

4. Energy Conservation in the Chemical Industry

4. ENERGY CONSERVATION IN THE CHEMICAL INDUSTRY

4.1 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, refinery, 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, there are very many processes involving heating and cooling of raw material and intermediate products, etc., resulting in much energy consumption. 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, latent, and waste heat as possible during heating and cooling for effective utilization.

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 6×10^6 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 equipment in use for chemical industries. In addition, the spray drier will be described in more detail.

4.2 Rationalization in the Use of Thermal Energy

4.2.1 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/Nm³.

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, fuel oils (A, B and C) and kerosene. Since fuel oil contains sulfur, the combustion gas usually contains 0.1 to 0.25% SO₂ and further 1 to 5% of such SO₂ is converted into SO₃, causing corrosion.

D) Calorific value

a. 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) respectively,

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

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

b. Calorific value of gaseous fuel

When combustible components contained in 1 Nm³ fuel for example, CH₄ and H₂ are represented by c_h and h₂ (Nm³) respectively,

$$\text{Higher calorific value, } H_h = 3,055 \cdot c_o + 3,036 \cdot h_2 + 9,498 \cdot c_{h_4} + 14,982 \cdot c_2 h_2 + 35,702 \cdot c_6 h_6 \text{ kcal/Nm}^3$$

$$\text{Lower calorific value, } H_l = H_h - 600 (18/22.4) (h_2 + 2 c_{h_4} + 2 c_2 h_2 + c_2 h_2 + 3 c_6 h_6) \text{ kcal/Nm}^3$$

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 4.1 to Figure 4.3 show relations between calorific values against solid, liquid and gaseous fuels at various air ratios and volume of combustion gas.

Figure 4.1 Relation between Low Calorific Value of Solid Fuel and Combustion Gas Amount, and Theoretical Air Amount

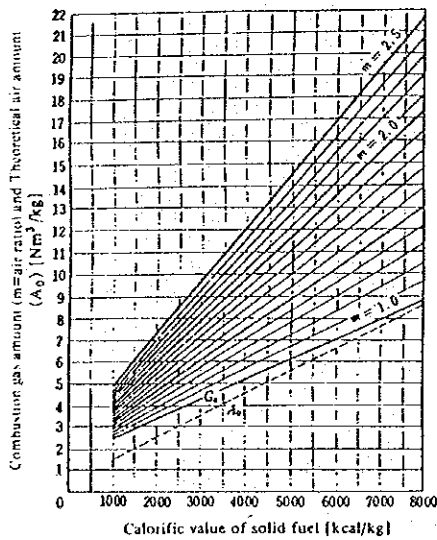


Figure 4.2 Relation between Low Calorific Value of Liquid Fuel and Combustion Gas Amount, and Theoretical Air Amount

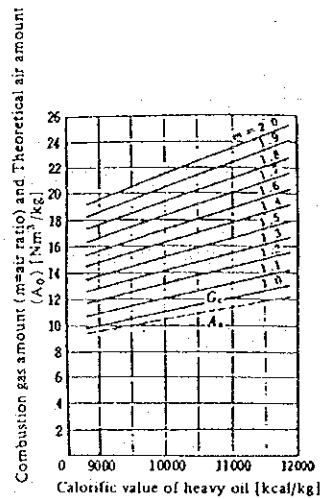
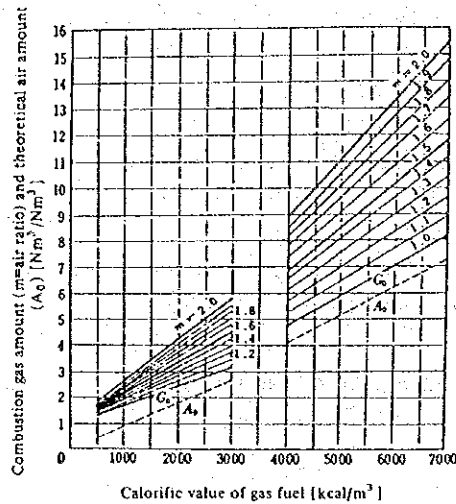


Figure 4.3 Relation between Low Calorific Value of Gas Fuel and Combustion Gas Amount, and Theoretical Air Amount



(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
 $M \times C_{pw} \times \Delta t$

Heat content carried out by combustion exhaust gas
 $(E \times C_{pe} \times \Delta t) + (S \times C_{ps} \times \Delta t) + 600 S$ (when based on higher calorific value)

Heat loss due to incomplete combustion
 $(E \times \frac{(CO)}{100} \times 3,050 \times F) + (8,100 \times (\text{amount of soot}))$

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.
 $\Sigma (hc + hr) (\Delta t) (A)$

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

$$hr = 4.88 [(T_o/100)^4 - (T_a/100)^4] \times \epsilon / \Delta t \quad \text{or} \quad \frac{\lambda (T_i - T_o)}{l} \cdot A$$

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 overall thermal efficiency against total heat input; and that against fuel calorific value is overall thermal efficiency against fuel calorific value. Since thermal efficiency varies depending on which item is regarded as effective heat, 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 ³ /h]
S	: Amount of water vapor exhaust gas	[kg/h]
A	: Radiating area	[m ²]
V	: Amount of air	[m ³ /h]
T _i , T _o , T _a	: Furnace temperature, furnace external wall temperature, ambient temperature	[K]
Δt	: Temperature difference with ambient temperature	[°C]
ℓ	: Thickness of furnace wall	[m]
C _p	: 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 _r	: Radiation heat transfer coefficient	[kcal/m ² h°C]
h _c	: Convection heat transfer coefficient	[kcal/m ² h°C]
	: 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 in the equipment heat balance 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 4.4 and Figure 4.5. Therefore,

Figure 4.4 Relation between Air Ratio and Waste Gas Loss

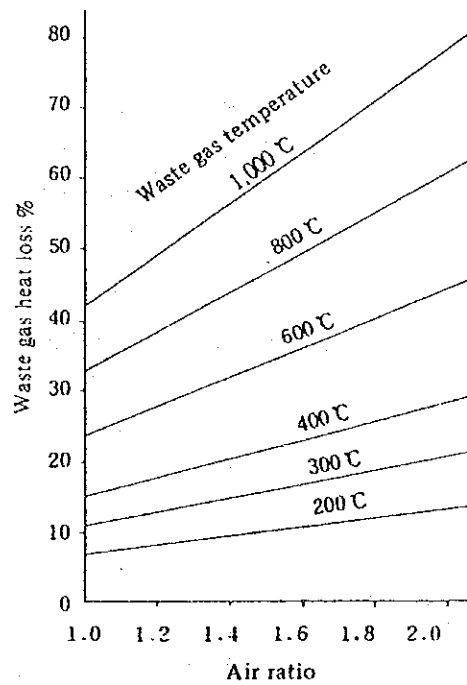
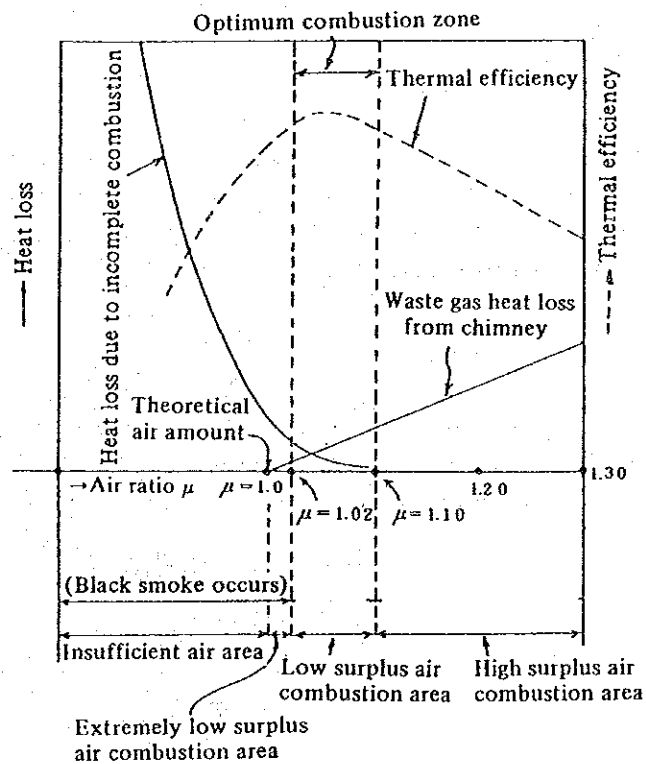


Figure 4.5 Relation between Air Ratio and Thermal Efficiency



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 1.1, the maximum value for thermal efficiency exists while the air ratio is between 1.02 and 1.10 (Figure 4.5)

However, at the general combustion equipment, the load usually fluctuates and, at that time, incomplete combustion may generate black smoke due to a low air ratio. Therefore, the equipment should be, in fact, operated at an air ratio of approximately 1.3, including some allowance. (Table 4.1)

Table 4.1 Standard Air Ratio

Classification	Standard air ratio
Melting furnace for metal casting	1.30
Continuous billet 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
Alumina kiln and 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 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.

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.

a. 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 4.6)

b. 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 4.7. Attention here should be paid to corrosion due to sulfur contained in fuel. Sulfur is in the form of SO_2 in the exhaust gas, and a portion of such SO_2 is converted into SO_3 - 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 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 4.6 New Suspension Preheater System Cement Plant

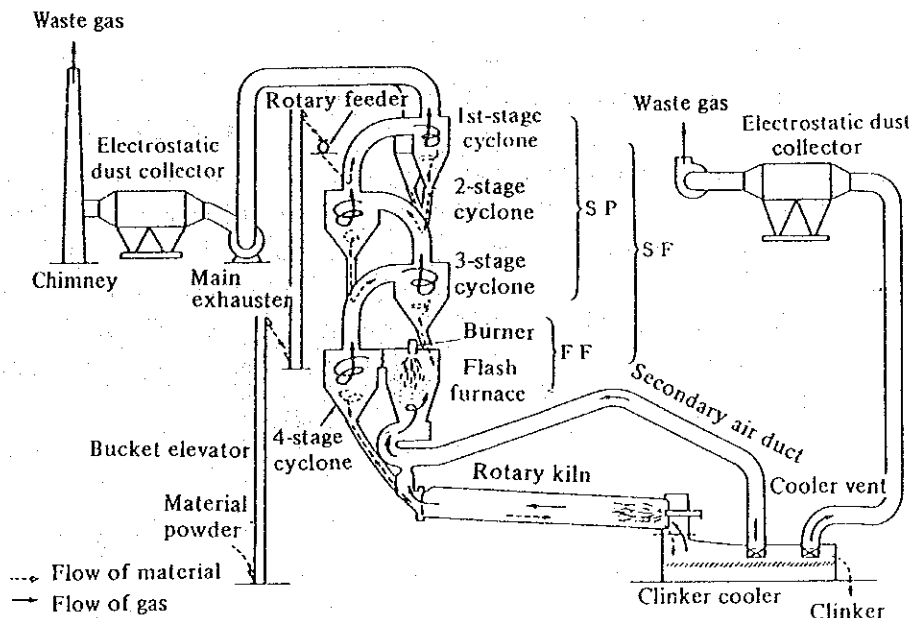
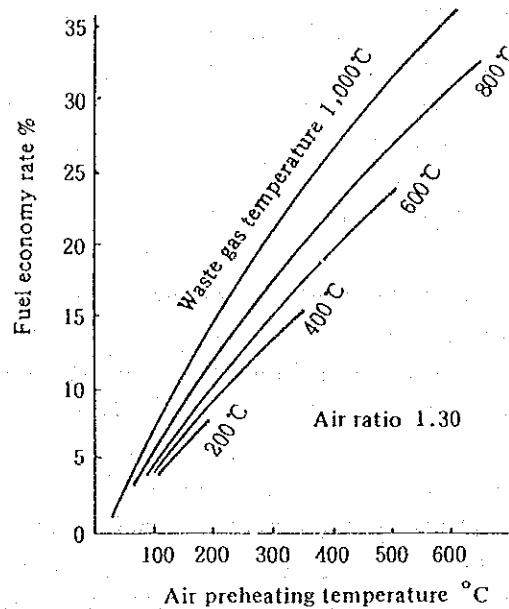


Figure 4.7 Fuel Economy due to Air Preheating



c. 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 are utilization of clinker cooling air as primary combustion air in cement plants (Figure 4.6) and waste heat boiler for quenching gas at cracker outlet in ethylene plants, etc.

4.2.2 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.

a. 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 (m^2)

Δt : Temperature difference between low and high temperatures ($^{\circ}\text{C}$)

ℓ : Thickness of plate (m)

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

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

b. In the case of cylindrical surface

Using the same symbols as item a.

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

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.

a. Mean heat transfer coefficient, α_m in natural convection when the fluid is air.

i) In the case of plate

Convection from lower surface

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

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

Note: Refer to Table 4.2.

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

ℓ : Representative length of plane (m)

Gr : Grashof number

Pr : Prandtl number

Convection from upper surface

$$\alpha_m = 2.27 (\Delta t / \ell)^{1/4} \quad (\text{kcal/m}^2\text{h}^\circ\text{C}) \quad 10^5 < \text{Gr} \cdot \text{Pr} < 2 \times 10^7$$

$$\alpha_m = 0.831 (\Delta t)^{1/3} \quad (\text{kcal/m}^2\text{h}^\circ\text{C}) \quad 2 \times 10^7 < \text{Gr} \cdot \text{Pr} < 3 \times 10^{10}$$

Convection from vertical surface

$$\alpha_m = 1.22 (\Delta t / H)^{1/4} \quad (\text{kcal/m}^2\text{h}^\circ\text{C}) \quad 10^4 < \text{Gr} \cdot \text{Pr} < 10^9$$

$$\alpha_m = 1.13 (\Delta t)^{1/3} \quad (\text{kcal/m}^2\text{h}^\circ\text{C}) \quad 10^9 < \text{Gr} \cdot \text{Pr} < 10^{12}$$

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

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

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

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

when D: Outside diameter of pipe (m)

Table 4.2 Dimensionless Terms Related to Heat Transfer

Name	Equation	Abbreviation
Nusselt number	hD/k	Nu, N_{Nu}
Stanton number	$h/C_p G$	$St, N_{St} = (Nu) (Re) (Pr)$
Condensation number	$h(v^2/g)^{1/3}/k$	CO, N_{Co}
Reynolds number	$DG/m, D\bar{u}/\nu$	Re, N_{Re}
Prandtl number	$C_p m/k$	Pr, N_{Pr}
Peclet number	$C_p DG/k$	$Pe, N_{Pe} = (Re) (Pr)$
Grashof number	$(D^3 g/\nu^2) (b t)$	Gr, N_{Gr}
Graetz number	$w C_p / k l$	$Gz, N_{Gz} = \frac{\pi}{4} (Re) (Pr) (D/l)$

Note: $D^3 g/\nu^2$ is referred to as Galilei number

$D^3 g/\nu^2 = (Re)^2/(u^2/gD)$, u^2/gD are referred to as Froude number.

