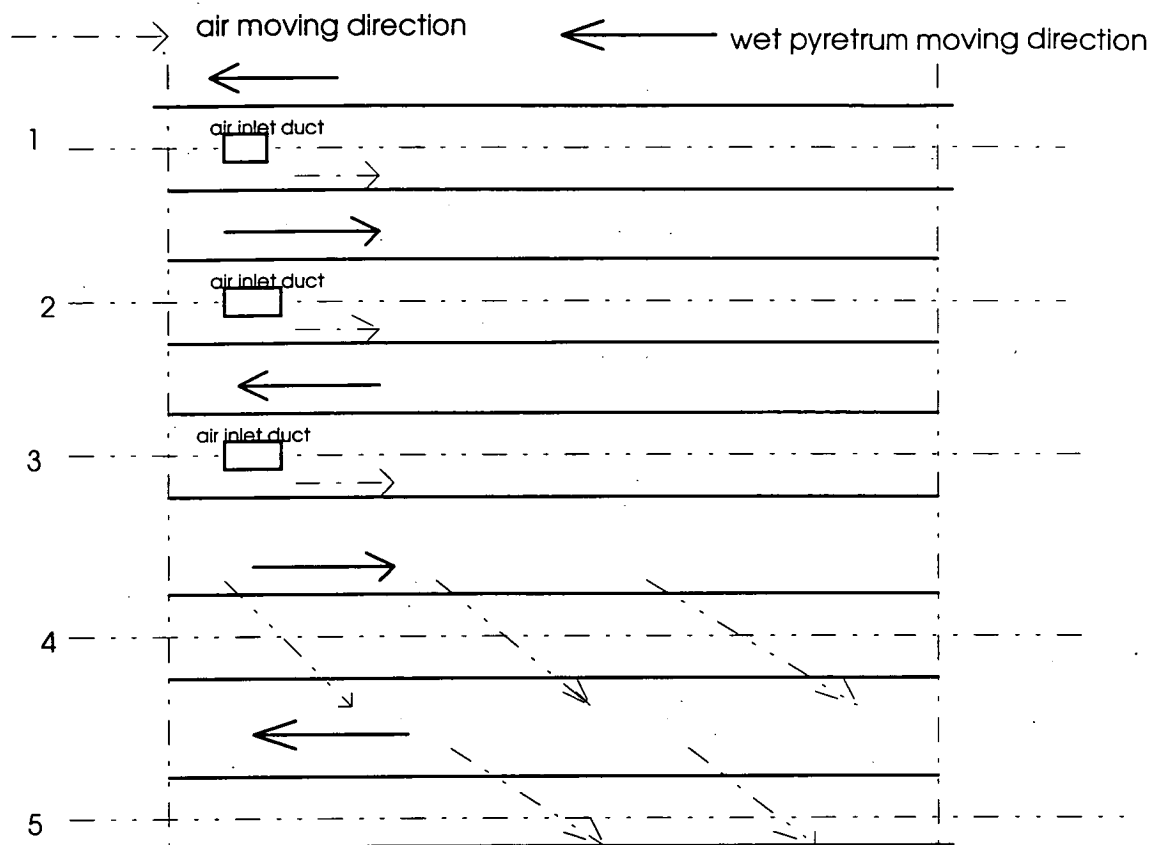
fig(6.1)

In this design, there aren't any air inlet duct. Putting air duct on the top zone can make air path longer, which will supply the lager heat transfer areas. Secondly, the air outlet is nearly the bottom zone. Under the suction of the air outlet, the warm air can go through the bottom transporting belts. Thirdly, the moisture within the wet pyrethrum become getting the final moisture, which means that the pyrethrum at the bottom zone needs smaller amounts warm air than that at the top zone. Finally, this Method can simplify the construction of the air system.

6.8.2) The place of air outlet

The fig(6.2) shows the place of the air outlet.

drying chamber

wet material in
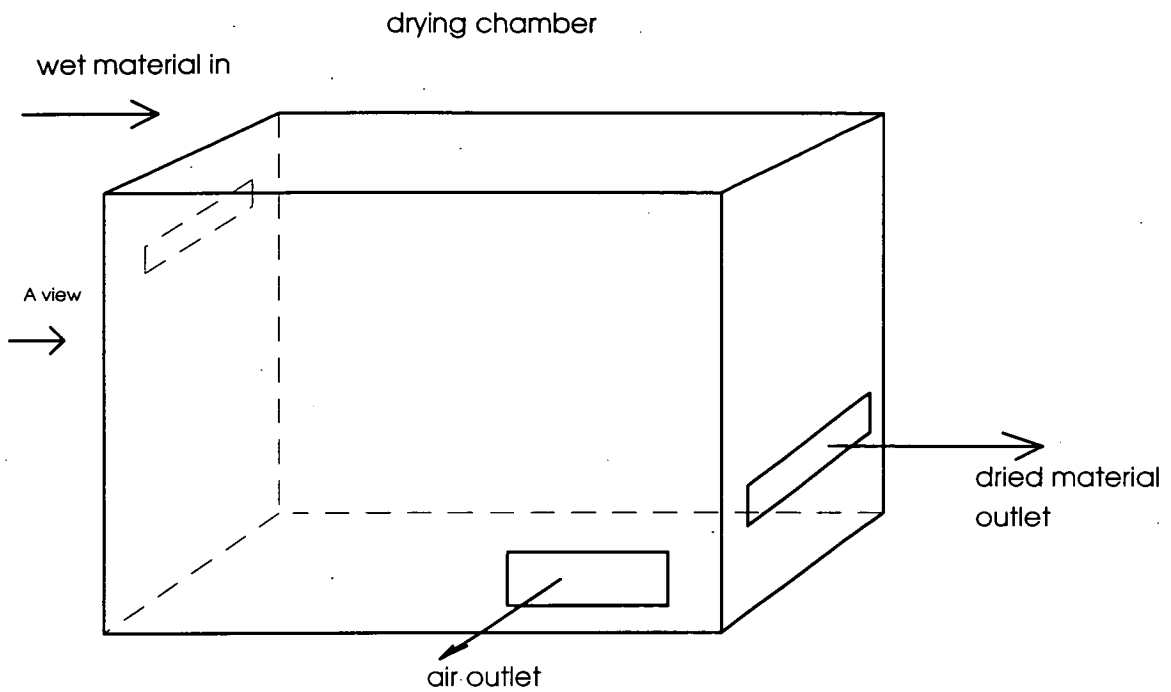
A view

air·outlet

fig(6.2) Place of the air outlet

A view

fig (6.3) the place of air out

Here it is a simple diagram to explain the place about the air out place.

6.9) Transporting belts

6.9.1)The numbers of transporting belts

$N_t = 6$.

6.9.2) The construction of transporting belts .

In the drying chamber, the transporting belt is driven be ordinary chain and gear. In this continuous dryer, there are two key factors employed.
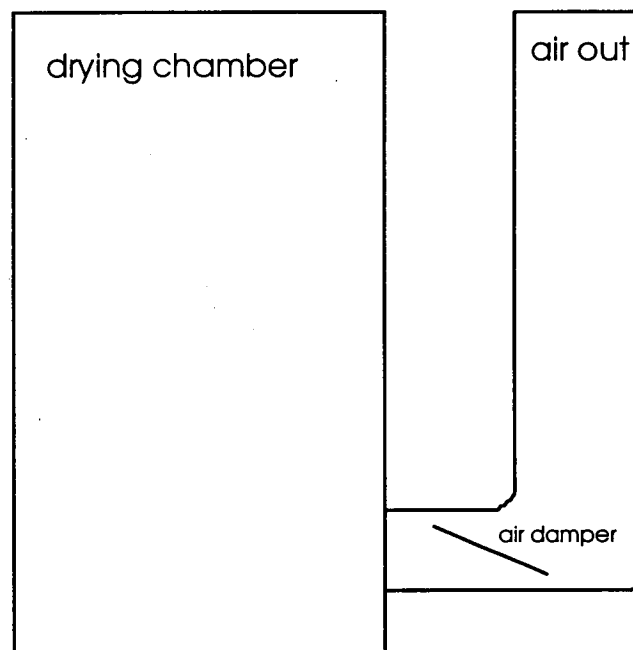
Firstly; It should note that the length of transporting belt is 3m. So, two supporting rails are necessary to design for supporting one chain on the two sides within the drying chamber. In order to reduce the friction between the axle of chains and rail there are two rollers installed on the both of sides of the axles of chains. This way can save driving dynamic power for chains.

Secondly, in order to represent to turn over the wet materials in the drying chamber, the tile form of chain construction is used , which is explained in the fig (6.4).

belt moving direction
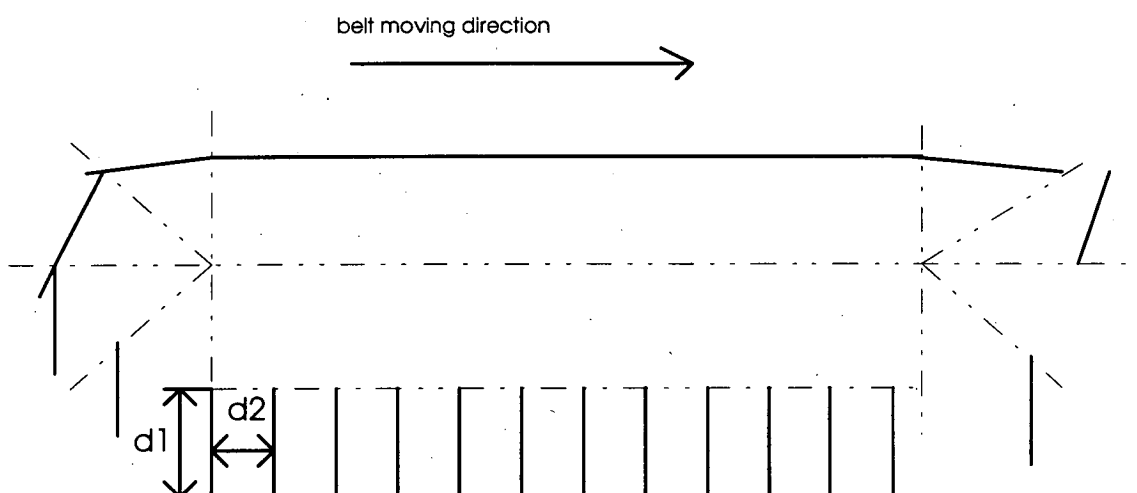
fig(6.4)

when size d1 is greater than size d2, the tile chain will be turned over by the gear automatically. So, the wet pyrethrum can be transported from top transporting belts to another transporting belts to represent the continuous moving within the drying chamber.

