

## **5. ENERGY CONSERVATION IN THE CHEMICAL INDUSTRY**



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### 5.1 Characteristics of Energy Consumption in the Chemical Industry

The chemical industry utilizes a change in quality, namely, chemical reaction in processing raw materials in major production processes. Moreover, physical and chemical treatment processes for pretreatment of raw materials, separation of products, purification, etc. are added to complete one production train, which is called "Process Industry".

Since few operations of each equipment in a chemical plant are generally performed at almost atmospheric temperatures and there are very many processes involving heating and cooling of raw material and intermediate products, etc., much energy is consumed. It leads to rationalization in the use of energy to select the optimum temperature, pressure and concentration, etc. to ensure the highest efficiency in each operation, and to recover as much sensible and latent heat as possible during heating and cooling for effective utilization.

In the chemical industry where fluids such as gases and liquids are, in many cases, used as raw materials, heat exchange and heat transfer are easier than in the other industries utilizing solids. Therefore, optimization of heat transfer operation allows designing of an excellent process in terms of heat efficiency.

Taking the case of an ethylene plant, a raw material, naphtha, is cracked at a temperature of 800 to 850 °C to manufacture ethylene and as much thermal energy as  $6 \times 10^8$  kcal per ton of ethylene is required. Taking the case of the ethylene plant which is striving for energy conservation, cracked gas and cracked fuel oil which are produced in this plant are used as fuel for the cracker and high temperature gas from the cracker provides waste heat boilers with heat in the quenching process to recover steam with different temperatures and pressures. This recovered steam is utilized separately for power, for reaction, and for heating according to the respective temperature and pressure. As a result, 17 % of the heat input to the cracker is used for cracking reaction and after that, 68 % is recovered: cooling loss and exhaust loss from the stack are only 15 %.

It is difficult to discuss energy conservation in chemical industries uniformly, because production processes and use of energy are respectively peculiar to the product and raw material used. However, a similar equipment in which so-called unit operation is performed is, in most cases, used in spite of different processes and there are many points in common also in the use of energy. Hence, this report will select and discuss several typical unit operation in use for chemical industries.

## 5.2 Rationalization in the Use of Thermal Energy

### 5.2.1 Combustion Equipment

#### (1) Fuel

##### a. Gaseous fuel

The typical gaseous fuel used for industrial purposes is natural gas. It generally has methane for its main component (88 to 99 %), the calorific value being 8,000 to 11,000 kcal/m<sup>3</sup><sub>N</sub>.

##### b. Solid fuel

Lignite and coal are mostly used industrially and have calorific values of 1,500 to 4,500 kcal/kg and 4,500 to 7,500 kcal/kg respectively. Their properties and composition greatly vary according to their places of origin.

##### c. Liquid fuel

Liquid fuel is generally of petroleum fuel, and represented by diesel oil or gas oil, and fuel oils. Since fuel oil contains sulfur, the combustion gas usually contains 0.1 to 0.25 % SO<sub>2</sub> and further 1 to 5 % of such SO<sub>2</sub> is converted into SO<sub>3</sub>, causing corrosion.

##### d. Calorific value

###### 1) Solid and liquid fuels

When carbon, hydrogen, sulfur, oxygen, moisture and nitrogen contents in 1 kg fuel are represented by c, h, s, o, and w (kg), higher calorific value is shown by the following formula approximately.

$$\text{Higher calorific value, } H_h = 8,100c + 34,500 (h - o/8) + 2,500 s \text{ kcal/kg}$$

A lower calorific value is obtained by subtracting the condensation heat value of vapor contained in a combustion gas from a higher calorific value. Its relationship to the total calorific value is expressed in the following formula.

$$\text{Lower calorific value, } H_l = H_h - 600 (9h + w) \text{ kcal/kg}$$

2) Calorific value of gaseous fuel

When combustible components contained in  $1 \text{ m}^3_{\text{N}}$  fuel for example,  $\text{CH}_4$  and  $\text{H}_2$  are represented by  $c\text{H}_4$  and  $h_2$  ( $\text{m}^3_{\text{N}}$ ) respectively,

$$\text{Higher calorific value, Hh} = 3,055 \cdot c\text{o} + 3,036 \cdot h_2 + 9,498 \cdot c\text{H}_4 + 14,982 \cdot c_2\text{H}_2 + 35,702 \cdot c_6\text{H}_6 \text{ kcal/m}^3_{\text{N}}$$

$$\text{Lower calorific value, Hl} = \text{Hh} - 600 (18/22.4) (h_2 + 2 c\text{H}_4 + 2 c_2\text{H}_2 + c_2\text{H}_2 + 3 c_6\text{H}_6) \text{ kcal/m}^3_{\text{N}}$$

e. Air ratio and volume of combustion gas

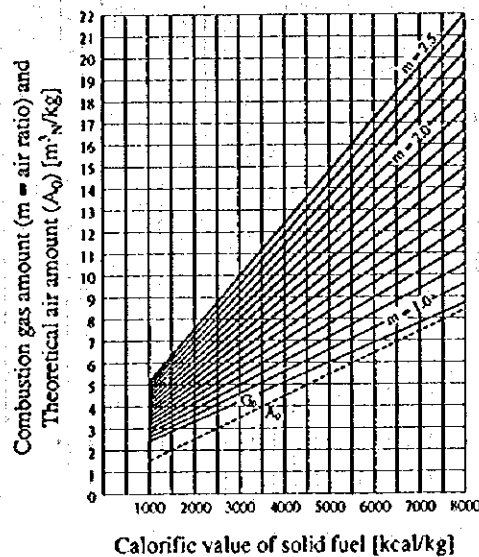
Ratio of  $A_a$ , actual volume of air used for combustion to  $A_o$ , volume of theoretical combustion air ( $A_a/A_o$ ) is called air ratio ( $m$ ) and is represented by the following equation:

$$m = \frac{21 (N_2)}{21 (N_2) - 79 [(O_2) - 0.5 (CO)]}$$

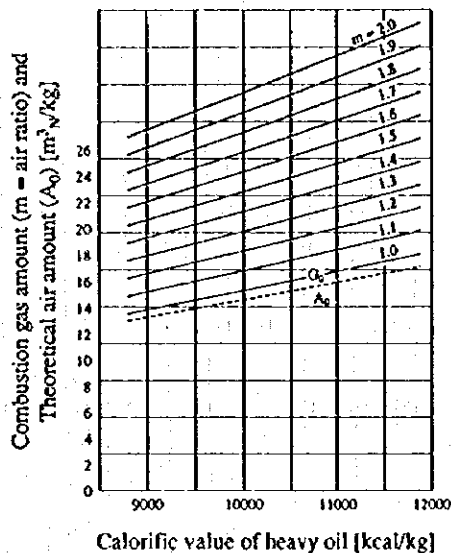
where  $(CO)$ ,  $(O_2)$  and  $(N_2)$  indicate in Vol.%  $CO$ ,  $O_2$  and  $N_2$  contained in dry combustion gas respectively.

Figure 5.1 to Figure 5.3 show relations between calorific values of solid, liquid and gaseous fuels against volume of air and combustion gas at various air ratios.

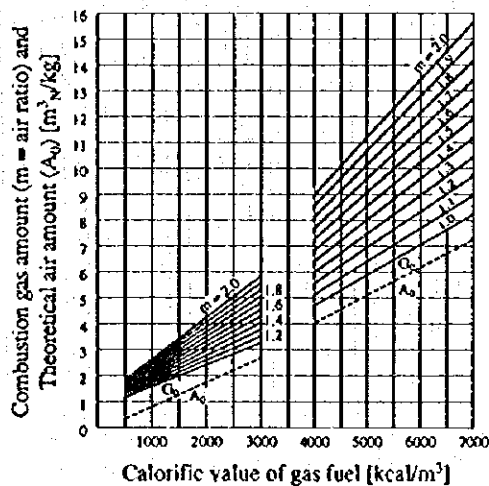
Figure 5.1 Relation between Low Calorific Value of Solid Fuel and Combustion Gas Amount, and Theoretical Air Amount



**Figure 5.2 Relation between Low Calorific Value of Liquid Fuel and Combustion Gas Amount, and Theoretical Air Amount**



**Figure 5.3 Relation between Low Calorific Value of Gas Fuel and Combustion Gas Amount, and Theoretical Air Amount**



(2) Heat Balance and Thermal Efficiency

Heat balance is prepared to make an important guideline on a basis of which the degree of rationalization in the use of energy is judged, through investigation of the heat energy provided to the combustion equipment and of its state of use in order to clarify the relation between heat input and output.

To calculate the heat balance,

- ① Properties of the used fuel
- ② Fuel consumption
- ③ Temperature of air
- ④ Composition of combustion products
- ⑤ Temperature of flue gas
- ⑥ Amount and temperature of heated matters
- ⑦ Amount and composition of unburnt matters
- ⑧ Chemical reaction in heated matters, etc. on a basis of which the following calculations are made:

- Heat input

Heat content retained by fuel

$$(Q \times F) + (F \times C_{pf} \times \Delta t)$$

Sensible heat of air

$$V \times C_{pv} \times \Delta t$$

Heat content carried in by heated matters

$$M \times C_{pm} \times \Delta t$$

Heat input due to chemical changes

$$H \times M$$

- Heat output

Heat content carried out by heated matters

$$M \times C_{pm} \times \Delta t$$

Heat content carried out by combustion exhaust gas

$$(E \times C_{pe} \times \Delta t) + (S \times C_{ps} \times \Delta t) + 600 S \text{ (when based on higher calorific value)}$$

Heat loss due to incomplete combustion

$$(B \times \frac{CO}{100} \times 3,050 \times F) + (8,100 \times (\text{amount of soot}))$$

Heat loss due to unburnt matters in combustion residue

$$F \times 8,100 \times \frac{an}{1-n}$$

Heat loss due to radiation, conduction, etc.

$$(h_c + h_r) (\Delta t) (A)$$

For  $h_c$ , refer to item "Basic Calculation of Heat Transfer" as mentioned later.

$$h_r = 4.88 [(T_o/100)^4 - (T_a/100)^4], \epsilon/\Delta t \frac{\lambda (T_i - T_o)}{\ell} \cdot A$$

Clarifying the heat balance in combustion equipment will tell how much of the given heat is used for the heating for which it is intended and how much is lost. How much of any given total heat is effectively used is expressed by "Thermal Efficiency": that against total heat input is thermal efficiency against total heat input; and that against fuel calorific value is thermal efficiency against fuel calorific value. Since thermal efficiency varies depending on which item is regarded as effective heat capacity, it is necessary to define the effective heat of each combustion equipment beforehand.

(Symbols)

F	: Fuel consumption	[kg/h]
Q	: Fuel calorific value	[kcal/kg]
H	: Heat of reaction	[kcal/kg]
M	: Amount of heated matters (input)	[kg/h]
W	: Amount of heated matters (output)	[kg/h]
E	: Amount of dry exhaust gas	[m <sup>3</sup> /h]
S	: Amount of water vapor in exhaust gas	[kg/h]
A	: Radiating area	[m <sup>2</sup> ]
V	: Amount of air	[m <sup>3</sup> /h]
T <sub>i</sub> , T <sub>o</sub> , T <sub>a</sub>	: Furnace temperature, furnace external wall temperature, ambient temperature	[K]
Δt	: Temperature difference with ambient temperature	[°C]
ℓ	: Thickness of furnace wall	[m]
C <sub>p</sub>	: Specific heat at constant pressure and the subscripts of f, v, m, w, e, and s indicate a value of fuel, air, heated matters (input), heated matters (output), dry exhaust gas, steam in exhaust gas respectively.	
(CO)	: Vol.% of CO in exhaust gas	
h <sub>r</sub>	: Radiation heat transfer coefficient	[kcal/m <sup>2</sup> h°C]
h <sub>c</sub>	: Convection heat transfer coefficient	[kcal/m <sup>2</sup> h°C]
λ	: Thermal conductivity of furnace wall material	[kcal/mh°C]
a	: Ash content in 1 kg fuel	[kg]
n	: Carbon content in 1 kg combustion residue	[kg]
	: Emissivity of wall surface	[kg]



### (3) Rationalization in the Use of Thermal Energy in Combustion Equipment

#### a. Reduction in air ratio

Heat carried out by combustion exhaust gas is greatly influenced by the volume of exhaust gas as mentioned in item (2), which is directly related to the air ratio. Heat loss due to the exhaust gas increases linearly with increase in the air ratio as shown in Figure 5.4 and Figure 5.5. Therefore, the less the air ratio is, the less heat loss ought to be. Since, however, heat loss due to incomplete combustion takes place when the air ratio is less than 1.01, the maximum value for thermal efficiency exists while the air ratio is between 1.02 and 1.10 (Figure 5.5)

Figure 5.4 Relation between Air Ratio and Waste Gas Loss

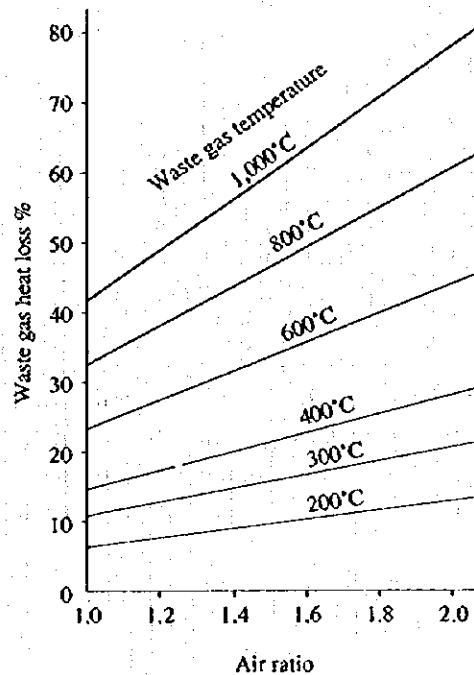
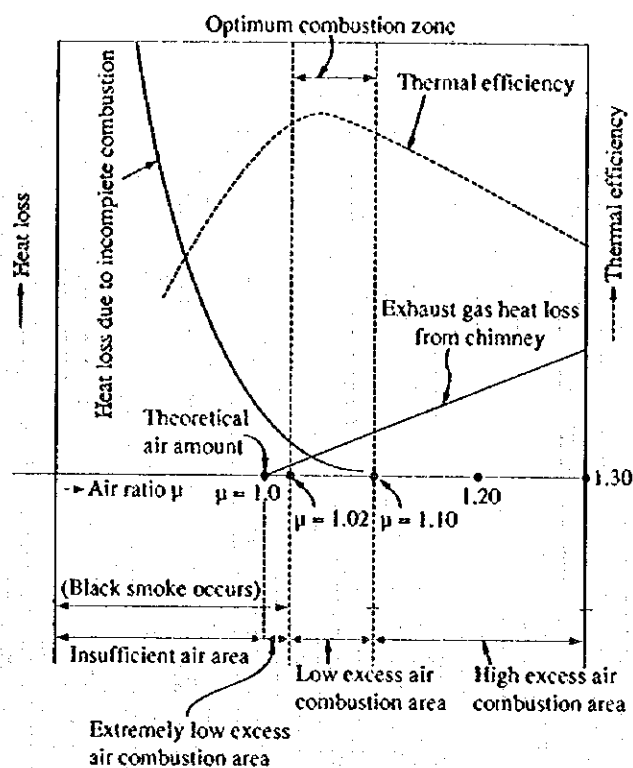


Figure 5.5 Relation between Air Ratio and Thermal Efficiency



However, at the general combustion equipment, the load usually fluctuates and, incomplete combustion may generate black smoke due to a low air ratio in the process of changes in the fuel amount. Therefore, the equipment should be, in fact, operated at an air ratio of approximately 1.2 to 1.3, including some allowance. (Table 5.1)

Table 5.1 Standard Air Ratio

Classification	Standard air ratio
Melting furnace for metal casting	1.30
Continuous billet reheating furnace	1.25
Continuous heat treating furnace	1.25
Petroleum heating furnace	1.25
Thermal decomposition furnace and reforming furnace	1.25
Cement kiln	1.3
Lime kiln	1.3
Continuous glass melting furnace	1.3

Recently, air and fuel flow rates are individually and directly measured and cross-limit type automatic control by means of a computer is performed so that the specified air ratio is always maintained even during fluctuation in load. Thus, it becomes possible to keep the air ratio at 1.02 to 1.10 at all times, resulting in a high energy conservation effect.

Since the air ratio at such a low level as this may cause locally incomplete combustion during minor load fluctuation, also a CO meter is, in some cases, used together for control.

#### b. Recovery of Waste Heat

When the temperature of exhaust gas at the furnace outlet is 1,000 °C even at an air ratio of 1.2, the exhaust gas loss is close to 50 %. This indicates that energy conservation of combustion equipment depends on recovery of heat in the exhaust gas.

##### 1) Preheating of raw material

Since raw material is usually charged at normal temperatures, a preheating chamber is provided at the material charging place and exhaust gas is introduced here to heat the raw material. Suspension preheater systems in cement plants are a good example of this method. (Figure 5.6)

##### 2) Preheating of combustion air

When temperature of combustion air is raised by the use of a heat exchanger, the used amount of fuel will decrease as can be seen from the heat balance. As one example, air preheating temperature and fuel economy rate at air ratio of 1.3 are shown in Figure 5.7. Here, corrosion due to sulfur contained in fuel should be paid attention to. Sulfur is in the form of  $\text{SO}_2$  in the exhaust gas, and a portion of such  $\text{SO}_2$  is converted into  $\text{SO}_3$ .  $\text{SO}_3$  further combines with water vapor in the combustion gas into sulfuric acid vapor, which reaches the dew point at low temperature walls to liquefy, corroding the heat exchanger. The dew point temperature, which is influenced by the concentration of S content in the fuel, is difficult to clarify theoretically and determined empirically. It is generally said to be 110 to 160 °C for fuel oil combustion. (Refer to the item for Boiler in a later section.)

Figure 5.6 New Suspension Preheater System Cement Plant

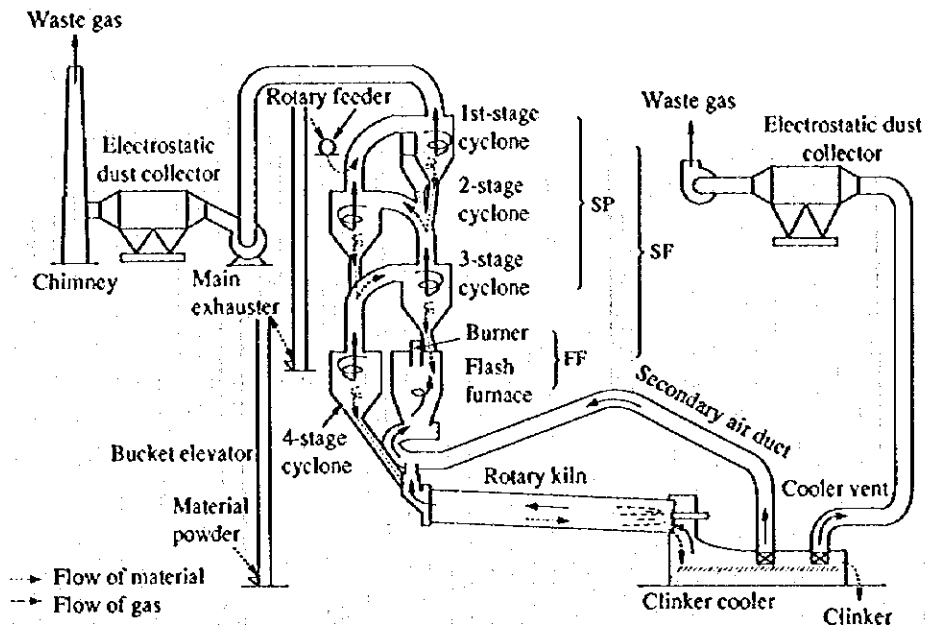
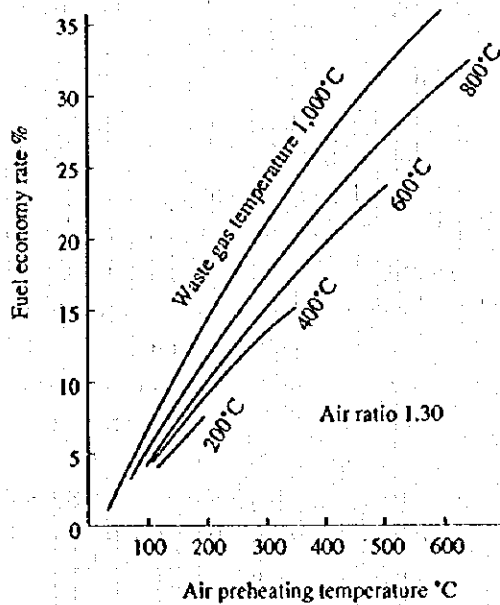


Figure 5.7 Fuel Economy due to Air Preheating



### 3) Utilization as other heating source

If sensible heat of the exhaust gas is suitable in heat content, temperature range, etc. for heating source of other equipment and it is located near the other equipment, the utilization should be considered. Also, if there is a demand for steam in the factory, it is advisable to install a waste heat boiler and utilize sensible heat of the exhaust gas for steam generation.

### c. Utilization of Sensible Heat of Heated Matters

Heated matters from combustion equipment are at high temperature, and as such they, except as subsequently treated in the next process, generally are cooled to ambient temperature or mostly quenched to prevent side reaction. In such a case, the sensible heat of heated matters should be recovered for effective utilization. Good examples of use include utilization of clinker cooling air as primary combustion air in cement plants (see Figure 5.6); a waste heat boiler for quenching gas at the outlet of the cracking furnace in ethylene plants; heat recovery to the fuel oil for the reheating furnace in the lubricating oil manufacturing process (Gulfinning process; hydro-refining process) (see Figure 5.8).



## 5.2.2 Heat Transfer Equipment

### (1) Basic Calculation of Heat Transfer

When there is a temperature difference between two objects, movement of heat (heat transfer) occurs, a mechanism of which is classified into the following three:

- Heat transfer by conduction
- Heat transfer by convection
- Heat transfer by radiation

Since heat transfer practically occurs under mechanism of combination of these three, it will be extremely complicated if precise calculations are made. However, the calculations can be, in most cases, simplified by the use of approximation or simplification of phenomena. Equations under the respective mechanism are described below:

#### a. Heat transfer by conduction

When the temperature at each portion does not vary according to time, namely, under a steady state, it is described.

##### 1) In the case of plane

When  $n$  sheets of plates lie one upon another, heat flow,  $Q$  transferring through these plates is:

$$Q = A_0 \cdot \Delta t \sum_{j=1}^n (\ell_j / \lambda_j) \quad (\text{kcal/h})$$

where  $A_0$ : Area of a surface perpendicular to the direction of heat transfer ( $\text{m}^2$ )

$\Delta t$ : Temperature difference between low and high temperature surfaces ( $^{\circ}\text{C}$ )

$\ell$ : Thickness of plate (m)

$\lambda$ : Heat conductivity of plate ( $\text{kcal/mh}^{\circ}\text{C}$ )

Assuming  $(\ell_j / \lambda_j) = R$ ,  $R$  may be called heat resistance.

##### 2) In the case of cylindrical surface

Using the same symbols as item a.

$$Q = 2\pi \Delta t \cdot L \sum_{j=1}^n \left[ \frac{1}{\lambda_j} \cdot \ell n(r_{j+1}/r_j) \right] \quad (\text{kcal/h})$$

where  $L$  : length of cylinder (m)

$r_j, r_{j+1}$ : Inside and outside diameters of  $j$ th layer (from inside) (m)

b. Heat transfer by convection

This involves various conditions such as specification of fluid, flow condition, shape of object, aspect of change in fluid phase, etc., for each of which theoretical equations and empirical formulae are individually made.

1) Mean heat transfer coefficient,  $\alpha_m$  in natural convection when the fluid is air.

i) In the case of plate

Convection from lower surface

$$\alpha_m = 1.13 (\Delta t/l)^{1/4} \quad (\text{kcal/m}^2\text{h}^\circ\text{C})$$

$$3 \times 10^5 < Gr \cdot Pr < 3 \times 10^{10}$$

Note: Refer to Table 5.2.

where  $\Delta t$ : Temperature difference ( $^\circ\text{C}$ )

$l$  : Representative length of plane (m)

Gr: Grashof number

Pr: Prandtl number

Convection from upper surface

$$\alpha_m = 2.27 (\Delta t/l)^{1/4} \quad (\text{kcal/m}^2\text{h}^\circ\text{C})$$

$$10^5 < Gr \cdot Pr < 2 \times 10^7$$

$$\alpha_m = 0.831 (\Delta t)^{1/3} \quad (\text{kcal/m}^2\text{h}^\circ\text{C})$$

$$2 \times 10^7 < Gr \cdot Pr < 3 \times 10^{10}$$

Convection from vertical surface

$$\alpha_m = 1.22 (\Delta t/H)^{1/4} \quad (\text{kcal/m}^2\text{h}^\circ\text{C})$$

$$10^4 < Gr \cdot Pr < 10^9$$

$$\alpha_m = 1.13 (\Delta t)^{1/3} \quad (\text{kcal/m}^2\text{h}^\circ\text{C})$$

$$10^9 < Gr \cdot Pr < 10^{12}$$

where H: Height of vertical surface

In addition, more simplified value equations may be employed.

Convection from the lower surface

$$\alpha_m = 1.5 \Delta t^{1/4}$$

Convection from the upper surface



$$\alpha_m = 2.8 \Delta t^{1/4}$$

Convection from the vertical surface

$$\alpha_m = 2.2 \Delta t^{1/4}$$

ii) In the case of horizontal pipe

$$\alpha_m = 1.14 (\Delta t/\Delta)^{1/4} \text{ (kcal/m}^2\text{h}^\circ\text{C)} \quad 10^4 < \text{Gr} \cdot \text{Pr} < 10^9$$

$$\alpha_m = 1.07 (\Delta t)^{1/3} \text{ (kcal/m}^2\text{h}^\circ\text{C)} \quad 10^9 < \text{Gr} \cdot \text{Pr} < 10^{12}$$

$$\alpha_m = 0.4 (\lambda/D) \text{ (When } D \text{ is small) (kcal/m}^2\text{h}^\circ\text{C)} \quad \text{Gr} \cdot \text{Pr} < 10^5$$

when D: Outside diameter of pipe (m)

Table 5.2 Dimensionless Terms Related to Heat Transfer

Name	Equation	Abbreviation
Nusselt number	$\alpha D/k$	Nu
Reynolds number	$D\bar{u}/\nu$	Re
Prandtl number	$C_p\mu/\lambda$	Pr
Grashof number	$(D^3g/\nu^2) (\beta t)$	Gr

Note:  $C_p$ : Specific heat at constant pressure

D: Diameter or representative length

$\Delta t$ : Temperature difference

u: Average velocity of flow

g: Gravitational acceleration

$\lambda$ : Heat conductivity

$\mu$ : Viscosity     $\rho$ : Density     $\nu = \mu/\rho$ : Kinetic viscosity

$\beta$ : Coefficient of thermal expansion

2) Heat transfer coefficient,  $\alpha$  in forced convection

i) Inside heat transfer coefficient

$$\alpha D/\lambda = 0.027(\text{Re})^{0.8} (\text{Pr})^{1/3} (\eta/\eta_w)^{0.14}$$

where D : Inside diameter of pipe (m)

$\eta$  : Viscosity of fluid

$\eta_w$  : Viscosity of fluid at tube wall temperature

ii) Outside heat transfer coefficient

$$\alpha D/\lambda = C \cdot (\text{Re})^m \times 1.11 \cdot (\text{Pr})^{0.31}$$

where D: Outside diameter of pipe (m)

C and m vary according to values of Re, as follows:

Re	C	m
$4 \times 10^{-1}$ to 4	0.891	0.330
4 to $4 \times 10$	0.821	0.385
$4 \times 10$ to $4 \times 10^3$	0.615	0.466
$4 \times 10^3$ to $4 \times 10^4$	0.174	0.618
$4 \times 10^4$ to $4 \times 10^5$	0.0239	0.805

c. Heat transfer by radiation

Heat flux, Q radiated around from an object at a temperature of T (K) is represented by the following equation:

$$Q = 4.88 \epsilon \cdot A \cdot (T/100)^4 \quad (\text{kcal/h})$$

where  $\epsilon$  : Emissivity of object

A: Surface area of object ( $\text{m}^2$ )

Heat flux, Q transferred between two objects at different temperatures (1, 2) is represented by the following equation:

$$Q = A_1 F_{12} \left( \frac{4.88}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1} \right) [(T_1/100)^4 - (T_2/100)^4] \quad (\text{kcal/h})$$

where  $A_1$  : Radiation area of object 1 ( $\text{m}^2$ )

$F_{12}$  : Coefficient determined by relative position of object (View factor)

$T_1, T_2$ : Respective temperatures (K)

$\epsilon_1, \epsilon_2$  : Respective emissivity

Radiation heat to wide space can be approximated in the following equation:

$$Q = A \cdot 4.88 \cdot \epsilon [(T_1/100)^4 - (T_0/100)^4] \quad (\text{kcal/h})$$

where  $T_1, T_0$ : Temperatures (K) of object and ambient respectively

d. Calculation example of heat transfer composed of three modes of heat transfer

Taking the case of heat transfer from lower plane surface of equipment to atmosphere, it is described.

Heat flow,  $Q$  = Conduction heat transfer through equipment wall

$$Q_k = \text{Convection heat transfer } Q_c + \text{radiation heat transfer } Q_r \dots\dots\dots (1)$$

Treating temperatures within the equipment, on its surface and of atmosphere as  $t_i$  (°C),  $t_w$  (°C) and  $t_o$  (°C) respectively,

$$Q_k = A \cdot (t_i - t_w) \sum_{j=1}^n (\ell_j / \lambda_j) \dots\dots\dots (2)$$

$$Q_c = 1.13 \left( \frac{t_w - t_o}{\ell} \right)^{1/4} \cdot A \cdot (t_w - t_o) \dots\dots\dots (3)$$

$$Q_r = 4.88 \epsilon \left[ \left( \frac{t_w + 273}{100} \right)^4 - \left( \frac{t_o + 273}{100} \right)^4 \right] \cdot A \dots\dots\dots (4)$$

If  $t_w$  is determined by solving the equation which is obtained by substituting equations (2) to (4) for equation (1), the heat flow can be calculated.