C_p : Specific heat at constant pressure

D : Diameter or representative length

Δt : Temperature difference

$G = \bar{u} \rho$: Mass velocity

\bar{u} : Average velocity of flow

$w = \frac{\pi}{4} D^2 G$: Mass flow

g : Gravitational acceleration

k : Heat conductivity

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

β : Coefficient of thermal expansion l : Tube length

b. Heat transfer coefficient, α in forced convection

i) Inside heat transfer coefficient

$$\alpha D/\lambda = 0.027(R_e)^{0.8} (P_r)^{1/3} (\eta/\eta_w)^{0.14}$$

where D : Inside diameter of pipe (m)

η : Viscosity of fluid

η_w : Viscosity of fluid at tube wall temperature

ii) Outside heat transfer coefficient

$$\alpha D/\lambda = C \cdot (R_e)^m \times 1.11 \cdot (P_r)^{0.31}$$

where D: Outside diameter of pipe (m)

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

Re	C	m
4×10^{-1} to 4	0.891	0.330
4 to 4×10	0.821	0.385
4×10 to 4×10^3	0.615	0.466
4×10^3 to 4×10^4	0.174	0.618
4×10^4 to 4×10^5	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 ϵ : Emissivity of object

A: Surface area of object (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 (m^2)
- F_{12} : Coefficient determined by relative position of object (View factor)
- T_1, T_2 : Respective temperatures (K)
- ϵ_1, ϵ_2 : Respective emissivity

Radiation heat to wide space can be approximated by the use of the equation in item (ii) 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 equipment to atmosphere, it is described.

Heat flow, $Q =$ Conduction heat transfer through equipment wall $Q_k =$ Convection heat transfer $Q_c +$ radiation heat transfer Q_r (1)

Treating temperatures within the equipment, on its surface and of atmosphere as t_i ($^{\circ}\text{C}$), t_w ($^{\circ}\text{C}$) and t_o ($^{\circ}\text{C}$) respectively,

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

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

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

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 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 resistance thereto and inside and outside convection heat transfer.

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

- 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
 λ : Heat conductivity of tube wall
 R_i : Inside dirt resistance
 R_o : Outside dirt resistance

Since the dirt resistance 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 dirt resistances is shown in Table 4.3. Value R will not decrease to zero even if the heat exchanger is completely cleaned, and heat transfer is greatly influenced by the degree and frequency of cleaning. 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 are shown in Table 4.4.

Table 4.3 Fouling Factor

(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	Brine (for cooling)
Quenching oil	0.0008	Refrigerant vapor	0.0004	
Vegetable oil	0.0006	Air		

Table 4.4 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 ² ·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 ^{**4}	"	350~ 750
	Organic matter viscosity 0.5 to 1.0cP ^{**5}	"	250~ 600
	Organic matter viscosity 1.0cP or below ^{**4}	"	25~ 400 ^{**2}
	Gas	"	16~ 250 ^{**3}
	Water	Brine	500-1,000
	Organic matter viscosity 0.5cP or below ^{**4}	Brine	200~ 500
Heater	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
	Gas	25~ 250 ^{**3}	
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 ^{**4}	Organic matter viscosity 0.5cP or below ^{**4}	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 ^{**4}	150~ 300
	Organic matter viscosity 0.5cP or below ^{**4}	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 scale coefficient and the allowable pressure loss on the controlling fluid side are assumed to be 0.006 m²·hr·°C/kcal and 0.35 to 0.7 kg/cm² respectively.

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

- *1. When scale coefficient is 0.0002 m²·hr·°C/kcal.
- *2. When pressure loss is 1.4 to 2.1 kg/cm².
- *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 absorber oil, a portion 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:

$$Q = A_o \cdot U_o \cdot \Delta t_m \tag{1}$$

where A_o : Heating surface based on outside tube

t_m : Mean temperature difference between both fluids

The temperature difference between both fluids, Δt , 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 Δt as variables is solved,

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

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

Equispacing equations (1) and (2),

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

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 4.8 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 t_m is calculated by the following equation:

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

Values F_T due to each channel configuration are shown in Figure 4.9

Figure 4.8 Shell/Tube Type Heat Exchanger

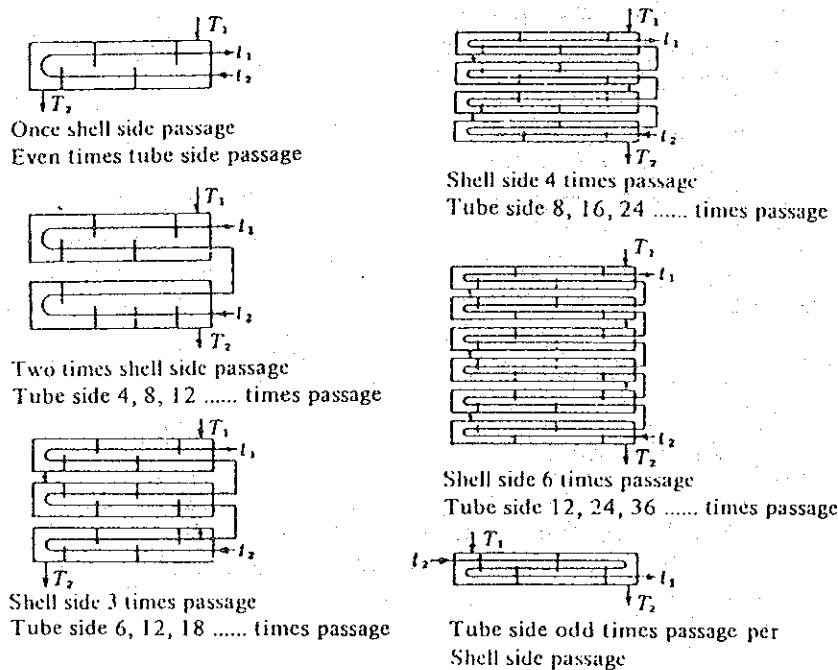
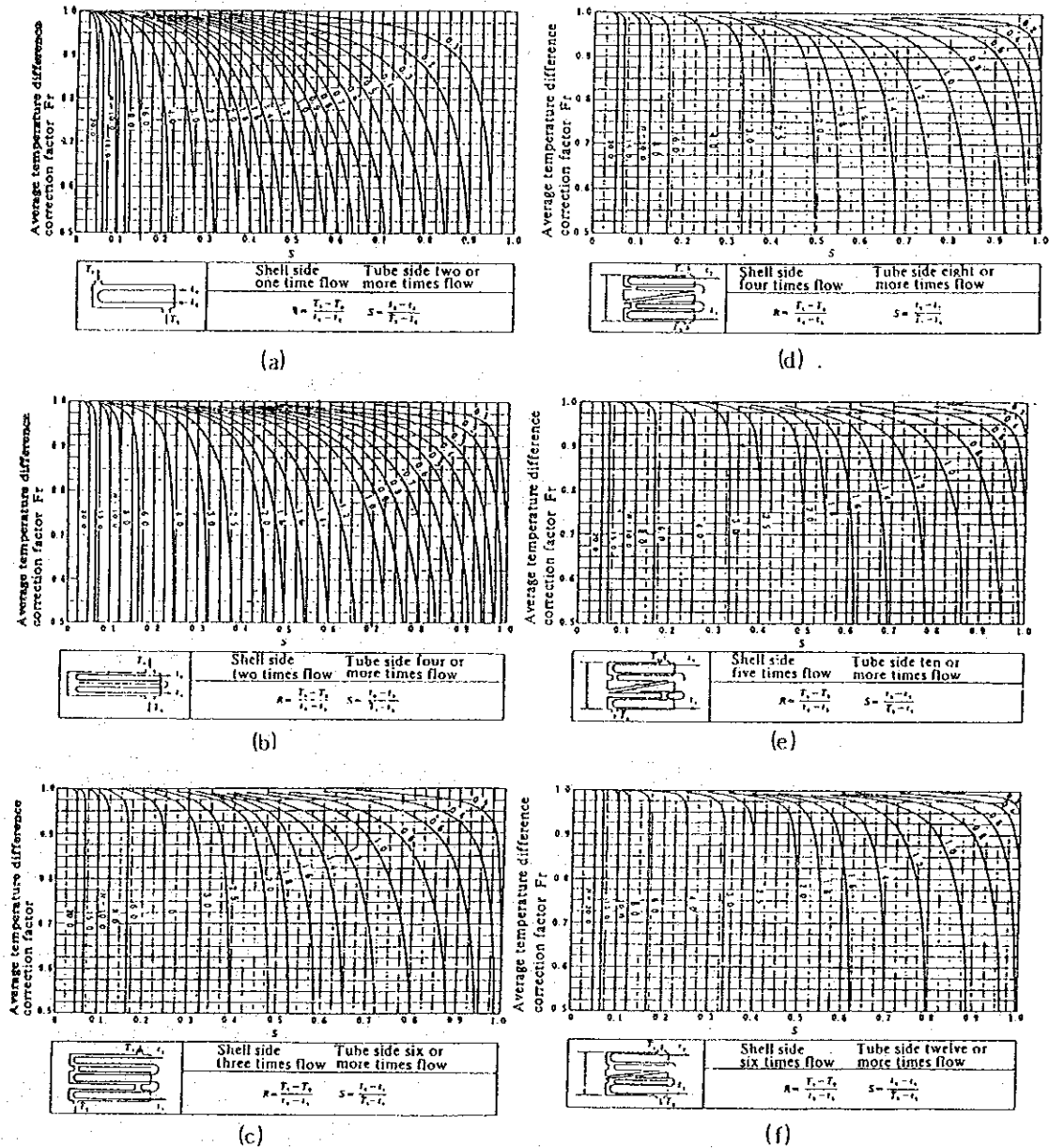


Figure 4.9 Correction Factor F_T



(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 4.10 to Figure 4.13)

- a. Coil type heat exchanger
- b. Trombone type (Cooler)
- c. Double tube type heat exchanger
- d. Multitubular heat exchanger
 - ① Fixed tube and plate type
 - ② Floating head type
 - ③ U-tube type

Figure 4.10 Coil Type Heat Exchanger

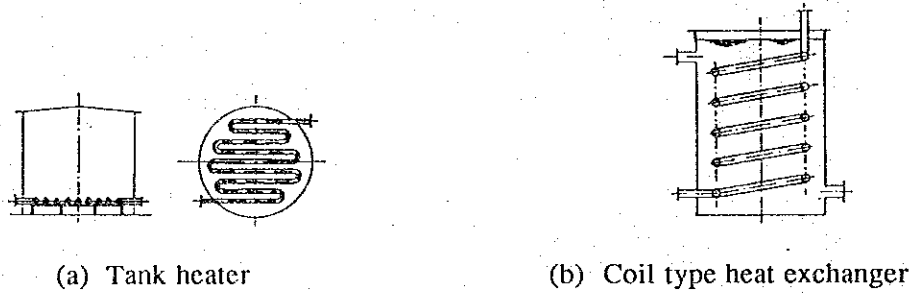


Figure 4.11 Trombone Cooler

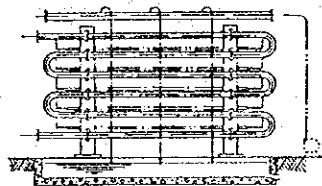


Figure 4.12 Double Tube Type Heat Exchanger

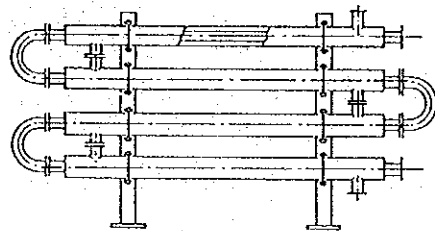
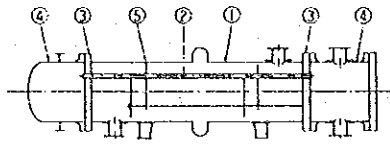
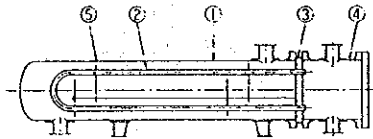


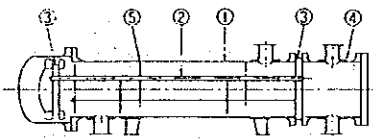
Figure 4.13 Multi-Tube Type Heat Exchanger



(a) Fixed tube sheet 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 4.14 to Figure 4.15)

- a. Jacket type heat exchanger
- b. Plate type heat exchanger
- c. Spiral type heat exchanger

Figure 4.14 Plate Type Heat Exchanger

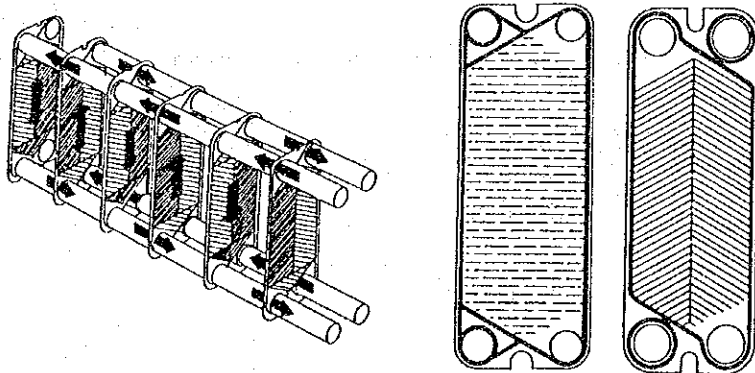
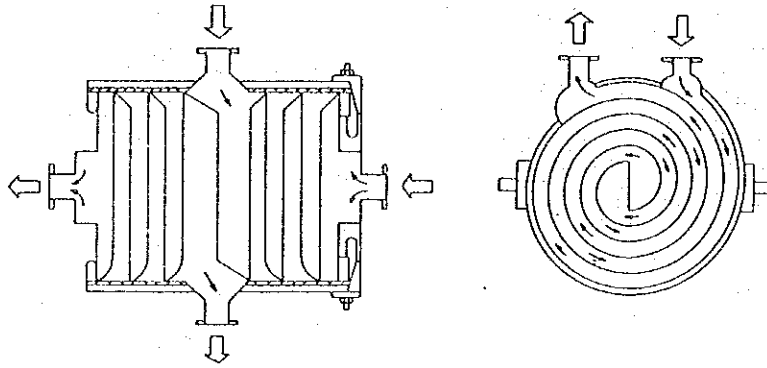


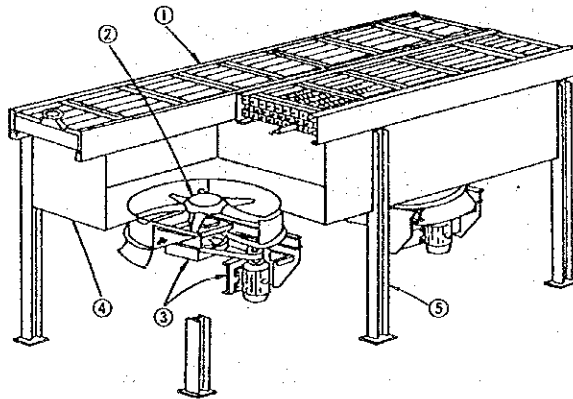
Figure 4.15 Spiral Type Heat Exchanger



C) Special type (Figure 4.16)

- a. Air cooling type heat exchanger
- b. Bayonet heat exchanger
- c. Compact heat exchanger

Figure 4.16 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 to the extent of 15 to 20 m².