7.0)Conclusion

This dryer constructer is very simple, the heat efficiency is reasonable. During drying pyrethrum, step by step to understand the drying characters about this dryer will result in improving the heat and operation efficiency. Compared with other dryers, we can say this design is reasonable. The table (6.2) gives some heat efficiencies about usually dryers used in industry drying. (This table is available in book' Hand Book of

Industrial Drying ' The Chapter ' Energy Aspects in Drying by Czeslaw Strumillo and Carlos Lopez-Cacido)

Weighed Average Annual energy Requirements and Drying Efficiency for industrial Solid Dryers

Table (6.2)

	Energy requirement $(10^9 \text{ MJ} / \text{year})$	Efficiency (%)
Direct continuous		
Tower	137 ±32	20--40
Flash	528±211	50--75
Sheeting	2.8	50-90
Conveyor	1.9	40-60
Rotary	66	40-70
Spray	9.5	50
Tunnel	< 1	35-40
Fluidised bed	23	40-80
Batch : tray	<1	85
Agitated pan	< 1	90
Vacuum rotary	11	up to 70
Vacuum tray	<1	
Indirect continuous		
Drum	2.4	85
Rotary	53	75-90
Cylinder	127±53	90-92
Infrared	<1	30-60
Dielectric	<1	60

From this table, it can be known that the heat efficient within conveyor is about 40%--60%. In drying pyrethrum, the heat efficient is about 50.95%. So, the heat efficient of this dryer is reasonable.

8.1) Reference for Chapter 6

1) Arun S. MuJumdar,1987, Hand book of industral drying, Chapter Energy Aspect.

2) Hu Jing Zhuang, Shen Jing Lin, 1988, Drying technology P126, P136.

Chapter 7
Drying Chinese Green tea

Introduction

The tea, tobacco, sugar industries provide the very important financial income for Yunnan local government in south China. These three industries produce nearly one of fourth of the income for local government. In South China, Yunnan province, the average annual tea product is about 50,000 ton. On the international market, the price of Yunnan tea is about U.S.A. $12,000 for one ton. In Australia domestic markets, Yunnan green tea, Wu Long tea and Jasmine tea are appeared at any large super market. The price of Yunnan green tea is about $A 22.000 for 1 ton.

The Yunnan Tobacco Industrial Company is one of the ten most profitable industrial companies in China. Annual output value is almost A$ 6.5 billions. Yunnan Tobacco has been exported to Japan, Singapore and other Asian countries.

In manufacturing tea, tobacco, and sugar, drying process is the key factor for top quality of these products. Any drying process is an energy consuming process. Developing drying technology will be magnificent for local economy and for saving energy.

Currently, the processing of natural plants is growing quickly in south China. The flower health food, non-polluted natural vegetables, perfume industries and essential oil industry are developing fast and export the products overseas. Drying technology is employed in many fields. Basic drying tea technology is imported to these plants, but dryers construction are total different to meet various different requirements. Drying tea technology represents some situations of Chinese drying industries.

Drying of green tea has a history longer than 3000 years. At present all except the best top tea is hand-manufactured, with product quality that is considered as the national gift. The manufacturing process of tea is through various machines, especially the drying process. By discussing the drying tea process we can understand some Chinese drying technology.

7.1)Different kinds of Chinese tea
In China, tea is grouped into six kinds according to various manufacturing methods.
1) Green tea.
2) Red tea.

3) Black tea.
4) White tea.
5) Yellow tea.
6) Wu long tea.

Within every kind of tea, there are subgroups as the symbol of different quality of tea. For example, Chinese green tea has a large number of varieties and within green tea. There are six grades. In every grade, the green tea is further sub-divided into two groups again. Before manufacturing tea products, it is necessary to understand clearly two things. One is to recognise the kinds of tea bush. Some tea bush leaves are used to manufacture black tea while another tea leaves are used for green tea. For the same kind of tea bush, the younger tea leaves can be manufactured as high grade tea with top price. The tough and old leaves are produced just as lower grade tea. Another things to understand well is the grade and kind of the final tea products. Then, an appropriate manufacture technology is selected. For example, some tea bush can be manufactured as black tea while another tea bush can be manufactured as green tea. During manufacturing black tea, the ferment technology is employed. The drying process of black tea is different from manufacturing green tea.

After manufacturing tea products, it is necessary to combine some differing grade teas together to suit the various tastes of various people at reasonable market price to get the largest profit.

7.2)The manufacturing process of green tea

In China, the whole tea manufacturing process should be segregated into three sections from harvesting wet tea leaves to the final selling of tea products at any supermarket.
i) Drying tea.
2) Refining tea. The manufacture of flower tea or tightly pressing tea, and packing small bag tea belong to this stage.
3) Merging different grades of tea to suit people's taste.

7.2.1)Drying tea

Removing moisture from the wet tea is an integral part of the tea process. Dried tea is less likely to spoil due to bacteria growth, moulds and insects.

For dried tea, many favourable qualities and nutritional values are enhanced. After being dried, the weight and the volume of the tea are less than that in the wet form. The table (7.1) explains some inorganic chemical ingredients in tea. (this table is obtained from the book' Tea' edited by T.Eden, P139)

table (7.1) Inorganic chemical ingredient in tea leaves

	percent of dry weight		per cent of dry weight
potassium	1.76	sulphur	0.088
calcium	0.41	aluminium	0.069
phosphorous	0.32	sodium	0.030
magnesium	0.22	silicon	0.024
iron	0.15	zinc	0.003
manganese	0.12	copper	0.002

As well as the above elements, some Vitamins such as B_2 and C always exist in the tea leaves. In manufacturing black tea, Vitamin C will be oxidised, but B_2 will persist during manufacturing and storage. When tea is brewed, some riboflavin goes into the cup.

7.2.2) The initial moisture contents within the wet tea

Usually the initial moisture contents in fresh wet tea leaves is about 70%--80% by weight. The initial moisture contents of wet tea varies with the age of tea leaves and different kind of tea bushes.

7.2.3) The final moisture contents within the dried tea

In Chinese national standard, the final moisture of Chinese tea is 6% or less by weight, whether it is green tea, black tea, or other tea.

As discussed in Chapter 1, the final moisture contents is the equilibrium moisture, that is, the balance with the humidity of ambient air at ordinary temperature. For porous plants, this equilibrium moisture is nearly 8%--15% under normal conditions.

From the point of enzyme activity, when the moisture content of dried materials is less than 10%, it is popularly accepted that enzyme doesn't grow at appreciable rates.

It is also necessary to consider the long preservation period of dried tea. During the valid preservation period, any rotten or mildew is not allowed. A lower final moisture that is 6% by weight is obtained helps prevent this occurring.

Some tea is like wine. The longer the preservation period is, the better the taste of the tea . Besides the requirements for final moisture of tea, uniform dimension, uniform moisture within tea bulk, the beautiful smell, and light green colour are very important requirements for tea. Before deciding on the drying process for tea, engineers must understand the total commercial requirements for tea and should consider some bio-chemical changes. For example, after plucking, the enzyme activity and amino-acid will increase. They will influence the tea colour, test, odour.

7.2.4) The stages of drying tea

Traditionally, the drying green tea is subdivided into three stages as follows:
a) Wither wet tea.
b) Rolling tea.
c) Drying tea.

Generally, the manufacture green tea and black tea are partly different from each other. Fermentation takes place in manufacturing black tea, but in drying green tea, fermentation is allowed just a little. So, the green tea colour and taste is different from black tea's taste and colour.

7.2.4.1)Wither wet tea.

In the tea manufacture process, the first stage is withering. After harvesting the wet tea, it is necessary to put the fresh wet tea leaves on the cleaning floor for 2 or 3 hours to naturally reduce the temperature within the tea bulk because the temperature of tea bulk will rise due to transportation of the tea leaves for the long distances and intense enzyme activity. Too much enzyme activity will damage the chloroplast and Vitamins.

The principle of withering tea is drying. The drying temperature and drying time are decided not only from the drying theory but also by bio-chemical consideration.

The residual time of tea withering depends on the moisture content of the tea leaves and on the withering temperature or wither equipment. For old leaves, the moisture contents is less than that in the younger leaves. So, during withering of old leaves, the residual time should be less than that during withering younger leaves.

During withering, some bio-chemical changes take place. After withering, some of the grass smell of tea disappears while a little tea smell appears. The fresh leaves become soft due to loss of moisture.

In the withering stage, the moisture mass in the wet tea leaves will reduced from 75% to 50% or 60% normally.

Besides the result of drying tea leaves, the actual wither is necessary to bring about increased permeability of the cell ingredients on .

The purpose of withering tea can be considered as follows:

1) To reduce enzyme activity during the following manufacture process.

2) Saving larger floor areas due to reducing the volume of the wet tea leaf. In the tea leaf picking season, a lot of tea leaves arrive at the factories. It is necessary to offer enough floor area to spread them in time to reduce the temperature that accumulates during transporting tea leaf.

3) Removing some moisture, and allowing the leaf to become softer. This is a good preparation work for rolling tea leaves.

i) Forced withering.
The temperature of withering is about 180 °C -- 230 °C. The time is very short. It is about 4--6 minutes. The equipment for withering is usually the special drum dryer, where the hot air is out side of this drum dryer, the wet tea leaves are inside, and this drum dryer is usually fixed, but wet tea leaves are continuously rotating in the drum dryer by machine or by human been. During withering process, rotation wet tea leaves are very important to get uniformity of the moisture within the tea bulk. The heat transfer method is conduction. The conduction drum dryer can supply a higher drying temperature than the convection dryer. Sometimes the simple kiln dryer is employed to wither the tea, in order to avoid rotten tea. The natural withering of tea

leaves is often used. Tea leaves are put on the multiple shelves in the workshop, and ambient air is blowing over them. They are not under the sun because sun light will influence the natural tea colour. The reason is very complicated.

High temperature is used in wither drying. Because there are some enzymes in the fresh tea leaves, which will induce some oxidation. High temperature can kill some enzymes. It should be noted that the withering time is very short. A long time will burn the tea. An outstanding feature of tea is its ability to suck any odours from the air. If a little tea burn, the burn smell will spread quickly within the whole workshop. The large tea bulk will be wasted.

The conduction drum dryer is usually employed in withering green tea. The wither temperature and wither time are important keys for the withering process. Different factories will select different temperatures and time. In general, withering temperature is not lower 180 °C --230 °C. The time in the wither conduction dryer is from four minutes to 12 minutes.

An empirical equation (6.1) is introduced in calculating heat energy requited for withering tea.(This Equation is from ' Chinese Manufacture Tea' in 1984 Vol 2 p 7 by Zhang Zheng Ji)

$$Q_{wi} = [C_1 + C_q(T_2 - T_1)]M_{ew} + (7.5\pi D_d L_d^2 - 1.244 M_{ew})C_a(T_2 - T_1)\rho_a + C_w M_{ew}[T_2 - T_1]$$

...(6.1)

Here: Q_{wi} = required heat energy at the wither stage.(kJ/hour)

C_1 =evaporation heat of the moisture during the withering tea.(kJ/kg).

C_1 =600(kJ/kg)

C_q = moisture vapour specific heat.(kJ/kg)

C_q = 0.446 (kJ/kg) suggested value for evaporated moisture.

T_2 = the gap between exhausted air temperature and ambient temperature.(C°).

T_1 = ambient temperature.(C°)

M_{ew} =the mass of moisture evaporated. (kg/hour)

D_d = the drum dryer diameter.(m)

L_d = length of the drum.(m)

C_a = the specific heat of air. $C_a = 0.245 KJ / kg\ C°$.