(2) Heat Transfer Calculation of Heat Exchanger

a. Overall heat transfer coefficient

Heat transfer coefficient through wall of single tube is expressed by overall heat transfer coefficient,  $U_o$  based on the outside diameter in the following equation, combining heat resistance of the tube wall and dirt thereto and inside and outside convection heat transfer coefficient.

$$1/U_o = (1/h_i) (D/D_o) + 1/h_o + (x/\lambda) (D/D_m) + R_i (D/D_o) + R_o$$

- where  $h_i$  : Inside tube convection heat transfer coefficient
- $h_o$  : Outside tube convection heat transfer coefficient
- $D_i$  : Inside diameter of tube
- $D_o$  : Outside diameter of tube
- $D_m$  : Mean diameter of tube
- $x$  : Thickness of tube wall
- $\lambda$  : Heat conductivity of tube wall
- $R_i$  : Inside fouling factor
- $R_o$  : Outside fouling factor

Since the fouling factor depends on type of fluid, temperature, fluid velocity, and the degree of cleaning, it is difficult to discuss generally. For reference, an example of various fouling factor is shown in Table 5.3. Heat transfer is greatly influenced by the degree and frequency of cleaning of the heat exchanger. Therefore, maintenance of the heat exchanger has a great influence on energy conservation.

In multitubular heat exchangers, the overall heat transfer coefficient calculated as a single tube cannot be used as-is, but there is another equation with somewhat modification and also correction is required.

The correction is determined by the layout of tubes, the number of arrangements, the flow direction, etc. and is complicated. Here, the description is omitted and actual examples of overall heat transfer coefficient are shown in Table 5.4.

**Table 5.3 Fouling Factor (m<sup>2</sup>h-c/kcal)**

(a) Fouling factor for water				
Temperature of high temperature fluid (°C)	Up to 115		115 to 205	
Water temperature (°C)	52 or below		52 or above	
Velocity of flow of water (m/sec)	1 or below	1 or above	1 or below	1 or above
Sea water	0.0001	0.0001	0.0002	0.0002
Service water, well water, cooling tower water, large lake, engine jacket, softened boiler feed water	0.0002	0.0002	0.0004	0.0004
Distilled water	0.0001	0.0001	0.0001	0.0001
Hard water (15 grains/gal or more)	0.0006	0.0006	0.001	0.001
River water (average)	0.0006	0.0004	0.0008	0.0006

(b) Fouling factor for various fluids				
Oil		Gas, vapor		Liquid
Fuel oil	0.001	Organic matter vapor	0.0001	
Machine oil		Steam (containing no oil)	0.0001	Organic matter liquid
Transformer oil	0.0002	Alcohol vapor		Refrigerant liquid
Clean circulating oil		Steam (containing oil)	0.0002	0.0002
Quenching oil	0.0008	Refrigerant vapor		Brine (for cooling)
Vegetable oil	0.0006	Air	0.0004	

**Table 5.4 Overall Coefficient of Heat Transfer of Multi-tube Heat Exchangers**

Service condition	High temperature fluid	Low temperature fluid	Overall coefficient of heat transfer (kcal/m <sup>2</sup> ·hr·°C)
Cooler	Water	Water	1,200-2,500 *1
	Methanol	"	1,200-2,500 *1
	Ammonia	"	1,200-2,500 *1
	Water solution	"	1,200-2,500 *1
	Organic matter viscosity 0.5cP or below**	"	350- 750
	Organic matter viscosity 0.5 to 1.0cP**5	"	250- 600
	Organic matter viscosity 1.0cP or below**	"	25- 400 *2
	Gas	"	16- 250 *3
Heater	Water	Brine	500-1,000
	Organic matter viscosity 0.5cP or below**	Brine	200- 500
	Steam	Water	1,000-3,500 *1
	"	Methanol	1,000-3,500 *1
	"	Ammonia	1,000-3,500 *1
	"	Water solution viscosity 2.0cP or below	1,000-3,500
	"	Water solution viscosity 2.0cP or above	500-2,500 *1
	"	Organic matter viscosity 0.5cP or below	500-1,000
	"	Organic matter viscosity 0.5 to 1.0cP**5	250- 500
	"	Organic matter viscosity 1.0cP or above	30- 300
Heat exchanger	Water	Water	1,200-2,500 *1
	Water solution	Water solution	1,200-2,500 *1
	Organic matter viscosity 0.5cP or below**	Organic matter viscosity 0.5cP or below**	200- 400
	Organic matter viscosity 0.5 to 1.0cP**5	Organic matter viscosity 0.5 to 1.0cP**5	100- 300
	Organic matter viscosity 1.0cP or above**6	Organic matter viscosity 1.0cP or above**6	50- 200
	Organic matter viscosity 1.0cP or above**6	Organic matter viscosity 0.5cP or below**	150- 300
	Organic matter viscosity 0.5cP or below**	Organic matter viscosity 1.0cP or above**6	50- 200

Note 1: Overall coefficients of heat transfer shown on the above table are, with the exception of \*1, \*2 and \*3, based on when the fouling factor and the allowable pressure loss on the controlling fluid side are assumed to be 0.0006 m<sup>2</sup>·hr·°C/kcal and 0.35 to 0.7 kg/cm<sup>2</sup> respectively.

Note 2: \*1 to \*6 on the above table are as follows:

- \*1. When fouling factor is 0.0002 m<sup>2</sup>·hr·°C/kcal.
- \*2. When pressure loss is 1.4 to 2.1 kg/cm<sup>2</sup>.
- \*3. Greatly varies with service pressure of the gas.
- \*4. Organic matters such as benzene, toluene, acetone, ethanol, methyl ethyl ketone, gasoline, light kerosene, naphtha, etc.
- \*5. Organic matters such as kerosene, hot gas oil, heat medium oil, a kind of crude oil, etc.
- \*6. Organic matters such as chilled gas oil, fuel oil, crude oil, tar, asphalt, etc.

**b. Mean temperature difference**

Heat transferred, Q in heat exchanger is expressed by the following equation:

$$Q = A_o \cdot U_o \cdot \Delta t_m \dots \dots \dots (1)$$

where  $A_o$ : Heating surface based on outside tube  
 $t_m$ : Mean temperature difference between both fluids

The temperature difference between both fluids,  $\Delta t$ , may, in most cases, differ according to each spot in the heat exchanger. In both high and low temperature fluids as for one passage type heat exchange, when a differential equation for heat balance with  $A_o$  and  $\Delta t$  as variables is solved,

$$Q = A_o \cdot U_o \cdot (\Delta t_1 - \Delta t_2) / \ln (\Delta t_1 / \Delta t_2) \dots\dots\dots (2)$$

the above equation is obtained, where subscripts of  $t$  show inlet and outlet of the heat exchanger respectively.

Equispacing equations (1) and (2),

$$\Delta t_m = (\Delta t_1 - \Delta t_2) / \ln (\Delta t_1 / \Delta t_2) \dots\dots\dots (3)$$

This is called logarithmic mean temperature difference. In many of the heat exchangers in practical use, the fluid channel is complicated as shown in Figure 5.9 and, as such, the temperature difference value calculated from equation (3) cannot be used as-is but needs some correction. Treating the correction factor as  $F_T$ , mean temperature difference  $\Delta t_m$  is calculated by the following equation:

$$\Delta t_m = F_T \cdot \Delta t_m = (\Delta t_1 - \Delta t_2) / \ln (\Delta t_1 / \Delta t_2) \dots\dots\dots (4)$$

Values  $F_T$  due to each channel configuration are shown in Figure 5.10

Figure 5.9 Shell/Tube Type Heat Exchanger

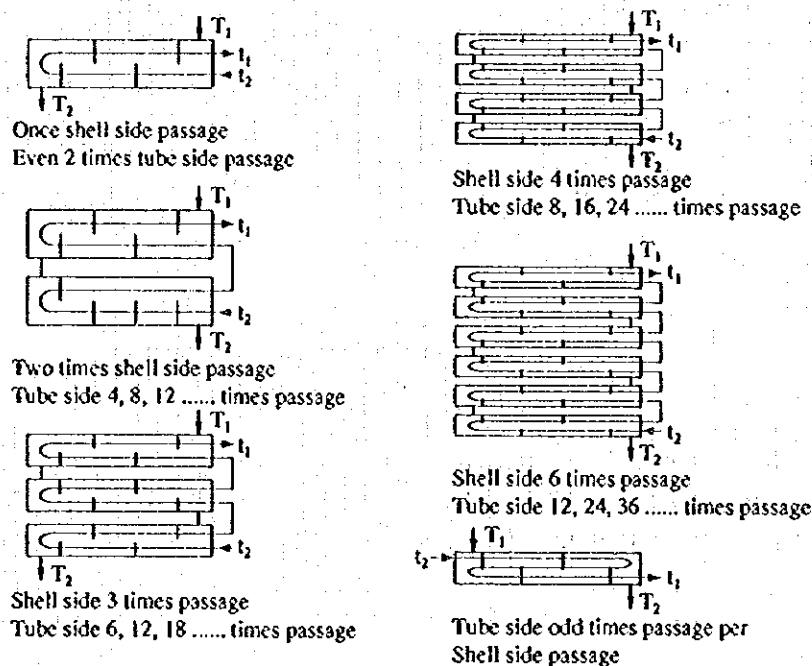
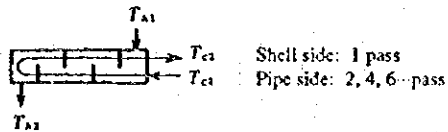
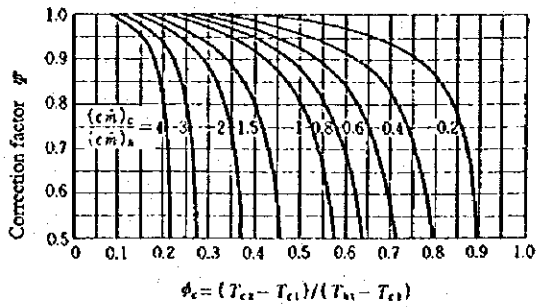
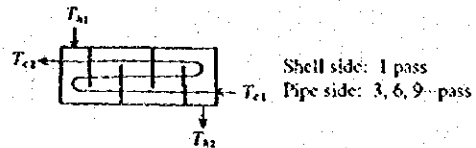
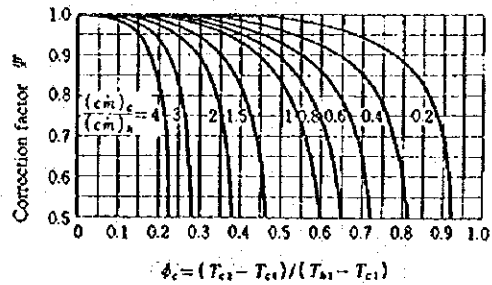


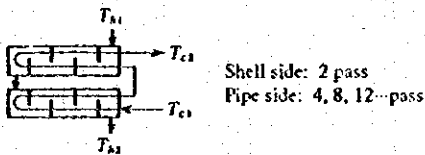
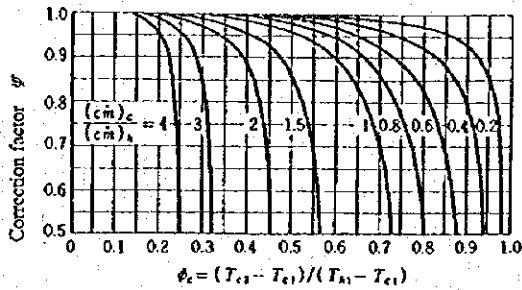
Figure 5.10 Correction Factor  $F_T$



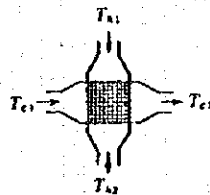
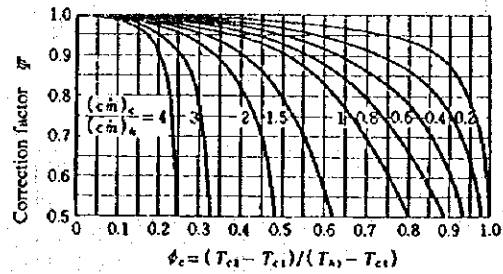
(a) Correction factor for 1-2 pass heat exchanger  $\psi^{(2)}$



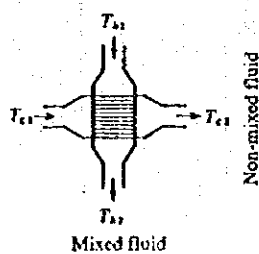
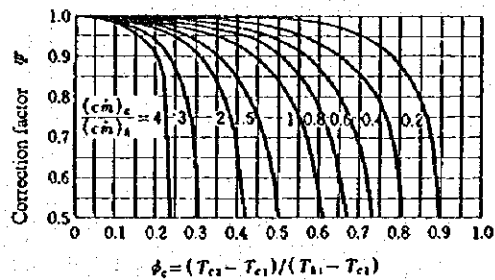
(b) Correction factor for 1-3 pass heat exchanger  $\psi^{(2)}$



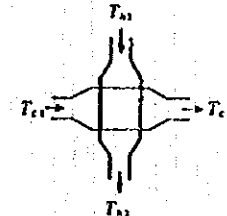
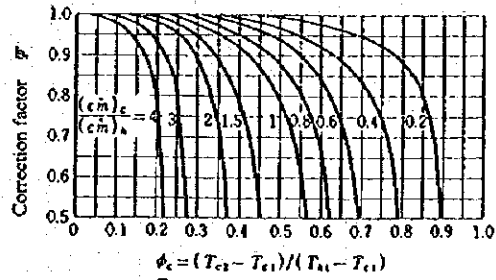
(c) Correction factor for 2-4 pass heat exchanger  $\psi^{(2)}$



(d) Correction factor for DC/AC heat exchanger where neither of the fluids mix  $\psi^{(2)}$



(e) Correction factor for DC/AC heat exchanger where only one fluid mixes  $\psi^{(2)}$



(f) Correction factor for DC/AC heat exchanger where both fluids mix  $\psi^{(2)}$

Source: "Handbook of Air-Conditioning and Sanitary Engineering" by  
The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan

(3) Types of heat exchangers

Heat exchangers are mainly divided according to type of heat transfer element from the constructional standpoint and further classified according to the type of container to house the heat transfer element. They are divided from the constructional standpoint as follows:

a. Tubular type (Figure 5.11 to Figure 5.14)

- 1) Coil type heat exchanger
- 2) Trombone type (Cooler)
- 3) Double tube type heat exchanger
- 4) Multitubular heat exchanger
  - ① Fixed tube plate type
  - ② Floating head type
  - ③ U-tube type

Figure 5.11 Coil Type Heat Exchanger

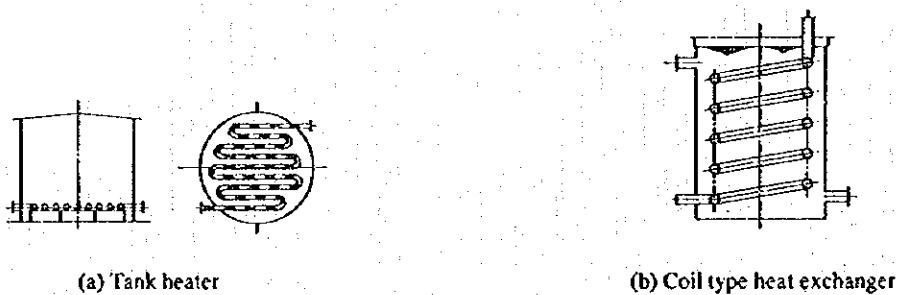
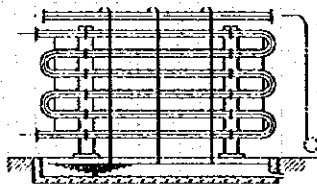
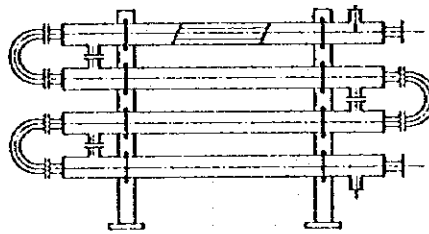


Figure 5.12 Trombone Cooler Exchanger

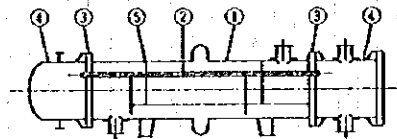




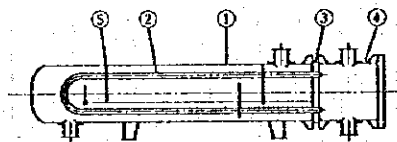
**Figure 5.13 Double Tube Type Heat Exchanger**



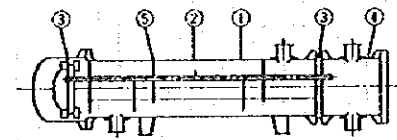
**Figure 5.14 Multi-Tube Type Heat Exchanger**



(a) Fixed tube plate type heat exchanger



(b) U-tube type heat exchanger



(c) Floating head type heat exchanger

① Shell ② Heating tube ③ Tube plate  
④ Partition chamber ⑤ Baffle

**b. Plate type (Figure 5.15 to Figure 5.16)**

- 1) Jacket type heat exchanger
- 2) Plate type heat exchanger
- 3) Spiral type heat exchanger

Figure 5.15 Plate Type Heat Exchanger

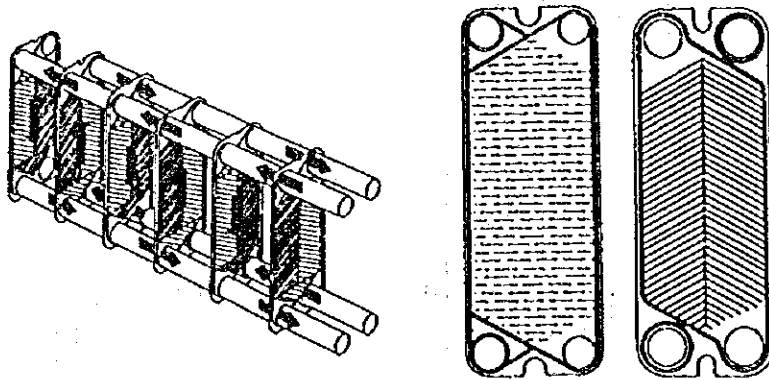
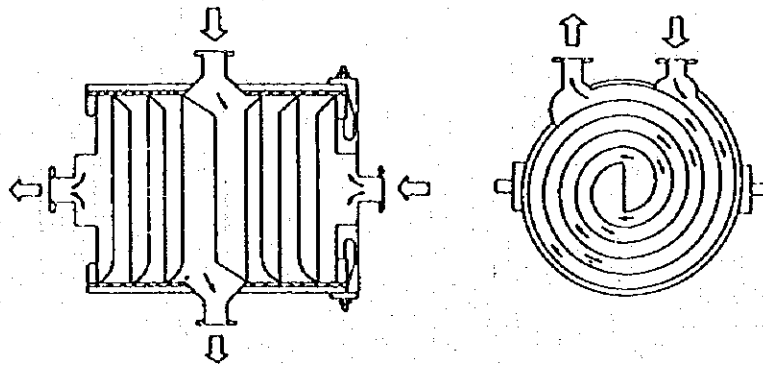


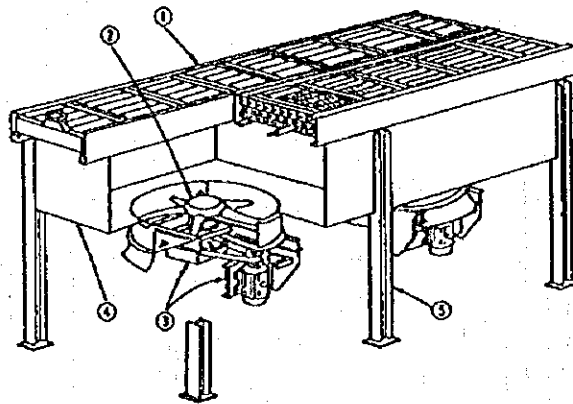
Figure 5.16 Spiral Type Heat Exchanger



c. Special type (Figure 5.17)

- 1) Air cooling type heat exchanger
- 2) Bayonet heat exchanger
- 3) Compact heat exchanger

**Figure 5.17 Air Cooling Type Heat Exchanger**



- ① Tube bundle (Fin-tube, header)
- ② Fan
- ③ Drive
- ④ Plenum chamber
- ⑤ Frame

Characteristics of typical ones of the above-mentioned heat exchangers are described.

**Coil type heat exchangers:**

Many of coil type heat exchangers are installed within storage tanks and reactors, etc. The overall heat transfer coefficient is greatly affected by the outside tube heat transfer coefficient. The construction is simple, the cost is low, and cleaning and replacement are generally easy.

**Trombone type cooler:**

Since Trombone type coolers consist of 180° bends and straight tubes, replacement of tubes and extension works are easy. Also, since there is little possibility of leakage, they are used for special processes such as a cooler for sulfuric acid and for fluid cooling.

**Double tube type heat exchangers:**

Double tube type heat exchangers are used for small-scale type with heating surface area to the extent of 15 to 20 m<sup>2</sup>.

#### Multitubular heat exchangers:

Multitubular heat exchangers are most widely used in chemical industries, have high reliability in practical use, and can be designed and manufactured to a wide variety of specifications for high temperature and high pressure to large capacities. The fixed tube plate type is low-cost and easy to manufacture, but the shell side fluid must be restricted to non-corrosive little contaminated material. Floating head type has advantages that it is easy to inspect and clean the heating tubes because the tube bundle can be drawn outside, and that no thermal stress is generated because thermal expansion due to the temperature difference in the fluid is absorbed. However, it is complicated in construction and expensive. U-tube type has no possibility of thermal stress, and its tube bundle can be easily drawn outside for cleaning. However, it has a defect in that it is difficult to clean the bent portion of the tube.

#### Plate type heat exchanger:

The heating area can be freely increased and decreased by adjusting the number of plates used and it is easy to assemble and clean. Since turbulence can be given to the flow, the heat transfer coefficient is great. However, the use is limited to a pressure of approximately 10 kg/cm<sup>2</sup> and temperature of approximately 150 °C from the construction standpoint because of its structural liability to leakage. Many of them are used in pharmaceutical and food processing industries, and general chemical industries use them.

#### Spiral heat exchangers:

Since the fluid rotates, turbulence increases the heat transfer coefficient. Like the plate type, it is possible to design a small-size type. Recently, structural improvement (of the weld zone) has allowed those of higher performance to be widely used.

#### Air cooling type heat exchangers:

Air cooling type heat exchangers consist of finned tubes, header, fan and its drive. Since the cooling medium is air, it is convenient when cooling water is dirty or in short supply. At their use, the installation place should be taken into due consideration so that cool fresh air can be introduced. Table 5.5 shows approximate values of overall heat transfer coefficients for heat exchangers.

Table 5.5 Approximate Values of Overall Heat Transfer Coefficients for Various Heat Exchangers (1/2)

Types of Equipment	Fluid ( $u$ : Flow velocity [m/sec])	Overall Coefficients of Heat Transfer $U$ [kcal/m <sup>2</sup> ·hr·°C]	Remarks
Shell tube type heat exchanger	Fluid-Fluid	700 ~ 1500	
"	Hot water-Hydrogen carbonate (outside tube)	200 ~ 430	
"	Fluid-Fluid (oils)	90 ~ 700	
"	Salt water ( $u=0.3 \sim 1$ )-Water ( $u=0.3 \sim 1.5$ )	250 ~ 2000	
"	Water ( $u=0.6$ )-Lubrication Oil ( $u=0.05$ )	75	
"	Water ( $u=0.6$ )-Kerosine ( $u=0.15$ )	200	
"	Crude oil ( $u=1.3 \sim 2.1$ )-naphthas	180 ~ 240	
"	Water ( $u=1$ )-Butane ( $u=0.6$ )	450	
Shell tube type condenser	Water ( $u=1$ )-Steam	2000 ~ 4000	
"	Water ( $u=1.2$ )-Freon 12	750 ~ 850	
"	Water ( $u=1 \sim 1.5$ )-Ammonia	750 ~ 2000	
"	Water ( $u=1$ )-Kerosine	250	
"	Water ( $u=1.5$ )-gasoline	450	
"	Crude oil ( $u=0.6$ )-gasoline	100 ~ 150	
Shell tube type heater	Oil-steam (condensed)	200 ~ 900	
Reheating boiler	Hydrogen carbonate-steam (condensed)	100 ~ 330	These values vary depending mainly on the degree of purity.
Tube type oil heater	Oil-fused salt	250 ~ 390	
Steam heater	Water-Steam (Condensed)	730 ~ 3900	Forced convection
"	"	240 ~ 1000	Natural convection
"	Oil-Steam (Condensed)	100 ~ 300	Forced convection
"	"	50 ~ 150	Natural convection
"	Butane (Boiled)-Steam (Condensed)	500 ~ 750	Horizontal tube reboiler
Condenser	Water-Organic matter steam	290 ~ 730	Forced convection
"	"	200 ~ 390	Natural convection
Air heater	Air-Steam (Condensed)	10 ~ 50	Forced convection
"	"	5 ~ 15	Natural convection, radiator
Warm water radiator	Air-fused salt	30	
"	Air-hot water	10 ~ 50	Forced convection
"	"	5 ~ 15	Natural convection
Cooler	Water-brine	240 ~ 730	Forced convection
"	"	100 ~ 300	Natural convection
"	Oil-Fluid	120 ~ 300	Forced convection
"	"	25 ~ 100	Natural convection

### 5.2.3 Reactors

Reactors are equipment which play a leading part among equipment in chemical industries, and generally occupy an important position also in thermal energy.

We follow their general classification and describe the respective characteristics:

#### (1) Classification by construction and form

##### a. Vessel type reactors

These reactors are most widely used in chemical industries. They are generally equipped with agitator, and jacket and coil, etc. for the heat exchanger. These types are used for both batch and continuous operation over a wide range of temperatures and pressures.

##### b. Tubular type reactors

These reactors are installed for both single tube and parallel multitubular type. Mostly, heat exchange is made between inside and outside tube fluids and heat transfer is accelerated when filled with catalyst.

##### c. Tower type reactors

These reactors are of a vertical, cylindrical type with a larger diameter than the tubular type. Some of them are filled with solid packings or catalytic particles, some are equipped with baffles, or some are only empty towers, etc.

#### (2) Classification by temperature control

##### a. Isothermal operation

Isothermal operation is made when heat of the reaction is small, when reaction mass is very small, or when inert fluid with great heat capacity is introduced, or heat exchange with the outside is so sufficiently performed that it is regarded as almost isothermal within the reactor.

##### b. Adiabatic operation

Adiabatic operation is made when no heat exchange is performed between the reaction system and the outside, but the reaction is adiabatically performed. In this case, generated heat or absorbed heat due to the reaction as-is becomes an increase or decrease in enthalpy of the reaction system.

When heat of the reaction is great, some factories use a method to bring temperature distribution in the reactor close to optimum temperature distribution, in which the reaction layer is divided into several stages, a heat exchanger (or heater or cooler) is inserted between each stage, or reaction fluid at low temperature (or high temperature) is introduced to adjust temperature at inlet of each adiabatic reaction layer. This is called multiple adiabatic operation and is used for an  $\text{SO}_2$  converter in a sulfuric acid plant and ammonia synthesis converter.

c. Heat exchange operation

This operation is widely used to transfer heat of reaction from reactor to outside of the system. This operation is divided into two; self-heat exchange type, and external heat exchange type. In the former type, a reaction fluid itself cools (or heats) the reaction chamber and, at the same time, itself is preheated (or cooled) and enters the reaction chamber. In the latter type, the reaction chamber is cooled or heated by an other heating medium.

(3) Rationalization in the use of thermal energy

Since chemical reactions of industrial purposes generally abound in exothermic reactions, it will be described.

To preheat raw material, heat should be obtained from the heat exchange with high temperature products after reaction or heat exchange within the reactor or in intermediate cooling, etc., and heating with fuel, steam, etc. from the outside of the system should be minimized.

For cooling for temperature control in the intermediate reaction layer or cooling of high temperature products at the reactor outlet, together with or separately from the raw material preheating method shown by Figure 5.8, it is desirable to effectively recover the heat of reaction and utilize it both outside and inside of the system by the following methods:

Heating of boiler feed water or steam generation.

Heating of air or of other fluids.

#### 5.2.4 Distilling plants

(1) Principle of distillation

When a mixed solution consisting of two or more volatile matters is evaporated, the vapor is richer in components of low boiling-point than the original solution, while the remaining liquid is more concentrated with components of high boiling-point.

This principle is applied in the distillation operation that separates the solution at higher concentrations in a specified component from the mixed solution.

Moreover, when vapor once generated is condensed and it is evaporated again, the low-boiling point component in the vapor is more concentrated and the remaining liquid will be increasingly rich in high-boiling point component on the same principle. This principle of distillation by air-liquid contact is incorporated into a multi-stage distillation tower. In the multi-stage distillation tower, vapor generated from one plate comes into direct contact with liquid on the upper plate and condenses, in which case the latent heat is released. This latent heat is further used for evaporation of liquid on the said plate. Since such a phenomenon occurs throughout all plates in the tower, the thermal energy required for the distillation is usually sufficed with only heat input to the bottom heater; cooling for condensation of vapor is sufficed by only the overhead condenser. Next, peculiar factors to the multi-stage distillation operation are described:

#### <Reflux>

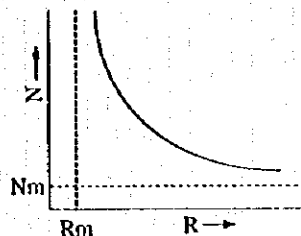
To keep the composition of the overhead product constant (in the case of continuous operation), or to improve separation from the high-boiling point component (for both batch and continuous operation), a portion of the overhead distillate is returned to the top, which is reflux. Ratio (Flow rate of reflux)/(Flow rate of overhead product) is called "Reflux ratio" and one of very significant factors in the distillation operation.