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 and 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/cm² and temperature of approximately 150 °C from the construction standpoint. Many of them are used in pharmaceutical and food processing industries and general chemical industries have begun to 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.

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.

Table 4.5 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 ² ·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 ($u = 1-1.5$)-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

Table 4.5 Approximate Values of Overall Heat Transfer Coefficients for Various Heat Exchangers (2/2)

Types of Equipment	Fluid (u): Flow velocity [m/sec]	Overall Coefficients of Heat Transfer U [kcal/m ² ·hr·°C]	Remarks
Economizer	Cold water-Flue gas	10 ~ 50	Tubes
Steam superheater	Steam-Combustion gas	10 ~ 30	Tubes
Gas heater	Gas-gas	10 ~ 30	Forced convection
"	"	3 ~ 10	Natural convection
Evaporator	Fluid (boiled)-high temperature gas	10 ~ 50	Forced convection
"	"	5 ~ 15	Natural convection
"	Fluid (boiled)-steam (condensed)	200 ~ 400	
"	Water (boiled)-steam (condensed)	1500 ~ 4000	
"	Oil (boiled)-steam (condensed)	240 ~ 730	
Tube with steam jacket	Organic matter fluid-steam (condensed)	240 ~ 2000	
Vertical long tube evaporator	Water-Steam (condensed)	1500 ~ 5900	
High-pressure boiler	Water (Boiled)-fused salt	490 ~ 730	
Steam heater	Steam-fused salt	340	
Catalytic container	Gas-fused salt	30	Outside tube (gas) with fin
Double tube heat exchanger	Salt water ($u = 1.25$)-Water ($u = 1.25$)	750 ~ 1500	
Carbate double tube heat exchanger	Water-water	1450 ~ 2450	
Double tube ammoniac condenser	Water ($u = 1.2$)-Ammonia (condensed)	1100 ~ 1700	Ammonia between 2" ϕ steel tube and 1 $\frac{1}{4}$ " ϕ steel tube
"	Water ($u = 1.8$)-Ammonia (condensed)	1400 ~ 2000	"
"	Water ($u = 2.4$)-Ammonia (condensed)	1700 ~ 2300	"
Carbate-trombone type cooler	Water-HCL (20°Be)	1450	Flow rate of water [= 2600 kg/hr-m
Horizontal 2" steel tube fluid film ammonia condenser	Water ($\Gamma = 600$)-Ammonia (condensed)	1200	Outside tube fluid film velocity (kg/hr-m [width])
"	Water ($\Gamma = 1200$)-Ammonia (condensed)	1600	"
"	Water ($\Gamma = 1800$)-Ammonia (condensed)	2000	"
Fluid film condenser	Water-steam (condensed)	2800 ~ 11200	Outside tube water= 600-30000 kg/hr-m

4.2.3 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, heat of evolution or heat of absorption 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 SO₃ converter in a sulfuric acid plant and ammonia synthesis converter.

C) Heat exchange operation

This operation is widely used to deal with heat of reaction and transfers heat of reaction from reactor wall 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 preheating method, it is desirable to effectively recover the heat of reaction and utilize it both outside and inside of the system by the following methods:

- a. Heating of boiler feed water or steam generation.
- b. Heating of air or of other fluids.

4.2.4 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 is materialized 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 4.17.

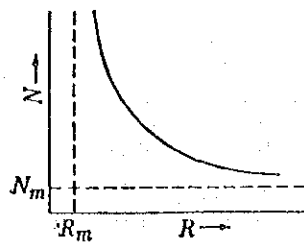
R cannot be made less than R_m , but the required plate number of the tower will be infinite when R is equal to R_m . Also, when R is increased, the required number of plates will decrease. Even if R is infinite, the plate number cannot be decreased less than N_m . R_m and N_m are called minimum reflux 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.

<Relation between reflux ratio and thermal energy>

Vapor flow rate which rises in a tower is 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.* 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.

Figure 4.17 Reflux Ratio vs Theoretical Number of Trays



(2) Classification of Distillation Towers

A) Plate tower

Plates used to hold liquid in the tower are provided in multi-stages and the plates themselves are turned into 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, 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 quality, by 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

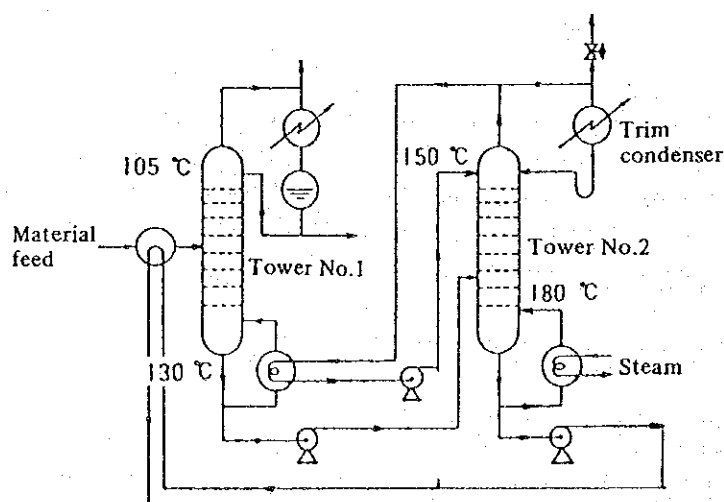
Vapor actually generated from each plate is not in an equilibrium composition with the liquid. Against this deviation, considering a plate efficiency and regarding the quotient obtained by dividing the required plate number theoretically calculated by the plate efficiency as the real plate number, actual 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 the tower at low temperatures and preheat feed with sensible heat retained in the bottom product. (See Figure 4.18)

Figure 4.18 Heat Recovery of Distillate



Also, heat in the overhead condenser can be utilized to generate low pressure steam when the vapor is at high a temperature. (See Figure 4.19)

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 4.20)

Figure 4.19 Steam Generation by Heat of distillate

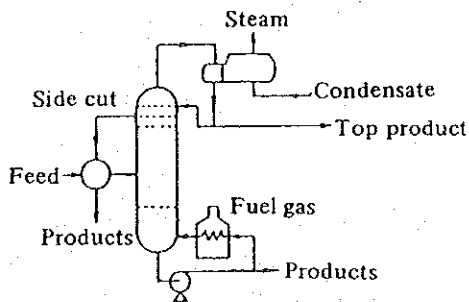
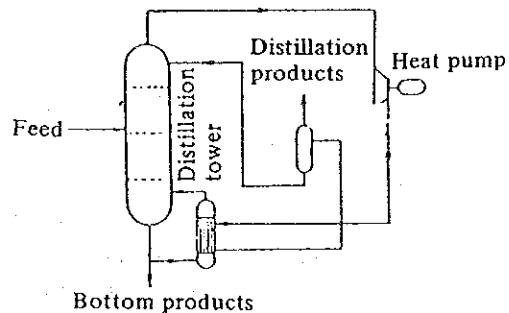


Figure 4.20 Use of Distillate Heat to Reboiler



D) Precautions for Heat Insulation

When the distillation tower proper 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.

4.2.5 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

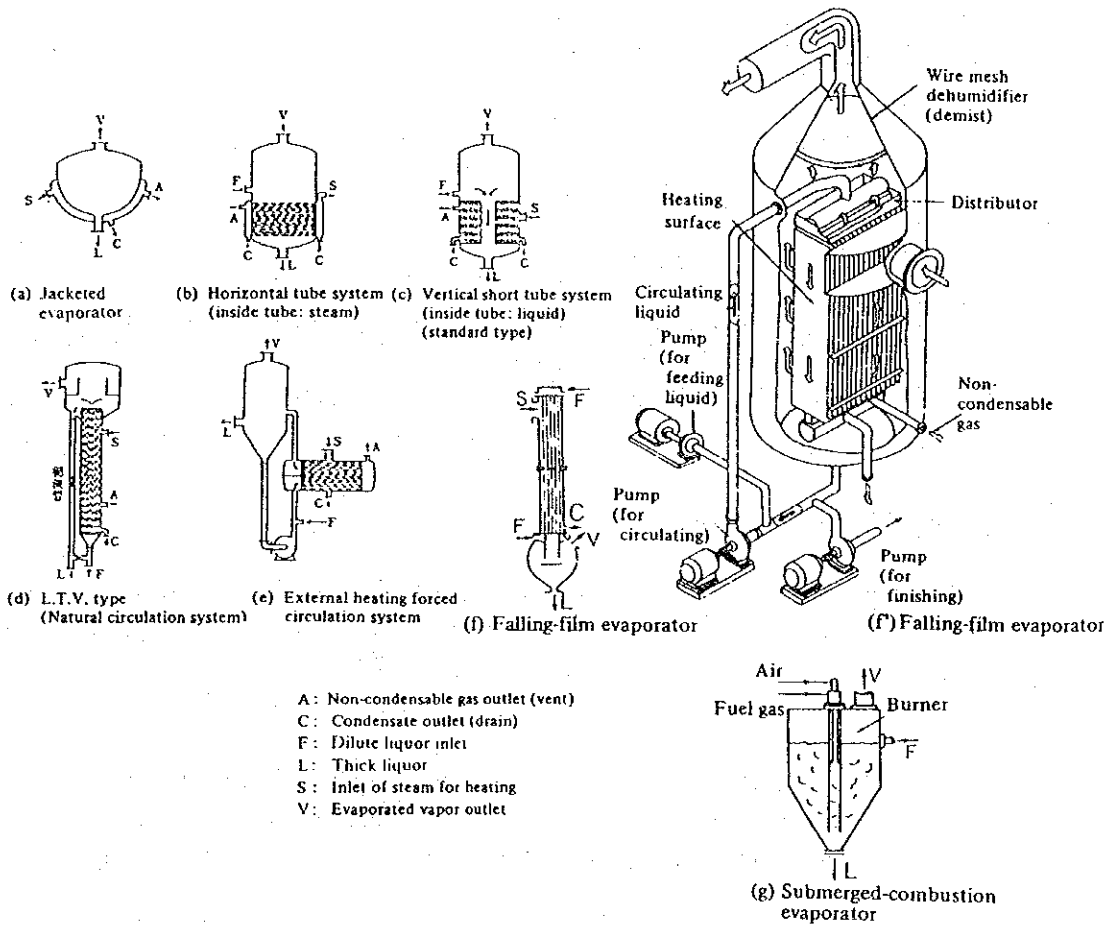
Construction of typical evaporators is shown in Figure 4.21.

(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) used for concentration of highly corrosive solutions such as sodium sulfate, phosphoric acid, dilute sulfuric acid, magnesium chloride, etc.

Figure 4.21 Example of Evaporators



(2) Effective Utilization of Energy

Since evaporation requires a lot of energy, several methods shown in Figure 4.22 are adopted with reference to use of steam from an energy economy standpoint.

a. Steam recovery method

Steam is utilized as-is; (a)

Steam is otherwise utilized after compressing it; (b)

b. Steam (re) compression method

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

- c. Back pressure utilization method

Utilization of turbine exhaust; (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 steam to preheat feed solutions, and is applied to desalination of sea water.

(3) Rationalization in the Use of Thermal Energy

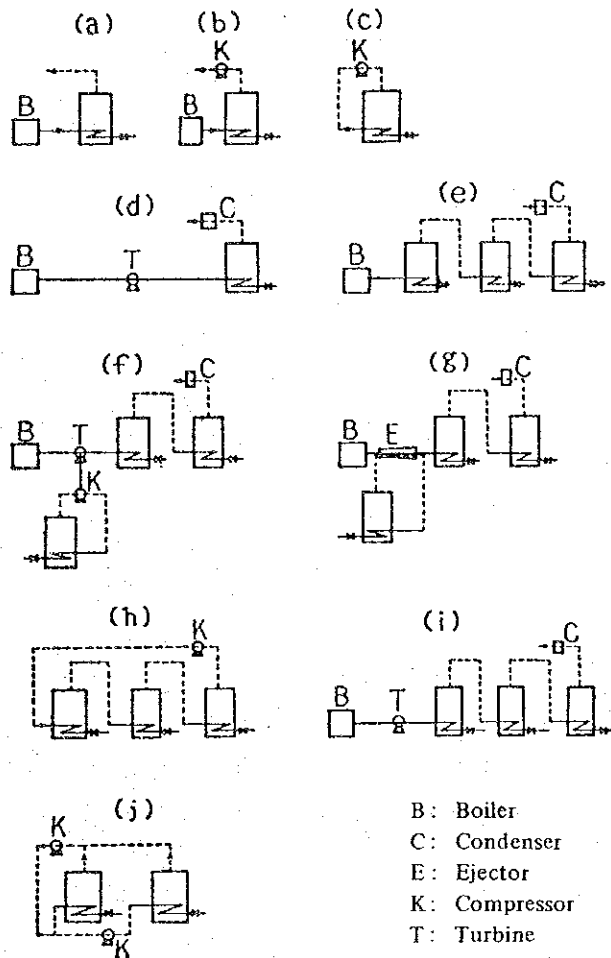
Although energy unit of evaporation largely depends upon the methods mentioned in the preceding item, it is also affected by many other factors, which will be described below:

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:

- a. Remove scale formation ingredients beforehand.
- b. Select pH, concentration, temperature, etc. of the liquid.
- c. Introduce suitable chemicals.
- d. Select the type of evaporator to which it is difficult for scale to stick, and to thoroughly clean.