ρ_a = the air density.(kg/m³)

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C_w=specific heat of moisture in the wet tea. (kJ/kg C°)

From the equation (6.1), it is clear that the heat energy required in the withering stage is determined by the evaporation moisture mass and the temperature at the inlet and outlet.

ii) Natural withering

Natural withering is the simplest form. In the withering workshop, natural withering can be carried out by opening windows, or air flow can be provided by various fans. Sometimes, in order to save the energy, the exhaust air from a dryer is introduced into another withering workshop. The exhaust air from another tea dryer has a temperature over 60 ° C.

In natural withering, the withering time is more longer than that in forced withering. The results of natural withering are not as good as those in forced withering. In larger industries, the natural withering has been abandoned.

Usually the degree of withering process depends on the different kinds of tea bushes, the age of tea leaves and the type of tea that will be manufactured.
It should be noted that it is necessary to avoid putting tea directly under the sun, because sun light can damage the colour of tea. So, natural withering always take place in the workshops.

iii) The relationship between water activity and enzyme activity

During drying tea or other porous materials such as drying meat and vegetables, it is necessary to pay attention to the enzyme activity because the enzyme activity will change the ingredients of tea and other foods.

It is obvious that the drying temperature and moisture within the wet materials will govern the enzyme activity. How do the temperature and moisture of wet porous materials influence on the activity of enzyme?

Acker in 1969 (the book 'fundamentals of food engineering') predicted that water activity rather than moisture content influence biological reactions. The relationship between water activity and moisture content is expressed by sorption isotherm. As a result of water adsorption on polar sites or when a monomolecular layer exists, there is little enzyme activity. Enzyme activity begins only above region of monomolecular adsorption, because in this region, some of water exists in the liquid state. (P320, in the Book' Fundamentals of food engineering' by Charm)

From this idea, it can be understood that if water exists in the vapour phase, there should be no chance for enzyme activity. The enzyme activity is decided by the phase of moisture, because when moisture exists in liquid, the dissolution and diffusion of glucose is possible. Here water is just as a medium for enzymatic process.

In order to form the vapour moisture to impede the enzyme activity, a higher temperature is necessary to be employed during drying process. So, in the whole drying tea process, the highest drying temperature only appears at the stage of withering to reduce the enzyme activity.

The shortcoming of Charm's idea is to neglect the moisture content's influence on the enzyme's activity. In fact, reasonable moisture content will improve the dissolution and diffusion of glucose which may be food for enzyme growth.

Deeper study of this relationship between the enzyme activity, moisture phase and moisture contents will induce the improvements in drying technology and processing food.

b) Rolling tea

After satisfactory withering, the next processing stage is rolling the leaves. After withering, it is necessary to cool the leaves of tea, then it is sent to the rolling machine. In the rolling machine, the tea leaves are twisted and broken up. The tea juice goes out from inside the cell to the surface. During the rolling process, the capillaries of the tea leaves are broken, the moisture moving path is shortened, but the tea leaves are not broken. The tea juice is sticky on the surface of tea. When tea is brewed, the special odour quickly goes into the cup.

In the rolling machines, the tea leaves are compressed and turned over by rolling machines. A typical roller consists of a circular table supported by three feet off the ground. Suspended above the circular table is a box without top or bottom which is moving eccentrically over the surface of the table under the control of a revolving crank. A cap which is between the table and box can be raised or lowered within the confines of the box through a worm gear. The box is charged with withered leaf. Pressure can be applied by lowering the cap on to the leaf. The pressure is controlled by spring compression.

Usually the rolling time is about half of hour. The rolling temperature is about 40 °C to 50 °C. It is not necessary to heat the tea leaf, just employ the heat from the withering.

At present during making the best green tea, rolling tea is finished manually in a pot that is heated by electricity or by fire. In this manual method, a combination withering tea with drying tea is a key. Temperature is controlled just by the worker's experience and while the drying is uniform and tea taste, colour and shape are wonderful, the production quantity is just a little .

After being rolled, the tea leaves become a small strip shape, which reduces the trend of tea leaves to be broken and the commercial uniform shape of tea leaves is nearly obtained. The most important reason for rolling tea is to allow effusion of the tea juice to the surface to get a beautiful odour quickly when the tea is brewed in a cup. As another result of rolling tea, the capillaries of tea leaves are broken. It is benefit for moisture transfer from inside of tea leaves.

At present, small tea bag and convenient drinks are becoming more and more popular in the world. The traditional manufacturing technology in making green tea is faced with challenges from other drinks. Using advantages from other modern drinks, but keeping the traditional advantages is necessary to improve the manufacturing of green tea in China. Chinese green tea has some international markets and it is understood clearly that not developing improved technology will cause a loss markets.

c) Drying Green Tea

After rolling green tea, the moisture in the tea leaves is about 50% -60%. The final moisture in the green tea is about 6%. In most factories, drying tea is divided into three stages, step by step to reduce the moisture from tea leaves. Different dryers are used at the different stages , where drying temperature and resident time are different from each other.

During drying green tea, the key factor is to set up a cooling period. A certain cooling period exists between two drying stages. The cooling period is expected to supply enough time for moisture diffusion from inside tea leaves to the surface of tea leaves because this will ensure the drying uniformity between the inside and the surface is nearly the same and this in turn can reduce tea's tendency to rot when kept a long time.

At the different drying stages, conduction dryer and convection dryer are used in turn. The two issues for employing the different dryers are as followings:

1) Conduction dryers can supply the higher drying temperature that is necessary to induce the nice tea odour and bright colour, but if a conduction tea dryer is always used, there is a trend to burn tea.

2) Convection dryer can supply a gentle drying process, which is helpful to increase the drying uniformity within tea.

After rolling tea, the typical methods in drying stage are as follows:

i) Conduction drying →Convection drying→Conduction drying.

ii) Convection drying →Convection drying.

iii) Conduction drying →Conduction drying →conduction drying.

In most tea industries, method (i) is often used, but different drying temperature and drying time are taken to produce various green tea. Method(ii) and method (iii) are usually taken by smaller tea industries, which are limited by available equipment and cost. In some special situations, some skilful workers can make the top green tea using only one conduction dryer.

Some parameters of the tea continuous convection dryer in China are in the table (7.2). (this table is on P140 from 'Drying Technology' edited by Hu Jing Zhuang , Shen Jing Ling)

Table (7.2)
Chinese continuous convection tea dryer parameters.

Tea dryer	drying area m²	warm air temperature °C (it can be adjusted)	warm air mass m³/h	moisture evaporation rate kg/h
6CH-10	10	120	4000⇒5000	90--100
			7000⇒8000	150--170
6CH-16	16	120		
			9000⇒11000	180--210
6CH-20	20	120		

6CH-25	25	120	11000⇒14000	230--260
6CH-50	50	120	19000⇒24000	420--440
6CH-6	6	120	2000⇒3000	50
6CH-5	5.3	120	2000⇒3000	45

d) Analysis the tea drying process

In drying Chines Green tea, the outstanding feature is the dividing of the whole drying process into a few stages. There is a cooling period between the drying stages. This cooling period is very important during drying tea, because it supply the enough time for moisture diffusion inside to the tea surface, which can keep the surface in a saturated situation. When the cooled tea leaves are send into the drying chamber again, at the same external conditions, a higher drying rate is obtained and a hard surface and cracks should be avoided due to full saturation on the surface.

During cooling periods, some mass transfer can occur in the tea bulk due to non-uniformity of moisture within the tea bulk after the initial drying stage. The dried tea leaves absorb the moisture from the more wet tea leaves. The cooling period enables improvement of moisture uniformity in the whole bulk and benefits the moisture diffusion mechanism inside of tea leaves.

Another feature of drying green tea is to employ different drying equipment at different drying stages. Although drying processes are different from each other at different sites, the point of using different dryers to finish a number of drying stages is the same. The purpose for taking a number of drying stages and using both of conduction and convection dryers is to get a uniform lowest final moisture , uniform shape, special bright colour , beautiful odour and taste.

e) Cooling period setting up when drying Chinese green tea.

During drying Chinese green tea, it is very important to segregate the whole drying process into a few steps and to set up the cooling period. In fact, the cooling period will result in an increased drying rate in drying chamber. It is hoped that the most reasonable cooling period will result in moisture diffusion within the wet plants to meet the requirements of saturation of the surface of wet solids better. If full saturation on the tea leaves is always maintained, the drying rate should be higher than

that in the situation of not-enough saturation of tea leaves. In order to describe the drying rate change, the term of character drying rate is introduced.

$$\vartheta = \frac{R_v}{R_w} ...(6.2)$$

Here: ϑ = the character of drying rate.

R_v = rate of drying for a unit surface area. (kg/hour)

R_w = the rate when the surface of tea is full saturated or the initial drying rate.(kg/hour)

In any drying process, at the initial drying stage the value of R_v is equal to the value of R_w. As the drying process develops progressively, the difference between the values of R_v and R_w will become larger and larger due to the mass of moisture evaporated and moisture diffusion controlled by internal conditions of wet tea leaves. The trend of value ϑ will be less and less than unity.

The cooling period during drying tea will result in overcoming some influence from the internal conditions. The change of value ϑ will be smaller than that without a cooling period, which means that the drying rate for a unit surface will be increased.

Another result of setting the cooling period is to save energy, because after the initial drying, the moisture on the surface is dried up and some difference in moisture pressure between the surface and inside of wet solids is set up by moisture gradients. Under this condition, moisture diffusion is transferred from inside to outside through moisture gradients. This moisture diffusion can finish without extra heat supply outside of a drying chamber during cooling periods. While one part of the tea leaves is cooled, another part of tea leaves is sent into the drying chamber. Thus higher density drying rate and continuous drying process are obtained.

It is obvious that the cooling period is widely used in large scale drying of wet porous plants.

For example, a cooling period is employed during drying tobacco too. The purpose of setting cooling period in drying tobacco is to reduce the thinned hard surface, crack on the surface of tobacco leaves, because after drying, the tobacco leaves are cut into a very thin thread like thing which should have enough integrity and a certain length. Broken tobacco leaves and cracks on the surface of tobacco must be avoided.