#### <Relation between reflux ratio and number of plates of towers>

Relation between a number of plates (called "Theoretical number of plate"),  $N$  required to separate product at a specified concentration from original solution and the reflux ratio,  $R$  is shown in Figure 5.18.

$R$  cannot be made less than  $R_m$ , but the required plate number of the tower will be infinite when  $R$  is equal to  $R_m$ . Also, when  $R$  is increased, the required number of plates will decrease. Even if  $R$  is infinite, the plate number cannot be decreased less than  $N_m$ .  $R_m$  and  $N_m$  are called minimum reflux ratio and theoretical minimum number of plates respectively, each of which is one of the important factors for design and operation of a distilling plant.

Figure 5.18 Reflux Ratio vs Theoretical Number of Plates





### <Relation between reflux ratio and thermal energy>

The latent heat amount of vapor which rises in a tower is almost the same at any plate in the tower, unless there is cooling or heat release in the tower, and such amount is  $(1 + R) \times (\text{Flow rate of overhead product}) \times (\text{Latent heat of evaporation})$ , being provided by the bottom heater, tower bottom stripping steam, etc.\* Accordingly, reduction in R directly leads to energy conservation in a distilling plant.

\*Note: This is when the feed being charged is at its boiling point and in any other cases, correction in a thermal state of the feed is necessary.

### (2) Classification of distillation towers

#### a. Plate tower

Plates used to hold liquid in the tower are provided in multi-stages and the perforated plates or many bubble caps are provided in order to make the contact between vapor rising from a lower plate and liquid on the plates better.

#### b. Packed tower

Packings which are of shapes to perform gas-liquid contact efficiently are packed in a tower to perform evaporation and condensation continuously instead of stepwise. Although this tower is inferior to A) in performance as a distillation tower, it has advantages in that the equipment is low-cost and the pressure drop in the tower is less. However, packings with better performance than the plate tower are recently sold on the market and utilized, though expensive.

### (3) Rationalization in the Use of Energy

#### a. Optimization of reflux ratio

Although reduction in R leads to energy conservation as mentioned above, increase in the high-boiling point component in the overhead product and increase in the low-boiling point component in the bottom product occur, resulting in lowered performance of separation in the distilling plant.

In general, taking into consideration adverse effects which may be caused by fluctuations in feed composition, fluctuations in pressure of heating steam, etc., it is, in most cases, seen that the operation is made at a larger value of R than required with margin. Although R is generally determined empirically, it is advisable to first endeavor to minimize the range of fluctuation in various fluctuating conditions and to determine the lowest value of R which will not affect the product by analyzing the composition and decreasing R gradually. Also, since value R is influenced by feed plates number, it is also a method to change the feed plates according to a method of trial and error.

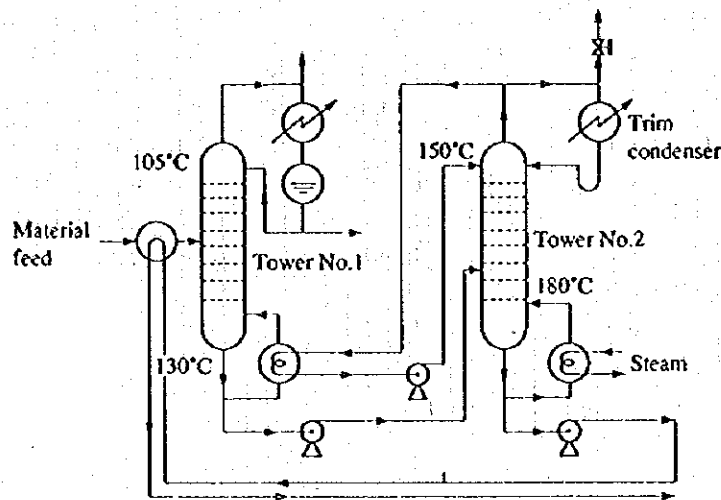
b. Cleaning of plates or packings

Vapor actually generated from each plate is not in an equilibrium composition with the liquid composition. Against this deviation, considering a plate efficiency and regarding the quotient obtained by dividing the required plate number theoretically calculated by the plate efficiency as the real plate number, actual equipment is made. When the plates or packings are contaminated by foreign matters contained in the liquid during operation, the plate efficiency will lower below the design value. Therefore, we cannot help but increase  $R$  to maintain the performance. To prevent this, it is important to release the tower periodically and inspect and clean the inside.

c. Recovery of waste heat due to heat exchanger

Since overhead vapor has latent heat, utilize this for the heater in another tower at low temperatures and preheat feed with sensible heat retained in the bottom product. (See Figure 5.19)

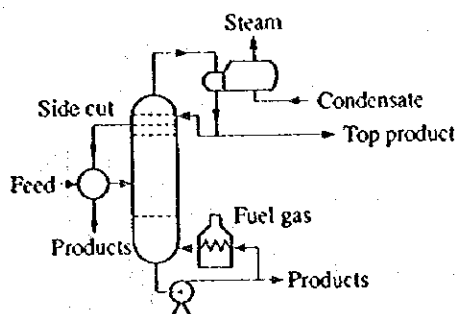
Figure 5.19 Heat Recovery of Distillate



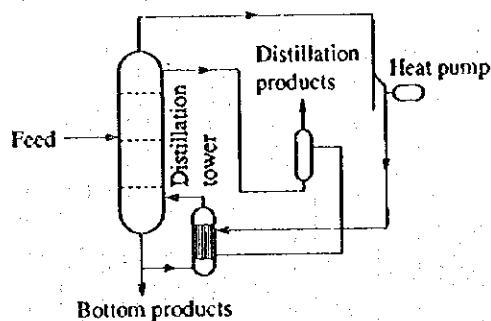
Also, heat in the overhead condenser can be utilized to generate low pressure steam when the vapor is at high temperature. (See Figure 5.20)

There is a method to utilize vapor in the overhead product for the bottom heater by pressurizing the vapor to raise the condensation temperature, though it may be a somewhat expensive plant. (See Figure 5.21)

**Figure 5.20 Steam Generation by Heat of Distillate**



**Figure 5.21 Use of Distillate Heat to Reboiler**



**d. Precautions for heat insulation**

When the distillation tower body is not heat insulated, or when it is poorly insulated, heat release from the tower wall will condense a part of rising vapor in the tower (It is called partial condensation.). When partial condensation occurs, reflux ratio,  $R$  will decrease at above plates, resulting in lowered separation performance in the distillation tower. If  $R$  is going to be maintained to prevent this, it will be necessary to supplement only an amount of heat loss from the tower wall by the bottom heater.

**5.2.5 Evaporators**

Evaporators are, in most cases, used for concentration and crystallization of solutions in chemical plants. Since solvent for solution is generally water and its latent heat of evaporation is great, evaporators are important equipment as the subject of energy conservation. As heat source, combustion gas, direct flame, electric heat, heating medium, etc. are used in addition to steam, but only steam heating type will be discussed here.

**(1) Types of evaporators**

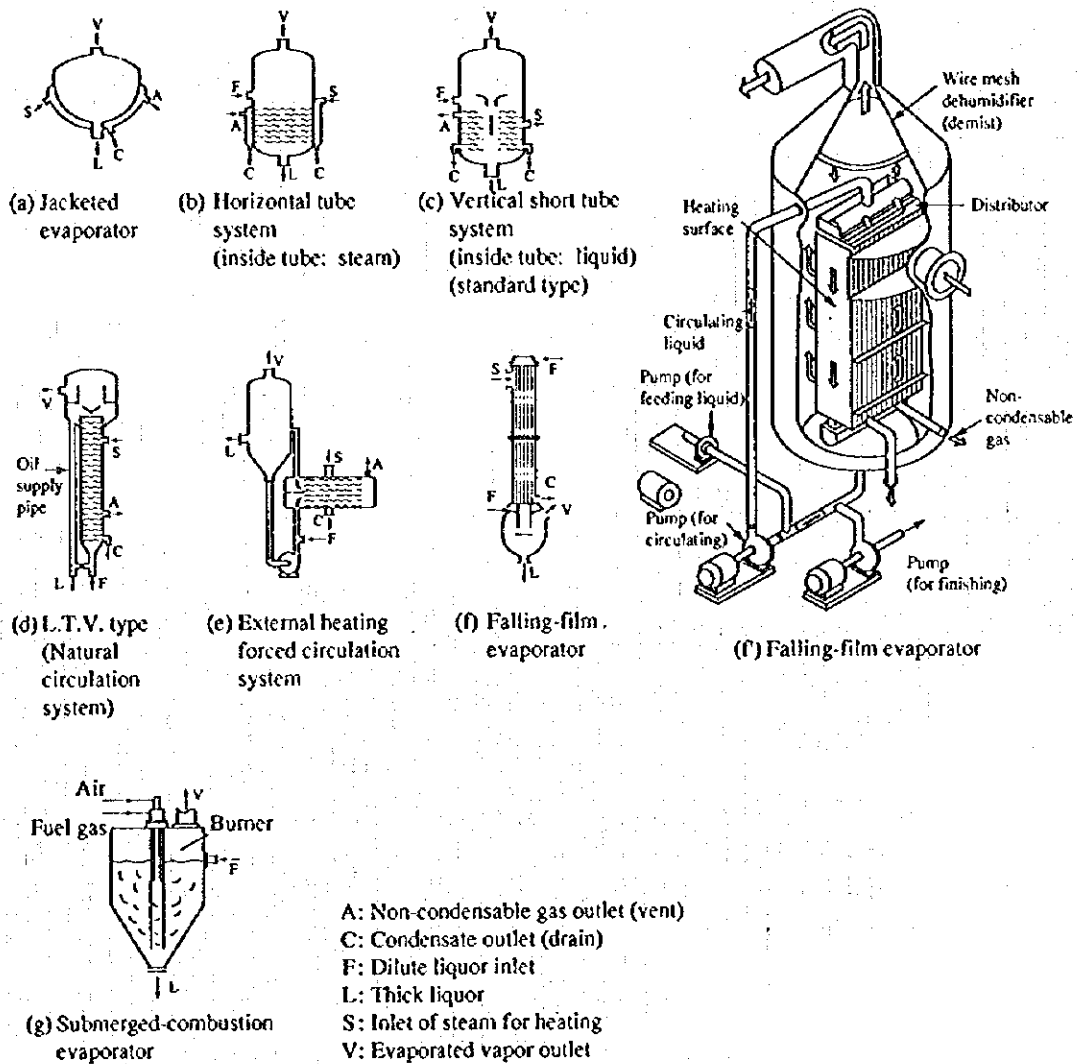
Construction of typical evaporators is shown in Figure 5.22.

(a) is often used for batch type.

(b) is low in equipment cost per unit heating area and easy to replace tubes.

In (c), liquid is naturally circulated, being heated while it falls down along a central large tube (called downtake), and rises within small tubes and this type is most widely used. In (d), solution becomes a vapor-liquid mixture in heating tubes and rises at a high rate in jet, and the efficiency is high. In (e), heating and evaporation areas are separated and it is easy to replace and clean tubes and convenient to operate. In (f) and (f'), solution evaporates while it is flowing down in the form of a film on the heating surface, and it is suitable for concentration of the solution with high viscosity and sensitivity to heat. Heat transfer portion has two types: one is vertical, long tube type (f), and the other is plate type (f'). The former is not suitable for solution which forms scale and crystal because of inside tube flow down system. Uniform distribution of solution on the heating surface is one of the important operating conditions for both types. In (g), evaporation is performed by blowing out hot gas in a liquid, or by installing a burner in the liquid, allowing it to burn directly and blowing out combustion gas at high temperatures in the liquid. Since evaporation is performed by direct liquid-gas contact in the presence of inert gas, concentration is performed at low temperatures, and the heat transfer capacity is great. (g) is used for concentration of highly corrosive solutions such as sodium sulfate, phosphoric acid, dilute sulfuric acid, magnesium chloride, etc.

Figure 5.22 Example of Evaporators



(2) Effective utilization of energy

Since evaporation requires a lot of energy, several methods shown in Figure 5.23 are adopted from an energy economy standpoint.

a. Vapor recovery method

Vapor is utilized as-is; (a)

Generated vapor is otherwise utilized after compressing it; (b)

b. Vapor compression method

Evaporated vapor is utilized for heating itself after compressing it; (c), (h), (j)

c. Back pressure utilization method

Utilization of turbine exhaust for heating; (d), (i)

d. Multiple effects method

Discussion later; (e)

e. Combination of above methods

Methods in conjunction with the multiple effects method; (f), (g), (h), (i)

In addition, there is a multi-stage flash evaporation method, which uses heat retained in generated vapor to preheat feed solutions, and is applied to desalination of sea water.

(3) Rationalization in the use of thermal energy

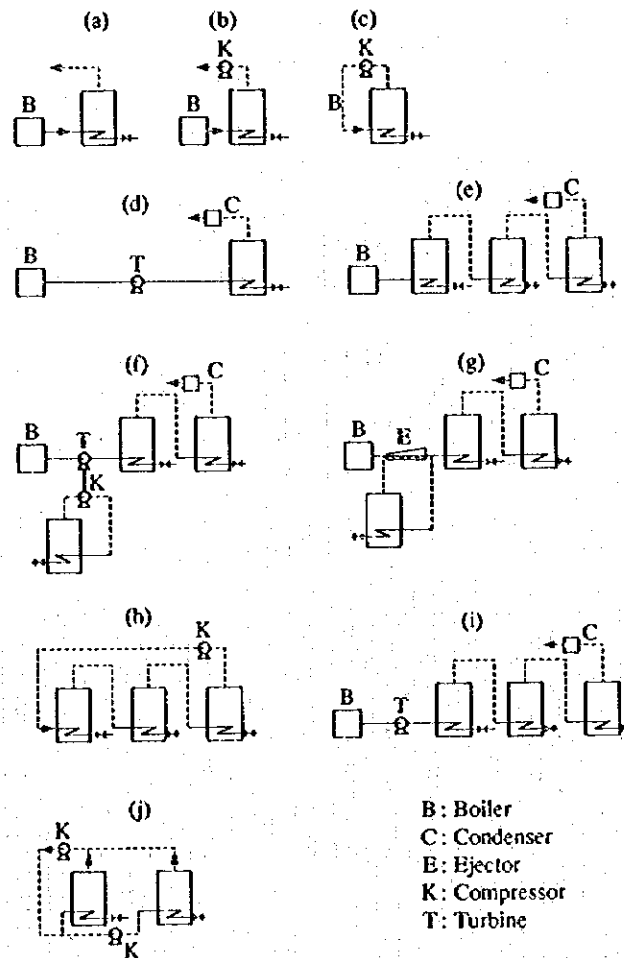
Although energy unit of evaporation largely depends upon the methods mentioned in the preceding item, it is also affected by many other factors, which will be described below:

a. Effect of scale

If salts which will form scale are contained in solutions, scale deposits on the heating surface become a heat transfer resistance or block, because the heating tube wall has the maximum temperature. Therefore, it is advisable to prevent this by the following methods:

- 1) Remove scale formation ingredients beforehand.
- 2) Select pH, concentration, temperature, etc. of the liquid.
- 3) Introduce suitable chemicals.
- 4) Select the type of evaporator to which it is difficult for scale to stick, and clean thoroughly.

Figure 5.23 Classification of Evaporations Systems



b. Steam consumption in steam ejectors

Steam ejectors are generally used to maintain pressure in evaporators and remove non-condensable gas such as air, etc. Driving steam is usually condensed by a barometric condenser, and the temperature of cooling water used for this condenser is related to an amount of driving steam. That is, the lower the temperature of water is, the less the amount of steam required is and also the lower the pressure of steam may be.

For example, steam pressure of 15 kg/cm<sup>2</sup> (G) is required when water in the barometric condenser is at 41 °C, but when the water temperature comes to 35 °C, a steam pressure of 10.6 kg/cm<sup>2</sup> (G) will suffice.\*

\*Note: Representing saturated pressure corresponding to water temperature in the barometric condenser as  $P_{t_1}$ ,  $P_{t_2}$ , and ejector driving steam pressure corresponding to each of them as  $P_1$ ,  $P_2$  respectively.

$$\frac{P_1 + 1.033}{P_2 + 1.033} = \frac{P_{t1}}{P_{t2}}$$

(Unit)  $P_{t1}, P_{t2}$ : Torr  
 $P_1, P_2$  : kg/cm<sup>2</sup>(G)

c. Air purge in steam heating chamber

When air or other inert gas is contained in steam, the gas accumulates in the heating chamber, heat transfer is impeded, and lowered steam partial pressure lowers heating temperature. As a countermeasure to prevent this, a purge valve is provided in the heating chamber and purging operation is periodically and slightly excessively performed. It is theoretically said that discharge should be continued until the temperature of the discharge gas reaches the saturation temperature of the steam used.

It is desirable that the air discharge valve should be located on the exact opposite side to the steam inlet and in the steam flow direction.

(4) Multi-effect method

When the boiling point of the solution in the next stage is brought below the temperature of condensation of generated steam in the preceding stage evaporator, by lowering the inside-evaporator pressure, generated steam in the preceding stage is introduced into the heating chamber in the next stage and its heat of condensation will be utilized for evaporation in the next stage.

It is a special feature of the multi-effect method that remarkably less steam consumption suffices than when a specified evaporation is performed in a single evaporator. When the number of effects (number of stages) is N, the heating steam will be theoretically 1/N of that of a single evaporator and the larger N is, the more advantageous it will be from a thermal economical standpoint. However, since the equipment and operation costs will in fact increase with N, there will exist an economically optimum value for N. Briefly assuming that steam cost is in inverse proportion to N and fixed cost is in proportion to N, the optimum number of effect,  $N_{opt}$  is expressed by the following equation:

$$N_{opt} = \sqrt{P/F_E}$$

where  $P = W_y \cdot C_s / K$

K : Mean steam economy (Amount of water evaporated by 1 kg of steam per evaporator; 0.85 to 0.9)

$W_y$ : Annual amount of evaporation (kg/y)

$C_s$  : Unit price of steam

$F_E$  : Fixed cost of evaporator



## 5.2.6 Dryers

Dryers which are constructed to evaporate moisture from a wet material by allowing hot air to contact will be discussed here. Since the material to be dried varies in a wide range in shape and physical and chemical properties, and its moisture content also differs, the drying operation will vary according to each case. Therefore, many types of dryers to meet respective material characteristics and operations are sold on the market. It is very important to select the equipment. However, this proposal will only give general consideration to problems for material and equipment here and describe general energy conservation of dryers.

### (1) Types of dryers

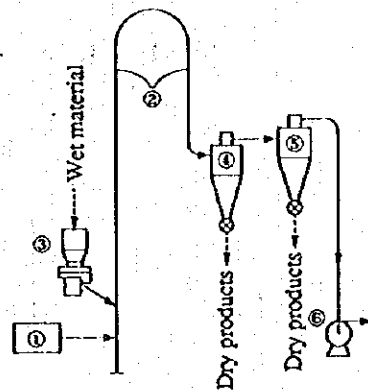
Dryers are classified by the relation between material moving system and heat transfer as follows:

#### a. Hot air dryers

##### 1) Hot air conveying types

##### ① Pneumatic dryer (See Figure 5.24)

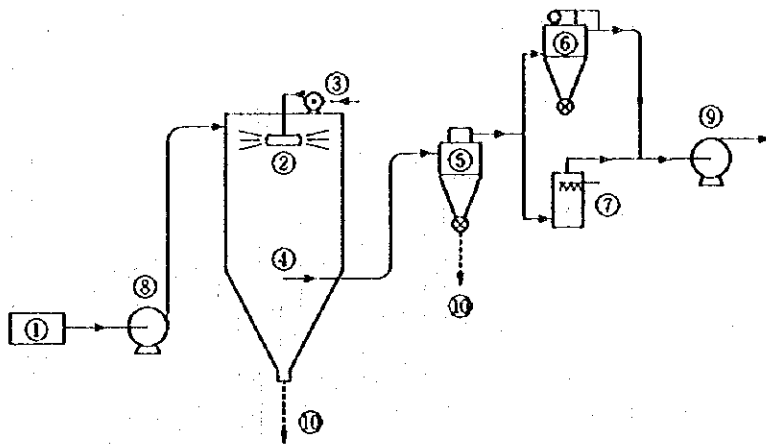
Figure 5.24 Pneumatic Dryer (Direct Feed System)



- ① Hot air producer    ② Drying tube    ③ Material feeding device  
④ Primary cyclone collector    ⑤ Secondary cyclone collector  
⑥ Exhauster

##### ② Spray dryer (See Figure 5.25)

Figure 5.25 Spray Dryer

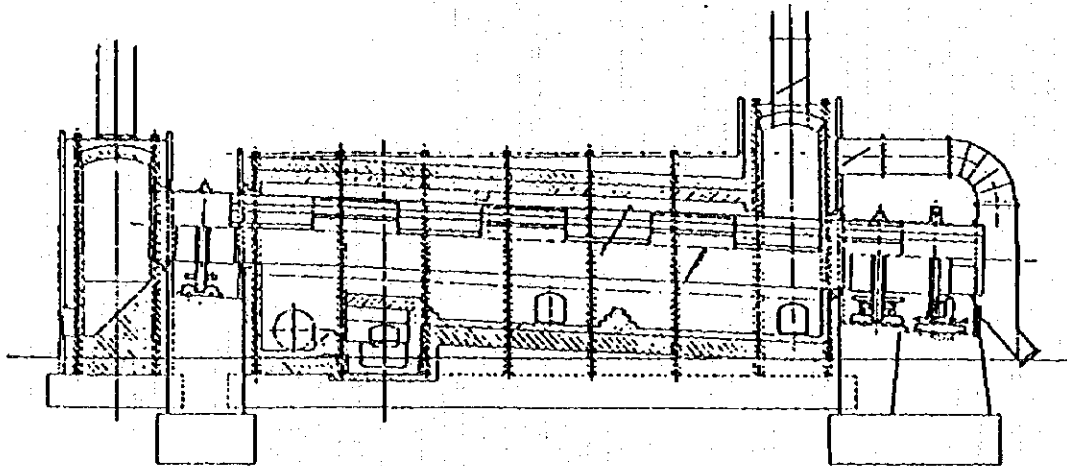


- ① Hot air producer
- ② Sprayer
- ③ Feed liquid pump
- ④ Drying tower
- ⑤ Cyclone collector
- ⑥ Bag filter
- ⑦ Scrubber
- ⑧ Blower
- ⑨ Exhauster
- ⑩ Dried products

2) Material agitation types

- ① Rotary dryers {
  - Single cylindrical direct heating type
  - Double cylindrical indirect heating type
  - External fire type (See Figure 5.26)

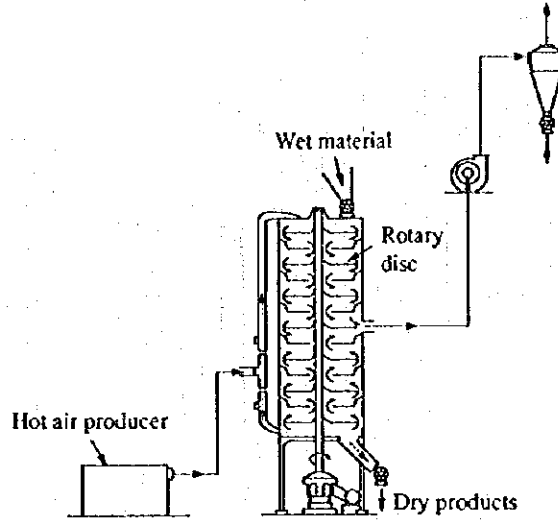
Figure 5.26 External Fire Type Rotary Dryer



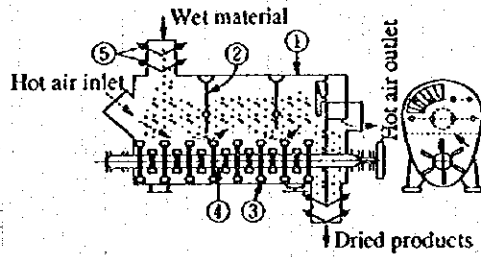
- ② Multiple-stage disk dryer (See Figure 5.27)
- ③ Agitator trough dryer (See Figure 5.28)
- ④ Fluidized bed dryers {
  - Multi-stage continuous type
  - One-stage continuous type (See Figure 5.29)
  - Batch type

⑤ Sheet dryer (See Figure 5.35)

**Figure 5.27 Multiple-Stage Disc Hot Air Dryer**

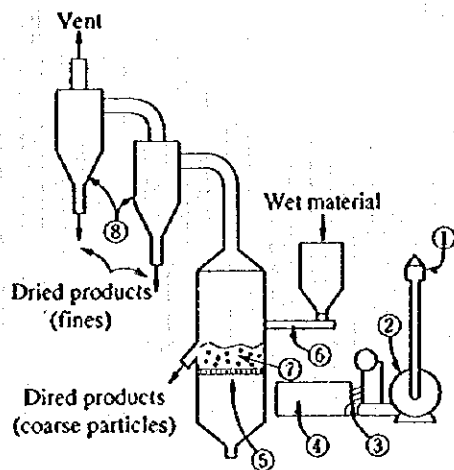


**Figure 5.28 Agitator Trough Dryer**



- ① Shell
- ② Partition plate
- ③ Agitation blade
- ④ Agitation shaft
- ⑤ Weight damper

**Figure 5.29 Continuous Fluidized Bed Dryer**



- ① Air filter
- ② Blower
- ③ Burner
- ④ Air heater
- ⑤ Distributor
- ⑥ Material feed device
- ⑦ Fluidized bed
- ⑧ Cyclone

c. Material conveying types and stationary types

- ① Through-circulation dryers
  - Band type (See Figure 5.30)
  - Rotary type (See Figure 5.31)
  - Vertical moving bed type (See Figure 5.32)
  - Box batch type (Figure 5.33)
- ② Tunnel dryer (See Figure 5.34)
- ③ Vertical nozzle jet dryer (See Figure 5.35)

Figure 5.30 Band Type Continuous Dryer

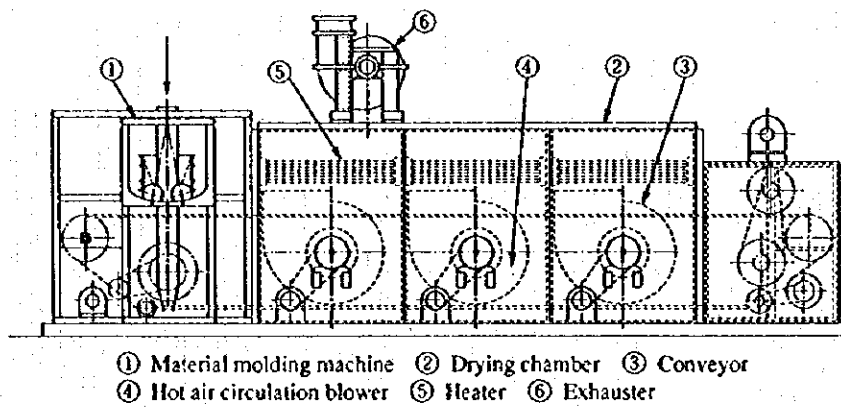


Figure 5.31 Rotary Type Continuous Dryer

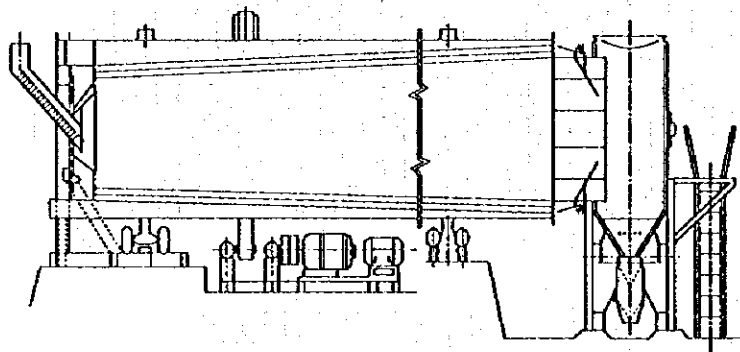


Figure 5.32 Vertical Moving Bed Dryer

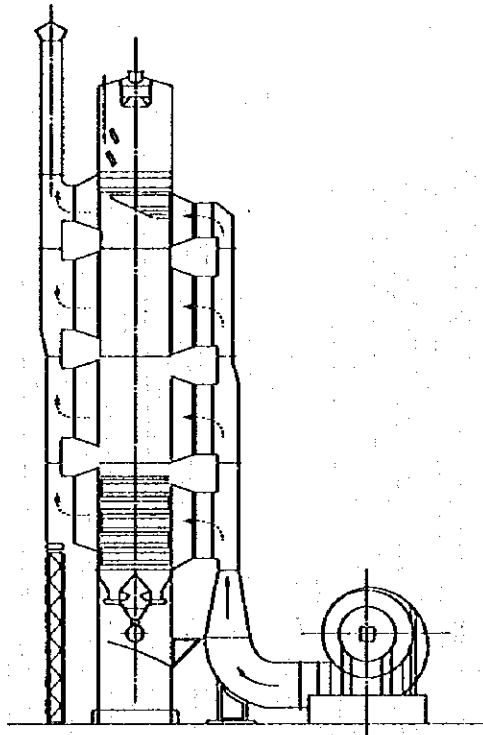


Figure 5.33 Box Type Dryer

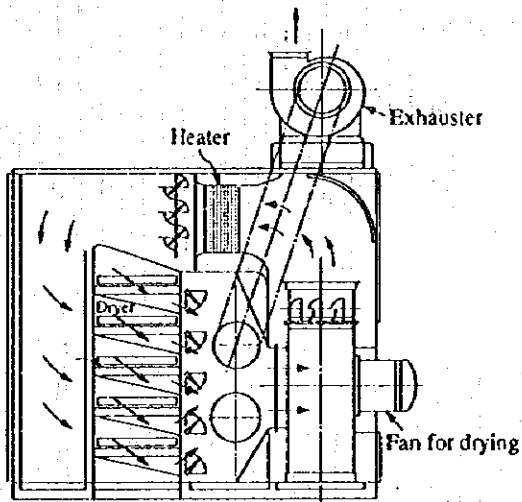
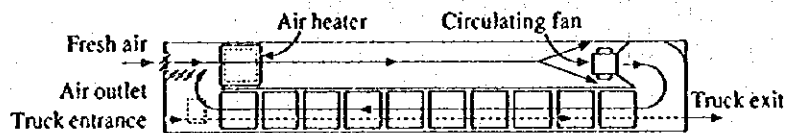
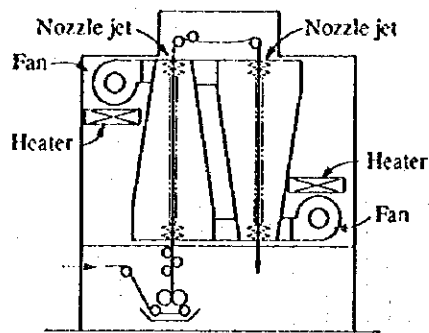


Figure 5.34 Tunnel Dryer



**Figure 5.35 Vertical Nozzle Jet Dryer**

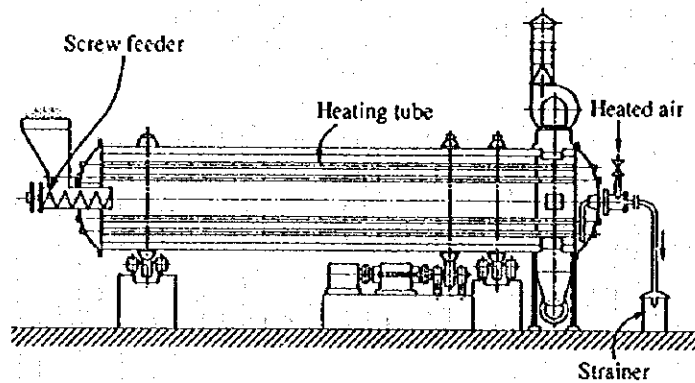


**b. Heat conduction dryers**

**1) Material agitation types**

- ① Agitator trough dryer
- ② Cylindrical agitation dryers { Atmospheric pressure type  
Vacuum type
- ③ Plate agitation dryer
- ④ Steam tube rotary dryer (See Figure 5.36)
- ⑤ Multi-stage agitation dryer
- ⑥ Vacuum rotary dryer

**Figure 5.36 Steam Tube Rotary Dryer**



**2) Material stationary types**

- ① Vacuum tray dryer
- ② Freeze dryer

3) Cylindrical types

① Drum dryers { Atmospheric pressure type  
Vacuum type

② Cylindrical dryer

Application examples of dryers, mainly spray dryers, will be shown in the following tables and figures.