Figure 4.22 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 atg 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 atg 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.

$$\frac{P_1 + 1.033}{P_2 + 1.033} = \frac{Pt_1}{Pt_2}$$

(Unit) Pt_1, Pt_2 : Torr
 P_1, P_2 : kg/cm²G

C) Air Purge in Steam Heating Chamber

When air or other inert gas is contained in heated steam and solutions, 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 temperature in the steam chamber.

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 is brought below the temperature of condensation of generated steam in the preceding stage evaporator, by lowering the inside-evaporator pressure on the 2nd stage and after below the pressure in each preceding stage in Figure 4.22, 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:

$$N_{opt} = P/K$$

where $P = Wy \cdot Cs / F_E$

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

Wy : Annual amount of evaporation (kg/y)

Cs : Unit price of steam

F_E : Fixed cost of evaporator

4.2.6 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) Class of Dryers

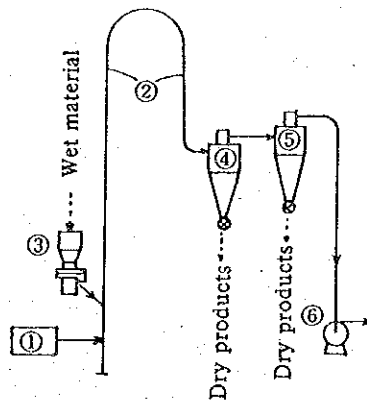
Dryers are classified by the relation between material moving system and heat transfer of the material to be dried, as follows:

A) Hot Air Dryers

a. Hot air conveying types

① Flash dryer (See Figure 4.23)

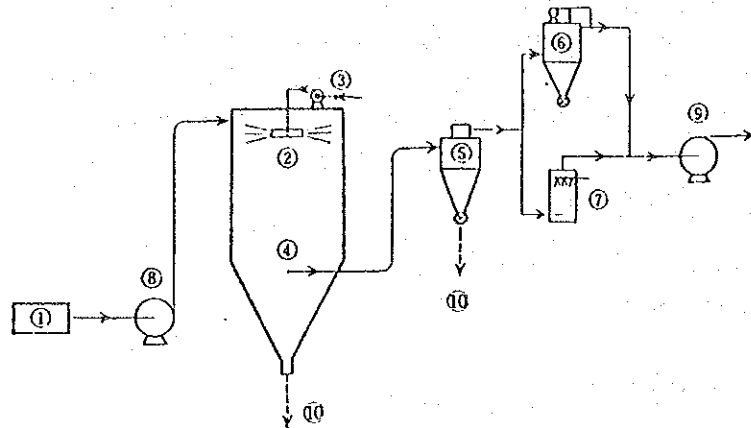
Figure 4.23 Distribution Diagram of Flash Dryer (Direct Feed System)



- (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 4.24)

Figure 4.24 Distribution Diagram of Spray Drying

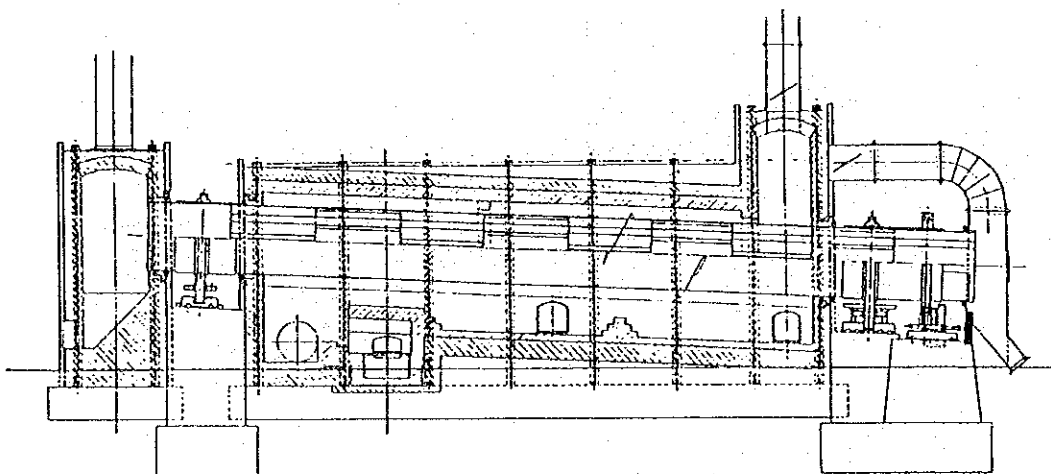


- ① Hot air producer ② Sprayer ③ Feed liquid pump ④ Blower
- ⑤ Cyclone collector ⑥ Bag filter ⑦ Scrubber ⑧ Exhauster
- ⑩ Dried products

b. Material agitation types

- ① Rotary dryers {
 - Single cylindrical direct heating type
 - Double cylindrical direct, indirect heating type
 - External heating type (See Figure 4.25)

Figure 4.25 External Fire Type Rotary Dryer



- ② Multiple-stage disk dryer (See Figure 4.26)
- ③ Groove type agitation dryer (See Figure 4.27)
- ④ Fluidized bed dryers
 - Multi-stage continuous type
 - Horizontal multi-chamber continuous type
 - One-stage continuous type (See Figure 4.28)
 - Batch type
- ⑤ Sheet dryer (See Figure 4.34)

Figure 4.26 Multiple-Stage Disc Hot Air Dryer

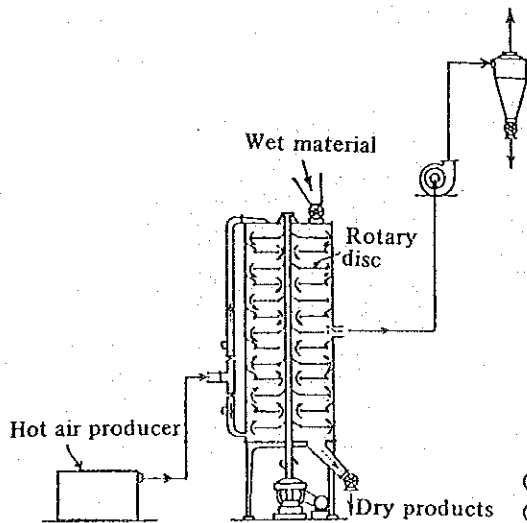
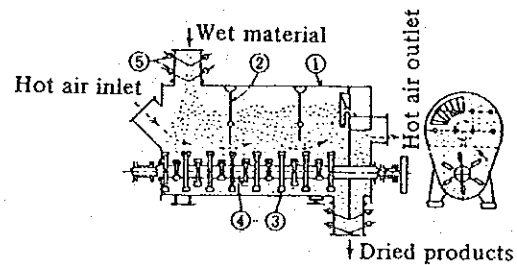
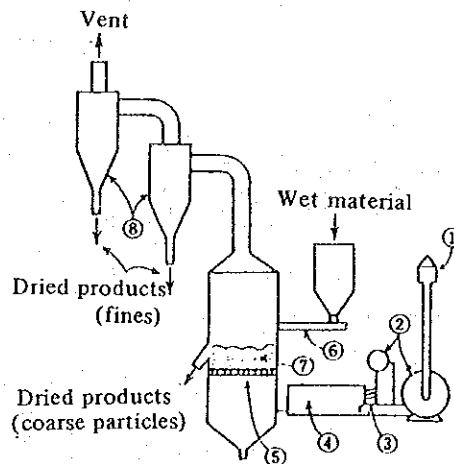


Figure 4.27 Hot Air Groove Type Agitation Dryer



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

Figure 4.28 One Stage Continuous Flow 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 4.29)
Rotary type (See Figure 4.30)
Vertical moving bed type (See Figure 4.31)
Box batch type (Figure 4.32) |
| ② Tunnel dryer (See Figure 4.33) | | |
| ③ Band dryer | | |
| ④ Box dryer | | |

Figure 4.29 Band Type Continuous Through-Circulation Dryer

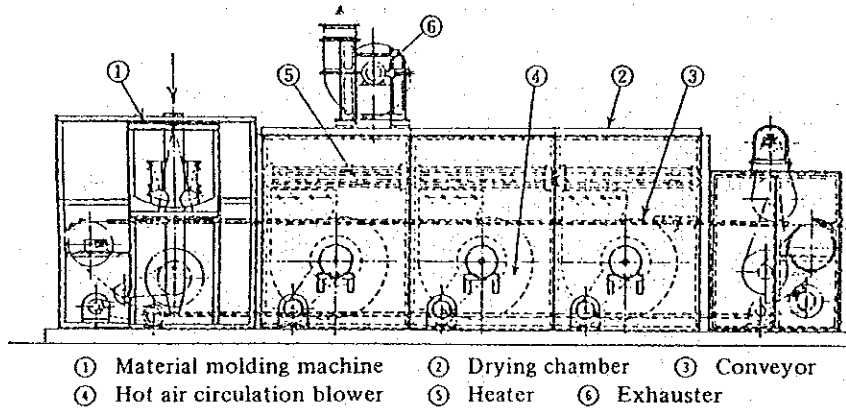


Figure 4.30 Rotary Type Continuous Through-Circulation Dryer

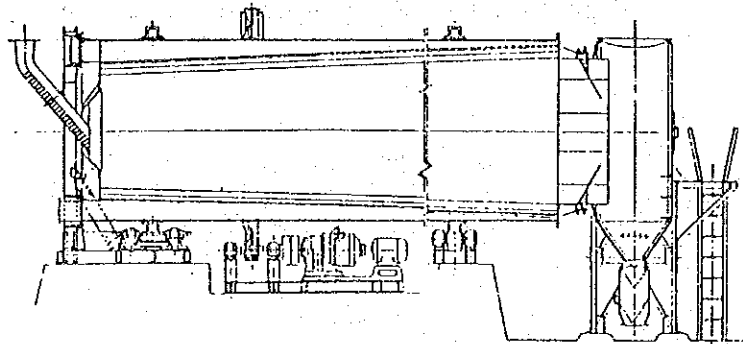


Figure 4.31 Vertical Continuous Moving Bed Through-Circulation Drying System

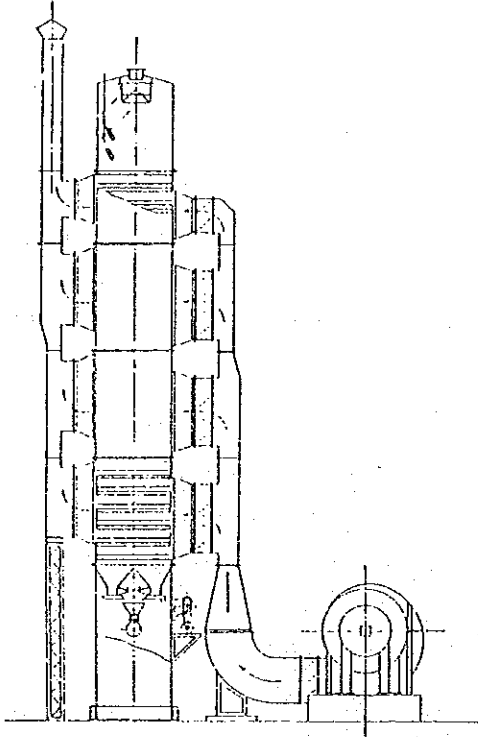


Figure 4.32 Box Batch Type Through-Circulation Dryer

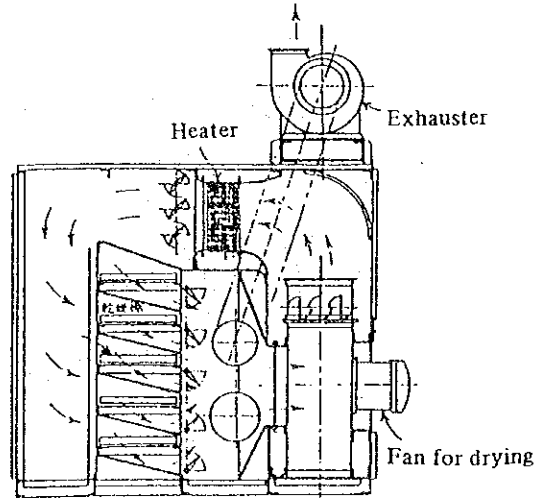


Figure 4.33 Distribution Diagram of Counter-Current Tunnel Dryer

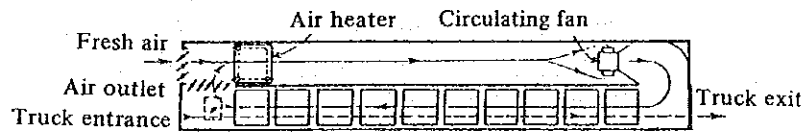
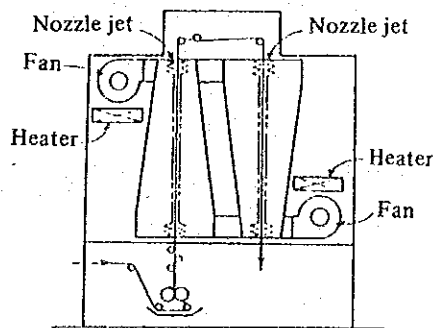