In China, the temperature and resident time in cooling period are different from each other in the tea industries. In industrial practice, the cooling temperature and cooling time are usually decided by a lot of experiments .

f) The drying curve

The ideal drying curve during drying green tea process is expressed in fig (7.1). This curve just represent the drying process, it doesn't represent the withering and rolling process.
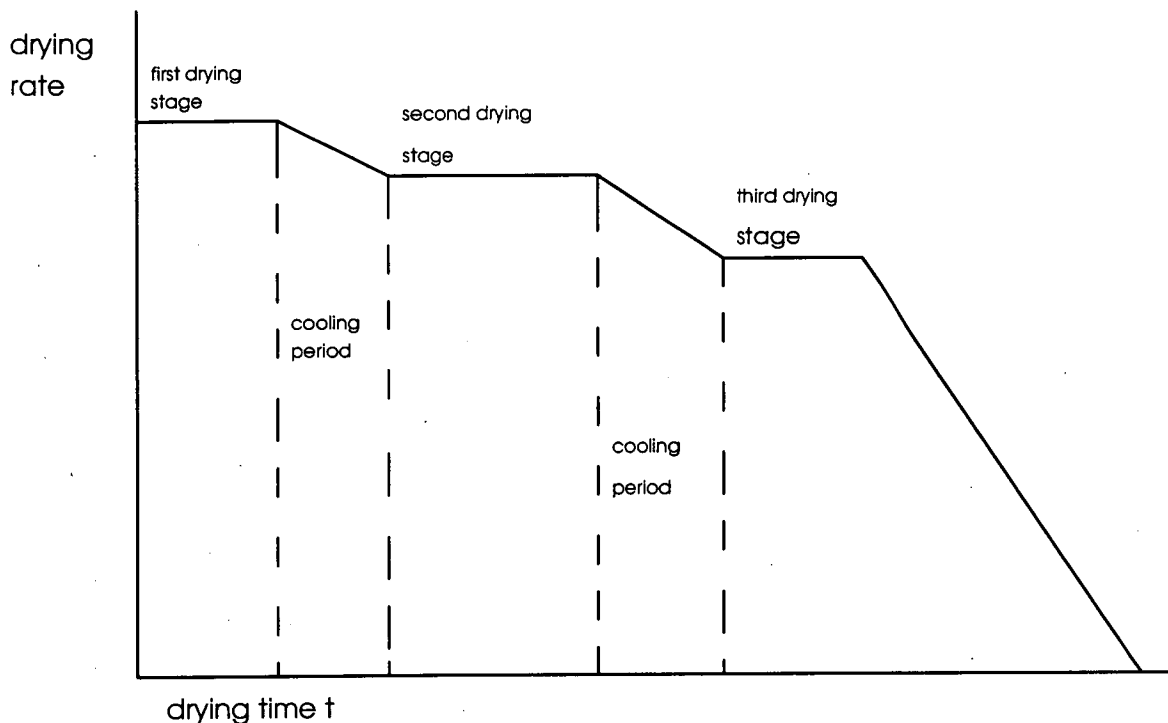
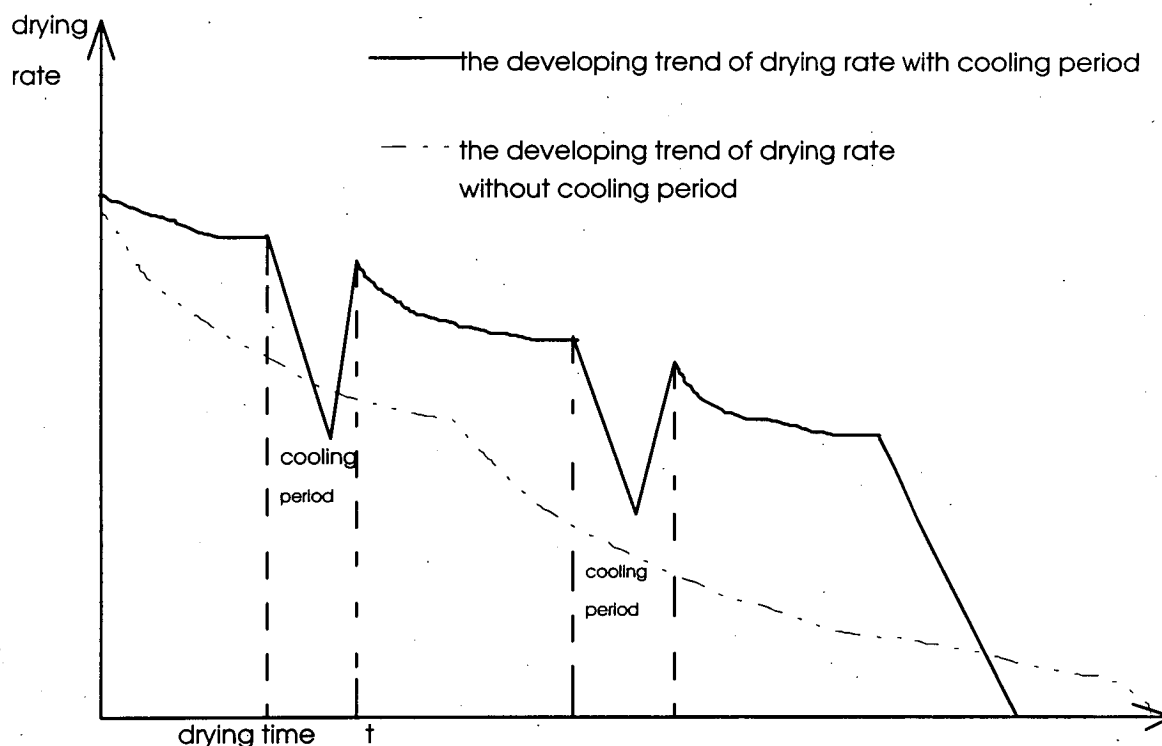Fig(7.1) ideal drying curve during drying green tea

In the ideal situation, it is hope that the drying rate should the constant at the same drying stage, but at the following drying stages the drying rates will be dropped down due to the mass of moisture evaporated.

In fact, during drying green tea, the internal conditions will govern the drying rate, because some free moisture has been dried up at the withering and rolling tea stages. Under the conditions of the moisture gradient, more and more bound moisture will disconnect into free moisture and transfer towards the surface, then saturate the surface. Usually the saturation rate on the wet surface will be less than the evaporation rate, which results in not enough saturation on the surface and the drying rate decreases. So, in the practical drying curve there must be a down slope which means the drying rate is reducing.

In order to get the high density drying rate, the drying rate should no dropped down too much. So, the cooling period is introduced. The principle is to make the surface

more saturated during the cooling period and make up for the gap between the rate of saturation on the surface and the rate of the moisture evaporated.

The fig (7.2) is introduced to discuss some influence of cooling period on the drying curve.

fig(7.2) The developing trend for drying rate during drying stage in drying green tea.

The Fig(7.2) is not real drying curve, but represent the developing trend of different drying curve.

In Fig(7.2), compared two different curve, it can be found that the slope of the curve with cooling periods is less than that of the curve without cooling period. The trend of the curve with cooling periods to have an reducing drying rate is smaller than that of the curve without cooling period. The drying time in continuous drying without cooling periods is longer than that in stage drying with cooling period. So, the cooling period is useful for impeding reduction of drying rate.

g) The central heat supply system in tea factory

In south China, in order to supply the warm air to various tea dryers, steam air heaters are employed due to lower operation cost, compared with electrical heaters. It is easy to adjust the warm air temperature easily while the heat efficiency in the steam heater is reasonable.

In order to produce enough steam, generally a few boilers are set up in the tea factory. The output of these boilers is a large mass of vapour, at low pressure. These boilers and a lot of pipes that transport the steam to the air heaters consist the central heat supply system. With this heat supply system, the operation cost for drying tea is lowered.

In order to improve the heat efficiency in the tea factory, recycle warm air technology is usually to be employed as the picture (7.3) shows.
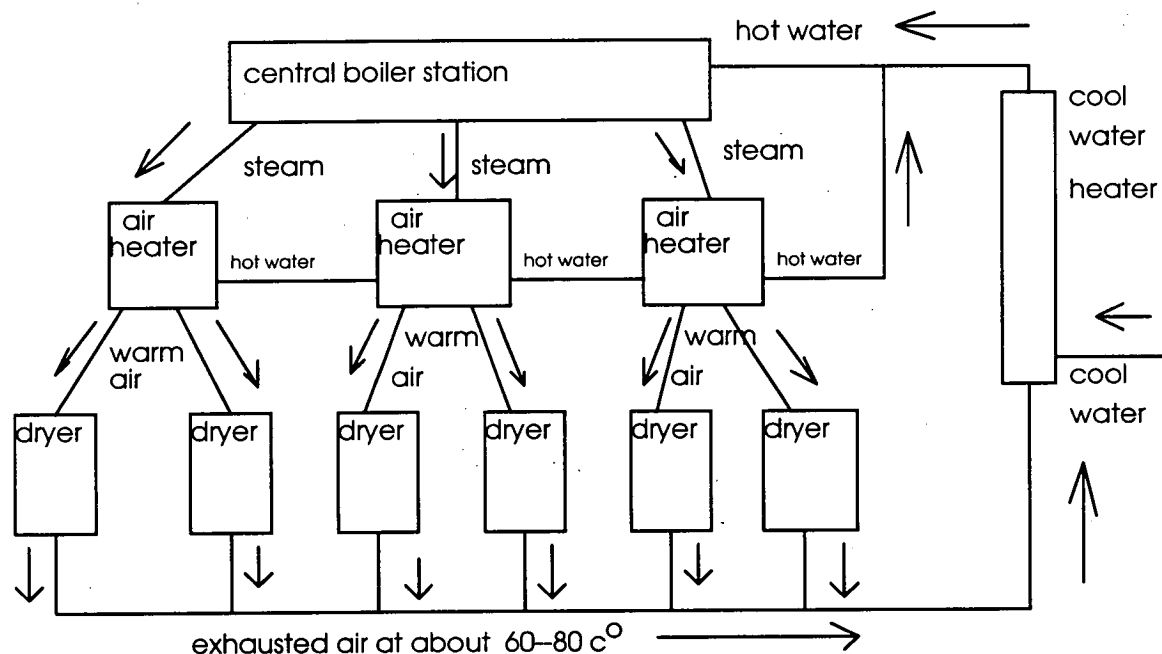
Fig(7.3) Recycle air system in tea factory

7.3) Refining green tea

The process of manufacturing flower tea or press packing tea is known as refining tea. Usually the flower tea is developed on green tea. During manufacturing flower tea, the absorbing smell property of tea is employed.

7.3.1) Manufacturing flower tea.

The processes is merging the dried tea that has moisture about 5% with fresh flower mature bud of the moisture contents about 90%. In generally, jasmine, osm-fragrant,

rose, and magnolia are used as resources of flower tea, because they have a very beautiful smell.

To manufacturing flower tea usually time is in the evening because ambient temperature in the evening is lower then that in the daytime. During manufacturing of flower tea, some heat and mass transfer take place due to moisture difference and temperature difference.

In general, the temperature of fresh flower bud is about 18 C°~20 C° while the temperature of dried tea is about 30 C°~35 C°. When mixing flower bud with dried tea together, the flower bud is open with a strong beautiful odour. The temperature of the mixing bulk will rise to 40 C° or 45 C° due to flower's fermentation. It is necessary to spread the whole bulk to cool it. When the temperature of the bulk has dropped to nearly 30 C°, it is necessary to heap it again. This spreading and heaping process keep going continuously until the tea absorbs the flower smell. This process takes 7 ~9 hours. Then the withered flowers are picked up from tea bulk.

After sucking up the flower smell, the final moisture of tea rises from 5% to 13%. It is necessary to dry flower tea again in order to reduce the moisture to 4%~6%.

Usually green tea is required to suck the flower bud smell two or three times. The best flower tea needs to suck different flower bud smell five or six times. The more sucked flower bud odour, the higher the tea quality. During manufacturing flower tea, drying equipment is a convection multiple continuous dryer.

As said above, the manufacturing green tea technology is centred on the drying temperature and drying equipment. Due to different drying temperature and drying time the various grade of green tea can be obtained, which have various tastes, and odour.