Table 5.6 List of Dryers

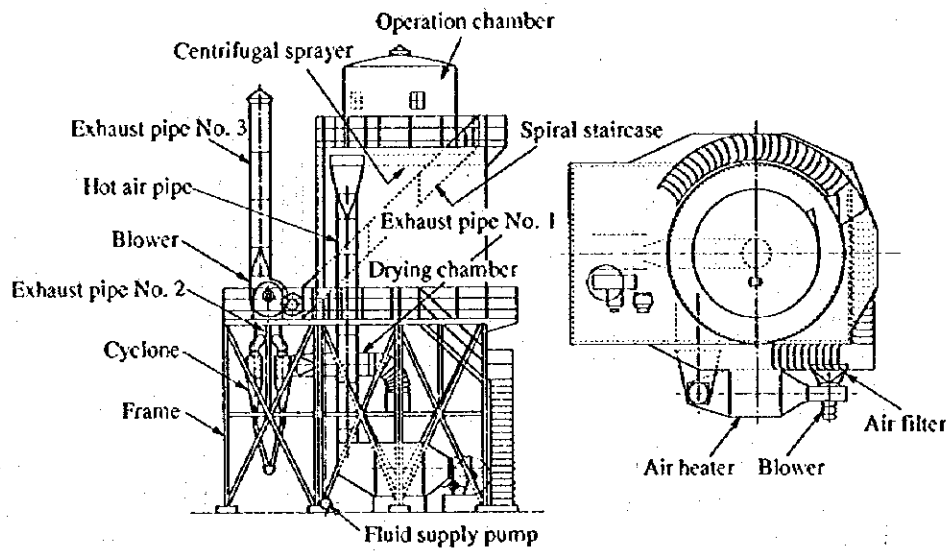
Name of Dryer	Dryer Mechanism and Main Characteristics	Heating capacity	Heat capacity coefficient $h_a$ (kcal/m <sup>2</sup> hr°C) or heat transfer coefficient $U$ (kcal/m <sup>2</sup> hr°C)	Properties of materials to be heated	Application	Others
Hot air carrying Pneumatic dryer	To dry materials while making them float in the hot air current and conveying them in parallel! ① Drying time is short (1 - 10 seconds) ② Even the use of high temp. air will do no damage to the material, thus allowing a safety operation. ③ Simple structure and easy operation ④ High thermal efficiency	Continuous large-scale treatment is possible. Example: Ammonium sulfate 15t/hr Coal 10t/hr	① $h_a = 2000 - 6000$ ② $300 - 600$ ③ $50 - 75$ ④ $1 - 3$	① Muddy, cakey, powder particle, lump ② $20 - 75\%$ (W.B)	① Suitable for removing absorbed moisture ② To dry coal, clay, synthetic resin, inorganic chemicals	① Moisture evaporation 1 - 1.5 kg/kg gas ② Low construction cost
Spray dryer	To spray fluid to be distributed and carried in concurrent, or counter-current ① Such processes as grinding, classification and filtering can be omitted. ② Powder particle products can be obtained in short process.	Evaporated moisture Maximum 6t/hr	① $h_a = 20 - 80$ ② Concurrent 200 - 300 ③ Concurrent 250 - 400 ④ $20 - 30$	① Solution Suspension ② $90 - 50\%$ (W.B)	① To dry milk, dyestuff, detergent, coffee, synthetic resin, etc. ② Spray granulation in which the molten material is sprayed to be hardened in cold air.	① Evaporated moisture should be 100 kg/hr or more; otherwise, it will be uneconomical. ② Large thermal consumption ③ Rotary disk spraying involves high maintenance cost. ④ Unsuitable for materials with high viscosity and large wearability
Material agitation Rotary dryer	Drying methods available are: direct contact method where the material agitated inside the cylinder and hot air are directly contacted; the method where the material and hot air are directly/indirectly contacted; external fire method in which the material inside the cylinder is indirectly heated from outside the cylinder. ① High operation safety ② Large-scale treatment ③ Wide-ranging material to be treatable	Continuous, large-scale drying is possible. Example: Clay 70 t/hr Limestone 60 t/hr Chemical fertilizer 120 t/hr	① $h_a = 100 - 200$ ② concurrent 250 - 800 concurrent 300 - 600 ③ $40 - 50$ ④ 2	① Powder particle ② Lump ③ $40 - 50$ (W.B or less)	① Rather rough drying where large-scale treatment is required ② Drying where material staying time will extend from 2 to 3 hours is possible. ③ To dry limestone, clay, fertilizer, lime, synthetic resin, inorganic chemicals, etc.	① High construction cost
Multi-stage disc dryer	Annular discs are placed on multiple stages, the material on each of which is agitated by rotation of the arm extending from the central shaft, and falls successively on the lower stage, while being contacted with hot air and dried. ① Smaller amounts of dust. ② Saving of floor space	Continuous and large-scale processing is possible.		① Powdered and granular	① Active carbon, medicines, etc. etc.	① Construction and operation costs are high.



**Table 5.7 Comparison of Spraying Methods**

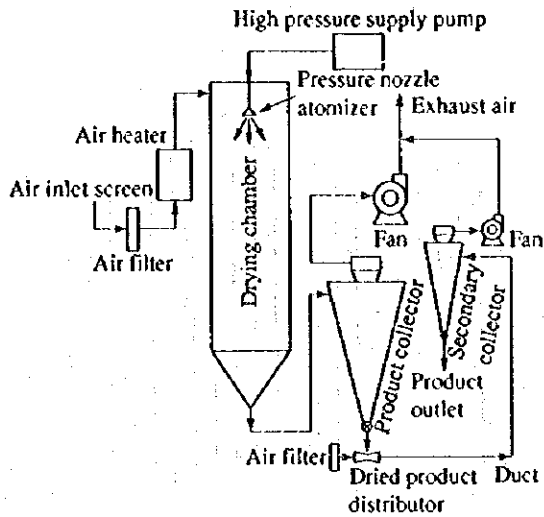
		Rotary disc type	Pressure nozzle type	Bi-fluid type
Properties of fluid	Solution	Suitable	Suitable	Suitable
	Slurry	Suitable	Suitable (Strainer is necessary)	Suitable (strainer is necessary)
	Easy to get sticky	Care should be taken.	Suitable	Suitable
	Highly viscous	Generally, 1 ~ 2 poise	Same as the left.  (For the thixotropic solution, this type is capable of treating up to 50 ~ 100 poise)	Generally 1 ~ 2 poise
Operation	Spraying volume	Treatable range: usually 0 ~ 5000 l/hr More than the above	50 ~ 2,500 l/hr for one nozzle For more than this, setting of many more nozzles is required	0 ~ 150 l/hr for one nozzle More than this may be treatable depending on the fluid
	Changing flow amount	Flexible	The particle diameter will be changed by 60 ~ 100 %	Particle diameter will be changed to 60 ~ 100 %
	Changing viscosity	Rather easy	Rather difficult	Rather easy
	Power	Generally same as the right No. of disc rotations: 3,000 ~ 2,500 rpm	Mostly same as the left Pump Pressure: 10 ~ 350 kg/cm <sup>2</sup>	Fluid pressure and air pressure: Up to 3 ~ 5 kg/cm <sup>2</sup> G
	Maintenance and inspection	Rather difficult	Easy	Easiest
	Chamber	Diameter: large	Diameter: small, High	Diameter: small
Cost	Equipment cost	High (sprayer)	High (3-plunger pump)	Low (However, compressed air supply is necessary)
	Maintenance cost	Almost same as the right	Almost same as the left	Minimum
Products	Particle diameter	Fine particle (Average dia: 30 ~ 100 μ)	Coarse particle (Average dia.: 40 ~ 350 μ)	Fine particle (Average dia.: 30 ~ 60 μ)
	Particle diameter distribution	Narrow	Narrow	Narrow
	Bulk specific gravity, moisture content, etc	No significant difference		

Figure 5.37 An Example of Spray Dryer

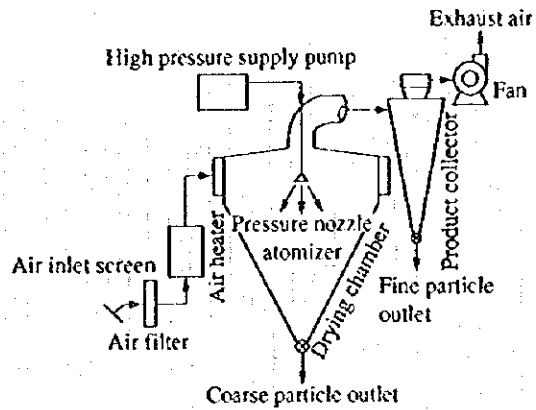


Undiluted solution (per hour)	Diameter and height of Drying chamber	No. of rotations of sprayer (each minute)	Diameter of Spraying Disc	Total Horsepower	Area of the building required for the equipment dot
Up to 10 liter	Diameter 1,400 Height 3,200	20,000	70 m/m	2	5.3 m <sup>2</sup>
Up to 50 liter	Diameter 3,000 Height 9,500	1,200	125 m/m	12.5	50 m <sup>2</sup>
Up to 100 liter	Diameter 3,800 Height 12,000	1,200	160 m/m	15	55 m <sup>2</sup>
Up to 250 liter	Diameter 5,090 Height 13,000	8,000	250 m/m	30	70 m <sup>2</sup>
Up to 500 liter	Diameter 6,300 Height 16,000	8,000	300 m/m	40	80 m <sup>2</sup>
Up to 1,000 liter	Diameter 7,000 Height 18,000	7,000	350 m/m	100	100 m <sup>2</sup>
Up to 2,500 liter	Diameter 9,500 Height 25,000	6,000	400 m/m	250	160 m <sup>2</sup>
Up to 4,000 liter	Diameter 10,200 Height 27,000	5,000	450 m/m	300	220 m <sup>2</sup>

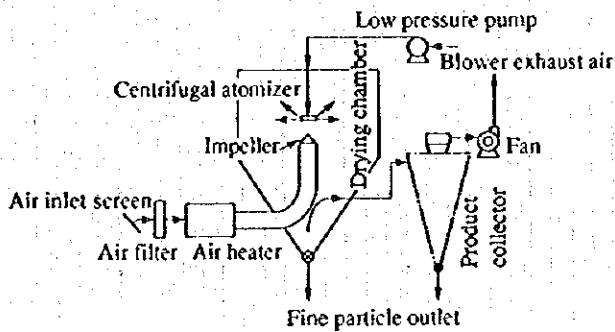
**Figure 5.38 Configuration Examples of Spray Dryers**



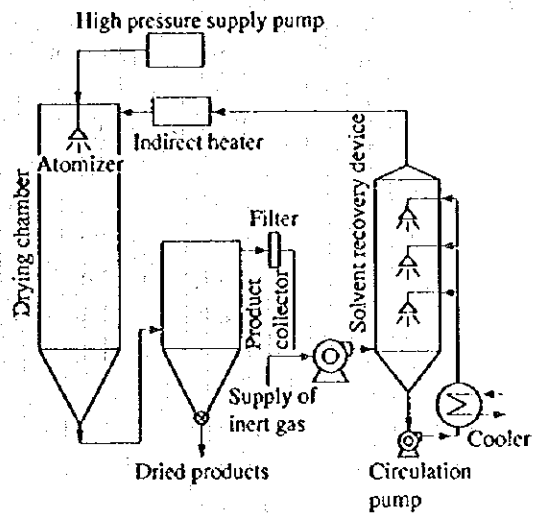
(A) System Diagram of Open Cycle Concurrent Type Spray Dryer for the Single-fluid Nozzle  
(This type is most practical for drying foods)



(B) System Diagram of Open Cycle Mixed Flow Conical Type Spray Dryer  
(This type features the high-pressure nozzle atomizing system and the tangential air inlet.)



(C) System Diagram of Open Cycle Concurrent Conical type Spray Dryer  
(This type of the system, designed in Europe, has a hot air duct inside the drying chamber, the bottom of which serves as a product collector)



(D) System Diagram of Closed Cycle Concurrent Spray Dryer  
(This type is so arranged that it will operate with inert gas as desiccating agent)

**Table 5.8 Application Examples of Spray Dryers**

Material	Inorganic	Organic powder	Powdered milk	Detergent	Detergent	Detergent	
Drying capacity (kg-Product/hr)	650	180	1,033	500	2,500	5,000	
Material temp. [°C]	45	20	40	50	50	50	
Material moisture content (DB%)	300-400	100	66.8	100	65	87	
Product moisture content (DB%)	2	2	3.1	8	7	7.5	
Product representation particle dia. [μφ]	63-74	60	60	350	495	800	
Product apparent density [g/cm <sup>3</sup> ]	0.3-0.4	0.6	0.65	0.28	0.26	0.3	
Hot air	Amount to be used [m <sup>3</sup> /min]	600	85	1,210	380	870	1,000
	Inlet temp. [°C]	300	230	160	190	230	250
	Outlet temp. [°C]	150	70	85	80	90	85
Spraying method							
Rotary Disc	Diameter [mm]	450	150				
	No of rotations [rpm]	4,500	7,500				
Pressure nozzle	Pressure [kg/cm <sup>2</sup> abs]				40	30-40	30-40
	Diameter [mm]			1.6	2.4 3.2	3-5	3
	No.			12	1	6-8	7
System type	Concurrent	Concurrent	Concurrent	Countercurrent	Countercurrent	Countercurrent	
Tower dia. [m]	9.5	6	8	4.2	6	6	
Length of the cylindrical section [m]	7	5	13	11	18	17	
Length of the conical section [°C]	9.3	5.9	0.5	4.3	5.5	5	
Material viscosity [cp]	48	100	3,000	3,000	5,000		

**(2) Rationalization in the use of thermal energy**

**a. Pretreatment of material**

It is advisable to remove as much moisture as possible in the preceding process and to charge soluble material into the drying process after thickening them as much as possible, or insoluble ones after dehydrating mechanically as much as possible. Although a dehydrater is comparatively expensive, the consumption energy is by far less compared with drying in which moisture is thermally removed by evaporation.

**b. Prevention of heat loss**

Since small-scale dryers have generally large specific surfaces and the heat loss is apt to be great, possibly exceeding 10 % of heat input, they must be completely heat insulated. Next, there may be much more loss due to leakage of hot air than is expected and as such it is necessary to provide flanges or connections between moving and fixed parts inlet of material and outlet of products, etc. with seals according to the respective internal pressure.

**c. Circulation of exhaust**

In hot air dryers, the amount of sensible heat carried out by exhaust is very great. To reduce this, it is important to reduce the amount of exhaust in addition to lowering the temperature. Circulating a portion of exhaust gas for re-use increases the thermal efficiency.

In the system of feeding large quantities of hot air at right angles to the material advance direction such as band through-circulation dryers, the exhaust is at high temperatures and has low humidity. Therefore, the efficiency can be increased by dividing hot air blowing into several sections and using exhaust on the latter side for the preceding side successively. When drying is performed at high temperatures, the drying rate hardly decreases because of the increase in humidity and as such circulation of the exhaust can be usually utilized.

d. Recovery of sensible heat from exhaust

Recover sensible heat carried out by exhaust and utilize it to preheat drying air, in which case a plate type heat exchanger, heat pipe, etc. are suitable for the heat exchanger. However, the latter has a difficulty in that the equipment is expensive. When a heat exchange system is adopted, attention should be paid to the fact that dust, moisture, and others contained in the exhaust contaminate the heating surface and possibly may cause corrosion. Periodic cleaning and inspection are required.

Next, a method to directly recover heat retained in the exhaust without using heat exchangers should be studied. For example, when the liquid to be dried is concentrated by allowing it to come into direct contact with the exhaust in spray dryers, almost all sensible heat of the exhaust can be utilized.

e. Recovery of latent heat from exhaust

The percentage of heat used for evaporation of moisture to heat consumed for the drying operation is very great. Since this evaporated vapor accompanies the exhaust, the thermal efficiency will remarkably increase if this latent heat is recovered. To recover, utilize it as a heating source for concentrating equipment by means of a heat pump. Taking into consideration temperature and humidity of the exhaust, it is necessary to study for what purpose it can be utilized in the plant.

f. Recovery of sensible heat from dried products

When dried products are at comparatively high temperature, recover heat retained in them to utilize for preheating the drying air. Since the temperature of the dried products is not so high mostly, preheat air by means of a fluidized bed may improve the efficiency.

g. Others

It is often seen in chemical plants that air is used to cool reaction products, distillate or condensers for refrigerators. Although the temperature of the exhaust air in these cases is not so high, it can be mostly utilized as drying air because large quantities of air flow are available. In some cases, the temperature of the exhaust is so high that it can be fed as-is into dryers, resulting in high energy conservation.

## 5.2.7 Heat Pump, and Refrigeration Unit

### (1) Types of heat pump

Pump is an equipment for pumping liquid from a low place to a high place. A heat pump is an equipment for utilizing low temperature thermal energy by raising its temperature. It absorbs heat at the evaporator and releases the heat at the condenser. Among such equipment, an equipment for gathering heat at a temperature below the ordinary temperature with the purpose of obtaining low temperature is the refrigeration unit.

Recently, a unique type of dryer which uses a compression type refrigerator as a heat pump has been contrived. In this case, wet air which has taken moisture from the material to be dried in the dryer is introduced to the evaporator of the refrigerator, and after condensing and separating the moisture, it will be heated and its temperature will be raised in the condenser portion of the refrigerator, and returned to the dryer again. In other words, the thermal energy that is used for drying the material to be dried, is recovered as condensation latent heat of water at the evaporator of the refrigerator, then it is released to air again at the condenser portion. Consequently, it composes a thermally closed system, and what is discharged to the outside is only the moisture taken from the material to be dried.

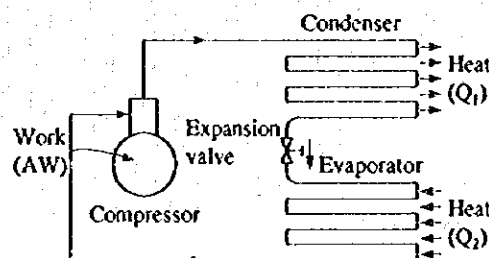
There are various methods of heat pump such as vapor compression type, steam ejector type, absorption type, and chemical type. However, from the standpoint of economics and performance, under current conditions, the vapor compression type and the absorption type are practical. The basic principle of these two systems is to transfer the heat by utilizing the process of evaporation and condensation of operating media.

### (2) Cycle of vapor compression system

The basic structure of vapor compression system is shown in Figure 5.39.

The operating media which have become high in temperature and pressure when they are compressed by the compressor, will emit heat to the outside by the condenser, and become liquid, then the pressure will be reduced after they pass through the expansion valve and enter the evaporator, where they absorb heat from the outside and become gas again, then enter the compressor.

Figure 5.39 Vapor Compression Type Heat Pump Cycle



During this cycle, the operating media receive workload in the compressor from the outside.

If we represent this workload by  $W$  kg-m, the heat amount absorbed by the evaporation by  $Q_2$  kcal, and that emitted from the condensor by  $Q_1$  kcal, the following relation will be obtained.

$$AW = Q_1 - Q_2$$

where

$$A = (1/427) \text{ kcal/(kgf-m)}$$

In order to know the various changes of the operating media in the cycle, there are the following charts used in general.

- a. Pressure-Enthalpy Chart (P-i Chart): A chart in which the Pressure  $P$  is taken on the Y axis (axis of ordinates), and enthalpy  $i$  is taken on the X axis (axis of abscissas).
- b. Temperature-Entropy Chart (T-s Chart): A chart that shows absolute temperature  $T$  on the Y axis, and Entropy  $s$  on the X axis.

P-i Chart is rather broadly used, because it is convenient in various design calculations and operation analysis.

Chart which indicates the cycle on the P-i Chart is Figure 5.40. Point A shows the condition in which the operating media are sucked into the compressor (low temperature and low pressure) and they will be compressed and become the condition of Point B (high temperature and high pressure).

At this time, theoretically, it is adiabatic compression and will be on the isoentropic line. The compression workload  $W$  (kgf-m/kg) will be

$$AW = i_B - i_A$$

where  $i_A$ : Enthalpy at the suction inlet of the compressor (kcal/kg)  
 $i_B$ : Enthalpy at the discharge outlet of the compressor (kcal/kg)  
 $A$ : 1/427 (kcal/kgf-m)

The refrigeration effect at the evaporator (refrigeration capacity per 1 kg of refrigerant)  $q_c$  will be

$$q_c = i_A - i_D \text{ (kcal/kg)}$$

where  $i_D$ : Enthalpy at the inlet of the evaporator (kcal/kg)

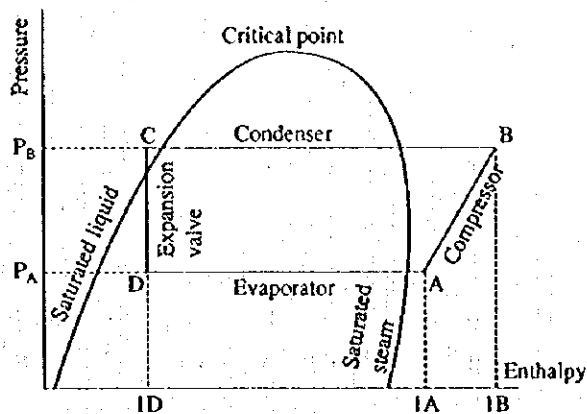
The ratio between the refrigeration effect and the compression workload is called the coefficient of performance, and if it is expressed by  $E$ ,

$$E = (i_A - i_D)/(i_B - i_A)$$

In the case of heat pump, the coefficient of performance shall be the ratio between the amount of heat that was utilized at the condenser and the compression workload.

$$E_h = (i_B - i_C)/(i_B - i_A) = 1 + E$$

Figure 5.40 P-i Diagram



Besides the closed cycle vapor compression heat pumps mentioned above, there are also open cycle heat pumps which directly compress the vapor generated in the distillation tower or evaporator, and utilize this as heat source.

### (3) Compressor

Depending on the compression mechanism, the compressors can be divided into the reciprocating type, the centrifugal type and the rotary type.

The reciprocating type can be designed for small capacity ones as well as large capacity ones and can be used for almost any kind of temperature conditions. However, when the capacity becomes large, the centrifugal type will become cheaper. On the other hand, in case the compression ratio is large, the centrifugal type will be more expensive, and if the capacity is rather small, the efficiency will not be so good. (i.e. at 40 m<sup>3</sup>/min. or less)

As for the screw compressor which belongs to the rotary type, there is not much difference in efficiency as far as capacity is concerned, but as to the compression ratio, new types of screw compressor in which 1 stage equals 2 ~ 3 stages of the reciprocating type have been developed, and are being widely used.



In case the compressor is operated at high compression ratio, the volume efficiency drops and the discharge gas temperature rises. Consequently, degradation or carbonization of the lubricant occurs, and damages of the discharge valves are liable to occur. Normally, the 1 stage compression should have a compression ratio of 8 ~ 10 or less. In case the compression ratio exceeds this level, 2 stage or 3 stage compression should be adopted.

#### (4) Refrigerant

Refrigerants are media for thermodynamic changes inside of refrigerating cycle, and they are substances which possess the following special properties:

##### a. Physical properties

- 1) The critical temperature is higher than the ordinary temperature, and the freezing point is low.
- 2) Heat of vaporization is large (The circulation amount of the refrigerant can be less.)
- 3) The ratio of specific heat of the gas, that is, (constant pressure specific heat)/(constant volume specific heat) is small.
- 4) The coefficient of performance is large.
- 5) The specific volume of the gas is small. (The volume of the compressor may be designed small)
- 6) The condensation pressure and the vaporization pressure are suitable.

##### b. Chemical properties

- 1) Under the usage conditions, they are chemically stable.
- 2) They are inert and have no corrosiveness.
- 3) Solubility towards lubricants is small.
- 4) At both the gas and liquid state they have low viscosity.
- 5) The thermal conductivity is large.

As refrigerants, together with ammonia, a lot of halogenated hydrocarbons are broadly used. However, recently, it has become clear that most of the halogenated hydrocarbons become the cause of breaking the ozone layer in the stratosphere, and their use was prohibited.

The characteristic values of refrigerants that are not restricted are as shown in Tables 5.9 and 5.10. Furthermore, the P-i Charts of the refrigerants are shown in Figure 5.41.