Figure 4.34 Vertical Nozzle Jet Dryer

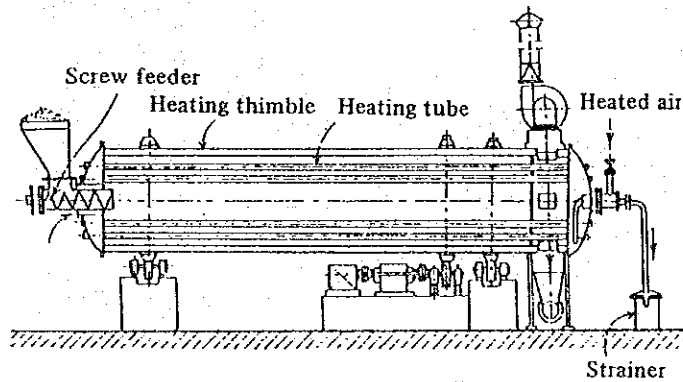


B) Heat Conduction Dryers

a. Material agitation types

- ① Groove type agitation dryer
- ② Cylindrical agitation dryers { Atmospheric pressure type
Vacuum type
- ③ Plate agitation dryer
- ④ Rotary dryer with steam heating tubes (See Figure 4.35)

Figure 4.35 Rotary Dryer with Steam Heating Tube



- ⑤ Multi-stage agitation dryer
- ⑥ Vacuum rotary dryer

b. Material stationary types

- ① Vacuum dryer
- ② Freezing dryer

c. Cylindrical types

- ① Drum dryers { Atmospheric pressure type
Vacuum type
- ② Cylindrical dryer

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

Table 4.6 List of Dryers

Name of Dryer	Dryer Mechanism and Main Characteristics	Heating capacity	Properties of materials to be heated ①Forms ②Treatable moisture content	Application	Others
Hot air carrying drying			<p>① Heat capacity coefficient ha (kcal/m³hr°C) or heat transfer coefficient U (kcal/m²hr°C) ② Hot air temperature [°C] ③ Thermal efficiency [%] ④ Critical moisture content [%]</p>		
Current 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/h	<p>① $ha = 2000 - 6000$ ② 300 - 600 ③ 60 - 75 ④ 1 - 3</p>	<p>① Suitable for removing absorbed moisture ② To dry coal, clay, synthetic resin, inorganic chemicals</p>	<p>① Moisture evaporation 1 - 1.5 kg/kg-gas ② Low construction cost</p>
Spray dryer	To spray fluid to be distributed and carried in concurrent, or countercurrent. ① Such processes as grinding, classification and filtering can be omitted. ② Powder particle products can be obtained in short process.	Evaporated moisture 6t/hr Maximum	<p>① $ha = 20 - 80$ ② Countercurrent 200 - 300 ③ Concurrent 250 - 400 ④ 20 - 30</p>	<p>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.</p>	<p>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</p>
Material Rotary agitation 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 Wideranging material to be treatable	Continuous, large-scale drying is possible. Example: Clay 70 t/hr Limestone 60 t/hr Chemical fertilizer 120 t/h	<p>① Powder particle ② Lump ③ 40 - 50 (W.B or less)</p>	<p>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.</p>	<p>① High construction cost</p>
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 amount of dust ② Saving of floor space	Continuous and large-scale processing is possible.	<p>① Powdered and granular</p>	<p>① Active carbon, medicines, ore, etc.</p>	<p>① Construction and operation costs are high.</p>

Table 4.7 Compatibility of Spraying Methods with Material Statuses

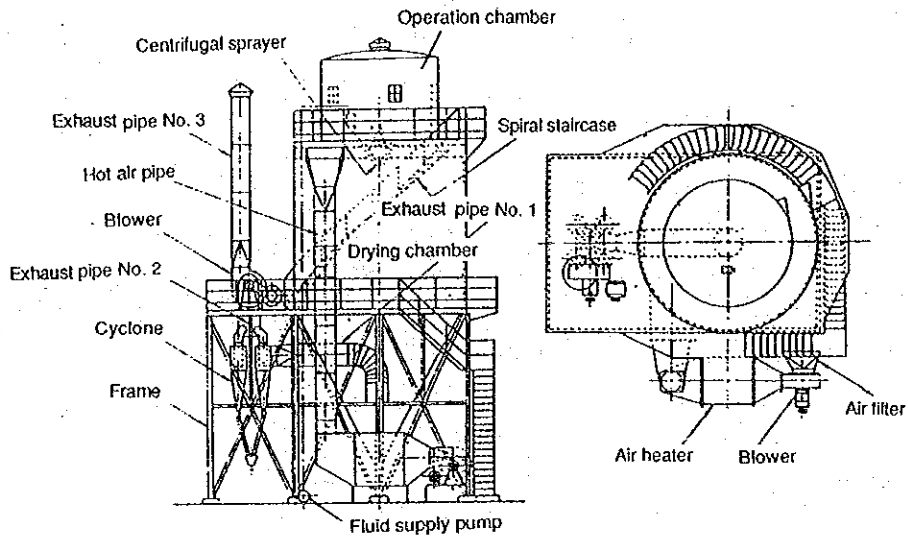
Heating method	Forms of material														
	Solution	Paste	Cakey	Foamy	Powdered	Granular	Lump-like	Flaky	Single fiber	Molding sheet	Continuous sheet	Scrap sheet	Paint/Printed products	Frozen	
Types of dryer															
Direct heating															
Box type dryer (concurrent)	Δ	Δ	Δ	X	●	●	●	●	●	●	X	●	○	X	
Box type dryer (through-circulation)	X	X→○	X→●	X	○→●	●	○	○	○	○	X	○	○	X	
Tunnel type dryer	Δ	Δ	Δ	X	●	●	●	●	○	○	Δ	Δ	Δ	X	
Band type dryer (concurrent)	X	Δ	Δ	X	○	○	○	○	○	○	Δ	Δ	Δ	X	
Band type dryer (through-circulation)	X	Δ→○	Δ→●	X	Δ→●	●	○	○	○	○	Δ	Δ	Δ	X	
Conveyor type dryer	Δ	Δ	Δ	X	○	○	○	○	○	○	X	○	○	X	
Rotary type dryer (Direct heating)	X	X	Δ	X	○	○	○	○	X	X	X	X	X	X	
Rotary type dryer (through-circulation)	X	X	X	X	Δ	Δ	○	○	○	X	X	X	X	X	
Multi-stage vertical dryer	X	X	Δ	X	○	○	○	○	X	X	X	X	X	X	
Fluidized layer dryer	X	X	X	X	●	●	Δ	Δ	X	X	X	X	X	X	
Jet layer dryer	X	X	X	X	○	○	○	○	X	X	X	X	X	X	
Current dryer	X	X	X→○	X	●	●	Δ	X	X	X	X	X	X	X	
Spray dryer	●	○	X→Δ	X	X	X	X	X	X	X	X	X	X	X	
Foamed layer dryer	X	X	X	●	X	X	X	X	X	X	X	X	X	X	
Continuous sheet dryer	X	X	X	X	X	X	X	X	X	X	●	X	○	X	
Indirect heating															
Vacuum box type dryer	Δ	Δ	○	○	●	●	○	○	Δ	Δ	X	Δ	X	X	
Vacuum agitation dryer	X	X	X→Δ	X	●	●	○	○	X	X	X	X	X	X	
Vacuum freezing dryer	X	X	X	X	X	X	X	X	X	X	X	X	X	●	
Agitation type dryer	X	X→Δ	X→Δ	X→Δ	○	○	○	Δ	X	X	X	X	X	X	
Rotary dryer (Indirect heating)	X	X	Δ	X	○	○	○	Δ	X	X	X	X	X	X	
Drum type dryer	●	●	Δ	X	X	X	X	X	X	X	X	X	X	X	
Cylinder dryer	X	X	X	X	X	X	X	X	X	X	X	Δ	○	X	
Plumping dryer	X	X	X	X	X	○	○	○	X	X	●	X	X	X	
Infrared dryer	X	X	X	X	Δ	Δ	X	X	X	Δ	●	●	●	X	
High-frequency dryer	X	X→Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	X	X	
Ultrasonic dryer	X	X	Δ	X	Δ	Δ	X	X	X	X	X	X	X	X	

Degree of compatibility: ● → ○ → Δ
 X : Unsuitable

Table 4.8 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 the a may be treatable depending on the fluid
	Changing flow amount	Flexible	The particle diameter will be changed by 60 ~ 100 %	Particle dismeter 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 ²	Fluid pressure and air pressure: Up to 3 ~ 5 kg/cm ² 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 (Hower, 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 4.36 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 ²
Up to 50 liter	Diameter 3,000 Height 9,500	1,200	125 m/m	12.5	50 m ²
Up to 100 liter	Diameter 3,800 Height 12,000	1,200	160 m/m	15	55 m ²
Up to 250 liter	Diameter 5,090 Height 13,000	8,000	250 m/m	30	70 m ²
Up to 500 liter	Diameter 6,300 Height 16,000	8,000	300 m/m	40	80 m ²
Up to 1,000 liter	Diameter 7,000 Height 18,000	7,000	350 m/m	100	100 m ²
Up to 2,500 liter	Diameter 9,500 Height 25,000	6,000	400 m/m	250	160 m ²
Up to 4,000 liter	Diameter 10,200 Height 27,000	5,000	450 m/m	300	220 m ²

Figure 4.37 Configuration Examples of Spray Dryers

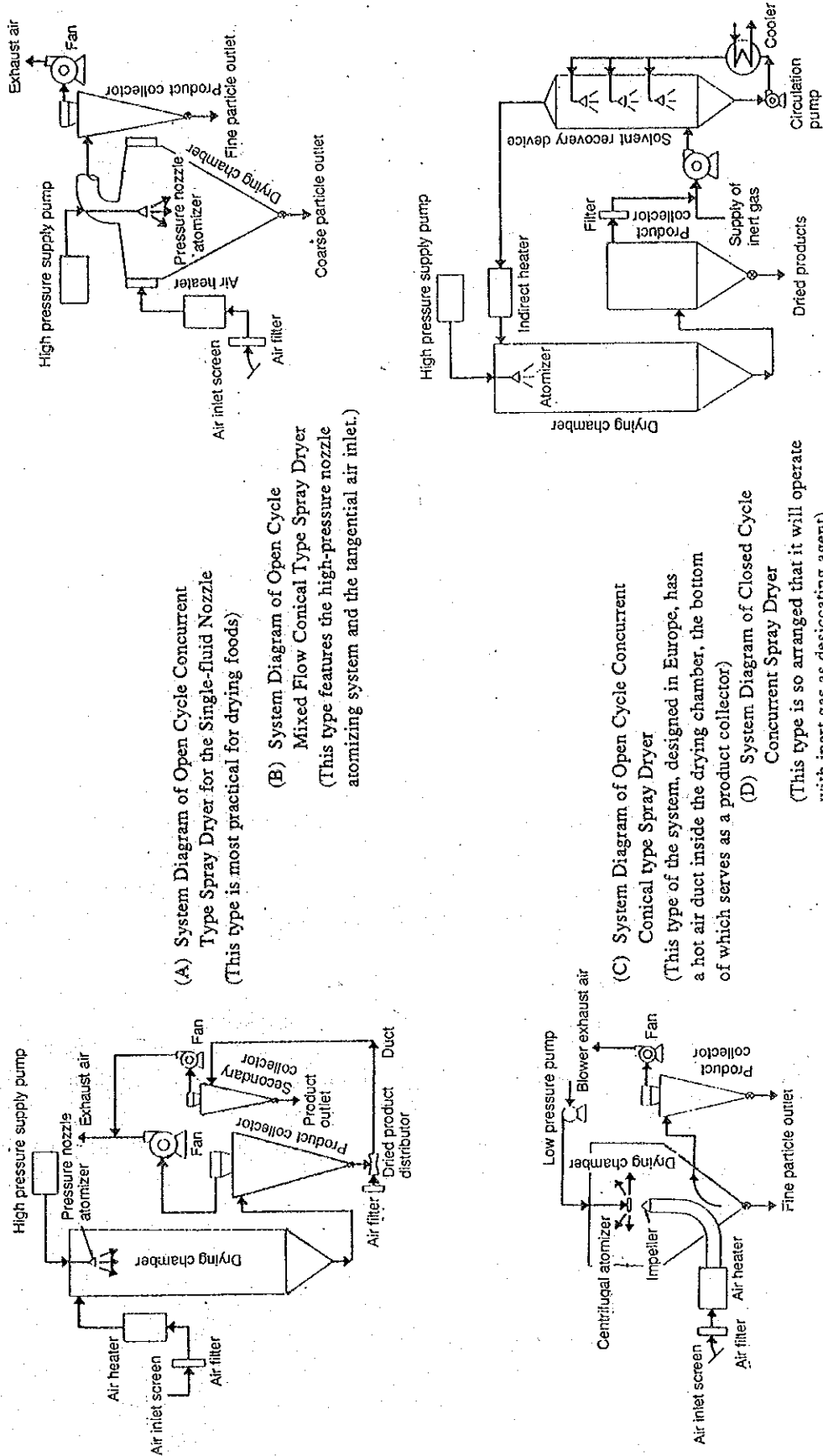


Table 4.9 Application Examples of Spray Dryers

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/cm³]	0.3-0.4	0.6	0.65	0.28	0.26	0.3	
Hot air	Amount to be used [m³/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/cm² abs]			40	30-40	30-40	
	Diameter [mm]			1.6	2.4-3.2	3-5	
	No.			12	1	6-8	
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]	1	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 dehydrator 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 exhaust is concentrated by allowing it to come into direct contact with the liquid to be dried in spray dryers, almost all sensible heat of the exhaust can be utilized close to the saturation.

E) Recovery of Latent Heat from Exhaust

The percentage of heat capacity used for evaporation of moisture to heat capacity 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 or recover 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, cool them by air and recover heat retained in them to utilize for preheating the drying air. Since the temperature of the dried products is not so high mostly, cool and at the same time, preheat air by means of a fluidized bed and the efficiency may be improved.

G) Others

It is often seen in chemical plants that air is used to cool reaction products, distillation towers and 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.

4.2.7 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 from the evaporator side of the refrigerant and releases the heat from the condenser side. Among such equipment, an equipment for gathering heat at a temperature below the ordinary temperature with the purpose of obtaining low 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 emitted to the outside is only the moisture taken from the material to be dried.