7.4)Conclusion

In general, tea drying technology depends on the drying theory, especially on the moisture diffusion within wet tea and tea bulk in the drying chamber. Step by step removal of moisture from wet tea is a typical feature of drying tea technology, which should include a cooling period between two drying process. It is obvious that the step by step drying is more beneficial for drying uniformity and to get a lower final moisture in the dried tea than that obtained in one step drying.

7.5) Reference to Chapter 7

1) Cham,1971, Fundament of food engineering. P320.

2) Hu Jing Zhuang, Shen Jing Lin, 1988, Drying technology. P140.

3)Zhang Zheng JI, 1984, Journalist' Manufacture Chinese tea' 1984,vol 2,p7.

4) T.Eden, 1965, 'Tea' P139.

Chapter 8

Vegetable drying and the kiln dryer used in developing Asia countries.

8.1)Introduction

Drying vegetable is the oldest method of storing vegetable. Although dried vegetable lose some water soluble nutrition, low production cost, small packing volume and low shipping costs makes drying vegetables get a large market. In China, every year many dried vegetables are exported overseas or from south China to north China due to north China's very cold in winter and no vegetables in winter, such as dried ginger, onion, carrot, soy-bean and various mushrooms and chilli.

For most wet vegetables, the initial moisture is about 75%--90%. In drying processes, the vegetables will lose much moisture. As a result of drying, the protein, fat and carbohydrates are enhanced in per unit weight of dried vegetables compared to their fresh situation. The table(8.1) compares the ingredients change in vegetables before and after being dried.(this table is from the book ' Commercial Fruit and vegetable edited by W.V.Cruess. P621)

Table (8.1) Approximate Comparative Food Value of Several Fresh and Dehydrated Vegetables (To 5% Moisture Bass)

Vegetables	per cent water	per cent protein	per cent carbohydrates	fuel value per pound calories
Cabbage				
fresh	91.5	1.6	5.6	145
dried	5.0	17.7	62.3	1613
Corn				
green	75.4	3.1	19.7	470
dried	5.0	11.8	75.7	1806
Peas				
green	74.6	7.0	16.9	385
dried	5.0	26.2	62.8	1728
Potatoes				
fresh	78.3	2.2	18.4	385
dried	5.0	9.5	80.2	1677
Pumpkin				
fresh	93.1	1.0	5.2	120
dried	5.0	13.6	71.1	1643

Carrots

fresh	90.0	1.1	5.9	126
dried	5.0	9.7	48.0	1039

In the preservation of vegetables micro-organism and biochemical process are the two principles causes of food deterioration. After harvesting, the vegetables are living, respiring materials. It is clear that dry vegetable is less susceptible to rot caused by the growth of bacteria, moulds and insects than whole fresh vegetables.

Some authors commented that ' The activity of many micro organisms and insects is inhibited in an environment in which the equilibrium relative humidity is below 70%' (In 'Industrial Drying Hand Book').

It can be said that the drying vegetables will inhibit the micro-organisms and bio-chemical processes. After being dried, the volume of vegetables is reduced due to loss of much moisture and shrinkage making them more easy to pack and transfer from one place to another .

Table (8.2) gives some data about relative space requirements per ton (fresh basis) of food cu. Ft. Per 2000 lbs.)

Table(8.2) (this data is obtained from the book ' the technology of food preservation' by Mr. Desrosier, P125)

Products	Fresh	Dehydrated	Canned or Frozen
Fruit	50-55	3-7	50-60
Vegetable	50-85	5-25	50-85
Meats	50-85	15-20	50-60
Eggs	85-90	10-15	35-40
Fish	50-75	20-40	30-75

From table (8.1) and (8.2), it can be seen that drying vegetable results in reducing the shipping volume to 1/10 --1/4 of original volume and enhancing nutrition.

8.2.) The initial moisture within wet vegetables.

There is much moisture in the various vegetables. During the drying process, moisture contents will influence some characters of vegetables. The table (8.3) gives the initial

moisture contents within some vegetables. (It is from the book 'Food Engineering Data Hand Book')

Table (8.3) water contents of vegetables.

Commodity	water content %	commodity	water content %
Artichokes		Leeks (green)	88.2--92.0
Globe	83.7	Lentils	12.0
Artichokes			
Jerusalem	79.5	lettuce	94.8
Artichokes			
Asparagus	93.0	Mushroom	90.1--91.1
Avocados	65.4	Mushroom(dried)*	30.0
Beans		Okra	89.8
Dried	12.5	Onions	87.5
Fresh	90.0	Parsley	65.0--95.0
Green or snap	88.9-90.0	Parsnips	78.6
Lima	65.5--66.5	peas(dried)	9.5
String	88.9	peas(green)	74.4
Beets (topped)	87.6	Peas (air dried)	14.0
Broccoli sprouts	84.9	peppers	14.0
Cabbage (late)	92.4	peppers	76.0
Cabbage(white, Fresh)	90.0--92.0	Potatoes	75.0
Carrots		Potatoes (late crop)	77.8
Bunch	86.0--90.0	Sweet potatoes	68.5
Boiled	92.0	pumpkins	93.6
Cauliflower	91.7	Radishes (spring, Prepacked)	93.6
Celeriac	88.3	Radishes (spring)	93.6
Celery	93.7	Rutabagas	89.1
Corn (sweet)	73.9	Sorrel	92.0
Corn (green)	75.5	Salsify	79.1
Corn (dried)	10.5	Spinach	85.7--92.7
Cucumbers	96.1--97.0	Squash	88.6--95.0
Eggplants	92.7	Tomatoes,(ripe)	94.1

Endive	93.3	Tomatoes (mature green)	85.0--94.7
Garlic (dry)	74.2	Tomatoes (Mature green)	
Kale	86.6	Turnips	90.9
Kohlrabi	90.0	Popcorn	92.4

* In China, usually the moisture contents of dried mushroom is 9%--12%.

8.2.2) The final weight of vegetables after being dried

In the industrial drying of vegetables, the final weight is important data for output quantity, packing , and shipping.

$$M_f = M_i - W_e ...(8.1)$$

Here: M_f=the final weight of dried vegetables.(kg)

M_i=the initial weight of dried vegetables.(kg)

W_e= the mass of moisture evaporated.(kg)

$$W_e = M_1 * (\frac{X_1 - X_2}{1 + X_1})...(8.2)$$

Here: M_1 = The initial weight of wet vegetables.(kg)

X_1 = the initial moisture content before drying vegetables.(%)

X_2 = the final moisture content after drying vegetables.(%)

8.3) A few typical problems in drying vegetables

Vegetables are porous capillary materials and the characteristics of drying are explained in chapter 2. A few typical problems govern the quality of dried vegetables. It is necessary to discuss them in detail.

8.3.1) Shrinkage

Shrinkage is a typical problem in drying vegetables, because the ratio of the surface area of vegetable to its mass is larger, which is easily to produce shrinkage during drying process.

Usually in food engineering, shrinkage of vegetables can be divided into two kinds:

a) Free shrinkage.

Free shrinkage means that the shrinkage is directly proportional to the change in moisture content.

b) Elastic shrinkage.

During drying vegetables, usually the elastic shrinkage is neglected due to not too much influence the drying characters of vegetables.

Some authors consider that the free shrinkage volume of vegetables is equals to the volume of moisture evaporated, while other authors considered the free shrinkage volume should be less than that of moisture evaporated, because some air will occupy the place of evaporated moisture in the capillaries.

Usually the shrinkage variation in drying vegetable is represented by the change of the vegetables longest length. The function (8.3) is introduced to explain the shrinkage.

$$\frac{\Delta L}{L_o} = \alpha * \Delta w ...(8.3)$$

Here: ΔL = the change in length.(mm)

L_o = initial longest length.(mm)

α = coefficient of linear shrinkage(mm

Δw = the moisture gradient.(kg/mm)

From the equation(8.3), it can be seen that the vegetable free shrinkage is decided by the moisture gradient within the vegetables and the coefficient of linear shrinkage of vegetables. During drying vegetables, the coefficient of linear shrinkage can be recognised as a constant. That the free shrinkage of vegetable depends on the moisture gradient within the vegetables.

The moisture gradient is related to some factors as follows:

1) the relative humidity within the warm air.

2) the drying temperature.

3) the warm air speed in drying chamber.

4) the initial moisture within the vegetables.

Studying the free shrinkage of vegetables is very important in designing the dryer, especially in deciding the volume of drying chamber and selecting the drying method.

For example, during drying Chinese edible fungus, the batch convection dryer is employed to maintain the beautiful shape, which can lead to the best market price. The initial moisture in Chinese edible fungus is nearly 90%. The shrinkage of wet fungus is very large. At the one of third drying time, or half of drying time, it is necessary to combine half dry mushroom from two plates or three plates into one plate to save places for new wet fungus, which will lead to saving heat energy and high density drying.

The shrinkage can be understood as the ratio between the apparent volume and initial's volume of the wet materials.

Mr. Md. Shafiur. Rahman and Prakash Lal Potluri at Department of food Science, University of New South Wales introduced an equation to calculate the shrinkage of squid flesh during air drying in Journal of Food Engineering.(1992).

$$\hbar = \frac{V_{ap}}{V_o} = \frac{\rho_{ao} * (1 - X_o)}{\rho_{ap} * (1 - X)} ...(8.4)$$

Here: $\hbar$ = the shrinkage of squid flesh.

V_{ap} = the apparent volume of squid flesh.(m^3)

V_0 = the initial volume of squid flesh.(m^3)

ρ_{ao} = the initial density of squid flesh.(kg/m^3)

ρ_{ap} = the apparent density of squid flesh.(kg/m^3)

X_o = the initial moisture contents in squid fish.(%)

X= the moisture content.(%)

Although shrinkage in drying squid is different from that in the drying plants, but both of them belong to the porous materials.

If the equation(8.4) is expressed by the term of porosity ε, some changes produce in this equation as follows:

$$\frac{V_{ap}}{V_o} = \frac{1}{1-\varepsilon} * [1 - \frac{\rho_{ao}X_o}{\rho_w} + \frac{\rho_{ao}X(1-X_o)}{\rho_w(1-X)}]...(8.2)$$

From the equation (8.2), it can be seen that the shrinkage is related to porosity. When porous materials are drying, moisture in the pores is evaporated. The space is occupied by warm air immediately. When the porosity is larger, the shrinkage will be smaller. In this equation, the apparent density term and moisture term are introduced. These two term's values are controlled by the drying temperature.

In fact, the drying temperature and drying rate are the key factors to induce the shrinkage of any wet materials.

8.3.2) Crack and Thermal Stress

During drying vegetables, due to thermal stress crack occurs, which is induced by non-uniform temperature and non uniform moisture during drying process. In general, crack is divided into elasticity crack and in-elastic crack. As drying vegetables or foods, under the influence of the thermal stress the crack produces. Firstly the elasticity crack produces, then it develops to the in-elastic crack. The equation (8.5) shows the thermal stress during drying vegetables.

$$S = E * \alpha * \Delta T ...(8.5)$$

Here: S=thermal stress. (kg/m^2).

E=modulus of elasticity

α=temperature coefficient of expansion.

ΔT= the difference temperature between both sides of the crack.