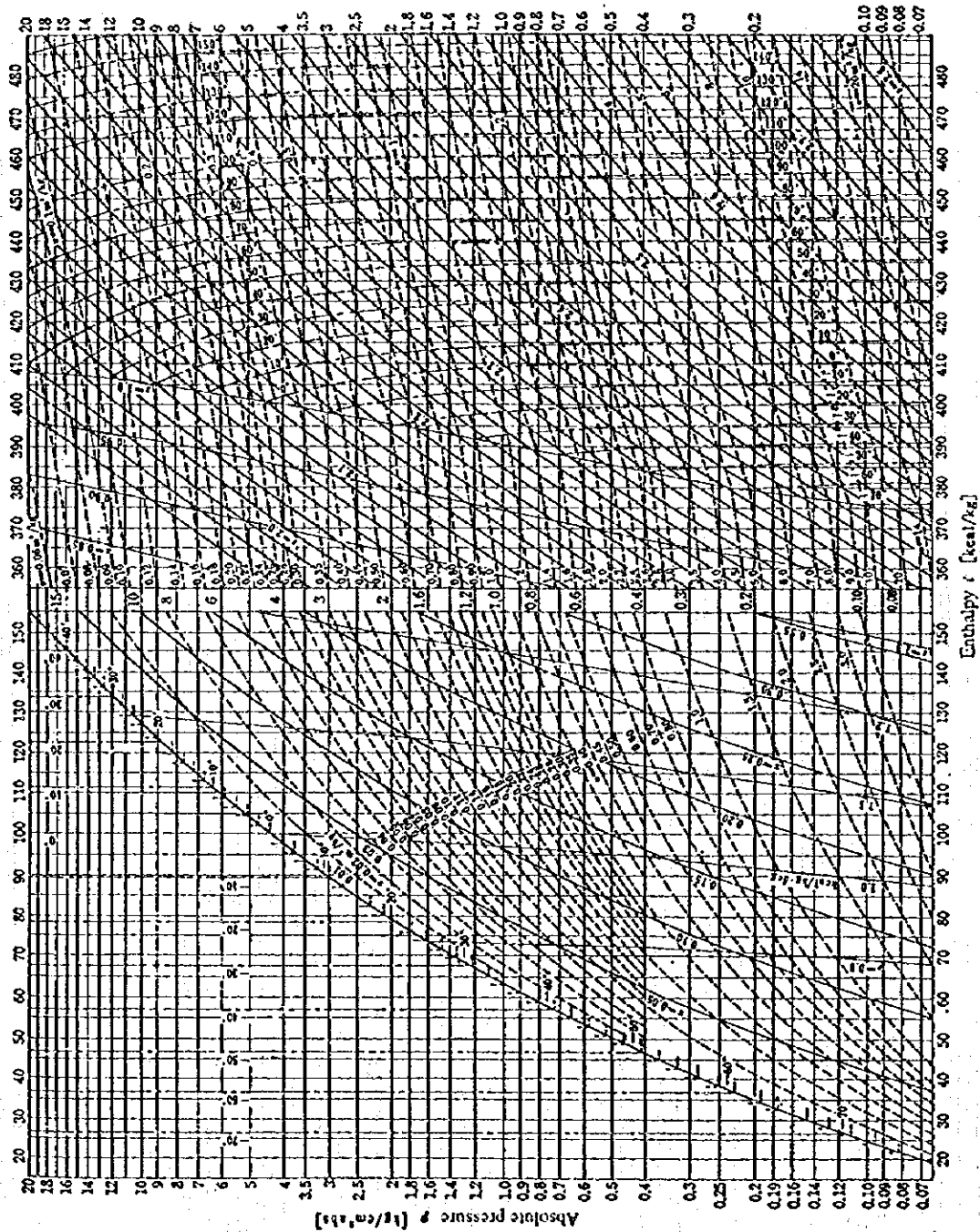
**Table 5.9 Refrigerant Properties (for High Temperature)**

Classification of refrigerants		Ammonia	Propane	Propylene	n-butane	i-butane
Chemical formula		NH <sub>3</sub>	C <sub>3</sub> H <sub>8</sub>	C <sub>3</sub> H <sub>6</sub>	C <sub>4</sub> H <sub>10</sub>	C <sub>4</sub> H <sub>10</sub>
Molecular weight		17.03	44.06	42.08	58.12	58.12
Boiling point (at atmospheric pressure)	°C	-33.3	-42.3	-41.0	-0.5	-11.7
Freezing point (at atmospheric pressure)	°C	-77.7	-189.9	-185.2	-135	-145
Critical temperature	°C	133	94.4	91.8	152.2	134.9
Critical pressure	kg/cm <sup>2</sup> (abs)	116.50	46.51	47.0	38.7	37.2
Evaporation pressure at -15 °C	"	2.410	2.946	3.70	0.576	0.921
Condensation pressure at 30 °C	"	11.895	10.918	13.10	2.92	4.18
Compression ratio at Te = -15 °C and To = 30 °C		4.94	3.706	3.54	5.07	4.54
Heat of evaporation at -15 °C	kcal/kg	313.53	94.56	96.10	95.00	88.6
Refrigerating capacity at standard refrigerating cycle	"	269.03	70.68	72.8	74.2	65.3
Refrigerant circulation amount per ton of Japan refrigerating capacity	kg/hr	12.34	46.97	45.6	44.7	50.8
Specific volume of saturated steam at -15 °C	m <sup>3</sup> /kg	0.5087	0.1548	0.142	0.623	0.400
Specific volume of saturated liquid at 25 °C	l/kg	1.6588	2.053	0.647	1.740	1.81
Compressor discharge temperature	°C	98	36.11	42.0	32.0	27.0
Theoretical piston displacement per ton of Japan refrigerating capacity	m <sup>3</sup> /hr	6.278	7.272	6.48	27.8	20.3
Theoretical indicated horsepower per ton of Japan refrigerating capacity		1.08	1.079	1.09	1.02	1.14
Coefficient of performance		4.87	4.80	4.78	5.10	4.53

**Table 5.10 Refrigerant Properties (for Low Temperature)**

Classification of refrigerants		Ethane	Ethylene	Methane
Chemical formula		$C_2H_6$	$C_2H_4$	$CH_4$
Molecular weight		30.07	28.05	16.04
Boiling point (at atmospheric pressure)	°C	-88.6	103.90	-161.49
Freezing point (at atmospheric pressure)	°C	-172	-169.5	-182.48
Critical temperature	°C	32.3	9.2	-82
Critical pressure	kg/cm <sup>2</sup> (abs)	49.8	51.7	45.80
Evaporation pressure at -100°C	"	0.536	1.28	26.60
Condensation pressure at -30°C	"	10.86	19.7	Critical point or above
Compression ratio at $T_e = -100^\circ\text{C}$ and $T_o = 30^\circ\text{C}$		20.3	15.4	—
Heat of evaporation at -100°C	kcal/kg	121.7	113.4	72.8
Refrigerating capacity at standard refrigerating cycle $T_e = -100^\circ\text{C}$ and $T_o = -30^\circ\text{C}$	"	77.0	69.3	—
Refrigerant circulation amount per ton of Japan refrigerating capacity	kg/hr	43.1	47.9	—
Specific volume of saturated steam at -100°C	m <sup>3</sup> /kg	0.880	0.378	0.022
Specific volume of saturated liquid at -30°C	l/kg	2.17	2.27	—
Compressor discharge temperature	°C	36	49	—
Theoretical piston displacement per ton of Japan refrigerating capacity	m <sup>3</sup> /hr	37.9	18.1	—
Theoretical indicated horsepower per ton of Japan refrigerating capacity		4.1	3.3	—
Coefficient of performance		1.7	1.6	—

Figure S.41 P-i Diagram of Ammonia



If refrigerants for high temperature use such as R-22 or ammonia are used at the vaporization temperature below  $-80^{\circ}\text{C}$ , the saturation pressure at the vaporization temperature will be extremely low and very high vacuum will occur. As a result, the volume efficiency of the compressor will drop considerably. Thus, in this temperature range, in most cases, a two-refrigerant system is adopted where refrigerants which have comparatively high saturation pressure such as ethane and ethylene are used as the low temperature side refrigerant.

(5) Absorption type cycle

The absorption type heat pump utilizes the changes in partial pressure corresponding to the changes in concentration when the operating media are absorbed by the absorption liquid.

Although it is not necessary to mechanically compress the operating media, steam, warm water, combustion exhaust gas will be required as driving heat energy for evaporating the operating media from the absorption liquid, and concentrating the absorption liquid.

The structure of the absorption type heat pump is shown in Figure 5.42. The operating media gained heat from the brine and were vaporized at the evaporator, and were absorbed in the absorbing liquid in the absorber. The absorption liquid of which the concentration dropped will be sent to the regenerator via the heat exchanger where it is heated, and the operating media are vaporized, and absorbing liquid were concentrated, and returned to the absorber. The operating media that were evaporated will be cooled by the condenser and liquefied, and their pressures are reduced at the expansion valve, then sprayed on to the evaporator.

The absorption type heat pumps consist of the aforementioned Type 1 Absorption Heat Pumps which require heat source for high temperature driving and the Type 2 Absorption Heat Pumps which do not require high temperature heat source but require low temperature cooling water.

The cycle of each is shown in the Dühring Charts of Figure 5.43 and Figure 5.44.

Figure 5.42 Absorption Type Heat Pump

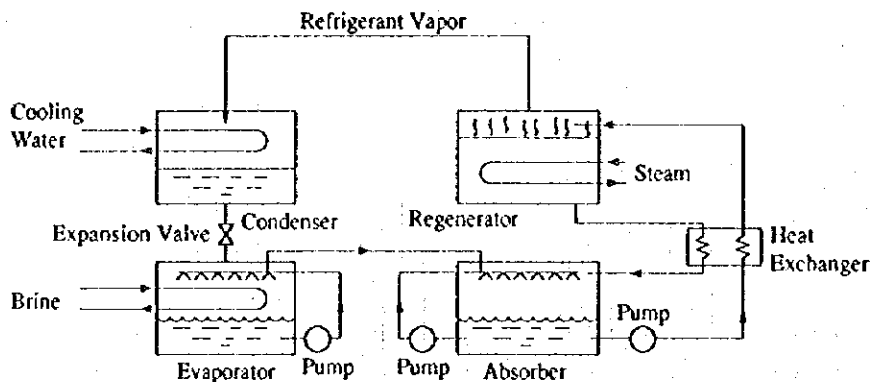


Figure 5.43 Dühring Chart for Heat Pump (Type 1)

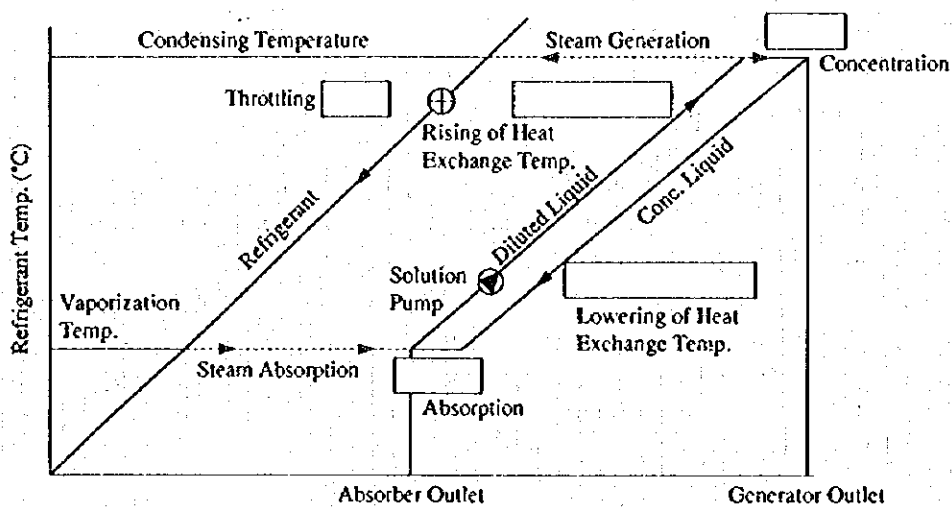
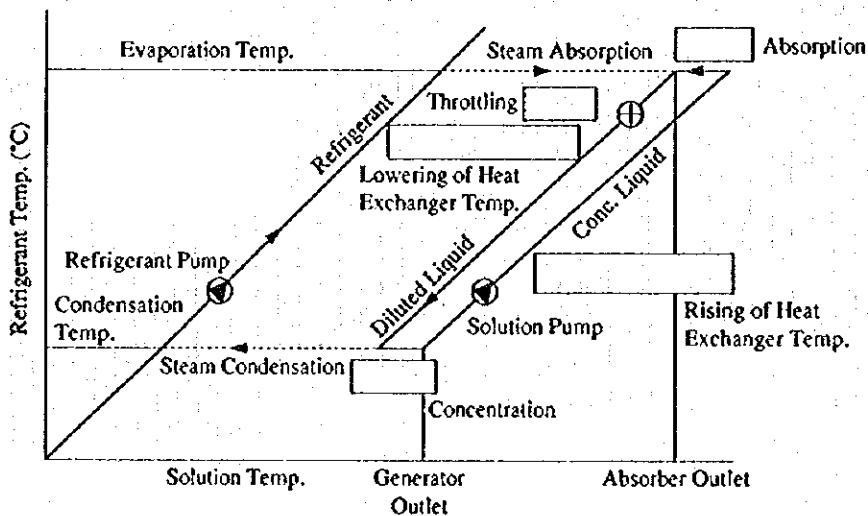


Figure 5.44 Dühring Chart for Heat Pump (Type 2)



In the case of Type 2 Absorption Heat Pump, the absorption heat generated at the time the operating media which were vaporized by the low temperature heat source such as warm effluent water are absorbed by the absorption liquid, is utilized.

Since heat of absorption liquid which has a temperature higher than the vaporization temperature by an amount equal to the boiling point rise will be utilized, a warm water having a temperature higher than the effluent temperature will be obtained.

For these absorption type heat pumps, as a combination of absorption liquid and operating media, there are aqueous solution of LiBr, LiCl, H<sub>2</sub>SO<sub>4</sub> and water, water and ammonia, tetra-ethylene glycol dimethyl ether and R22, LiBr and Methanol etc. The absorption type heat pumps are suitable for applications of comparatively large capacity.

(6) Brine

The salt solution which acts as an intermediary for cooling in the indirect freezing method is called brine. The most widely used type of brine is calcium chloride (CaCl<sub>2</sub>). Besides this, there are also sodium chloride (NaCl), magnesium chloride (MgCl<sub>2</sub>), methanol, ethanol, ethylene glycol, glycerine, etc. In Figure 5.45, the specific heat of brine is shown, and in Figure 5.46 the specific gravity and freezing temperature are shown.

Figure 5.45 Specific Heat of Brine

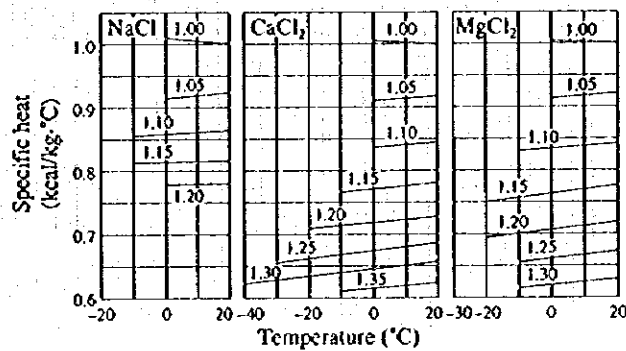
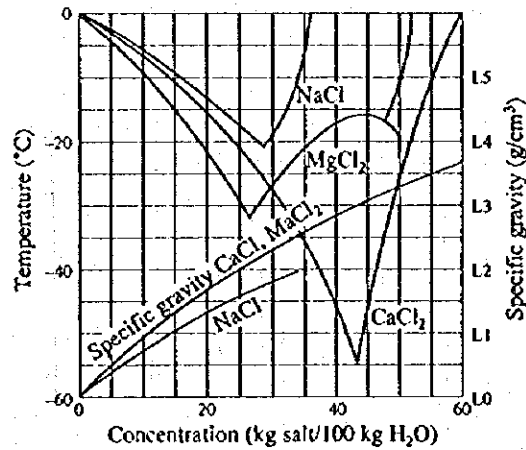


Figure 5.46 Freezing Temperature and Specific Gravity of Brine



(7) On the unit of refrigerating capacity

It is convenient to fix a unit to indicate the refrigerating capacity of refrigerator. However, since this varies with each country, it is necessary not to confuse them. Next, some examples are shown.

(Japan)

The refrigerating capacity to freeze 1 ton of 0 °C water into 0 °C ice in 24 hours is called 1 ton of refrigeration, and it is equivalent to 3,320 kcal/h.

(USA)

200 BTU/min. is called 1 ton of refrigeration. This is equivalent to heat quantity required to melt 2,000 pounds (lbs.) of 32 °F ice in 24 hours. (200 BTU/min. = 3,023 kcal/h)

(8) Rationalization of the use of refrigerating energy

In Table 5.11, the energy saving method of refrigerator and heat pump equipment is shown.



**Table 5.11 Energy Conservation Method of Refrigerator and Heat Pump Equipment**

Method of Energy Conservation	Freezer		Heat Pump	Remarks		
	Steam Comp.	Absorp.				
Decrease in Load Conv. Dr.	Decrease in Freezing (Heating) Load	○	○	○		
	Decrease in Conveying System Drive	○	○	○		
Improvement of Efficiency	Cycle Improvement	Adoption of Supercooling Economizer	○	—	○	
		Steam Temperature Rise	○	○	○	High Heat Transfer Pipe
		Condensation Temp. Drop	○	○	○	High Heat Transfer Pipe
		Selection of Optimum Refrigerant	○	△	○	Mixed Refrigerant, etc.
		Heat Transfer Promotion in Heat Exchanger	—	○	—	High Heat Transfer Pipe
		Decrease in Solution Circulation	—	○	—	
	Others	Decrease in Auxiliary Equipment Power	○	○	○	
		Waste Gas Heat Recovery	—	○	—	Direct Firing
	Partial Load Efficiency Increase	Division into Number of Units complying with Annual Load Conditions	○	○	○	
		Good Capacity Control System of Partial Load Characteristics	○	○	○	
Volume Change of Cooling Water (Brine) Side		○	○	○		
Inlet Temperature Control of Cooling Water (Brine)		○	○	○		
Optimum Air Ratio Control		—	○	—	Direct Firing	
Load Change Response Improvement	Optimum Operation by Microcomputer	○	○	○		
	Electronically Controlled Expansion Valve	○	—	—	For miniatures	
	Microcomputer Control of Solution Circulation Amount	—	○	—		
	Cascade Control by Cycle Temperature	—	○	—		
	Decrease in Solution Retention	—	○	○		
Control	Fouling Countermeasure	○	○	○	Automatic Tube Cleaning	
	Accurate Hot-Cold Switchover	—	○	○	Direct Firing	
	Maintenance of Air-Tightness	○	○	○		

\*1) In case of absorption type heat pump 0.

**a. Improvement of cycle**

Install a supercooler next to the condenser, and by super cooling the operating media with the cooling water, increase the refrigerating effect and aim at decreasing the circulation amount of the media.

Make compression by two stages, and connect the intermediate stage with the economizer.

If the liquid pressure of the condenser outlet is reduced to the intermediate stage pressure by the economizer, a portion of it will vaporize, and the media temperature will drop to the saturation temperature equivalent to the intermediate stage pressure. Consequently, the refrigeration effect will be increased. As a result, although the second stage compression power will not change much, the compression power of the first stage can be reduced.

b. Capacity adjustment

In case the load is reduced, if the amount of cooling water is decreased in accordance with the load, the pump power can be reduced.

In case the amount of cooling water and the cooling water temperature entering the evaporator are kept constant, when the load is low, the cooling water temperature of the outlet, that is, the vaporization temperature will rise, and the compressor power will be decreased.

As a means to decrease the suction amount of the compressor, in case of the reciprocating compressor, the following methods are executed.

- 1) "Suction valve opening system" which makes the suction valves idle in accordance with the load, and makes the cylinder No-Load in steps, in case of the multi-cylinder type.
- 2) "Cylinder head by-pass system" in which by-pass valves are installed on each cylinder, and do not let the compression process take place.
- 3) "Hot gas by-pass system" in which high temperature exhaust gas is charged between the expansion valve and the evaporator.
- 4) "Clearance increment system" in which a clearance pocket is made to the cylinder, and the apparent volume efficiency is lowered.
- 5) "Motor speed control system" in which the drive motor speed is changed.

The systems of a, b, and e will be related to the reduction in power consumption. Since the power consumption remains unchanged in case of System c, it is preferable to utilize this for reducing the capacity to 0 ~ 25%.

In the case of centrifugal compressor, the simplest method is to close the discharge valve. However, when it enters the surging zone, it will hinder the operation. In the "suction vane control system", several guide vanes are installed to the suction inlet, and the volume is varied by changing the tilting angle of the vanes. So it is a good system in which power consumption can be reduced without worrying about surging.

c. Purging of non-condensable gas

Sometimes non-condensable gases are mixed in the circulating refrigerant. The components of these non-condensable gases are  $N_2$ ,  $O_2$ ,  $H_2$ ,  $Cl_2$ , hydrocarbons, etc. The cause of such gases being mixed can be attributed to insufficient purging of the air in the equipment when the refrigerant is charged, decomposition of the lubricant, chemical reactions inside of the equipment, etc. In case non-condensable gases are mixed in the refrigerant, it will hinder the heat transfer of the condenser or occupy a certain space in the equipment and decrease the heat transfer surface. As a result, the condensation pressure will increase, and the input of the refrigeration unit will increase or the refrigerating capacity will lower.

In order to check whether non-condensable gas has been mixed or not, stop the equipment and run water through only the condenser. After sufficient time has elapsed, if the pressure at the time the water temperature and the refrigerant temperature have become equal is higher than the saturation vapor pressure of the refrigerant, it means that non-condensable gas has been mixed.

For instance, if there is a pressure difference corresponding to  $10\text{ }^\circ\text{C}$ , it is said that during actual operation, the condensation temperature will rise by about  $20\text{ }^\circ\text{C} \sim 25\text{ }^\circ\text{C}$ . The purging of the non-condensable gases is done by attaching special purging equipment to the upper portion or end portion of the condenser where the gases are liable to accumulate.

d. Fouling of the heat transfer

In case of the water cooled condensers, if hard well water or contaminated water is used for the cooling, scales will adhere to the heat transfer surface, and the heat transfer will be hindered. As a result, the condensation temperature and the pressure will rise (Figure 5.47). Consequently, the power consumption of the compressor will increase. (Figure 5.48)

Since the condensation pressure will be influenced the most by the cooling water temperature, we should confirm the relation between the cooling water temperature and the condensation pressure when the heat transfer surface is clean, and during the operation we should always compare the actual value with the normal value at clean condition and when the pressure difference becomes great, clean the heat transfer surface.

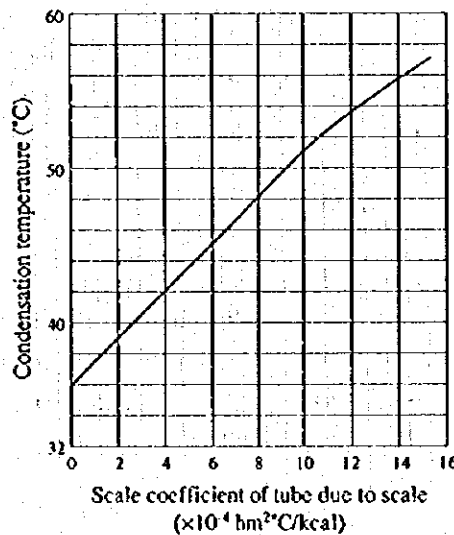
In the case of air-cooled condensers, since the temperature of the cooling air will have an influence on the consumption power, avoid installation near heat emitting equipment or indoors. Fresh outdoor air should be utilized.

In the case of evaporators, if the heat transfer surface becomes dirty, the vaporization temperature and pressure which gives the necessary coldness will drop (Refer to Figure 5.49). Since it will bring the increase in power consumption, attention should be paid to this matter during operation.

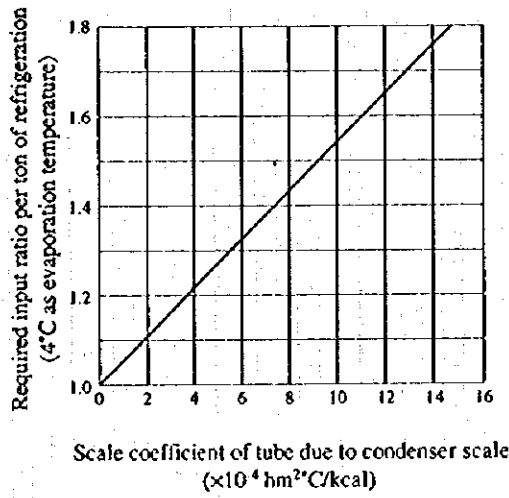
e. Cold insulation

In case the cold temperature portions of the equipment or piping is somewhat exposed, heat will enter and the freezing load will increase. Furthermore, the air in contact with the surface will reach dew point, and dew condensation will occur. As a result, the cold insulation material will absorb this moisture, the heat conductivity will become large, and the cold insulation effect will be lowered significantly. The cold insulation materials should be adhered to the surface by adhesives, and the outside should be covered completely with asphalt roofing (2 ~ 3 layers) so that the outside air cannot penetrate the cold insulation. With such structure, the decrease in cold insulation effect by the condensation of moisture in the air can be prevented.

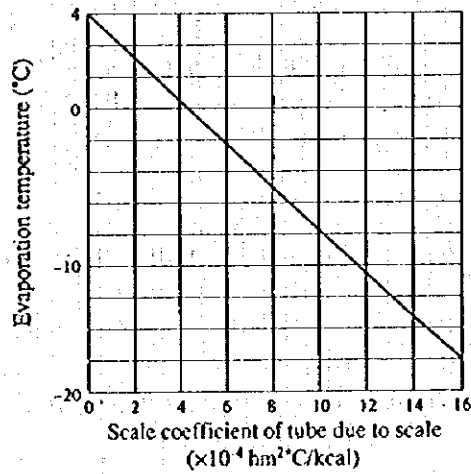
Figure 5.47 Heat Transfer Surface Fouling and Condensation Temperature



**Figure 5.48 Effect of Scale on Refrigeration Capacity**



**Figure 5.49 Effect of Scale on Evaporation Temperature**



### 5.2.8 Heating Furnace

In the chemical industry, there are many heating processes of the raw material for reaction or separation. The temperature range is also very broad, ranging from 100 °C to 1,000 °C or above.

By putting into consideration the safety against fires and the decomposition, in most cases steam is used as heat source, but combustion gas and heating oil are also used.

There are various types of heating furnace. Suitable ones will have to be selected depending on the condition of the material to be heated, heating temperature, amount to be treated, continuous or batchwise, etc. The heating furnaces are designed empirically, and they are classified by business types, by applications, by product conveying systems, by fuel types, by heating systems, by heat recovery systems, and by shapes. In this guideline, classification will be made mainly by applications such as heating, melting, or reacting, and heating methods such as direct or indirect, and furnace shapes such as vertical, horizontal, or tank type.

a. Fluid heating furnace

Boiler, pipe still, etc.

b. Solid melting furnace

Open hearth furnace, reverberatory furnace, crucible furnace, convertor etc.

c. Solid heating furnace

Direct heating type such as tunnel kiln, ring kiln, intermittent heating furnace, and indirect heating type such as retort furnace, muffle furnace, etc.

d. Rotary furnace

Internal heating cement kiln, external heating kiln, rotary type melting furnace

e. Vertical furnace

Gas producer, blast furnace, carbonization furnace, etc.

f. Fluidized bed furnace

Fluidized bed gas producer

g. Flash reaction furnace

Kopper's type gasification furnace

h. Multiple bed or rotary hearth type furnace

Herschhoff's furnace

i. Sintering furnace

j. Reaction furnace

Ammonia synthesis gas reformer, hydrogen chloride reactor, etc.

In the following paragraphs, as typical furnaces, pipe still and thermal media heating equipment will be described.

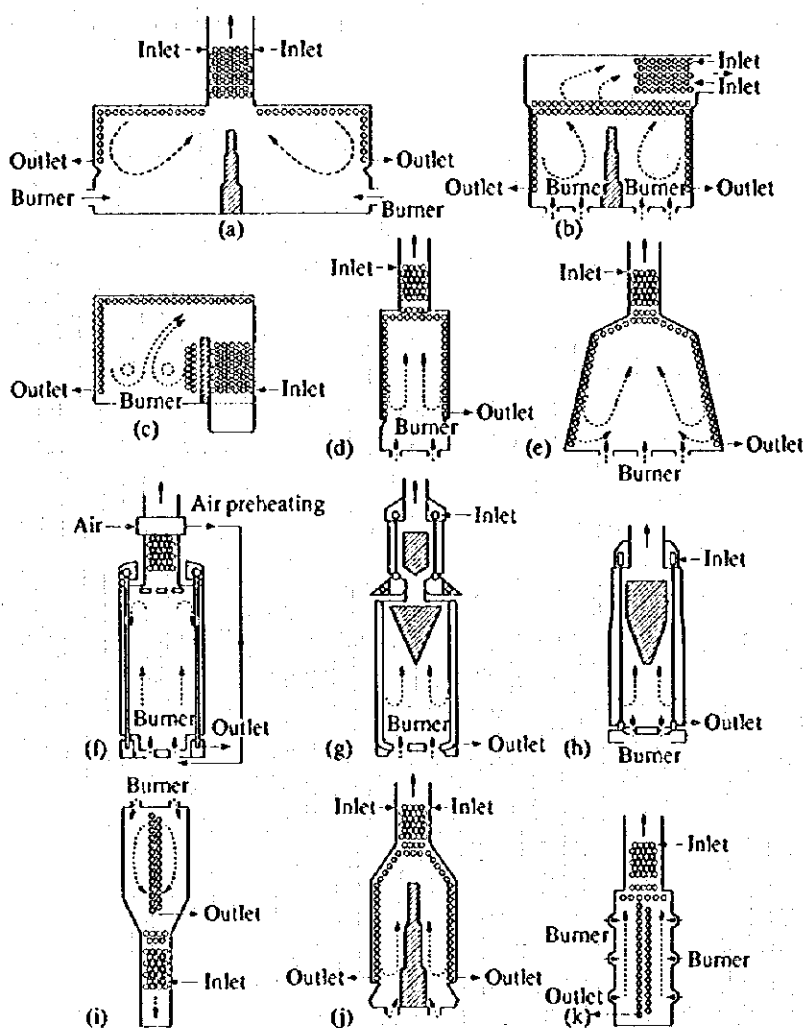
(1) Pipe still

In petroleum refining and in petrochemical industries, lots of pipe stills are utilized in the heating of petroleum. The pipe stills consist of the radiation portion and the convection portion. The radiation portion is the place where the radiation heat is absorbed directly from the flame, and the convection portion is the place where the heat is absorbed by convection heat transfer from the combustion gas.

Figure 5.50 shows a typical form of pipe stills. In the figures, the layout of the heating tubes and the flow direction of the combustion gases are illustrated.

The outstanding features and the drawbacks of each type are explained below.

Figure 5.50 Various Furnace Types of Pipe-Still



- (a) Large box-type (b) Separate-convection (Lummus)  
 (c) Down-convection (d) Straight-up (Born) (e) A-frame (Kellogg)  
 (f) Circular (DeFelorez) (g) Large isoflow (Petrochem)  
 (h) Small isoflow (Petrochem) (i) Equiflux (UOP)  
 (j) Double-upfired (UOP) (k) Radiant-upfired (Selas)

a. Collision of flames

In case the flame is too large, the tubes will be easily damaged. In particular, the inlet of the convection portion of the (c) type and the bottom portions of the (j), (d) types will be easily damaged.

b. Heat distribution

Since the (a), (c) types have large empty spaces in the furnace, the heat distribution will easily become non-uniform. Other models have less problems.



c. 2 system heating

Since all types except the (c) type have symmetric shapes, if 2 systems are laid out in a similar way, it is possible to gain approximately uniform heating.

In case the heating amounts of the 2 systems vary, use the model having a partition.

d. Heating control

The (i) and (k) types can adjust the heating amount arbitrarily. In particular, it is suitable for high temperature heating in the range of  $540^{\circ}\text{C} \sim 810^{\circ}\text{C}$ . In the case of cylindrical types such as (f), (g) and (h), and models having many radiation receiving surfaces, a low load operation is possible.

e. Models such as (c), (d), (h), (i), and (k) are suitable for small capacities and models such as (a), (b), (e), and (j) are suitable for large capacities.

f. Stacks

Models (a), (b), (c), and (i) require stacks, but in the case of other models, the furnace itself plays the role of stacks, and no stacks will be required.

g. Others

Since Models (g) and (h) use fin tubes at the convection portion, sometimes the amount of heat transfer at the convection portion will be greater than that of the radiation portion. In case the combustion gas is circulated, the flame temperature will drop, but the convection heat transfer will increase.