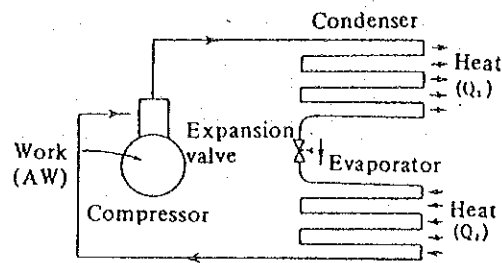
There are various methods of constituting a heat pump such as steam compression type, steam ejector type, absorption type, and chemical type. However, from the standpoint of economics and performance, under current conditions, the steam compression type and the absorption type are practical. The basic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

(2) Cycle of steam compression system

The basic structure of steam compression system is shown in Figure 4.38.

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 and become gas again, then enter the compressor.

Figure 4.38 Refrigeration 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

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

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 or Mollier 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 4.39. 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 isentropic 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

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

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

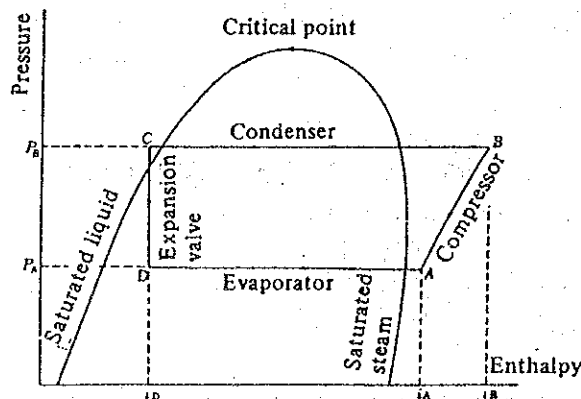
The ratio between the refrigeration effect and the compression workload is called the performance coefficient, and if it is expressed by E,

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

In the case of heat pump, the performance coefficient 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 4.39 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 costwise. 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 m³/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 now 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

- a. The critical temperature is higher than the ordinary temperature, and the freezing point is low.
- b. Heat of vaporization is large (The circulation amount of the refrigerant can be less.)
- c. The ratio of specific heat of the gas, that is, (constant pressure specific heat)/(constant volume specific heat) is small.
- d. The performance coefficient is large.

- e. The specific volume of the gas is small. (The volume of the compressor may be designed small)
- f. The condensation pressure and the vaporization pressure are suitable.

B) Chemical properties

- a. Under the usage conditions, they are chemically stable.
- b. They are inert and have no corrosiveness.
- c. Solubility towards lubricants is small.
- d. At both the gas and liquid they have low viscosity.
- e. 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 the trend is to restrict their use.

The characteristic values of refrigerants that are not restricted are as shown in Tables 4.10 and 4.11. Furthermore, the P-i Charts of the refrigerants are shown in Figure 4.40 and Figure 4.41.

Table 4.10 Refrigerant Properties (for High Temperature)

Classification of refrigerants		Ammonia	Freon	Propane R-22	Propylene	n-butane	i-butane
Chemical formula		NH ₃	CHClF ₂	C ₃ H ₈	C ₃ H ₆	C ₄ H ₁₀	C ₄ H ₁₀
Molecular weight		17.03	86.48	44.06	42.08	58.12	58.12
Boiling point (at atmospheric pressure)	°C	-33.3	-40.8	-42.3	-41.0	-0.5	-11.7
Freezing point (at atmospheric pressure)	°C	-77.7	-160	-189.9	-185.2	-135	-145
Critical temperature	°C	133	96	94.4	91.8	152.2	134.9
Critical pressure	kg/cm ² (abs)	116.50	50.34	46.51	47.0	38.7	37.2
Evaporation pressure at -15 °C	"	2.410	3.025	2.946	3.70	0.576	0.921
Condensation pressure at 30 °C	"	11.895	12.269	10.918	13.10	2.92	4.18
Compression ratio at T _e = -15 °C and T _o = 30 °C		4.94	4.056	3.706	3.54	5.07	4.54
Heat of evaporation at -15 °C	kcal/kg	313.53	51.998	94.56	96.10	95.00	88.6
Refrigerating capacity at standard refrigerating cycle	"	269.03	40.16	70.68	72.8	74.2	65.3
Refrigerant circulation amount per ton of Japan refrigerating capacity	kg/hr	12.34	82.67	46.97	45.6	44.7	50.8
Specific volume of saturated steam at -15 °C	m ³ /kg	0.5087	0.0778	0.1548	0.142	0.623	0.400
Specific volume of saturated liquid at 25 °C	ℓ/kg	1.6588	0.8384	2.053	0.647	1.740	1.81
Compressor discharge temperature	°C	98	55.00	36.11	42.0	32.0	27.0
Theoretical piston displacement per ton of Japan refrigerating capacity	m ³ /hr	6.278	6.420	7.272	6.48	27.8	20.3
Theoretical indicated horsepower per ton of Japan refrigerating capacity		1.08	1.064	1.079	1.09	1.02	1.14
Coefficient of performance		4.87	4.87	4.80	4.78	5.10	4.53

Table 4.11 Refrigerant Properties (for Low Temperature)

Classification of refrigerants		Ethane	Ethylene	Methane
Chemical formula		C ₂ H ₆	C ₂ H 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 ² (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°C and T _o = 30°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°C and T _o = -30°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 ³ /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 ³ /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 4.40 P-i Diagram of Ammonia

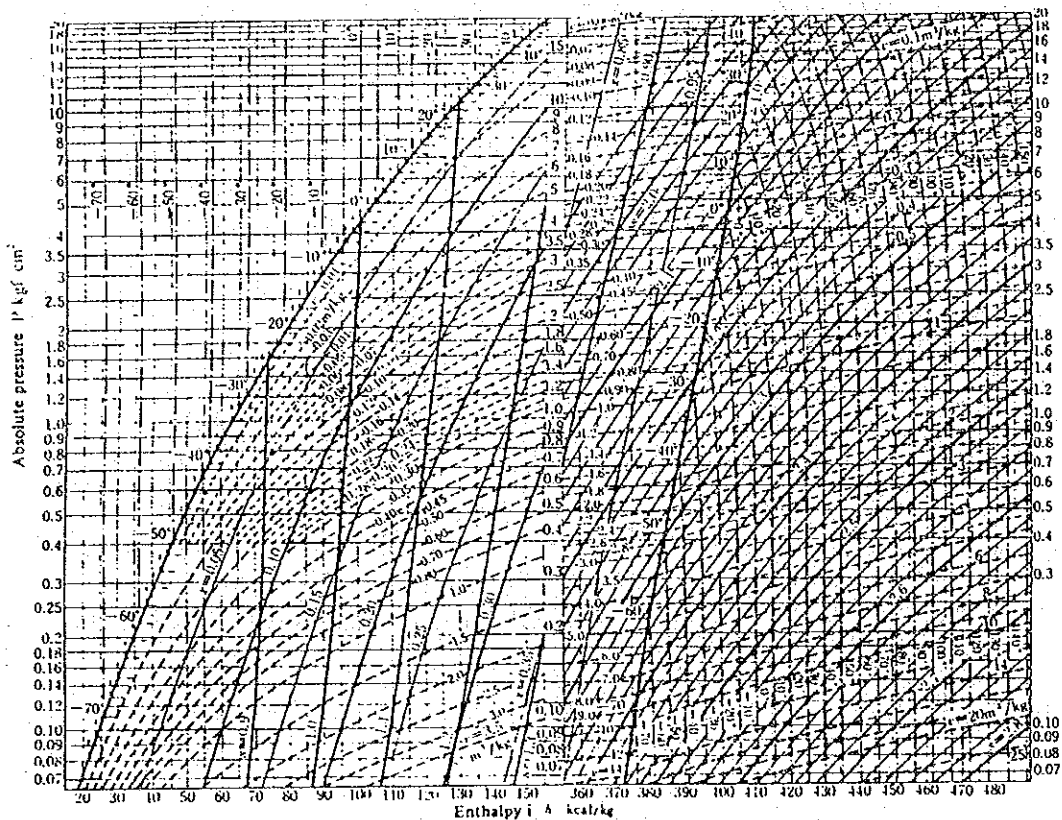
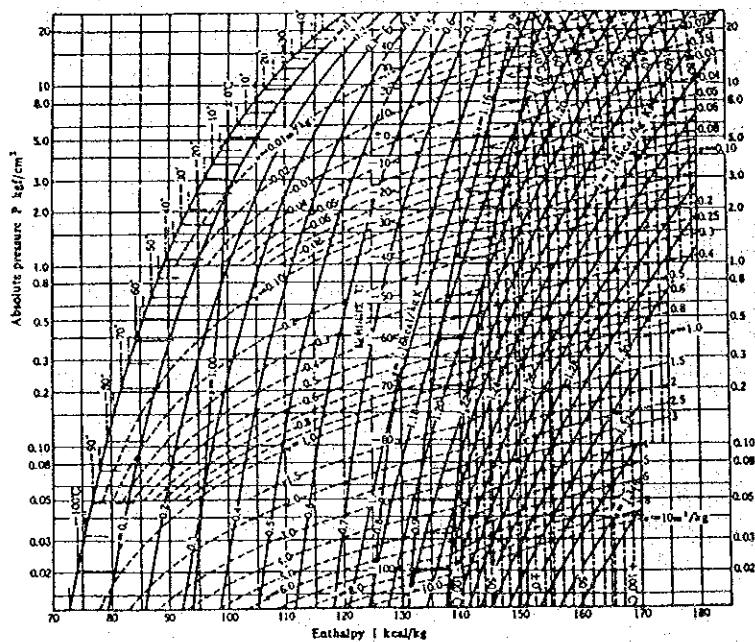


Figure 4.41 P-i Diagram of R22



If refrigerants for high temperature use such as R-22 or ammonia are used when the vaporization temperature becomes below -80°C , the saturation pressure which is equivalent to the vaporization temperature will be extremely low, and very high vacuum will be required. 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 4.42. At the evaporator, the operating media which gained heat from the brine and were vaporized are 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, 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 Class 1 Absorption Heat Pumps which require heat source for high temperature driving and the Class 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 4.43 and Figure 4.44.

Figure 4.42 Adsorption Type Heat Pump

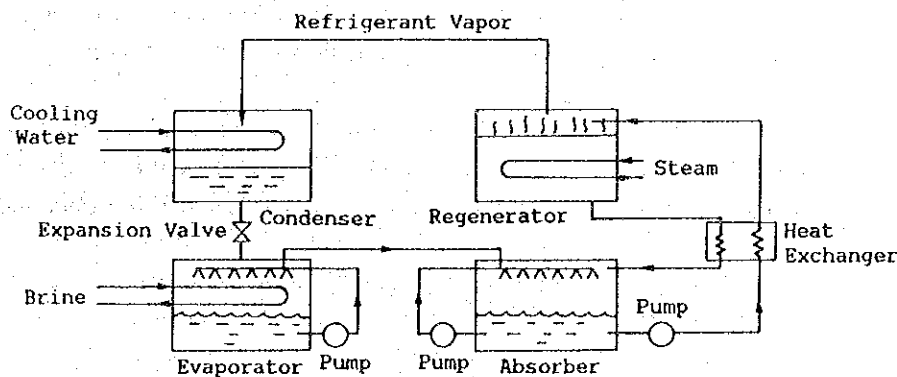


Figure 4.43 Dühring Chart for Heat Pump (Type 1)

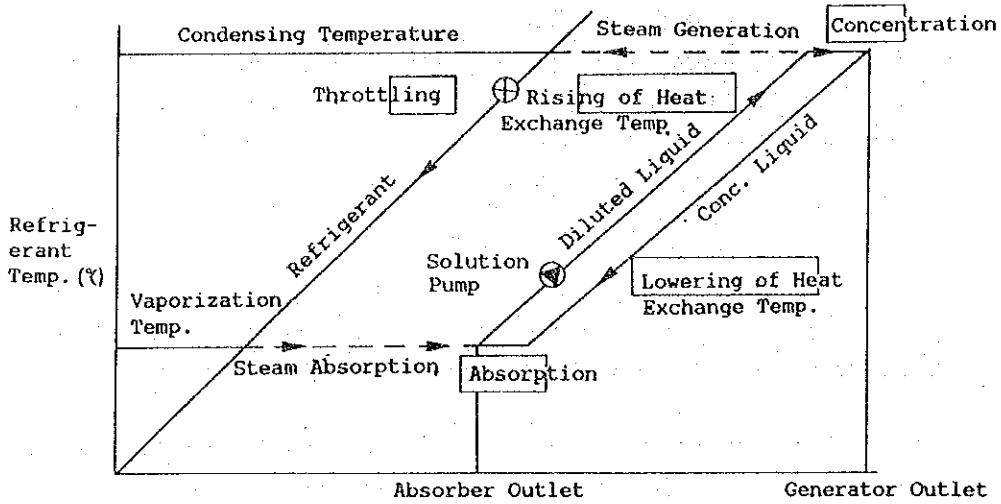
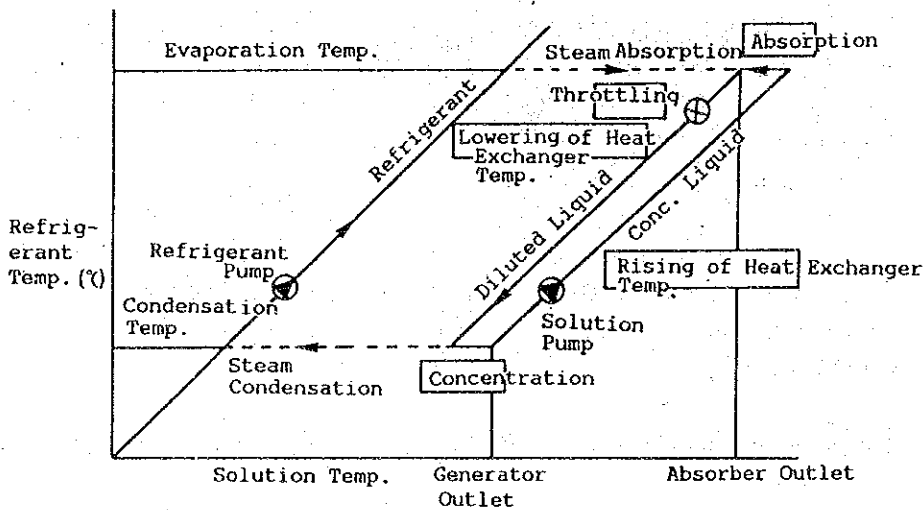


Figure 4.44 Dühring Chart for Heat Pump (Type 2)



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

Since heat of absorption liquid which has a temperature that is higher than the vaporization temperature by an amount equal to the rise in boiling point will be utilized, a warm water having a temperature which is higher than the warm waste 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, H₂SO₄ 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_2). Besides this, there are also sodium chloride (NaCl), magnesium chloride (MgCl_2), methanol, ethanol, ethylene glycol, glycerine, etc. In Figure 4.45, the specific heat of brine is shown, and in Figure 4.46 the specific gravity and freezing temperature are shown.