From the equation (8.5), it can be understood that the thermal stress is proportion to the difference temperature between both sides of the crack due to the modulus of elasticity and temperature coefficient of expansion are constants. In order to overcome the crack, it is necessary to uniform the temperature within the wet materials.

8.3.3) Water activity and

In drying vegetable, the water activity is introduced to describe the living situation for micro-organisms, because the micro-organism is continuously growing after being harvested and during the drying process.

The water activity means the ratio of the partial pressure of water vapour above a solution to that above the solvent. The water activity in pure water is unity. In dried vegetables, the water activity is nearly 0.2. The table (8.4) represents the water activity within some vegetables. (It is from the book' Food Engineering Data Hand Book')

Table(8.4)

a_w	Organism inhibited by lower value	Examples of Foods having this lower a_w value
1.00-0.95	Gram-negative rods; spores of Bacillaceae	Foods containing c.40 wt% sucrose or c.7 wt% NaCl Bread crumb
0.95--0.91	Most cocci, lacto-bacilli and vegetative cells or	Foods containing c.55 wt% sucrose or c. 12 wt% NaCl Raw ham
0.91--0.88	Most moulds yeasts	Flour, rice, pulses with c. 17% H_2O
0.88--0.80	Most moulds staph. aureus	Flour, rice, pulses with c.17 % H_2O Fruit cake Dry sausage

0.80--0.75	Most halophilic bacteria	Foods containing c.26 wt % NaCl Jams and Fondant creams
0.75--0.65	Xerophilic moulds	Marzipan, marshmallow Fishmeal with c.5% H_2O
0.65--0.60	Osmophilic yeasts	Liquorice, gums Medium salted cod with c.12% H_2O
<0.60	All micro-Organisms	Toffees, boiled sweets Raisins

8.3.4)Oxidation

During drying vegetables, the oxidation of vegetables take place. There are two situations of oxidation, either induced by enzymes or without enzyme. Both of situations are the result of a few environments factors.

a) Oxidation without enzyme

Oxidation without enzyme is explained by Franked (1984) in ' water activity : theory and application to Food').
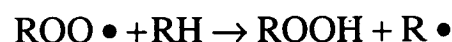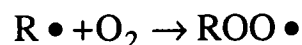
He divided the oxidation process into four stages : initiation, propagation, branching and termination.

1) Initiation

$$RH \rightarrow R \bullet + H \bullet$$

The initiation stage is produced by loss of a hydrogen radical due to getting heat, light or trace metals.

2) Propagation

$$R \bullet + O_2 \rightarrow ROO \bullet$$

$$ROO \bullet + RH \rightarrow ROOH + R \bullet$$

In propagation stage, the lipid free radical reacts with oxygen to form proxy free . This proxy free radicals react further with more lipid molecules to form hydro peroxides.
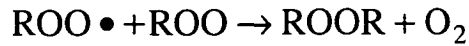
3) Branching

$$ROOH \rightarrow RO \bullet + \bullet OH \xrightarrow{2RH} 2R \bullet + ROH + H_2O$$
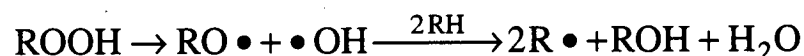
(Monomolecular decomposition)

$$2ROOH \rightarrow ROO \bullet + RO \bullet + H_2O$$

(Bimolecular decomposition)

In the branching stages, free radicals increase geometrically from decomposition of hydro peroxide.

4) Termination

$$ROO\bullet + ROO \rightarrow ROOR + O_2$$

$$R\bullet + R\bullet \rightarrow R - R$$

$$R\bullet + ROO\bullet \rightarrow ROOR$$

In the termination stage, the transfer of the radical to a compound to form a stable radical or the elimination of free radicals by addition of two free radicals.

In 1975 Labuza predicted that when a_w is lower then the monolayer value, the oxidation rate decrease with increasing a_w. The rate reaches a minimum around the monolayer value and increases with a further increase in a_w. The picture (8.1) is introduced to explain this relationship.

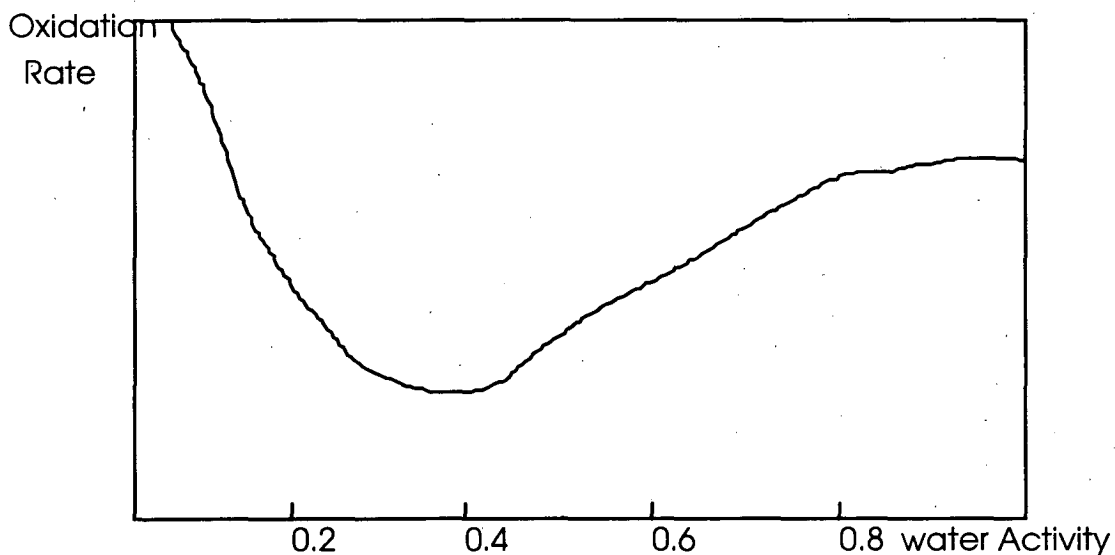It can be concluded that the oxidation without enzyme is controlled by water activity.

Fig (8,1) Rate of lipid oxidation as influenced by a_w in food.

b) Oxidation by enzyme

Various enzymes are naturally present in raw vegetables. In fact, oxidation by enzymes is helped by water activity and enzyme can make their food through oxidation process within the vegetables. As a result of enzyme making their food, the oxidation is produced. It is clear that enzyme activity increase with increasing water activity a_w, because with the help of water activity, the enzyme can make a lot of their food to meet the requirements of their growing. The picture (8.2) is introduced to explain the relationship between water activity and enzyme activity.
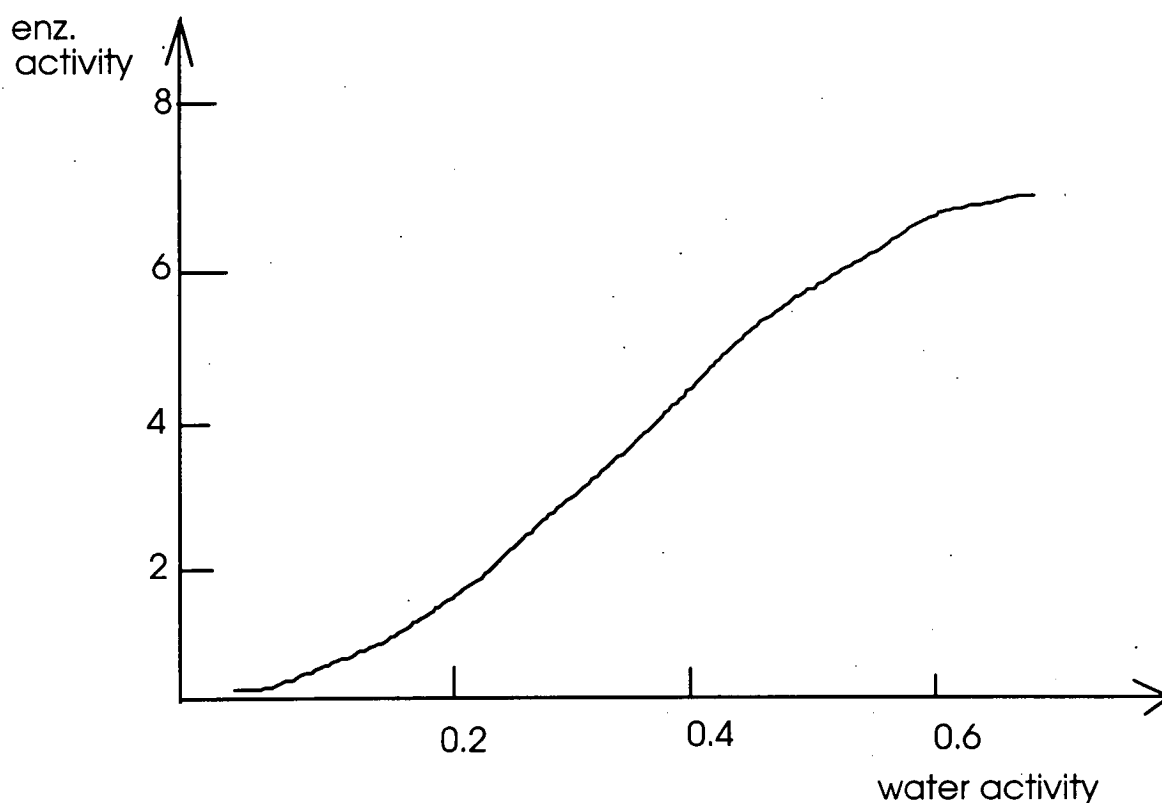
Fig (8.2) Effect of a_w on enzymatic oxidation of sunflower seed oil by lipoxygenase at 25 C°. (Adapted from P 45 in Book ' water activity ').

8.3.4) Conclusion

During drying vegetables, shrinkage, crack and oxidation will influence the appearance, colour, odour and taste, which are very important factors for dried vegetables commercial quantity. They are very complicated physical-chemistry phenomena that are governed by water activity. Drying is a dehydration process. The water activity will have a strong influence on these phenomena. It is clear that for different vegetables there are different influences because the vegetable fabric limits water diffusion during the drying process.

Traditional drying theory is based on the moisture diffusion mechanism. Currently drying theory is developing in the area of bio-chemistry.

8.4) The kiln dryer used in developing Asia countries

In Asian developing countries, such as Burma, Laos, Vietnam, Thailand and China, belong to the tropics. Much tropical fruit, vegetables and grain must be dried before transporting overseas. But electrical energy is scarce and has a high cost which are the problems for these developing countries, and limits the use of electrical dryers in drying industries. At present , the kiln dryer is popular in these areas. Coal, coke, natural gas, marsh gas or timber can be as fuel to supply the kiln dryer. Usually the

kiln dryer construction is divided into two parts: one is the firing room, the another is the air heater.

8.4.1) Firing Room.

In the kiln dryer, the firing room should meet some requirements as follows:

1) It can make suitable fuels burn fully.

2) It can provide enough heat energy to air heater.

3) It can be supplied with different fuels.

4) It has good heat insulation.

5) Its manufacture cost is low, and it can be easily to produced.

In general, the firing room consists of the space of firing room, a room for dust of the fuel and the gate for supporting fuels.