Furnaces having symmetric shapes will have uniform heat load, and it will have many advantages such as no coking, or no decomposition. Generally speaking, the radiation heat transfer amount is  $16,000 \sim 54,000 \text{ kcal/m}^2\text{h}$ , but if the cokes accumulate, the heat transfer coefficient drops significantly. Thus, it is necessary to remove them periodically.

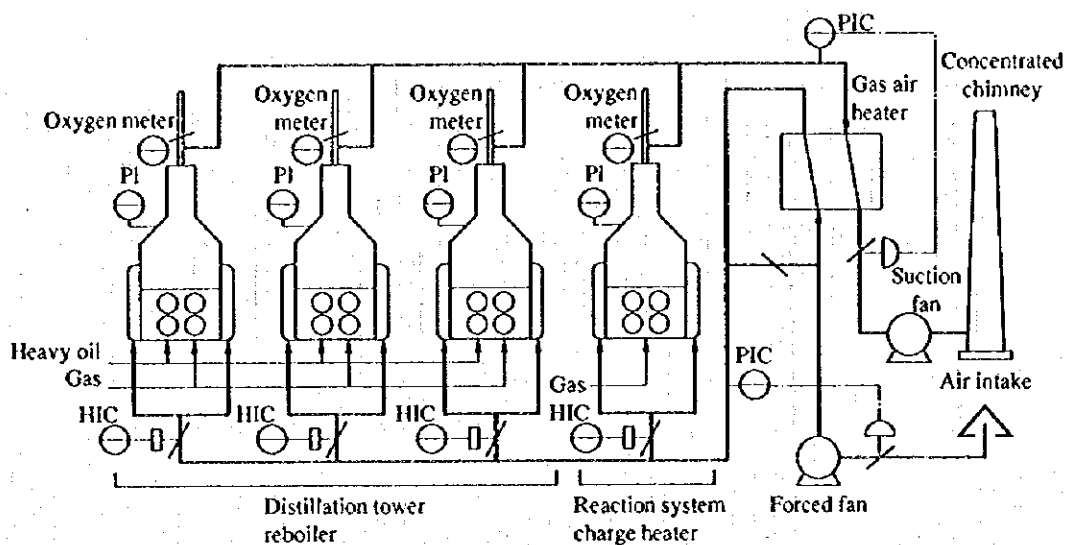
By lowering the exhaust gas loss, and by recovering the heat retained by the fluid, it is possible to raise the heat efficiency of the pipe still to  $80 \sim 90 \%$ .

As energy saving countermeasures of pipe still, an example case in Japan is shown.

- Improvement of efficiency by using stud tubes for the tubes of furnace convection portion
- Pre-heating of air (About  $290^{\circ}\text{C}$ , Figure 5.51) by installation of heat exchanger for exhaust gas/combustion air

- Stable combustion at low excess air ratio (1.2 or less) by the adoption of low excess air burner and prevention of air ingress.

Figure 5.51 Energy Conservation Measures for Pipe Steel



## (2) Thermal media heating equipment

In the vacuum distillation of plasticizers, fatty acids, higher alcohol, and organic chemicals, in the vacuum deodorization of vegetable oil, and hardened oil, and in the various reactions such as esterization reaction, condensation reaction, hydrogenation and dehydrogenation reactions, in many cases operations at 250 ~ 350 °C are required. By the use of thermal media (thermal fluids), for instance, a heat source of 300 °C can be obtained at 1 atm, so it is a very convenient method in comparison with electric heating method, direct firing method, or hot water heating method. Besides the pressure being low, it possesses outstanding features such as uniform heating, precision temperature control, rapid heating and cooling. However, on the other hand, the capital investment and thermal media (thermal fluids) are expensive.

The thermal fluids which are used in general are shown in Table 5.12. At a temperature range of 250 ~ 350 °C, thermal fluids of the organic type are used. In the temperature range of 350 ~ 500°C molten salts such as  $KNO_3$  and  $NaNO_2$  are used, and in the temperature range of 450 ~ 700 °C molten metals such as Na, K, and Hg are used.

As for the heating of the thermal fluids, can-type or tubular type heaters resembling a boiler are used. (Refer to Table 5.13)

In case air remains in the jackets, heating tubes, and the coils of the users, the heat transfer coefficient will drop significantly and the degradation of the thermal fluids owing to oxidation will be advanced. Thus, it is necessary to remove the air in the system completely. In case of the coils, it is very difficult to remove the air. Thus, in such a case, a vent box should be installed at the end of the coil to vent from this box or prior to charging the thermal fluids, it is preferable to make the system vacuum in order to remove the air as much as possible.

Table 5.12 Physical Properties of Thermal Fluids

Property	Dowtherm A*	Dowtherm B*	Fused salt Hi Tec †	Oil Mobiltherm 600 ‡	Oil Mobiltherm light ‡	Hydrochem § 750-200	Hydrochem § 700-160	Therminol ¶ FR-2	Mercury	NaK
Chemical formula	(C <sub>2</sub> H <sub>5</sub> ) <sub>2</sub> O	C <sub>2</sub> H <sub>5</sub> Cl <sub>2</sub> (C <sub>2</sub> H <sub>5</sub> ) <sub>2</sub>	NaNO <sub>2</sub>	NaNO <sub>2</sub> KNO <sub>3</sub>					Hg	44 wt. NaK
Molecular weight	165	147	92							
Specific gravity at 212°F	0.997	1.181	1.98(300°F)	0.90	0.930	1.11	1.08	1.38	13.35	0.84(600°F)
Melting point, °F.	53.6	-6.7	288	20(pour point)	-20(pour point)	5(pour point)	-40(pour point)	20(pour point)	-38.2	65
Boiling point, °F. (atm. pressure)	495.8	352		>600	>400		644	674.4	1,518	
Flash point, COC, °F	255	155		360	250	475		379		
Specific heat of liquid, B.t.u./(lb.)(°F.)	0.326(496°F)	0.412(352°F)	0.373(300°F)	0.589(500°F)	0.58(300°F)	0.56(600°F)	0.64(500°F)	0.33(500°F)	0.033(212°F)	0.25(600°F)
Heat of vaporization, B.t.u./lb.	125.0	119.0							117.0	
Heat of fusion, B.t.u./lb.	64	38	35						5.1	
Cubical expansion coefficient	0.00043		0.00020	0.00035			0.00039	0.00010		
Absolute viscosity of liquid, centipoise	0.30(600°F)	0.30(490°F)	1.7(800°F)	0.595(500°F)	0.873(300°F)	0.572(600°F)	0.605(500°F)	0.63(500°F)	1.23(200°F)	0.24(600°F)
Surface tension (contact with air), (contact with air), dynes/cm	43	37				37			487	105
Thermal conductivity liquid, B.t.u./hr. (sq. ft.) (°F./ft.)	0.076	0.064	0.35	0.067	0.0652	0.0590	0.072	0.057	4.85	15.6

\* The Dow Chemical Company.

† E. I. du Pont de Nemours & Co., Explosives Department, Wilmington, Del.

‡ Mobil Oil Corp.

§ American Hydrochem Corp.

¶ Monsanto Co.

**Table 5.13 Thermal Fluids Heaters**

Type	Vertical type	Horizontal multi-tube type	Marine type	Water tube type
Heat capacity (kcal/hr)	50,000 ~ 2000,000	50,000 ~ 15,000	100,000 ~ 6000,000	600,000 or more
Thermal efficiency (%)	50 ~ 55	50 ~ 55	about 70	70 ~ 75
Radiant section thermal load (kcal/m <sup>2</sup> ·hr)	15,000	—	15,000	—
Convection section thermal load (kcal/m <sup>2</sup> ·hr)	8,000	8,000	1,000	15,000~20,000
Construction	Simple-Small	Simple-Large	Simple-Medium	Dual drum water tube type
Thermal fluid	Small quantities	Large quantities	Large quantities	1 m <sup>3</sup> /10,000 kcal
Natural circulation system	Unsuitable	Suitable	Suitable	Unsuitable
Burner	Short flame burner	Fore-fire burner	Short flame burner	Easily adjustable burner
Applications	for small capacity	for small capacity	for general purposes	for large capacity

## **6. ENERGY CONSERVATION IN THE CEMENT INDUSTRY**



## 6. ENERGY CONSERVATION IN THE CEMENT INDUSTRY

### 6.1 Introduction

The cement in a broad sense is a general term for hydraulic inorganic chemical binders. The cement currently used widely as fundamental material for construction is, in a narrow sense, portland cement. Generally, however, this portland cement is commonly called cement, and the "cement" appearing in this guideline will also be limited to this portland cement.

Japanese Industrial Standard (JIS R5210) specifies that "portland cement shall be manufactured as follows: Raw materials mainly of calcareous material (lime) and argillaceous material (clay) are well blended in proper ratio, and the mixture is calcined until it is partly fused. The clinker thus obtained is then pulverized with a suitable amount of gypsum." The manufacturing process is principally based on the patent titled "Improvement of Artificial Stone Manufacturing Method" which was established in England in November of the year 1824. Since then, there has been no significant theoretical change in the process for these 170 years.

Meanwhile, the cement manufacturing equipment have undergone various changes, and still now need to be further improved. The target is to attain both the desired product quality and quantity at the same time and yet at a high efficiency. Hence the history of the cement manufacturing technology may be, in a sense, regarded as the history of energy conservation.

In Japan, cement was first manufactured in 1885, that is, about 50 years after the above-mentioned invention in England. For the period of about 100 years thereafter, the cement industry in Japan has been making a steady progress owing to the stable demand growth, abundant raw materials and skilled manpower, although it has undergone many severe trials such as some economic depressions, the confusion after the World War II, oil shocks, etc. Looking back at the progress of the cement industry may provide us with many useful suggestions in terms of energy conservation.

This guideline omits a detailed description of equipment components of the plant facilities, and provides only their comparative description in terms of energy conservation. Nor does the guideline mention any performance of general-purpose equipment including fans, transportation equipment or motors.

However, the mill and kilns, which are main components of the cement plant, are described in more detail including their theoretical background in order to clarify their characteristics. On the common background obtained through understanding of the information described herein, those involved in energy conservation are expected to have free discussion with engineers engaged in the cement industry and thus promote energy conservation measures based on a firm and clear perspective.

## 6.2 Cement Production Process

### 6.2.1 Raw Materials and Chemical Reaction

Approximately 1000 kg of black mineral called clinker can be produced by pulverizing the mixture of 1,200 to 1,250 kg of limestone and 300 to 350 kg of clay, burning it at a temperature from 1,350 to 1450 °C and then cooling it rapidly. To this clinker, an about 4% plaster is added and ground into a fine powder, which is portland cement.

Table 6.1 shows the main constituents of various raw materials usually used for cement manufacture, and Table 6.2 gives those of the cement products.

**Table 6.1 Main Constituents of Raw Materials for Cement Manufacture**

Chemical constituents	Calcium oxide	Silicon dioxide	Aluminium oxide	Ferric oxide	Sulfur trioxide	Carbon dioxide	Remarks
Raw materials	CaO (%)	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	SO <sub>3</sub> (%)	CO <sub>2</sub> (%)	
Limestone	47~55					37~43	Carbon dioxide is not used as material.
Clay*1		45~78 (30~57)	10~26 (12~32)	3~9			
Silica		77~96					
Iron oxide material				40~90			
Gypsum*2	26~41				37~59		

Note: \*1 For clay material, not only natural clay but blast furnace slag and also coal ash are used, the values of which are indicated in the parentheses.

\*2 For gypsum used for cement manufacture, a large amount of by-product gypsum produced in flue gas desulfurization, phosphonic acid manufacture, titanium refining, etc. is used. For natural one, imported gypsum produced in Australia is used.

**Table 6.2 Main Constituents of Cements**

Main constituents	Calcium oxide	Silicon dioxide	Aluminium oxide	Ferric oxide	Sulfur trioxide	Other chemical components
Types of cement	CaO (%)	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	SO <sub>3</sub> (%)	
Ordinary portland cement	63~65	20~23	3.8~5.8	2.5~3.6	1.5~2.3	Cement also contains a small amount each of magnesium oxide (MgO), sodium oxide (Na <sub>2</sub> O), potassium oxide (K <sub>2</sub> O), manganese oxide (MnO), phosphorus pentoxide (P <sub>2</sub> O <sub>5</sub> ), etc.
High-early-strength portland cement	64~66	20~22	4.0~5.2	2.3~3.3	2.5~3.3	
Blast furnace slag cement (class B)	52~58	24~27	7.0~9.5	1.6~2.5	1.2~2.6	



The burned clinker is composed of 4 kinds of compounds as shown in Table 6.3, among which calcium silicate occupies 70 to 80 % (of which  $3\text{CaO}\cdot\text{SiO}_2$  amounts to two-thirds.)

**Table 6.3 Composition of Clinker**

Chemical compounds		Chemical composition <sup>1)</sup>	Remarks <sup>2)</sup>
Calcium silicate compounds	Alite	$3\text{CaO}\cdot\text{SiO}_2$ ( $\text{C}_3\text{S}$ )	These contain very small amounts of aluminium, iron, magnesium, sodium, potassium, titanium, manganese, etc.
	Belite	$2\text{CaO}\cdot\text{SiO}_2$ ( $\text{C}_2\text{S}$ )	
Pore phase substance	Aluminate phase	$3\text{CaO}\cdot\text{Al}_2\text{O}_3$ ( $\text{C}_3\text{A}$ )	These contain small amounts of silica, magnesium, sodium, potassium, etc.
	Ferrite phase	$4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$ ( $\text{C}_4\text{AF}$ )	

- Note: 1) The symbols in the parentheses are abbreviations used in the cement chemical field. C, S, A, and F stand for  $\text{CaO}$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ , respectively.  
 2) The chemical composition of each compound is not 100 % pure but usually contains such substances as shown in the remarks.

$3\text{CaO}\cdot\text{SiO}_2$  (abbreviated as  $\text{C}_3\text{S}$ ) plays an important part in demonstrating characteristics of portland cement, which is capable of generating high strength in only a short time. This compound is very unstable; therefore to produce this compound in laboratory is practically impossible, even if pure constituents were compounded in ideal ratio.

Heating the above-mentioned mixture to about  $1,250^\circ\text{C}$  first forms a compound of  $2\text{CaO}\cdot\text{SiO}_2$  and  $\text{CaO}$ , and then gradually produces  $\text{C}_3\text{S}$  as the temperature rises. These are again decomposed into  $\text{C}_3\text{S}$  and  $\text{CaO}$  as they get nearly fused at around  $2,130^\circ\text{C}$ .

Thus, there has been no example of manufacturing cement industrially by means of fusion. Therefore, as a measure actually taken in cement production, such other component as will form a fusion phase in a temperature range where  $\text{C}_3\text{S}$  can exist is added to the mixture of  $\text{CaO}$  and  $\text{SiO}_2$ , to allow  $\text{C}_3\text{S}$  to crystallize in the fusion phase.  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  contribute to forming this fusion phase.

However, if the mixing ratio of these components exceeds a fixed ratio, a great lump will be formed or a large amount of coating will stick on the brick in the kiln, preventing the smooth operation and making it impossible to produce a high-quality stable product. Besides,  $\text{CaO}$  needs to react completely with  $\text{SiO}_2$  in the burning process to form  $\text{C}_2\text{S}$  and  $\text{C}_3\text{S}$ , without leaving any part unreacted. The free lime in the product causes a considerable inconvenience to the cement hardening process.

There are no international rules available concerning the product quality. In trade negotiation, therefore, ASTM, BS, DIN, or JIS should be applied depending on the user's situation. Table 6.4 shows JIS standard for cement.

Table 6.4 JIS Standard for Cement

Type of cement	Chemical composition (%)			Mineral composition (%)		Heat of hydration (cal/g) (J/g)	Fineness specific surface (Blaine method) (cm <sup>2</sup> /g)	Time of setting		Compressive strength (kg/cm <sup>2</sup> ) (N/mm <sup>2</sup> )				
	I <sub>g</sub> loss SO <sub>3</sub> , MgO Alkalies Cl			C <sub>3</sub> S	C <sub>2</sub> S			C <sub>3</sub> A	Initial (min)	Final (hr)	Soundness	1 day		
	SO <sub>3</sub>	MgO	Alkalies	7 days	28 days	3 days	7 days	28 days						
Portland cement														
Ordinary	≤3.0	≤5.0	≤0.75	≤0.02	22,500	≥60	≤10	Good	≥70(686)	≥150(1471)	≥300(2942)			
High early strength	≤3.0	≤3.5	≤5.0	≤0.75	≤0.02	≥24,000	≥45	≤10	Good	≥130(1275)	≥230(2256)	≥330(3236)		
Super-high early strength	≤3.0	≤4.5	≤5.0	≤0.75	≤0.02	22,500	≥45	≤10	Good	≥200(1961)	≥280(2746)	≥350(3432)		
Moderate heat	≤3.0	≤3.0	≤5.0	≤0.75	≤0.02	58	570(293)	583(347)	≥60	≤10	Good	≥50(490)	≥100(981)	≥230(2256)
Sulphate resisting	≤3.0	≤3.0	≤5.0	≤0.75	≤0.02	54	≥60	≤10	Good	≥70(686)	≥140(373)	≥280(2746)		
Portland blast furnace slag cement														
Class A	≤3.0	≤3.5	≤5.0		23,000	≥60	≤10	Good	≥70(686)	≥150(1471)	≥300(2942)			
Class B	≤3.0	≤4.0	≤6.0		23,000	≥60	≤10	Good	≥60(588)	≥120(1177)	≥250(2444)			
Class C	≤3.0	≤4.5	≤6.0		23,300	≥60	≤10	Good	≥50(490)	≥100(981)	≥280(2746)			
Portland pozzolan cement														
Class A	≤3.0	≤3.0	≤5.0		23,000	≥60	≤10	Good	≥70(686)	≥150(1471)	≥300(2942)			
Class B	≤3.0	≤3.0	≤5.0		23,000	≥60	≤10	Good	≥60(588)	≥120(1177)	≥250(2450)			
Class C	≤3.0	≤3.0	≤5.0		23,300	≥60	≤10	Good	≥50(490)	≥100(981)	≥210(2059)			
Portland fly-ash cement														
Class A	≤3.0	≤3.0	≤5.0		22,500	≥60	≤10	Good	≥70(686)	≥150(1471)	≥300(2942)			
Class B	≤3.0	≤3.0	≤5.0		22,500	≥60	≤10	Good	≥60(588)	≥120(1177)	≥260(2550)			
Class C	≤3.0	≤3.0	≤5.0		22,500	≥60	≤10	Good	≥50(490)	≥100(981)	≥210(2059)			

- Note 1. Ordinary portland cement can be blended either uniformly with blast-furnace slag, pozzolan, fly-ash, and lime stone, or the pozzolan whose total content is less than 5 % of the gross weight.
2. Total alkali content (%) of portland cement (low alkali type) shall not be more than 0.6 %.
3. Proportion of Admixture for Blended Cement as follows:

Type	Volume of blast furnace slag (W/%)	Volume of pozzolan (W/%)	Volume of fly-ash (W/%)
A	> 5 ≤30	> 5 ≤10	> 5 ≤10
B	>30 ≤60	>10 ≤20	>10 ≤20
C	>60 ≤70	>20 ≤30	>20 ≤30

4. Values in Parentheses are indicated by SI unit
5. Alkalies (%) = Na<sub>2</sub>O (%) + 0.658 K<sub>2</sub>O (%)
6. Strength tests  
 <Sand for strength tests>  
 Natural sand, max, 1 % retained on sieve with apertures 297 μ, and min. 95 % retained on sieve with apertures 105 μ.  
 <Preparation of specimens for bending and compressive strength tests>  
 Specimens 40 × 40 × 160 mm. Mix proportion of cement to sand 1:2, water/cement ratio 0.65. Compressive strength test on broken prisms from bending strength test.

## 6.2.2 Production Process

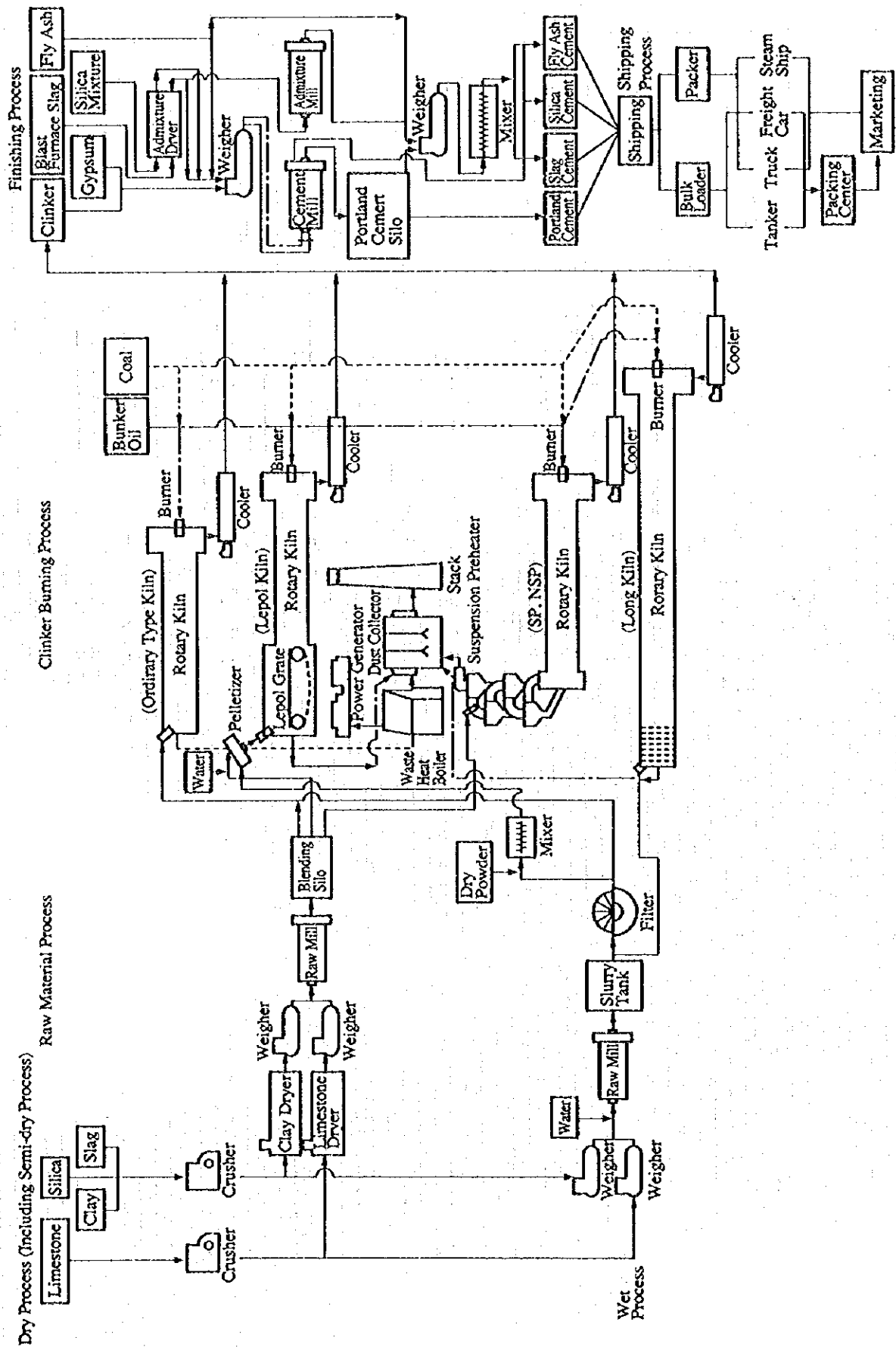
The production method consists roughly of three processes, that is, raw material process, clinker burning process, and finish grinding process, each of which has the functions shown in Table 6.5.

**Table 6.5 Cement Production Processes**

Process	Raw materials	Burning	Finish-grinding
Functions	Storage	Drying	Blending
	Crushing	Preheating	Grinding
	Drying	Calcining	Storage
	Finely grinding	Burning	
	Mixing		
	Feeding		

Figure 6.1 represents these processes according to the material flow. Actually, as the previous stage before the raw material department, there is a quarry or mining department, at which efforts for quality control and energy conservation should start. Also, following the finishing process is a shipping process. However, since the situation for these processes differs largely depending on the factory location, and should not be easily generalized, they will not be dealt with in this guideline.

Figure 6.1 Cement Production Process



The raw material department is roughly divided into the wet process and the dry process. In the dry process, the material is made into a dry powder, while in the wet process, the material is made into muddy slurry with an about 40 % moisture. The main equipment used is the mill, which includes a ball mill and a roller mill.

The ball mill has two methods — the open circuit method and the close circuit method as shown in Table 6.6. The close circuit process requires a separator. In wet process grinding, the open circuit system is mostly employed, while in the dry process, either system is used.

Table 6.6 Types of Mill

Ball Mill	Open circuit system	Wet process and dry process
	Closed circuit system	Dry process
Roller mill	Vertical mill	Dry process
	Roll press	Dry process

The roller mill includes the so-called vertical mill and the roll press. Since the vertical type has a separator incorporated to allow simultaneous smooth operations of drying and grinding, it is now getting increasingly popular. The roll press is usually used as a primary crusher in combination with the ball mill.

The main equipment in the burning stage is a kiln. Kilns include 4 types of rotary kilns and shaft kilns as listed in Figure 6.1. They have each the following characteristics.

Table 6.7 Types of Kiln

Names of kilns	Length/diameter (L/D) ratio	Annual production (in 10 thousand tons)	Energy consumption (kcal/kg)	Process type	Auxiliary equipment
Ordinary kiln (Short kiln)	Around 20	5~20	1,200~1,500	Wet type	Slurry filter
				Dry type	Waste-heat boiler
Lepol kiln	Around 20	10~30	1,000~1,200	Semi-dry	Pelletizer Grate-type preheater
SP, NSP kiln	15~20	30~200	750~950	Dry type	Suspension preheater Calclner
Long kiln	30~40	10~50	1,500~1,700	Wet type	Chain curtain
				Dry type	
Shaft kiln	3~4	2~10	1,000~1,200	Semi-dry	Pelletizer

Shaft kilns with the longest history among these kilns have such advantages as low investment cost, suitability for small-scale production, relatively low fuel consumption, etc. However, their product quality is obviously inferior to that of a rotary kiln. Therefore, they are now less used for the burning of cement except in India and China.

When rotary kilns were first introduced, short kilns with a short length for the diameter were mainly used. Thereafter, as the wet-type production method has proved to have various advantages, long kilns have come to be widespread, still now being operated in many countries. However, they consume a large amount of energy to evaporate about 40 % water content which is added in the raw material grinding process. Thus, they are now rapidly being replaced by newly developed SP or NSP kilns. SP is the abbreviation for a suspension preheater, and NSP is an SP with a calciner. These SP and NSP will prevail for a long while from now on.

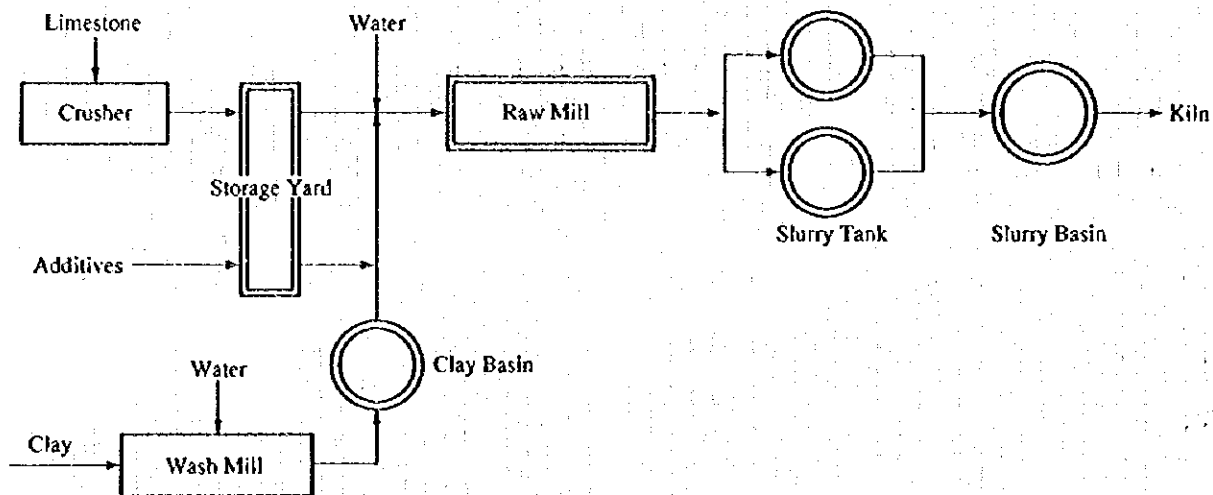
The finish grinding department is common irrespective of the type of raw material process and the clinker burning process. The equipment used for this finishing process are theoretically identical to those for dry-process raw material grinding. However, clinker, which is harder than the raw material and difficult to be ground, consumes energy about twice as much as for the raw material process to produce 1 ton of product. This causes severe wear on the grinding media and the lining material. Thus, the selection of equipment type and materials is subject to various restrictions. Figure 6.1 shows the equipment for the production of blended cement in the open circuit system.

### 6.2.3 Cement Production Equipment

#### (1) Wet-process raw material mill

Figure 6.2 illustrates a typical wet-process grinding system.