Figure 4.45 Specific Heat of Brine

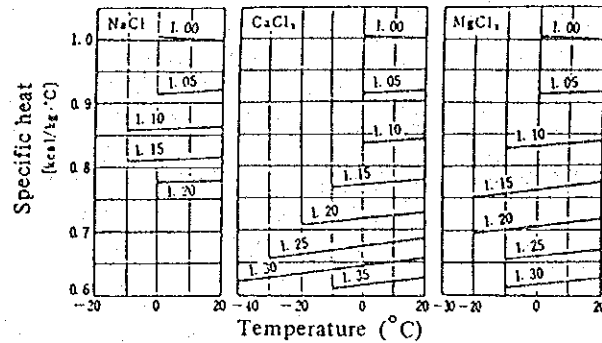
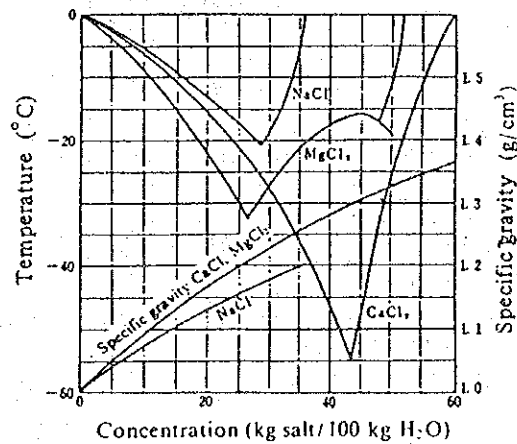


Figure 4.46 Freezing Temperature and Specific Gravity of Brine



(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 BUT/min. = 3, 023 kcal/h)

(8) Rationalization of the use of refrigerating energy

In Table 4.12, the energy saving method of refrigerator and heat pump equipment is shown.

Table 4.12 Energy Saving Method of Freezer and Heat Pump Equipment

	Method of energy saving	Freezer		Heat Pump	Remarks	
		Steam Comp.	Absorp.			
Decrease in Load Conv. Dr.	Decrease in Freezing (Heating) Load	○	○	○	Refer to Table 4.24	
	Decrease in Conveying System Drive	○	○	○	Refer to Table 4.24	
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 Solution Heat Exchanger	—	○	—	High Heat Transfer Pipe
		Decrease in Solution Circulation	—	○	—	
	Others	Decrease in Auxiliary Equipment Power	○	○	○	
	Waste Gag 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	—	○	*1)		
Control	Soiling 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.

- a. "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.
- b. "Cylinder head by-pass system" in which by-pass valves are installed on each cylinder, and do not let the compression process take place.
- c. "Hot gas by-pass system" in which high temperature exhaust gas is charged between the expansion valve and the evaporator.
- d. "Clearance increment system" in which a clearance pocket is made to the cylinder, and the apparent volume efficiency is lowered.
- e. "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) Soiling 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 4.47). Consequently, the power consumption of the compressor will increase. (Figure 4.48)

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 4.49). 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 4.47 Heat Transfer Surface Staining and Condensation Temperature

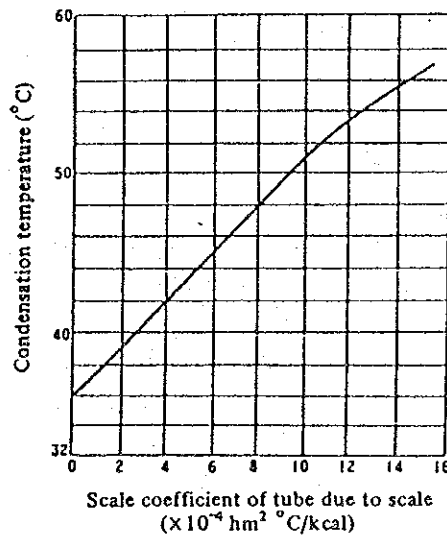


Figure 4.48 Effect of Scale on Refrigeration Capacity

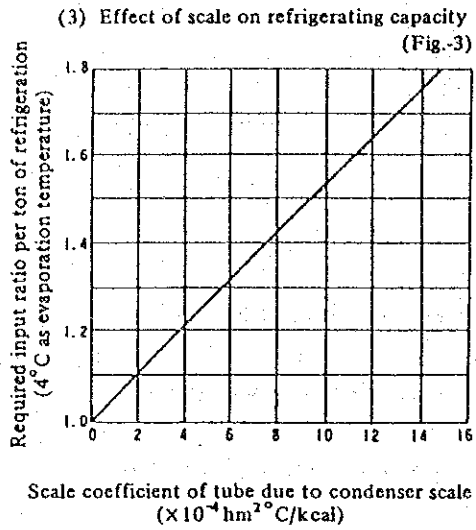
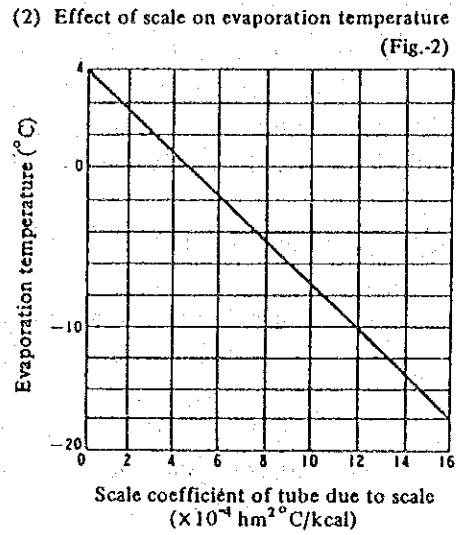


Figure 4.49 Effect of Scale on Evaporation Temperature



4.2.8 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 type furnace

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

c) Solid heating type 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, dry distillation 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 reactor, hydrogen chloride reactor, etc.

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

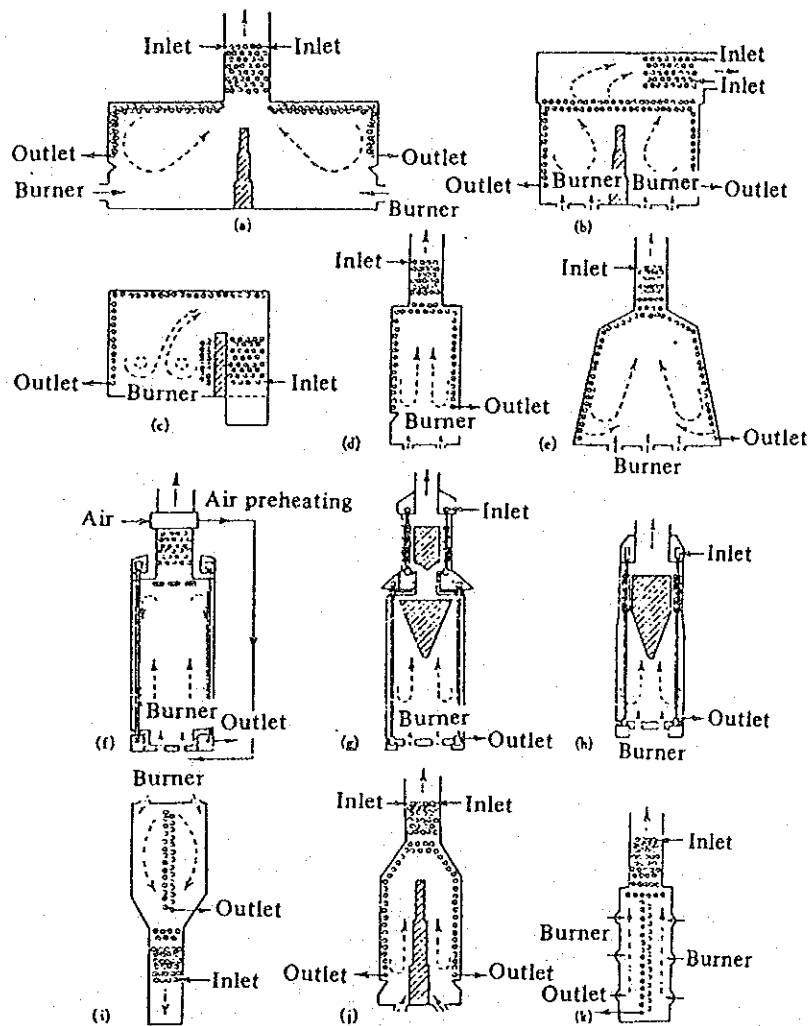
(1) Pipe still

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 4.50 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 4.50 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 (DeFlorez) (g) Large isoflow (Petrochem)
 (h) Small isoflow (Petrochem) (i) Equifiux (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 similar (analogous) 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), (c), 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 similar shapes will have uniform heat load, and it will have many advantages such as no coking, no discoloration, 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.

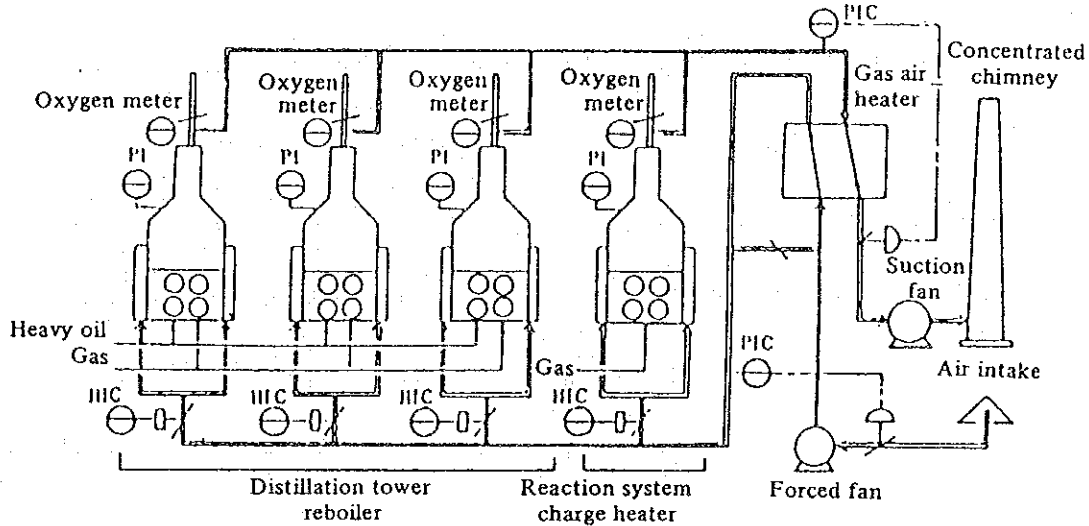
By lowering the exhaust gas loss, and by recovering the heat retained by the fluid, it is possible to raise the heat efficiency of the pipe still to $80 \sim 90 \%$.

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°C , Figure 4.51) 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

Figure 4.51 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 4.13. 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 8.9)

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 users' 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 4.13 Physical Properties of Thermal Fluids

Property	Dowtherm A*	Dowtherm B*	Fused salt Hi Tec †	Oil Mobilthem 600 ‡	Oil Mobilthem light ‡	Hydrothem § 750-200	Hydrothem § 700-160	Therminol ¶ FR-2	Mercury	NaK
Chemical formula	(C ₂ H ₅) ₂ O (C ₂ H ₅) ₂	C ₂ H ₅ Cl ₂	NaNO ₂ NaNO ₃ KNO ₃						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.)	0.526(496°F)	0.412(352°F)	0.373(300°F)	0.580(500°F)	0.58(300°F)	0.56(600°F)	0.64(500°F)	0.333(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	0.000101		
Absolute viscosity of liquid, centipoise	0.30(600°F)	0.30(400°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./ft.(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 Hydrothem Corp.

¶ Monsanto Co.

Table 4.14 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 ² -hr)	15,000	—	15,000	—
Convection section thermal load (kcal/m ² -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 ³ /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

5. Energy Conservation in the Vegetable Oil Industry

5. VEGETABLE OIL

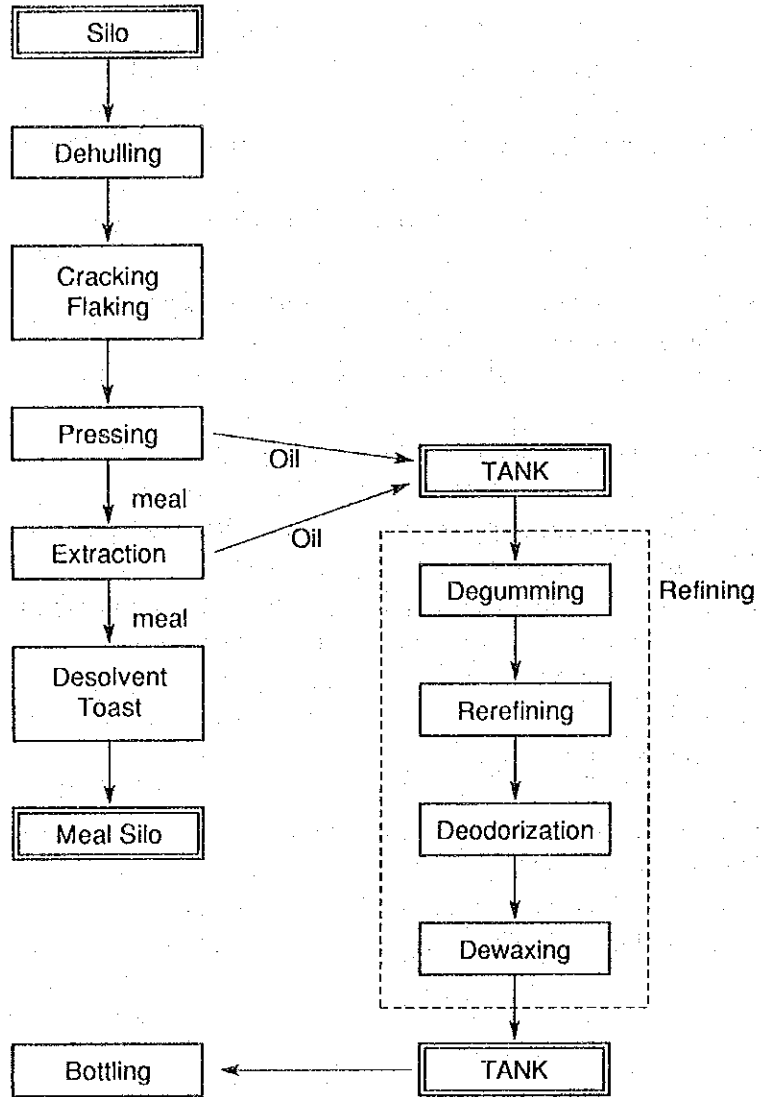
(1) Production process

Edible oils can be broadly classified into two types; vegetable oils and animal fats. The plant covered by our study project is a vegetable oil manufacturing plant. The seeds of soybean, rape, sunflower and palm are often used as materials of the edible oils throughout the world, and sunflower is often used in Bulgaria. The sunflower seeds contain 40 to 45 % oil; they contain much linoleic acid and oleic acid in particular. The sunflower is grown in the former Soviet Union, Australia, East Europe and the United States. Except that the vegetable oils are partly taken by the expression process, they are extracted from the seeds containing oil of 20 % or less directly by hexane (extraction method). When more oil is contained in the seeds, generally, the expression process is used first; then extraction method is used after oil has been reduced (prepress and solvent expression).