A) Heat Balance in firing room

The equation(8.6) is introduced to explain the heat balance in the firing room.

$$Q_f = Q_d...(8.6)$$

Here: Q_f is the heat energy obtained from fuel firing room.(kJ/hour)

Q_d is the heat energy goes into of the air heater.(kJ/hour)

$$Q_f = Q_1 + Q_2 + Q_3...(8.7)$$

Here: Q_1= the heat energy obtained from firing fuels.(kJ/hour)

Q_2= the enthalpy within air that is blown into the firing room.(kJ/hour)

Q_3=heat energy within fuel due to temperature rising up to the firing temperature.(kJ/hour)

$$Q_1 = \frac{B * Q_u}{3600} * \eta_1...(8.8)$$

Here: η_1 is the heat transfer efficiency of the firing room. Usually, η_1 is about 75%--85%.

B is the fuel amount firing in unite time.(kg)

Q_u is the quantity of heat within a unit fuel (kJ/kg)

$$B = \frac{3600 * Q_w}{Q_u * \eta_d * \eta_1}...(8.9)$$

Here: B= The requirement amount of fuel for drying known wet materials. (kg)

Q_w= The necessary heat energy for drying known wet materials.(kJ/kg)

Q_u= the quantity of heat energy within a unit fuel.(kJ/kg)

η_d= the heat efficiency of the dryer. (%)

η_1=the heat efficiency of the kiln.(%)

$$Q_2 = M_a * h_a ...(8.10)$$

Here: M_a= the air mass blown into the firing room.(kg/s)

h_a = the enthalpy within the air.(kJ/kg)

$$Q_3 = C_f * t_f ...(8.11)$$

Here: C_f= the specific heat within fuel. (kJ/kg C°)

t_f= the firing temperature.(C°)

The heat energy goes out of firing room is explained by equation (8.12).

$$Q_d = Q_g + Q_{\ell 1} + Q_{\ell 2} + Q_{\ell 3} ...(8.13)$$

Here:Q_d= the total heat going out of firing room. (kJ)

Q_g=the heat energy within the smoke.(kJ)

$Q_{\ell 1}$=heat lost due to fuel poorly burning.(kJ)

$Q_{\ell 2}$= heat lost through the wall of the firing room.(kJ)

$Q_{\ell 3}$= heat lost through slag.(kJ)

The heat efficiency is introduced to explaining the performance of the firing room.

$$\eta_r = \frac{Q_g}{Q_d} ...(8.14)\ (\%)$$

From the equation (8.14), it can be understood that complete burring and reducing heat loss through the wall and slag will produce higher heat efficiency. In fact, to reduce the heat lost through the wall, the double layers of wall constructer is employed. Cold air is blown into the gap between the double walls. That means the firing room is used as air heater too.

B) The size of the burning room.

The size of the firing room should be adequate to supply enough amount of oxygen to meet the requirements of firing fuel.

$$V = \frac{B * Q_u}{3600 * k_q} ...(8.15)$$

Here: V= The volume of the firing room. (m³)

B= the amount of necessary fuel. (kg)

Q_u= the quantity of heat within a unite fuel. (kJ/kg)

k_q=The heat transfer efficiency of the firing room. (kJ/m³)

The value of k_q is decided by the method of air passage through the gate, the kind of the fuels and the shape of the gate. The table (8.5) represents some value of k_q.

Table (8.5) the value of k_q (this table is obtained from ' Drying Technology by Hu Jing Zhang, Shen Jing Lin. P151.)

Kind of different fuel	k_q in the drying kiln $(10^3 \, W / m^3)$	k_q in the boiler $(10^3 \, W / m^3)$
anthracite coal	292--350	350--525(the wall is cooled by cooling water)
ordinary coal	233--292	292-522 (the wall is cooled by cooling water)
firewood	233--292	233-292 (fuel is brown coal)
coal gas with fire during firing	233-408	233--408
coal gas without firing during firing	580-1740	580-1740

C) The size of the gate for supporting fuel

$$A_g = \frac{B * Q_u}{3600 * k_g} \quad ...(8.16)$$

hear: A_g= the areas of the gate for supporting fuel.

B= the amount of necessary fuel.

Q_u = the quantity of heat within a unite fuel.

k_g= the heat transfer coefficency (w/m²).

The table (8.6) represents the value of k_g.(this table is from the book' Drying technology by Hu Jing Zhang, Shring Jing Lin. P152)

Table (8.6) the value of k_g.

The kind of different fuel	k_g In natural air $(10^3$ w/m²)	k_g in forced air (590-980 P_a) $(10^3 w / m^2)$
anthracite coal	464-697	930--1164
ordinary coal	464--697	1047--1164
brown coal	233--464	930--1047
firewood	697	
wood slack	350--580	
chaff	233-408	

D) The burning temperature

$$t_a = \eta_a * t...(8.17)$$

Here: t_a is the actual burning temperature.

η_a is the temperature co efficiency that depends on the kind of fuels, burning method and constructor. Normally, η_a=0.65--0.85.

t is the theoretical burning temperature.

$$t = \frac{H_{sa} - 595 * (w_s / 1000)}{C_g + 0.47 * (w_s / 1000)} ...(8.18)$$

Here: H_{sa} = the enthalpy within smoke.(kJ/kg)

w_s = the amount of moisture within smoke.(g/kg)

C_g The specific heat within smoke.(kJ/kg C°) $C_g = 0.24 kJ / kgC^o$.

If the heat loss in the firing room is neglected, the total heat obtained by burning fuel is used to heat air, and the temperature of the smoke air rises to the theory temperature.

$$H_{sa} = \frac{Q_u + C_r t_r + \alpha * M_a * h_a}{M_{sa}} ...(8.19)$$

Here: Q_u = the quantity of heat during burning unite fuel. (kJ/kg).

C_r = the specific heat of fuel (kJ/kg C°)

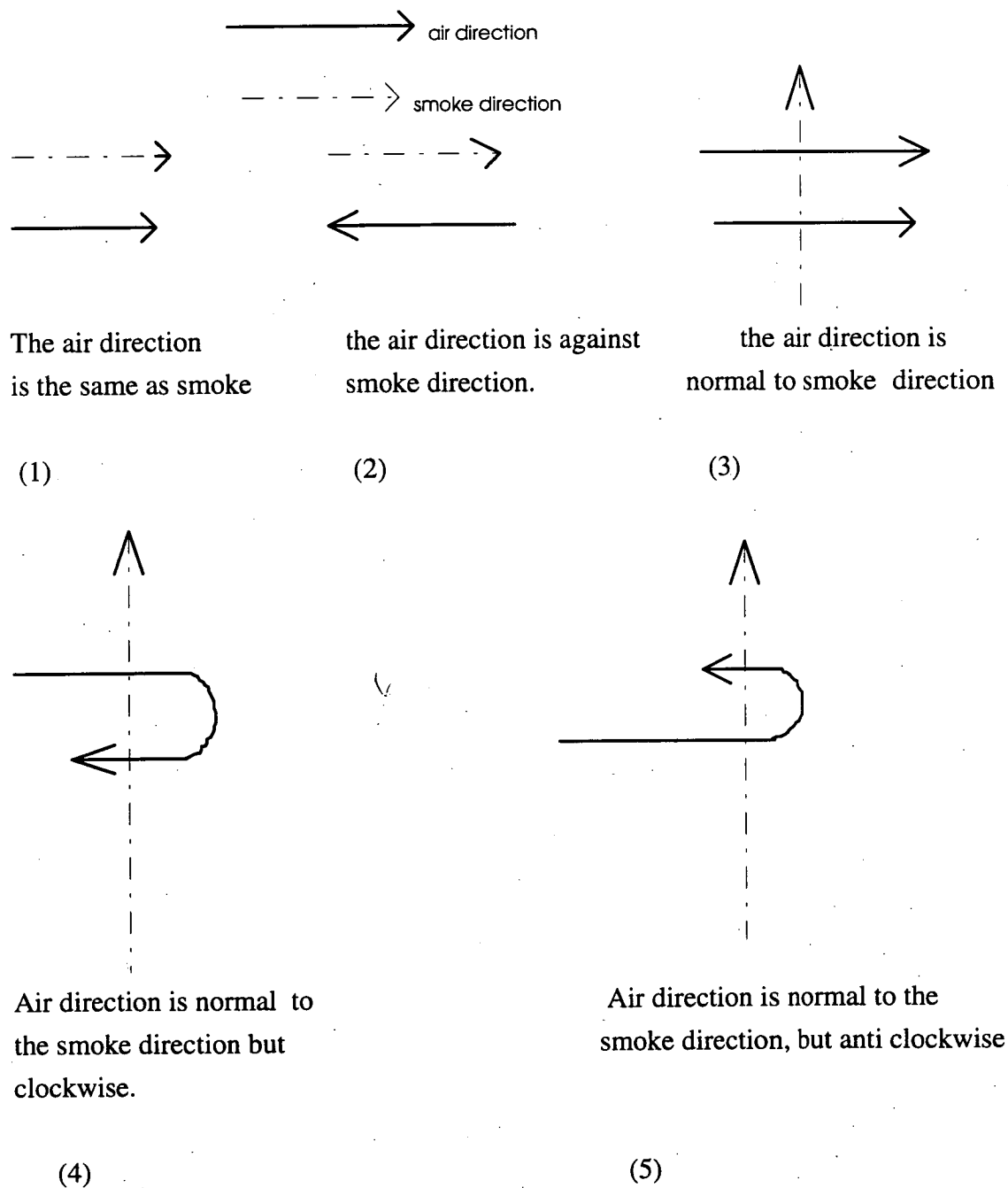t_r fuel temperature before sent into the burning room. (C°).

α = the air coefficency, $\alpha = 1.5$-2;

M_a = the fresh air mass blown into the burning room.(kg)

h_a = the enthalpy within the fresh air . (kJ/kg)

8.4.2) Air heater

In the furnace, an air heater is employed to transfer heat energy from smoke to the cleaning air. Air heater works based on the heat conduction and radiation. In a Chinese furnace, many pipes make the air heater. There are five forms of air heater.

The air direction is the same as smoke

(1)

the air direction is against smoke direction.

(2)

the air direction is normal to smoke direction

(3)

Air direction is normal to the smoke direction but clockwise.

(4)

Air direction is normal to the smoke direction, but anti clockwise

(5)

fig(8.3) air direction within air heater

Comparing these five different air heaters, it can be fond that The form(2) can produce smoke with the higher temperature than that by form(1),because the outlet for cleaning air is the inlet for smoke with highest temperature. There is a large temperature gap between inlet and outlet of air heater. So, some thermal stress and distortion should exist. This kind of air heater requires better materials in its manufacture. Form (1) makes cleaning temperature lower, but the temperature distribution is more uniform than form(2). There is no special requirements for manufacture materials to manufacture the form(1).