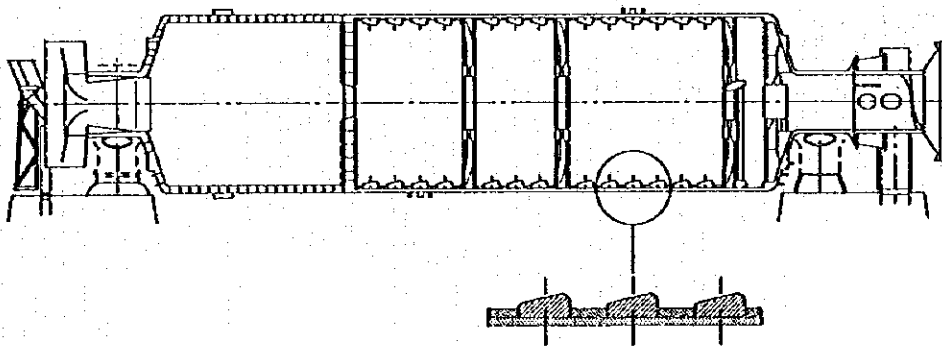
Figure 6.2 Wet-process Raw Material Grinding System



The blended materials are added with water and then ground by the mill. After the constituent mixing ratio of the product is corrected in the slurry tank, it is conveyed via the slurry basin to the kiln. Although the function of the slurry basin is to homogenize materials, re-correction of the mixing ratio is also available in the basin if necessary. The stabilization of raw material components is important for stabilizing the kiln operation. Water content serves the purposes of not merely mixing of raw materials but also prevention of static electricity and cleaning of the mill inside, thus contributing to the improvement of the grinding efficiency.

Energy consumed here is mainly for the mill body and the air compressor driving motor for the mixing of raw materials. Usually the total of these values is less than the power consumption for the dry-type grinding process. However, the thermal energy required for evaporating the water content (38 to 40 %) added here by far exceeds the difference. The internal structure of the mill is shown in Figure 6.3.

Figure 6.3 Structure of a Ball Mill



## (2) Dry-process raw material mill

Figure 6.4 shows three typical examples. Raw materials received by a plant contain 3 to 10% of water. Therefore, drying needs to be performed before the grinding process or incorporated into the grinding process. For the heat source, a hot gas generator is installed or the waste gas from the preheater is utilized. The difference between a, b, and c comes from the differences in the portions enclosed by the chain lines, that is, the differences in the combination of the drying device and the mill, and in the type of the mill itself.

Example a is a conventional system provided with a rotary dryer at the front of the open circuit tube mill. The rotary dryer can be replaced by a rapid dryer or impact dryer as necessary.

Example b is a closed circuit system with an air separator and a mill combined, into which hot air is actively supplied, thus eliminating the use of a dryer. The original target is to enhance the grinding efficiency by means of the air swept effect in the mill. This can reduce the water content of the raw material to around 5 %. A large amount of air increases the power for the fan, but the power required for the mill is considerably reduced, which leads to power saving of approximately 10 %.

Example c is an example of vertical roller mill. This mill, which has a structure and a grinding mechanism entirely different from those of the ball mill, can be employed even in the field where dry-process grinding has been regarded as unsuitable. Moreover, energy consumption is 20 % smaller than in example b. Its disadvantage is, however, a severe wear of the roller and the table liner. Since nowadays raw materials can be accurately judged as to their appropriateness, it may be desirable to send a sample to the mill maker and have it checked for its guaranteed service life before the application (See Figure 6.5).



Figure 6.4 Dry-process Raw Material Grinding

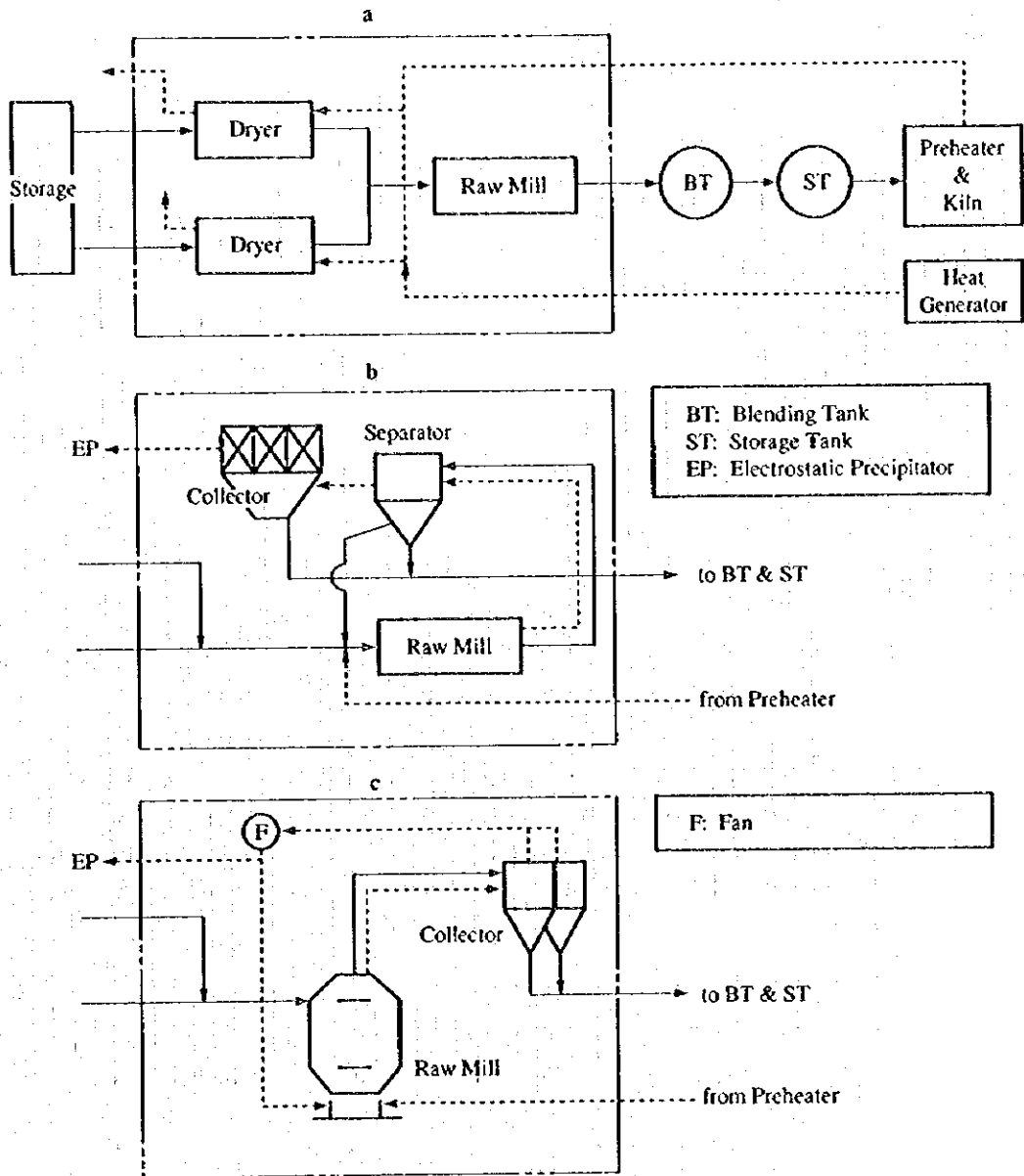
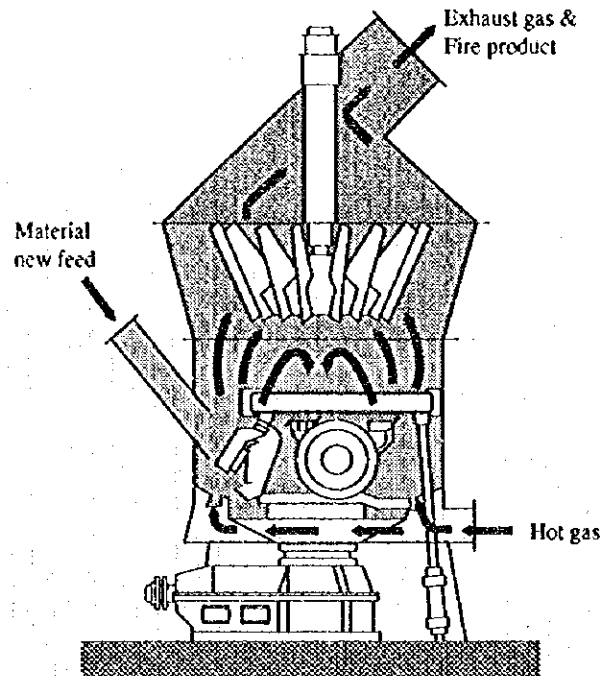


Figure 6.5 An Example of Vertical Type Roller Mill



(3) Wet-process kiln

Figure 6.6 is an explanatory drawing of the wet-process long kiln. The size of the kiln varies depending on the capacity, but usually it is a steel cylindrical type kiln having a diameter of 2.4 to 4.5 m and a length of 80 to 180 m. This kiln with the inside protected by fire refractory brick is installed with an inclination of 2.5 to 4 % and rotates at 0.5 to 1.5 rpm.

Slurry-like raw material is fed from the upper end of the kiln, and becomes red-hot clinker through the processes of drying, preheating, calcining and sintering. The hot clinker is then cooled by the cooler, coming out as a semi-finished product. The broken line in the graph indicates a change in the gas temperature, while the solid line indicates that in the raw material temperature. In the area hatched at the tip end of the kiln, there is a chain curtain provided, through which the slurry passes to be formed into a dry powder.

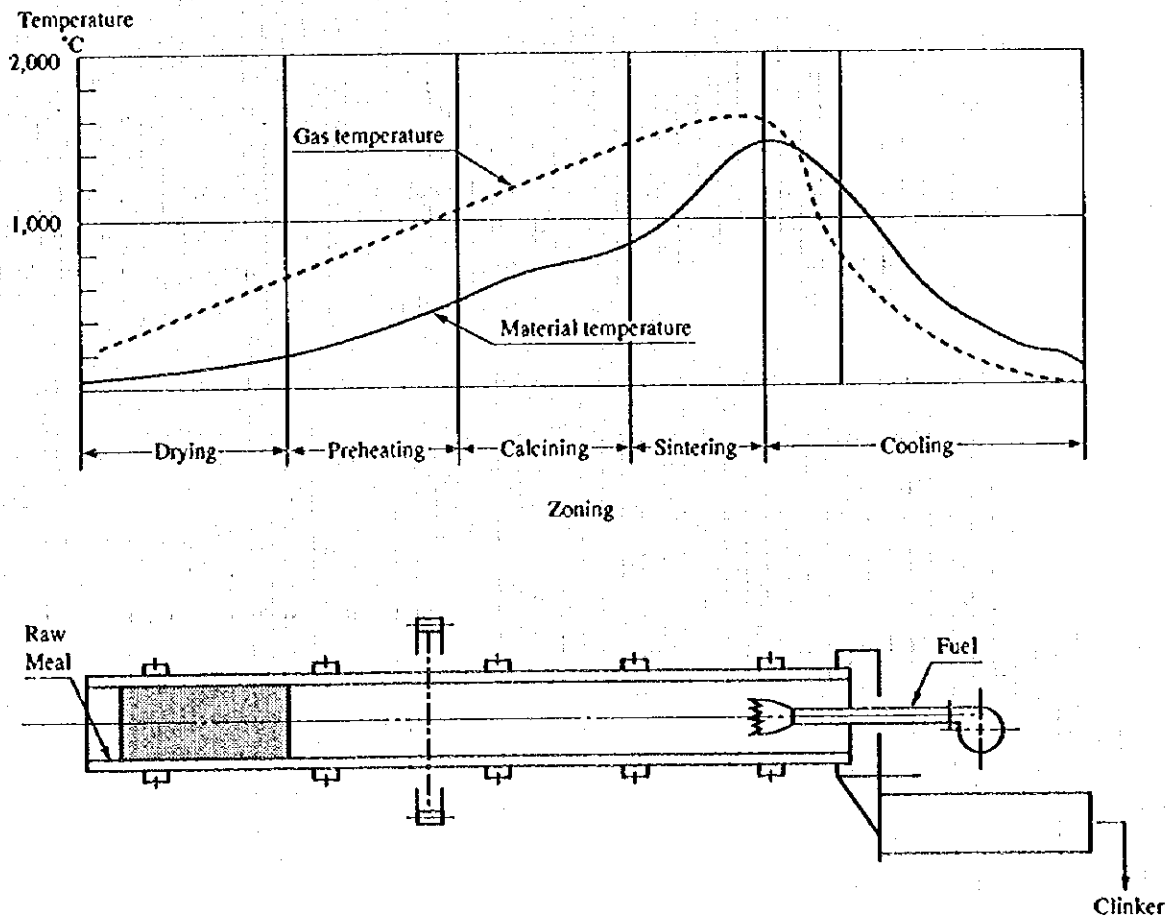
The material temperature rapidly rises after removal of the moisture, advancing the decomposition of  $\text{CaCO}_3$  into  $\text{CaO}$  and  $\text{CO}_2$ . Theoretically this reaction is supposed not to occur unless the temperature reaches  $896^\circ\text{C}$  or more for pure limestone. Actually, however, it starts at around  $600^\circ\text{C}$ . This is because  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3$  exist together as the blended clay materials. This heating decomposition occurs more actively as the temperature of a product approaches  $900^\circ\text{C}$ . Since this is a great endothermic reaction, the temperature remains stable as long as  $\text{CaCO}_3$  stays there.

Along with the decomposing reaction of  $\text{CaCO}_3$ , combination of the generated  $\text{CaO}$  with  $\text{SiO}_2$  advances, thus forming a new compound of  $\text{C}_2\text{S}$  (Belite). Upon completion of  $\text{CaCO}_3$  decomposition the temperature sharply rises, and when it exceeds  $1,250^\circ\text{C}$ , new substances,  $\text{CaO}$  and  $\text{C}_2\text{S}$  are combined to form  $\text{C}_3\text{S}$  (Alite), finishing the sintering process at the stage where  $\text{CaO}$  is completely used. The reaction between these solid substances is also based on the precondition of the existence of  $\text{Fe}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3$ . Prior processing such as accurate blending of raw materials, control of the fineness, mixing, etc. exerts a decisive influence on the burning process.

In wet-process kilns, the four processes are operated collectively by one kiln and a burner, as mentioned above. Although simplicity both in the equipment and the operation may be the advantage of this type of kiln, the drying and calcining area which consume a large amount of calory is located far away from the burner, preventing smooth and quick operation. Besides, extra calory of about  $400\text{ kcal/kg-cl}$  is necessary for evaporating the water content of around 40% contained in the material slurry, which is a fatal disadvantage.

As a countermeasure for it, the use of a filter (dehydrator) allows the water content at the inlet of the kiln to be reduced to about 20%. This, however, when used singly, will raise the temperature of the kiln exhaust gas and necessitate the addition of a waste-heat boiler, resulting in the loss of equipment simplicity.

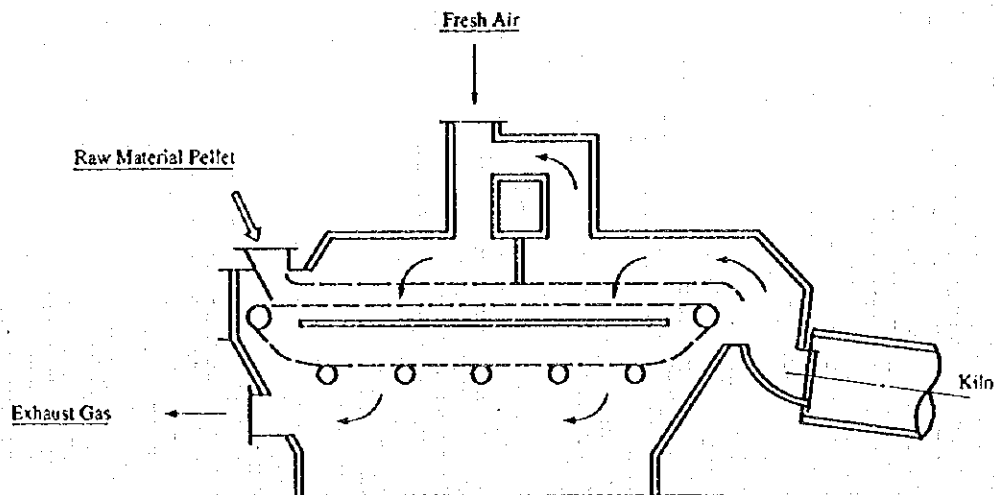
Figure 6.6 Structure and Temperature Profile of a Wet-process Long Kiln



(4) Semi-dry process kiln

The typical examples of this type of kiln include Lepor kilns and shaft kilns. The Lepor kiln has a material preheater — called Lepor grate — at the front of the short kiln. The structure is such that an endless horizontally travelling grate is installed inside, and the upper part is covered with pelletized materials. While the material pellets are moving from the material feed end to the kiln side, they contact with the kiln exhaust gas, causing heat exchange to take place.

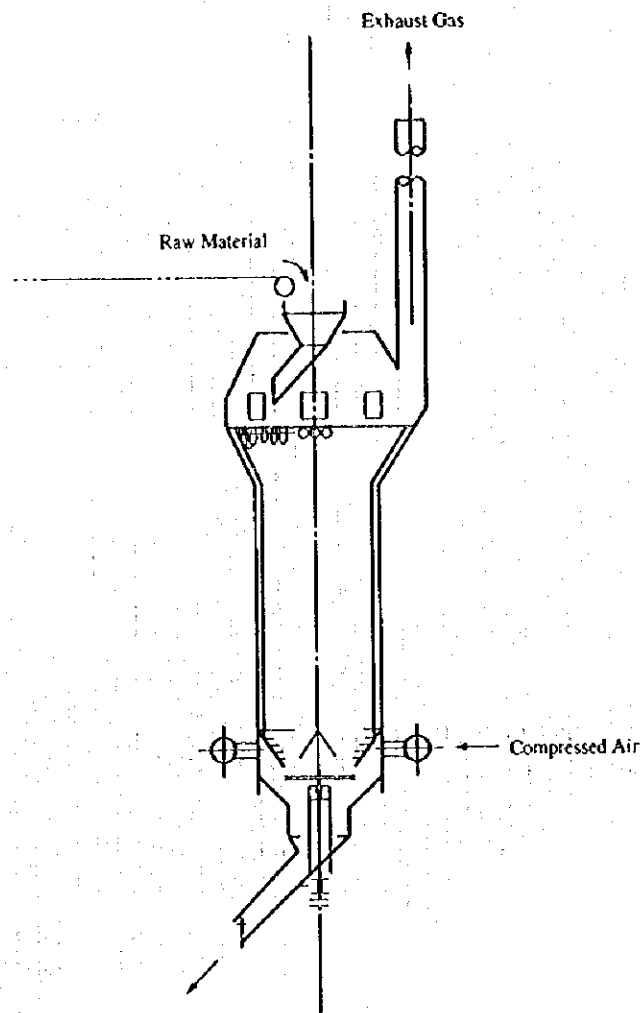
Figure 6.7 Grate Preheater



The material thickness, its passing speed and the flow of the heat gas are such that they can be changed in various ways to provide high energy efficiency. Because of rather delicate operation and less easy maintenance, kilns of this type have been successively replaced by SP kilns since they were introduced. Thus, the Lepor kiln system may hardly be employed from now on, but it deserves special mention since it introduced a concept of separating the raw material drying and pre-heating processes from the kiln, contributing to the development of SP or NSP kilns.

Figure 6.8 illustrates a shaft kiln. In this kiln, powder of raw materials and fuels (cokes or anthracite coal) is added with water content of around 12 %, pelletized, and sent to the kiln. This is a semi-wet process. The shaft kiln conducts heat exchange on the vertically moving bed, whereas the Lepor kiln does it on the horizontally travelling bed. Although the heat efficiency is not so bad, the material and gas flow is uneven, producing a disparity in the quality of the product in spite of the continuous discharging operation. Thus, the shaft kiln will inevitably be superseded by a rotary kiln unless a drastic measure is taken to improve the structure.

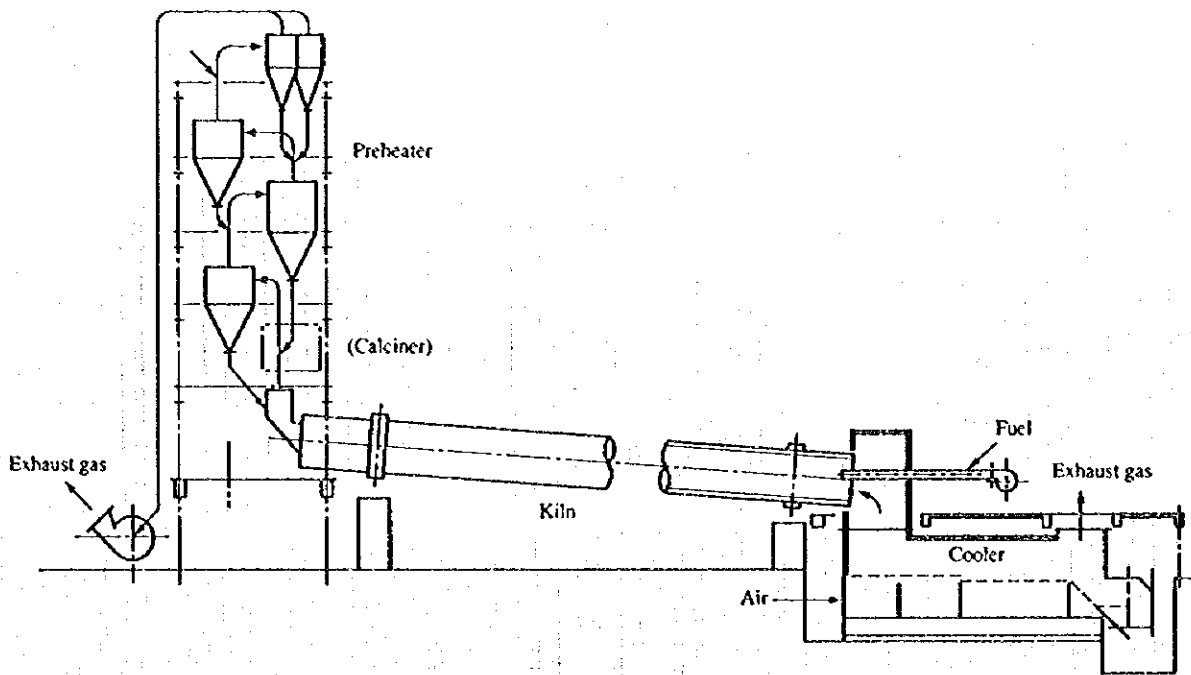
Figure 6.8 Shaft Kiln



(5) Dry-process kiln

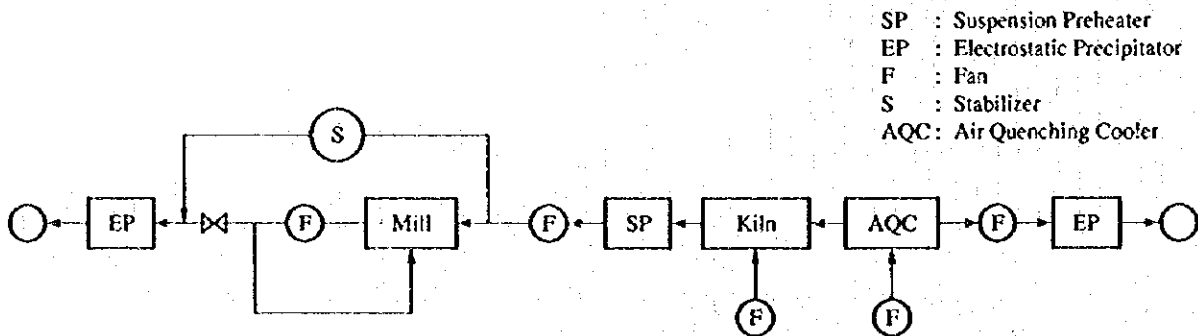
Figure 6.9 shows an SP (Suspension Preheater) kiln, which is a typical dry process kiln. The raw materials are fed to the inlet duct of the top cyclone in the form of powder containing water content of less than 1 %. When added with a calciner in the area of the duct enclosed by the chain line it will make an NSP.

Figure 6.9 Dry-process Kiln with Suspension Preheater



The cyclone exhaust gas of usually around 350 °C is utilized as a heat source for drying the raw materials, as shown in Figure 6.10.

Figure 6.10 Gas Flow Diagram of SP Kiln

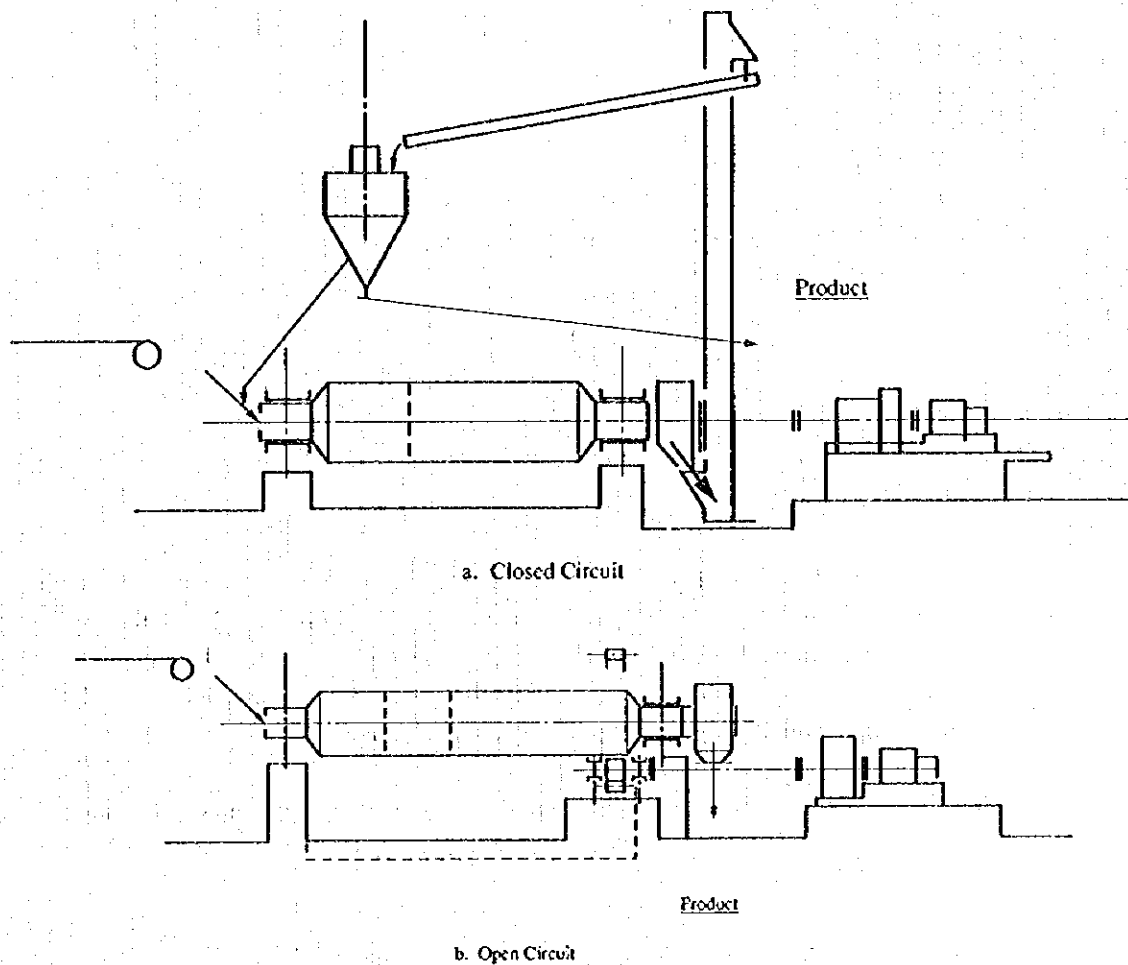


(6) Finishing mill

In the finish grinding stage there is no division of the wet process or the dry process as mentioned earlier. Nor is there any fundamental difference in the clinkers to be ground. If anything, much of the clinkers obtained through the dry process are finer, whereas those obtained through the wet process are sometimes too much burned, and difficult to be ground. The mill used here is usually a ball mill similar to the dry-process raw material mill.

"a" in Figure 6.11 shows an example of closed circuit system. The total amount of the mill product is sent to a separator, which separates fine powders from coarse powders. Then the fine powders are taken out from the separator, while the coarse powders are again returned to the mill for further grinding. Air is supplied to the mill inside. Cool air is also introduced into the separator. The exhaust air from these devices is filtered by a bag filter, from which fine powders can be obtained. The fineness of the product is adjusted by increasing or decreasing of the feed amount to the separator and the mill.

Figure 6.11 Clinker Grinding System

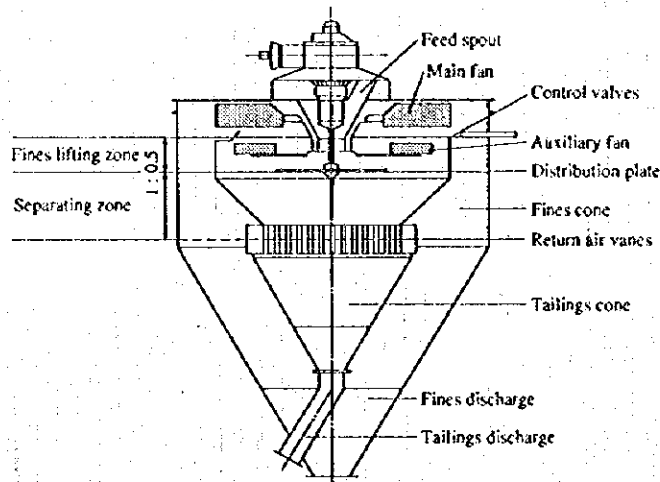


"b" in Figure 6.11 is an example of open circuit system. It has a longer mill shell ( $4 < L/D < 5$ ) instead of a separator. The mill inside is divided by the partitions with slit into 3 or more zones including a rough-crushing zone, a fine-grinding zone and intermediate zones between these. The increase or decrease of the material feed amount has a direct influence on the fineness of the product. The temperature of the product should be kept at  $120\text{ }^{\circ}\text{C}$  or lower. For this purpose, the mill surface or mill inside is sprayed with water.

In the closed circuit system "a", the power consumption for circulating the material and driving the separator and mill body is smaller by 10 % or more including that for the driving of the fan than in the open circuit system, "b". The open circuit system may gradually go out of use from now on.

Figure 6.12 shows the configuration of a separator.