In practical design, sometimes two or three forms of air heater are employed in the same air heater to get better heat transfer results. In the furnace, the air heater is different from an electrical air heater, because smoke as the working agent has various temperatures within the air heater. So, the heat transform equation (8.20) is expressed by differentiation.

$$dQ = K_\Sigma * (t_y - t_k) * dA \quad ...(8.20)$$

Here: dQ= the heat energy transferred at the unite area dA. (kJ)

K_Σ= average value of heat transfer co-efficiency through the whole heat transfer. In fact, K_Σ is a variable. In order to simplify calculation, a average value is employed. ($W/m^2 * C°$)

t_y= the initial temperature of working agent.($C°$)

t_k= the initial fresh air temperature at the air heater.($C°$)

dA= the unite heat transfer area. (m^2)

If the difference between t_y and t_k is considered as a constant Δt, the total heat transferred between working agent and fresh air can be expressed by equation (8.21).

$$Q = \int_0^A K_\Sigma * \Delta t * dA \quad ...(8.21)$$
$$= K_\Sigma * \Delta t * A$$

From the equation (8.21), it is very clear that three factors can lead to an increase in the heat transfer energy between the working agent and fresh air.

a) Increasing the heat transfer areas.

b) Increasing the difference between initial temperature of working agent and initial temperature of fresh air.

c) Increasing the heat transfer coefficency of K_Σ.

Usually increasing the heat transfer areas are employed in drying kiln, because it is easy to do. Increasing the difference between initial temperature of working agent and initial temperature of fresh air is usually used too. In practical designing, sometimes the construction of air heater is combined with firing room to get a higher temperature of the working agent. Keeping the air heater at the highest temperature of the kiln and increasing the heat transfer areas at the highest temperature zone are the best way to get higher heat transfer cofficency.

The value of K_Σ depends on the temperature of the working agent and the thermal characters of air heater. The equation (8.22) is introduced to calculate the value of K_Σ.

$$K_\Sigma = \frac{1}{(\frac{1}{a} + \frac{s_b}{\lambda} + \frac{1}{b})} \quad ...(8.22)$$

Here: a= heat conduction co-efficiency between working agent and wall of air heater.(w/m² C°).

s_b= the thickness of wall at air heater.(m)

λ= heat conduction cofficency of the wall of air heater.(w/m* C°)

b= heat conduction co-efficient between cool fresh air and wall of air heater.(W/m² C°).

The equation (8.22) represents the relationship between the value of K_Σ and some thermal characters of working agent , cool air and the wall, but from another corner, the value of K_Σ is also influenced by the speed of the working agent and cooling air. Some author stated that at the higher temperature zone, increasing the speed of cooling fresh air will lead to an increasing the value of K_Σ, but at the lower temperature it isn't obvious for the value of K_Σ to increase with increasing the speed of cooling air. (P 166 ' Drying technology ' by Hu Jing Ling, Shen Jing Zhang).

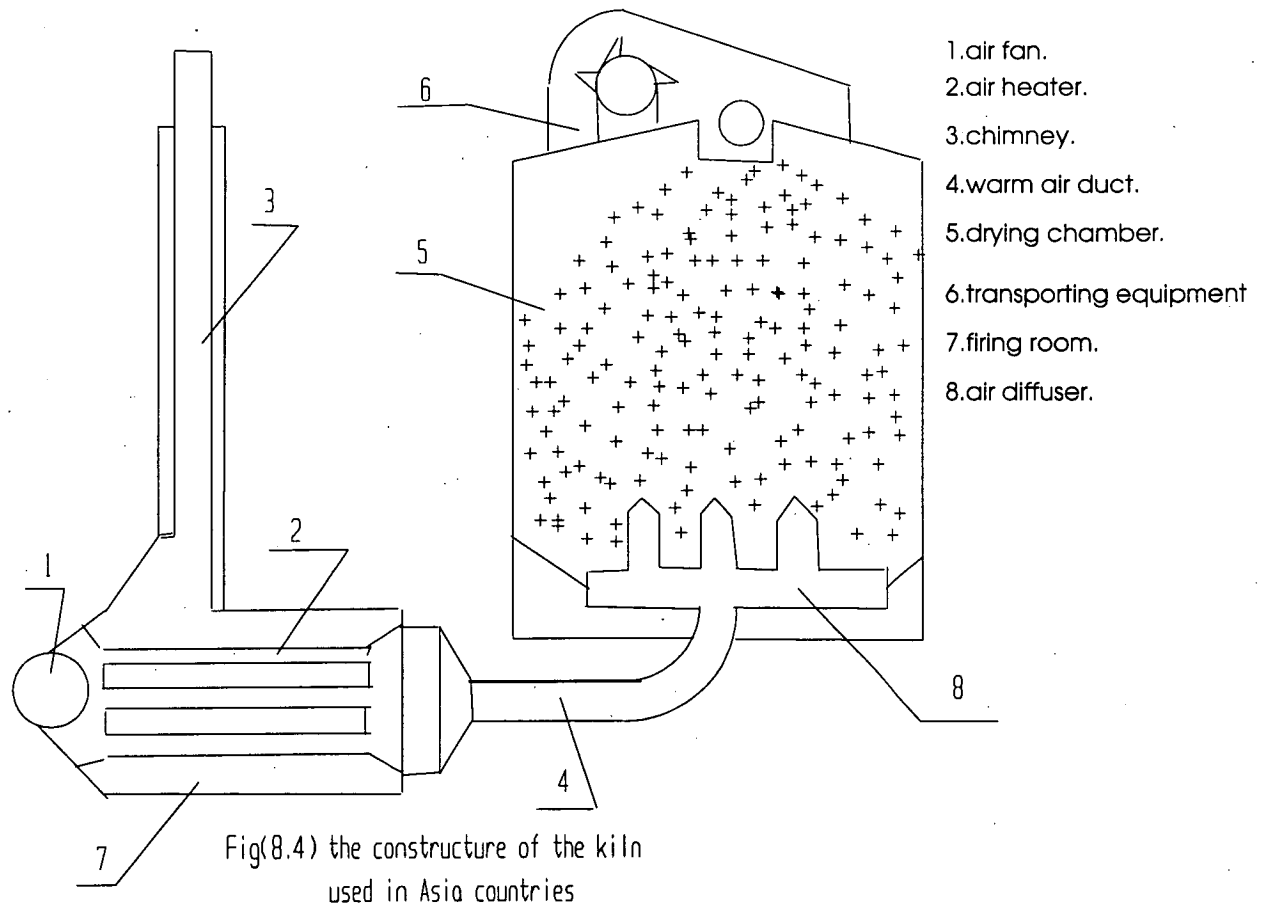## 8.4.3) The construct of the kiln used in Asia developing countries.

A) The advantages

a) Lower manufacture cost.

b) Higher heat transfer cofficency. Usually the heat transfer efficient can get to 60%-70%.(heat transfer of electricity heater is nearly 80%).

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c) Simple Construction. Usually the construction of air heater is combined with firing room.

The picture (8.4) represent the constructer of the typical kiln used in Asia countries.

1.air fan.
2.air heater.
3.chimney.
4.warm air duct.
5.drying chamber.
6.transporting equipment
7.firing room.
8.air diffuser.

Fig(8.4) the constructure of the kiln used in Asia countries

B) The shortcoming of Asia Kiln dryer

The typical shortcoming for the Asia kiln dryer is pollution, which can be divided into two kinds of pollution. One is the pollution of the working environment due to firing fuel. Another is the pollution of dried materials due to air heater breakdown, where smoke as the working agent goes into the cleaning fresh cool air, which is hard to detect in time during drying process. When this kiln dryer is employed for drying agricultural products and food, a few sensors to detect the ingredients of warm air are installed   in drying chamber   to monitor the contamination of warm air, but the introduction of the sensor will increase the manufacture and operation cost.

From design view, in order to overcome the contamination of clean air at the air heater, the pressure of clean cool air should be higher than that of the smoke. A suction system of clean cool air with negative pressure is instead by a blowing system

with positive pressure. At the connection places of the air heater where it is easily to make the smoke go into the pipe of clean air. Manufactures should use special materials to seal the connection places. Within the chimney, aluminimzation is used to protect the wall from oxidation due to high temperature.

In order to overcoming the pollution for environments the cyclone is introduced to collect the dust from the smoke.

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Chapter 9
Conclusion
9.1Introduction

Drying technology is the very important applied science, which strongly influence on our daily living. Looking back the human being history, we can find drying science connected with the human being society progress. For example, when primary human been understood to dry plants under the sun in order to store them as winter food, the human being society jumped the big step. Although today the world faces with the 21 centuries, the food shortcoming still exists in some developing countries. Developing drying technology will push the Food engineering and Agricultural engineering.

9.2) Factors and trends affecting the drying pyrethrum
9.2.1) Heat and Mass transfer within the wet pyrethrum

As discussed before, the heat and mass transfer process is the control factor during any drying process. It is clear that heat and mass transfer should take place within the warm moisture air and within the bulk of wet materials and inside wet materials. With the help of the psychrometric theory and Fick's law, the heat and mass transfer within the moisture air can be explained perfectly. The mathematical model of heat and mass transfer between warm air and wet pyrethrum has been set up to discussing how to get better heat energy efficiency in the drying chamber.

Heat and Mass transfer process within the bulk of wet materials and inside the wet materials are discussed too, because the resistance for heat and mass transfer is mainly from the wet materials, not from the warm air, which will govern the drying heat efficiency.

Pyrethrum belongs to the porous plants. The porous plants drying properties and heat and mass transfer feature have been discussed too in order to design the dryer well.

In industry drying, high density drying with high heat efficiency and with top dried products is the direction of drying technology. In order to improve the heat efficiency, some different technology are employed. For example, the multiple transporting belts are employed in the drying chamber. In fact, recycle warm air technology, stages drying and setting cooling period will improve the heat transfer efficiency and the quality of the dried products.

9.2.2) The relationship between drying process and enzyme action

When drying plants, enzyme activity more or less influence the quality of the dried products, especially influences on the colour, smell, and taste. It is known that enzyme action is controlled by these factors as follows:

a) Concentration of enzyme.

b) Concentration of substrate.

c) Time.

d) Temperature.

e) pH.

f) Presence or absence of activities or inhibitors.

g) Moisture.

It is clear that the temperature and moisture of the wet materials are the most importance factors among them, because the other factors will be changing continuously due to moisture and temperature changing.

In the paper, some relationship between water activity and enzyme has been analysed. During drying pyrethrum, it is necessary to adjust drying temperature in order to control evaporation rate and to impede the enzyme to action.

It is obvious that setting the accurate mathematical models to discussing the relationship between water activity, drying temperature and enzyme activities necessary further to do research, which should be based on the bio-chemistry and machines technology.

9.2.3) Fragmentation

The crack should be another problems due to transporting pyrethrum and return them in the drying chamber, which will pollute the working environments. As above discussed, the crack is induced by thermal stress due to un-uniform heating. So, uniformly loading wet pyrethrum and blowing warm air uniformly are the key factors to overcome the fragmentation of pyrethrum.

9.3) Suggestions

a)The heat and mass transfer mathematical model is fundamental of drying porous plants. During drying plants, the changing of porosity and its influence on heat and mass transfer is very complicated problems. In future its resolve will push the drying theory developing.

b) The Oxidation with or without enzyme is the big problem during drying porous plants. Further developing accurate mathematical model to discussing this problem will improve the drying quality of agricultural products.

c) In order to improve the drying efficiency, the large scale drying equipment should be used instead the small dryers.

Appendix

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