Figure 6.12 Air Separator



(7) Clinker cooler

Raw powder is heated to 1,350 to 1,450 °C in the sintering zone and then it is discharged out of the kiln as a granular material of 1,250 °C called clinker. Here, the clinker has a sensible heat of 300 kcal/kg-cl or more, which should be preferably recovered by all means. The clinker cooler plays a role for these two purposes, of which the latter will be more important from the viewpoint of energy conservation.

This clinker is finely ground with a small amount of gypsum mixed to make a final product. At this time, the clinker needs to be cooled until it becomes 120 °C or below in terms of quality.

So far, there have been three types of coolers as clinker cooling equipment available, that is, rotary cooler, satellite (planetary) cooler and grate cooler. The rotary cooler, which is a rotating cylinder with a simple structure similar to a rotary dryer, sprinkles water on the surface of the shell to accelerate the cooling function and also to prevent overheating. For the satellite cooler, about 10 slender rotary coolers are installed around the outer circumference of the kiln, rotating along with the kiln. The name "satellite" comes from the kiln being compared to the sun. Since the cooler proper has a large specific surface, a great amount of radiation heat is lost from the shell surface. Usually, therefore, no sprinkling is performed.



In recent years, as SP or NSP kilns have become more widely used, some problems have arisen with the above-mentioned two types of coolers in terms of function or performance. One of them is that it is difficult to extract from the cooler a high-temperature secondary air for the calciner; another is that the air volume for cooling the clinkers largely exceeds the volume of secondary air necessary for the kiln. This gap increases as the thermal efficiency in the calcining process improves and the required amount of secondary air decreases with a decline in the fuel consumption. However, the use of a grate cooler can solve these problems and furthermore allows the temperature of the secondary air to be maintained at a constant level.

Figure 6.13 shows an example of heat balance of an SP kiln with heat consumption of 840 kcal/kg-cl. The treatment method of excessive heat (77.4 kcal/kg-cl) differs depending on the type of the cooler. In this case, it is impossible to emit all of the surplus heat from the shell surface when a satellite cooler is to be used. Therefore, in order to prevent the rising of the clinker temperature at the outlet, an excessive amount of secondary air must be unavoidably taken into the kiln, resulting in a great loss of energy. For a grate cooler on the other hand, only a high-temperature portion of the heated cooling air can be used as a secondary air when required. The remaining low-temperature part of air is discharged out of the system and utilized for power generation in recent many cases.

Figure 6.14 shows an example of grate cooler. Recently, there have been several types available for practical use, and any of these is, in principle, a horizontally moving bed of cross flow type.

Figure 6.13 Heat Balance of Clinker Cooler

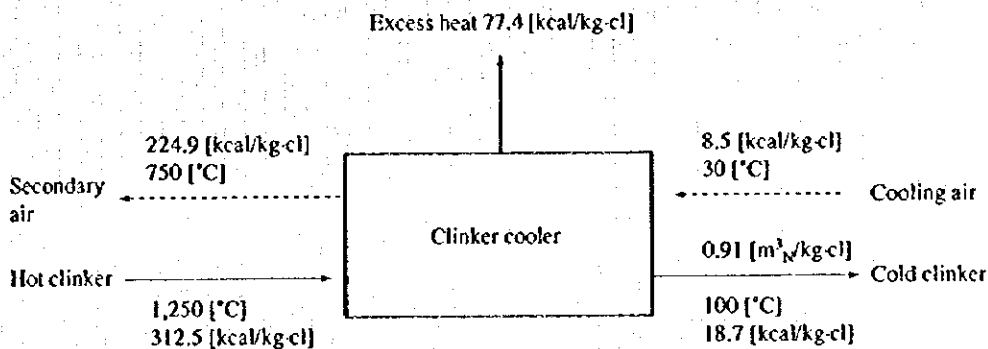
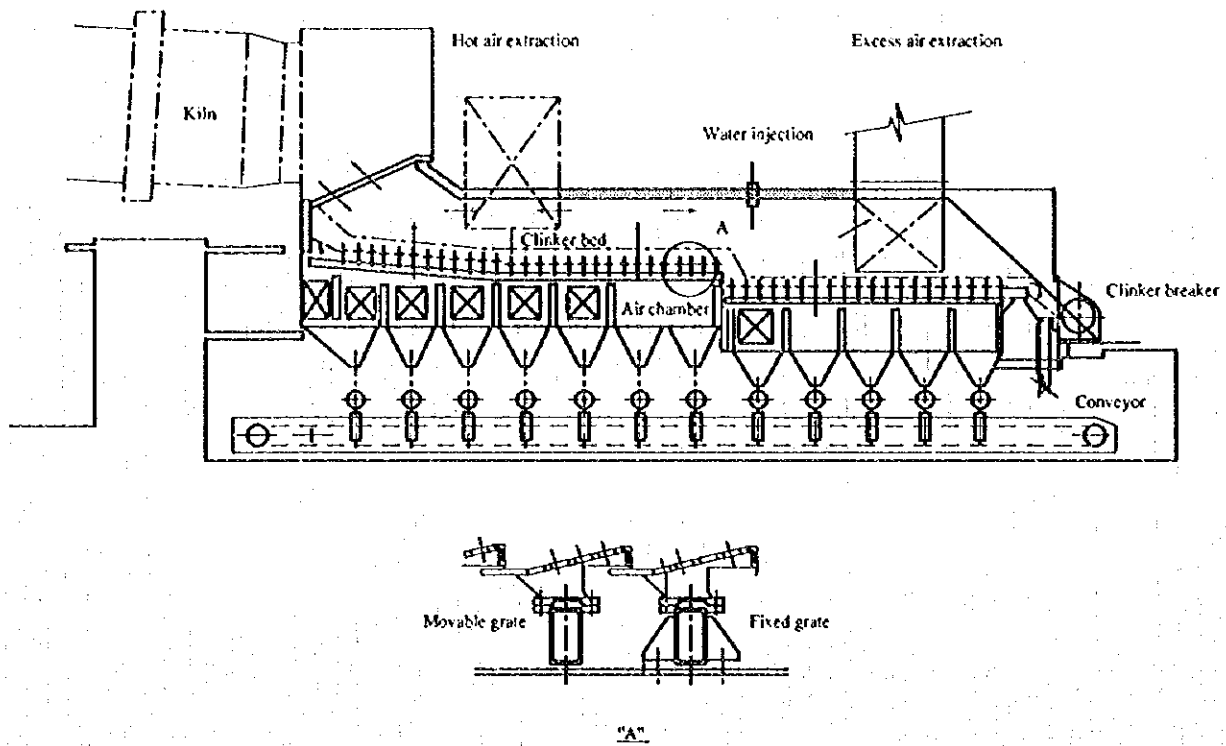


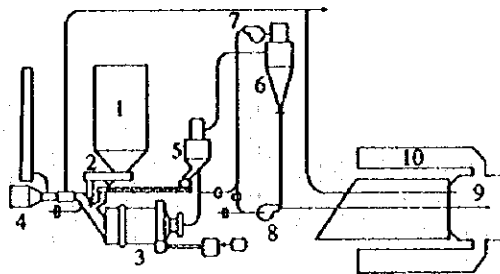
Figure 6.14 Grate Cooler



(8) Coal Firing mill

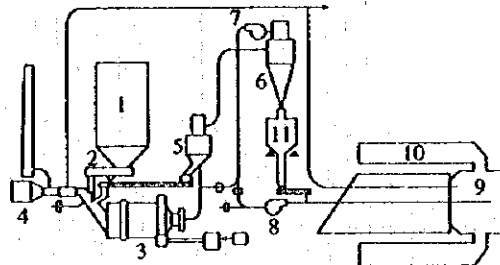
Coal is pulverized and fed to the kiln or the calciner. Grinding, which is generally conducted simultaneously with drying, is classified into the three categories according to the material weighing method and the dry exhaust gas processing method, as shown in Figure 6.15. Although the indirect firing method c is the most rational, the pulverized coal is easy to ignite. Therefore, the closest attention should be paid to its handling.

Figure 6.15 Coal Firing System



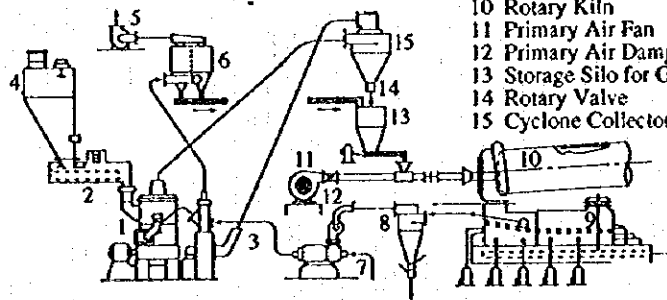
a. Direct Coal Firing Mill

- Notation
- 1 Raw Coal Silo
  - 2 Weigh Belt Feeder
  - 3 Air-swept Ball Mill (Tirax-mill)
  - 4 Air Heater (Auxiliary Firing)
  - 5 Separator
  - 6 Cyclone Collector
  - 7 Circulating Air Fan
  - 8 Primary Air Fan
  - 9 Rotary Kiln
  - 10 Satellite Coolers (Unax-cooler)



b. Semi-direct Coal Firing Mill

- Notation
- 1 Raw Coal Silo
  - 2 Weigh Belt Feeder
  - 3 Air-swept Ball Mill (Tirax-mill)
  - 4 Air Heater (Auxiliary Firing)
  - 5 Separator
  - 6 Cyclone Collector
  - 7 Circulating Air Fan
  - 8 Primary Air Fan
  - 9 Rotary Kiln
  - 10 Satellite Coolers (Unax-cooler)
  - 11 Feed Hopper (Working Bin)



c. Indirect Coal Firing Mill

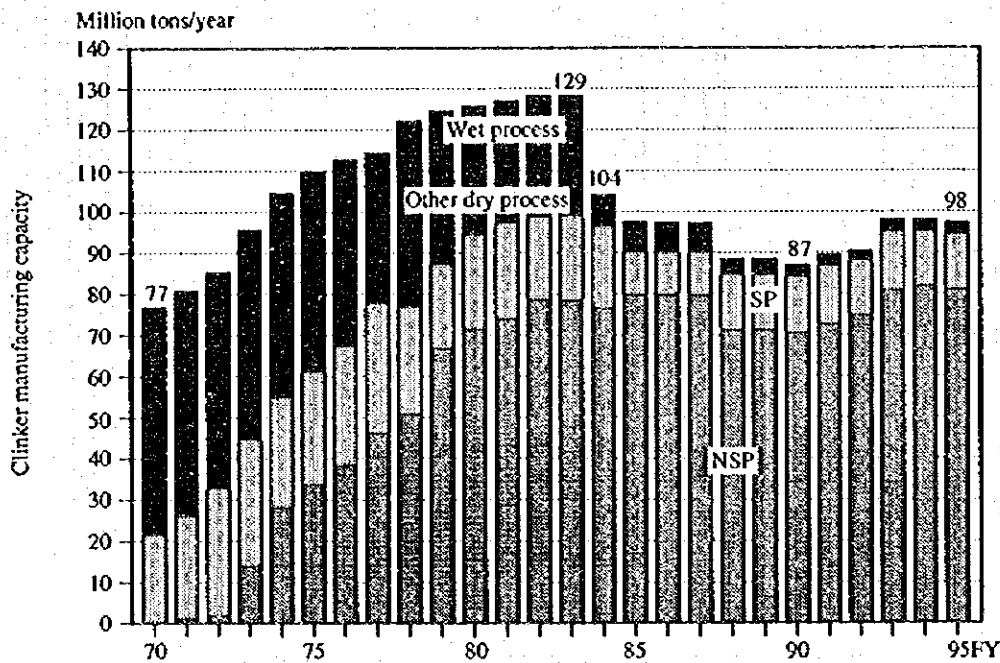
- Notation
- 1 Ball Mill
  - 2 Weigh Belt Feeder
  - 3 Damper
  - 4 Raw Coal Silo
  - 5 Vent Fan
  - 6 Dust Collector
  - 7 Booster Air Heater
  - 8 Dust Trap
  - 9 Clinker Cooler
  - 10 Rotary Kiln
  - 11 Primary Air Fan
  - 12 Primary Air Damper
  - 13 Storage Silo for Ground Coal
  - 14 Rotary Valve
  - 15 Cyclone Collector

## 6.2.4 Energy Consumption Characteristics

### (1) Changes in the cement production system

So far various types of systems have been described for each process. Actually, however, the type of production system to be actually employed varies depending on such factors as factory location conditions, economic conditions, social environment, market needs, etc. Figure 6.16 shows the changes in the production method which took place during the past 20 years in Japan. The graph reveals that the total production capacity has remained at a level of approx. 90 million tons/year, while the system has been rapidly changed from the wet process to the dry process, and among all to the NSP process. Japan which depends for nearly 100 % of fuel on import and is always exposed to inter-enterprise competitions, may be placed in special circumstances. Judging from various viewpoints, this type of change is supposed to go rapidly widespread in a short time as an international trend

Figure 6.16 Changes in the Production Capacity for Each Process in the Japanese Cement Industry

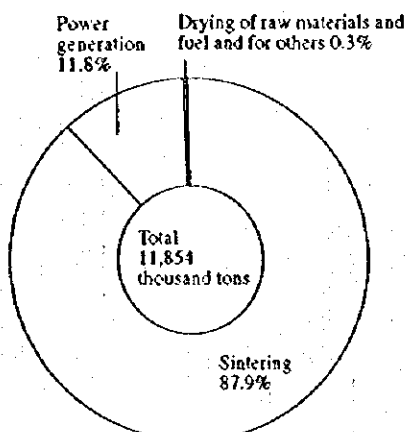


### (2) Component ratio of fuel consumption by process

Figure 6.17 shows the actual energy consumption by the entire cement industry in 1992 in Japan surveyed by Japan Cement Association (JCA). In that year 81 kilns operated to produce 91.212 million tons of cement.

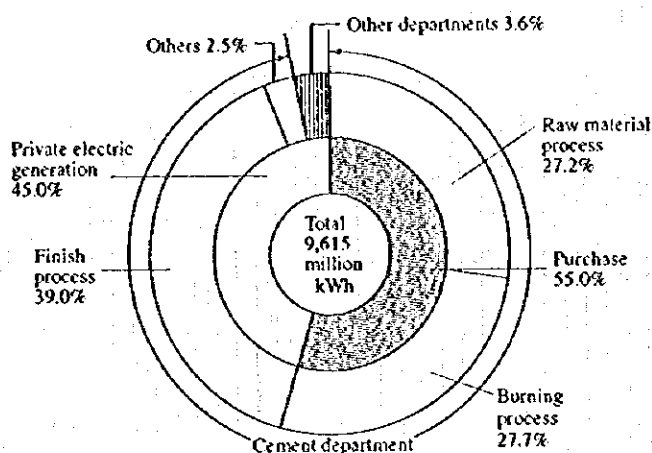
**Figure 6.17 Component Ratio of Energy Consumption by Japanese Cement Industry**

Component ratio of fuel consumption by use



(Note) Total is expressed in a value converted into coal (calorific value: 6,200 kcal/kg)

Component ratio of electric power consumption by department



The left graph represents fuel consumption in values converted into coal. When converted into a calorific value, the total amounts to about 720 kcal/kg-cem. Ninety percent or more of the fuel is consumed by the sintering department only with about 8% for power generation and 0.5% for drying of raw materials. The sintering process is regarded to consume the heat of the exhaust gas from the kiln utilized for drying of raw materials.

The right graph shows the electric power usage. The finish grinding process consumes about 40%, and the raw material process and the clinker burning process each consumes electric power a little under 30%. When expressed in a value converted into electric power consumption per ton of cement as mentioned above, it is a little under 100 kWh/t. The cement production process mostly employs SP or NSP kilns, for which coal is used as fuel. In wet-process kilns, these two departments — material department and clinker burning department — consume only smaller amounts of power, with the finish grinding department occupying a relatively high component ratio.

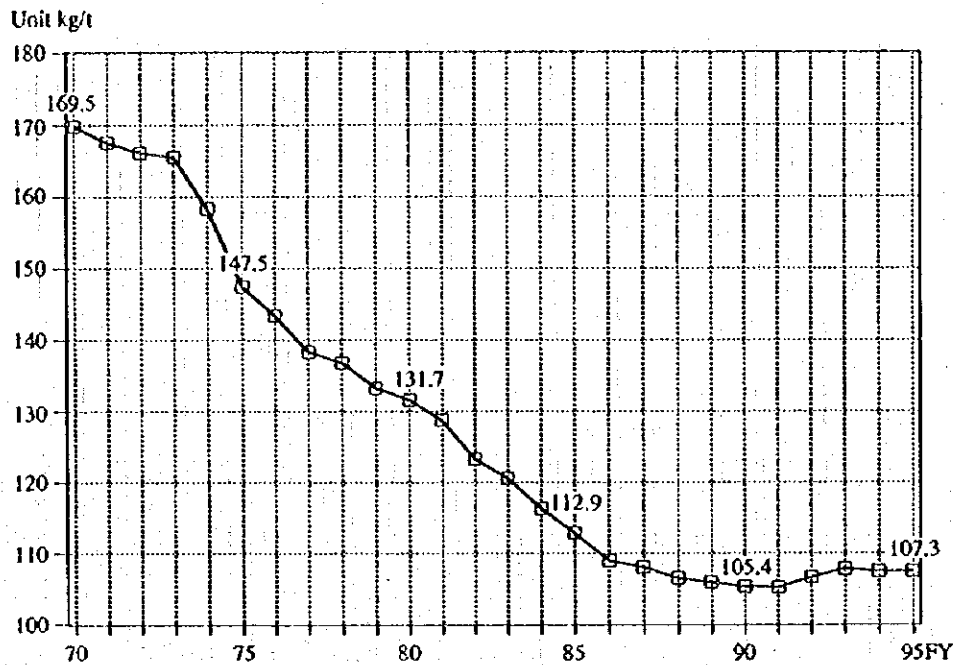
### (3) Change in energy intensity

Figure 6.18 shows fuel intensity in the Japanese cement industry expressed in a value converted into coal of 6,200 kcal/kg. Since 1973, when NSP kilns began to be widely used, the fuel intensity was sharply decreasing. This period coincides with the first oil crisis during which oil was used for cement sintering. The fuel consumption began to decline again in 1980, which corresponds to the second oil crisis period. Thereafter fuel was changed from petroleum to coal. Meanwhile, every possible effort for energy conservation has been made.

Figure 6.19 also shows a change in the electricity intensity. A temporary rise during 1972 to 1974 is supposedly due to a rapid change to NSP. Its rise during 1978 to 1980 after the temporary decline results from the change of fuels.

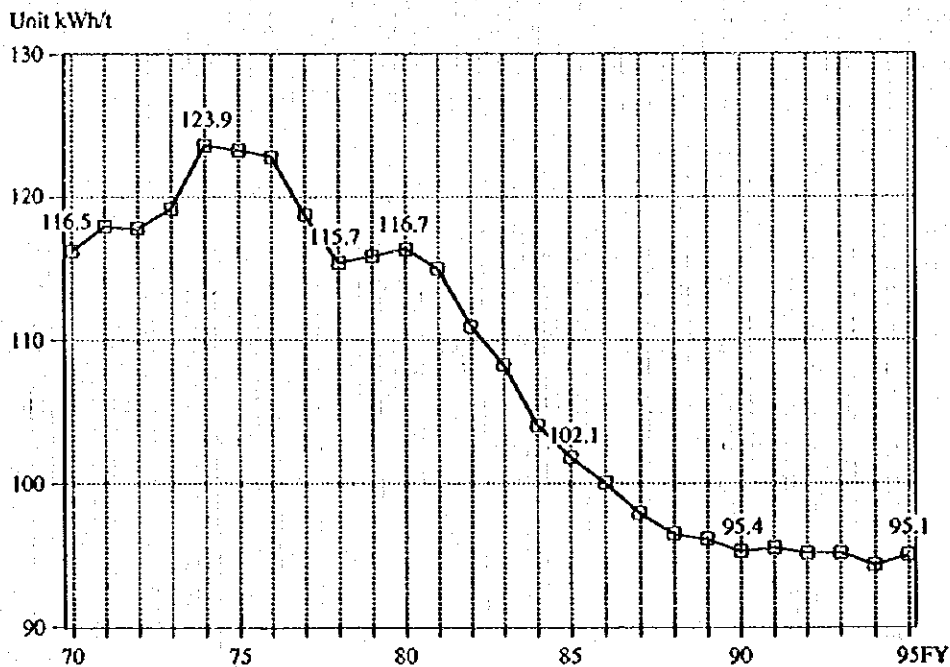
Figure 6.20 shows the total energy intensity by the entire cement industry and the average consumption rate expressed in calorific values converted from electric power. As far as energy intensity concerns, it demonstrates a steady decline.

**Figure 6.18 Change in the Fuel Intensity in Japanese Cement Industry  
(Coal 6,200 kcal/kg conversion)**



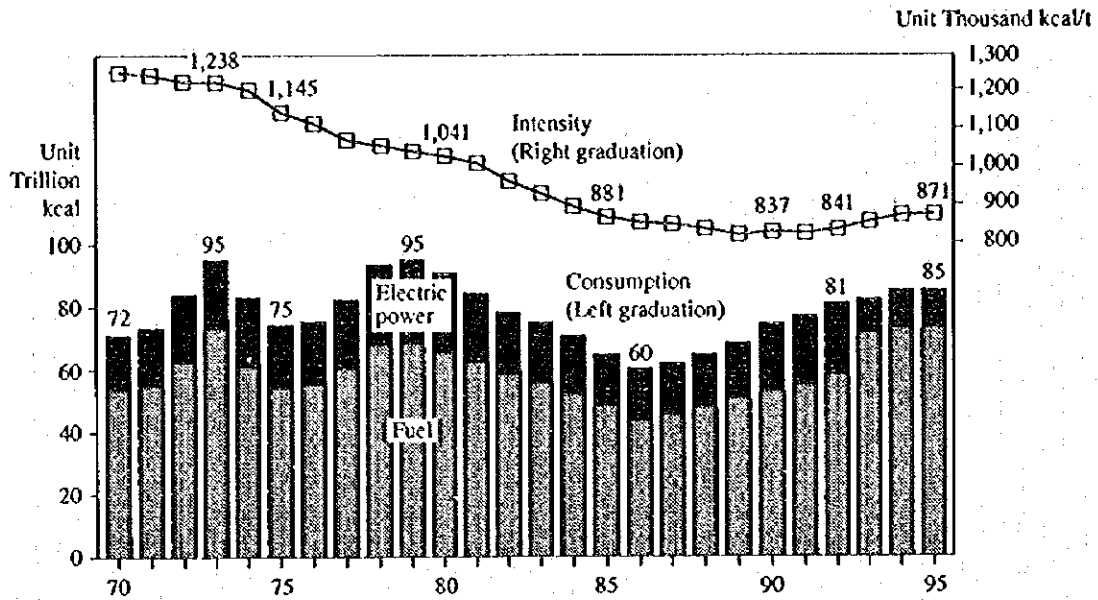
Note: Intensity = Fuel consumption (excluding generation of electricity) / Cement production

**Figure 6.19 Change in Electricity Intensity in Japanese Cement Industry**



Note: Intensity = Electric power consumption / Cement production

**Figure 6.20 Changes in Total Energy Consumption and Intensity in Japanese Cement Industry  
(Converted into calorific values)**



Note 1: Total energy consumption = Fuel consumption  
(including generation of electricity)  
× calorific value + purchased electric energy  
× 2,250 kcal/kWh

2: Total energy intensity = Total energy consumption/Cement production

**(4) Equipment investment**

Figure 6.21 represents a change in the equipment investment amount in the entire cement industry. It shows three peaks which occurred during 20 years, in each of which the investment target is placed on changing of production systems, conversion of fuels, and saving of energy, respectively. This could remarkably decrease the energy intensity, which is as shown in Figures 6.18, 6.19 and 6.20. During this period the production amount changed as indicated in Figure 6.22, while the labor productivity remarkably improved as shown in Figure 6.23 and Table 6.8. This indicates that investment has been timely performed with multiple purposes, producing good results.

Figure 6.21 Equipment Investment in Japanese Cement Industry

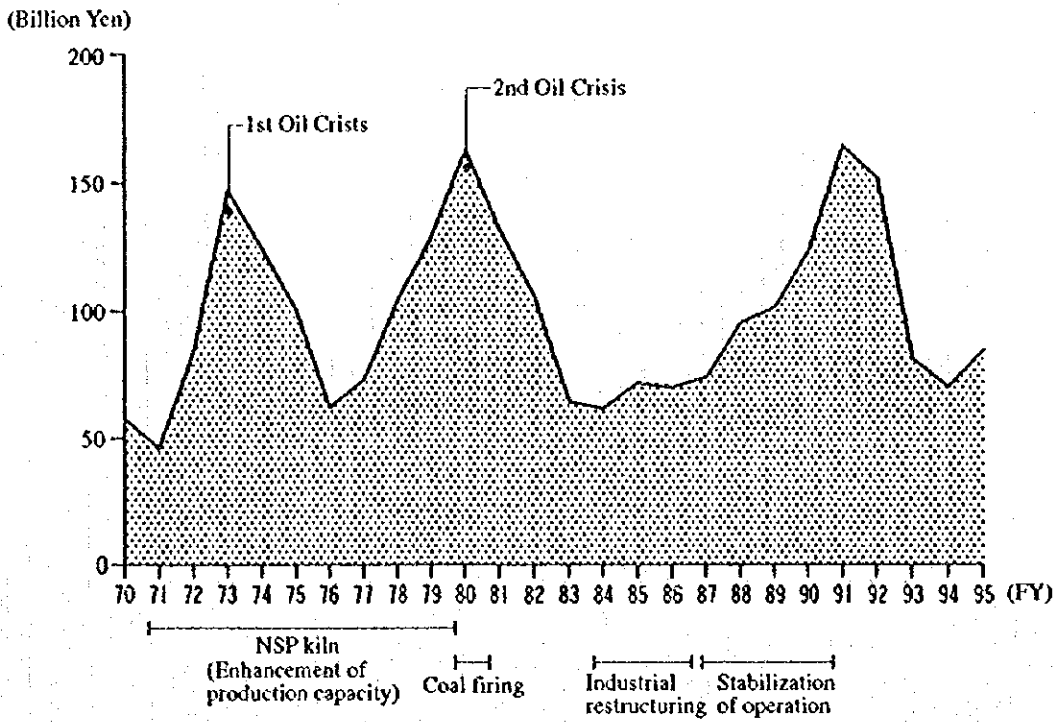


Figure 6.22 Change in Cement Production in Japan

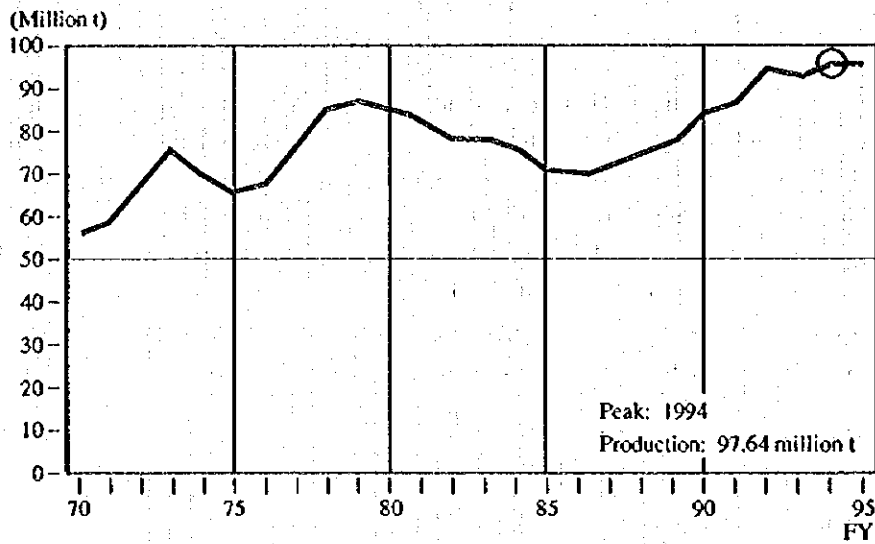




Figure 6.23 Improvement of Labor Productivity in Japanese Cement Industry

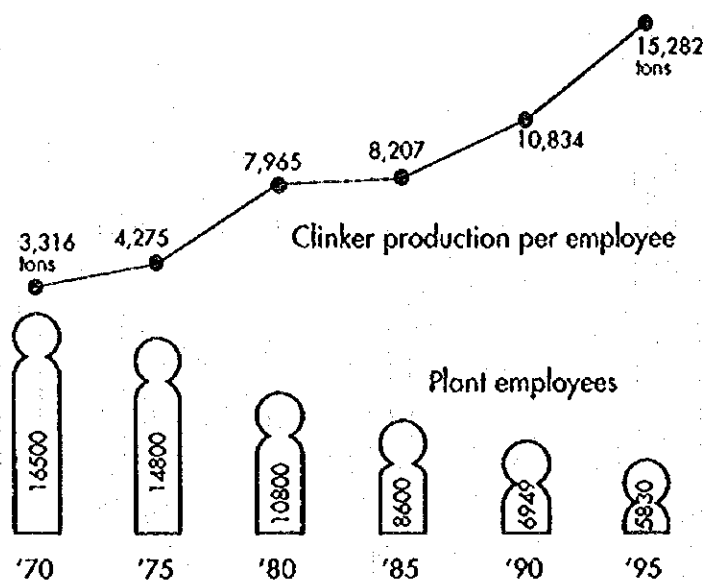


Table 6.8 Rationalization in Japanese Cement Industry

FY	Company	Plant	Kiln	Kiln capacity (1,000 tons)	Silo capacity (1,000 tons)	Production worker	Production* per worker (tons)	Energy use [1,000 kcal] [ton cement]
1970	22	58	226	86,449	1,711	16,549	3,316	1,254
1975	22	58	246	120,763	2,743	14,774	4,275	1,146
1980	24	53	192	126,352	3,689	10,830	7,965	1,041
1985	22	44	98	97,981	4,205	8,617	8,207	881
1990	23	41	80	87,175	4,360	6,949	10,834	837
1995	20	41	81	97,574	4,521	5,830	15,282	871

Note: \* Calendar year base.