Oils taken by these methods contain a great deal of impurities, and cannot be used as edible oils as it is, and a variety of impurities such as free fatty acid, coloring matter, wax, odorant components must be removed in the refining process. Table 5.1 shows the sunflower seed oil manufacturing process in the plant covered by our study project. Defatted meal is generated as by-products in the vegetable oil manufacturing plant, and the generated amount is greater than that of the oil. Defatted meal is often used as feeds containing much protein, so factories are required to produce high-quality defatted meal. The production process differs slightly according to the quality of materials or oil and meal required, technical standards and method.

In the plant we surveyed, sunflower seed oils are the major products, and soybeans are partly processed. Oil content of the soybeans is below 20 %, so oil is generally directly extracted without being pressed. In this plant, however, the prepress and solvent expression is used to make up for the insufficient capacity of extraction.

Figure 5.1 Process Flowchart of Sunflower Oil

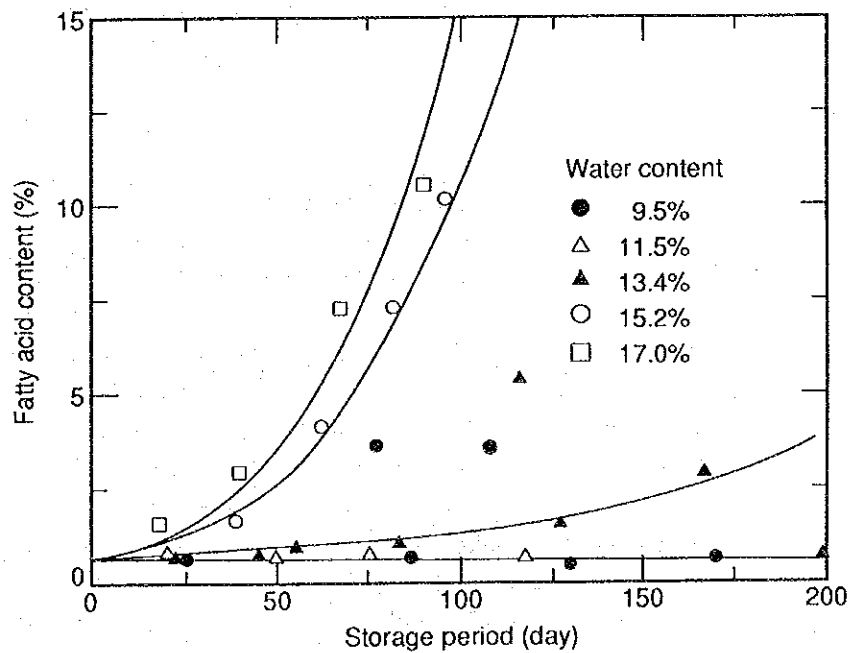


a. Expression process

Stalks, leaves and other foreign substances are removed from the oil materials, and are dried to a specified moisture level if they contain much water; then they are stored. If materials containing much water are stored for a long time, heat will be generated and acid value of the oil will increase, and decoloration will become difficult; furthermore, seed protein will denature, resulting in "damaged seed".

Figure 5.2 illustrates the relation between the water content of the cotton seed and acid value of the extracted oil after storage. It shows that the water content of the stored material should be below 12 %.

Figure 5.2 Relation between Water Content and Value



1) Preparatory process

In the expression process oil is squeezed by the press, and forms, water content and temperature of the material seed are controlled in advance in order to ensure expression operation under the optimum conditions. The process before the expression process is called the pre-treatment process.

The product standards for defatted meal specify protein contents. To ensure the amount of required protein, the amount of the hull may be adjusted in the hulling process. The sunflower seed oil materials used in the plant of our study contain 22 to 23 % hulls, of which about 13 % are removed in the hulling process. The removed hulls are used as fuels for boilers. Defatted meal of soybeans is sometimes used as food, and hulls are removed in this case as well.

After hulling, the materials are crushed by the crush roll, and are flaked by flaking roller; then they are provided with heat treatment in the cooker where water content and temperature are adjusted. The flake thickness is about 0.2 to 0.4 mm. It is recommended to minimize the amount of powder to be produced.

In addition, the material containing much water may be dried by the dryer or preheated by the preheater before the flaking roller. The water content of the sunflower is as low as 6 to 7 %, so dryers are not often used. In the plant of our survey, the dryers are installed, but are not used because the water content is low. It is not provided with any preheater before the flaking roller.

2) Press

After water content and temperature have been adjusted in the cooker, the materials are pressed to get oil. Figure 5.3 illustrates the cooker and the press. The amount of oil obtained by the press differs according to the water content and temperature at the inlet. Generally, higher temperature and lower water content tend to produce meal containing less residual oil at the press outlet. In the case of sunflower, materials are pressed with the water content of 3 to 5 % and temperature of 100 to 120°C at the press inlet, and are fed to the extraction process after the oil content of the meal at the press outlet is reduced to about 20 %.

The oil (pressed oil) taken out of the press is fed to the refining process with extracted oil. As much meal is contained in the pressed oil, it is removed by the filter or similar device. Generally, pressed oil is easier to refine than the extracted oil.

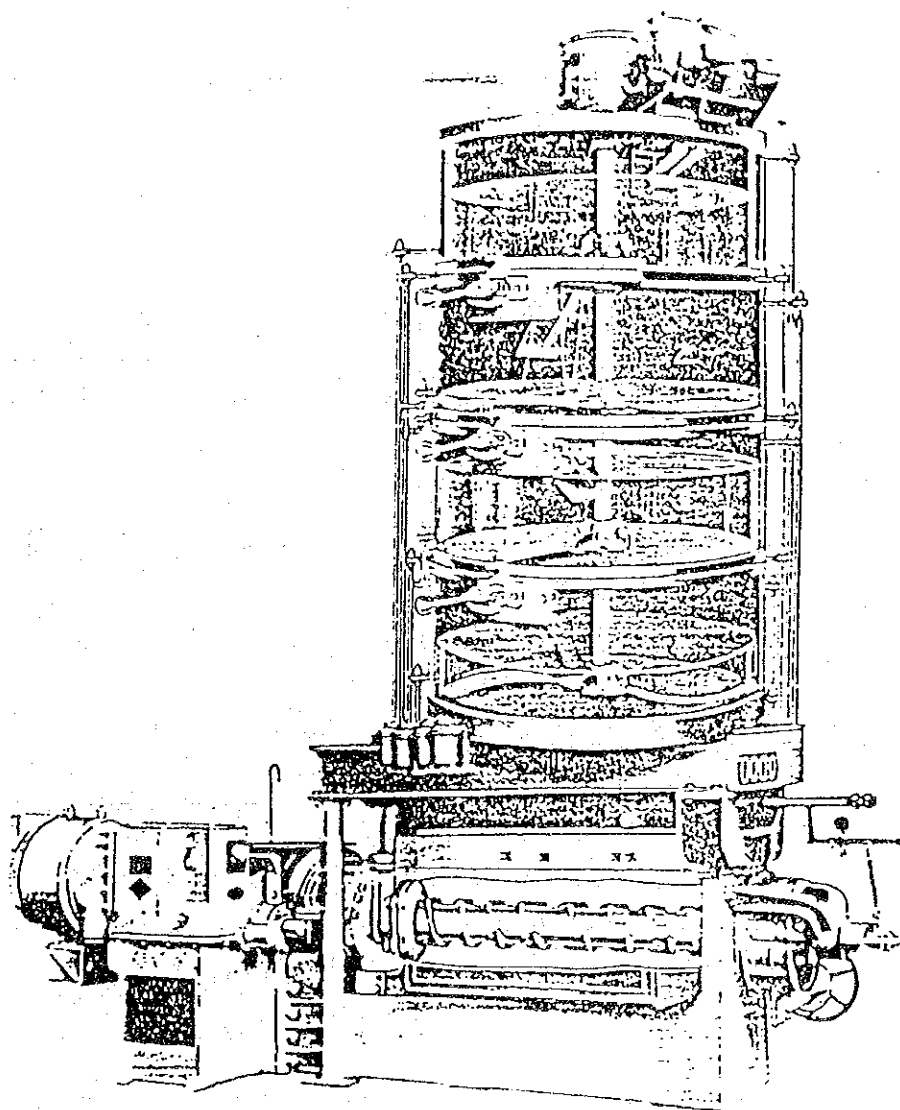
In the expression process, energy unit consumption shows a trend that steam unit consumption is smaller for the material of less water content. Electric power unit consumption tends to increase as the oil contained in the meal at the press outlet is reduced. Since the materials are natural products, the quality, including water content and oil content, differs according to the place of origin and year of the product, and the unit consumption also differs accordingly. The following shows the energy unit consumption in the rape seed expression process in Japan. As shown below, great variations occur according to the quality of the material and ambient temperature.

Energy unit consumption in the rape seed expression process in Japan

Steam : 80 to 120 kg/t (material: in tons)

Electric power: 25 to 35 kWh/t (material: in tons)

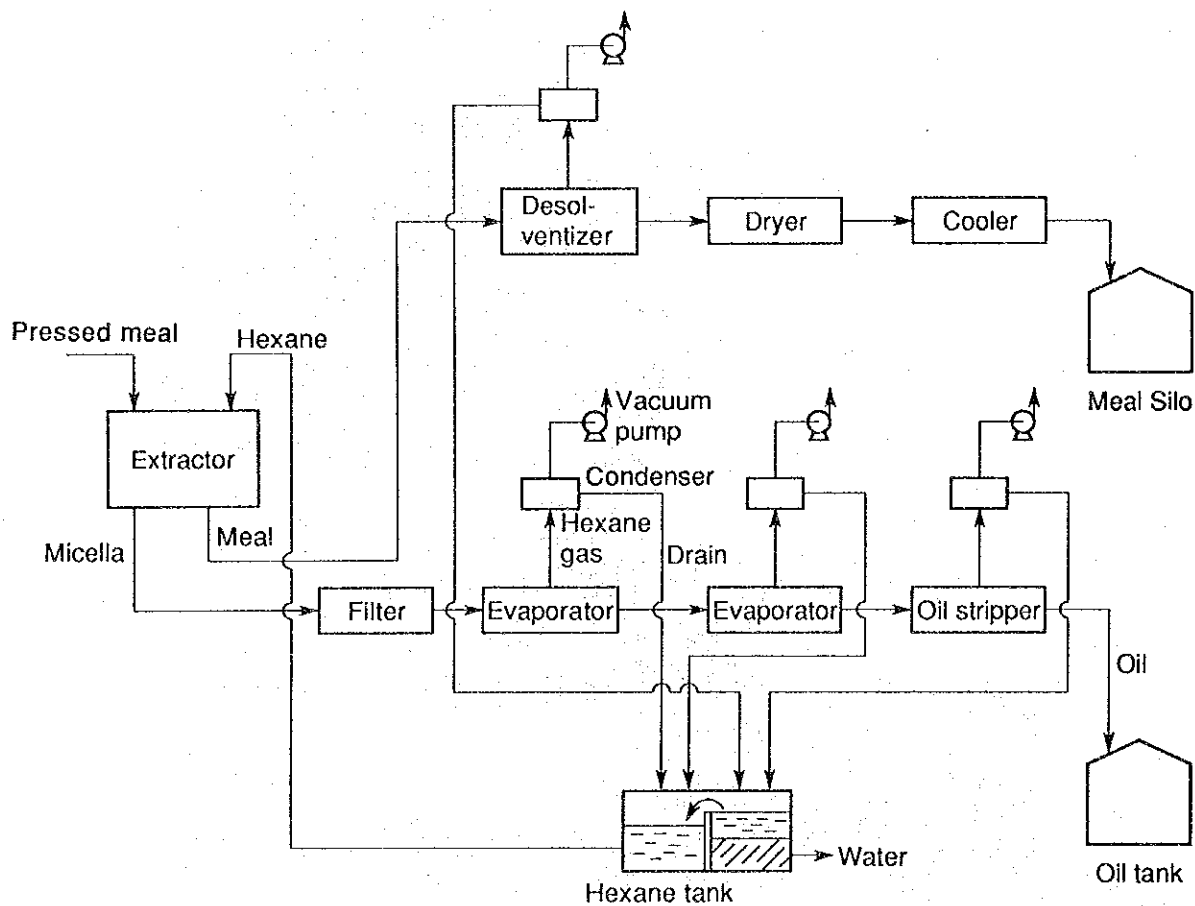
Figure 5.3 Cooker and Press



b. Extraction process

After the expression process, the meal is fed to the extractor, and is divided into the mixture between solvent and oil (called micella) and extracted meal. The percentage of oil in the micella is about 15 to 25 %. It is fed as extracted oil to the refining process with the pressed oil after solvent is separated by evaporation. The extracted meal contains about 30 % solvent, and is fed to the extracted meal storage silo after the solvent is removed by the desolventizer. Figure 5.4 illustrates the flowchart of the extraction process.

Figure 5.4 Flowchart of Extraction

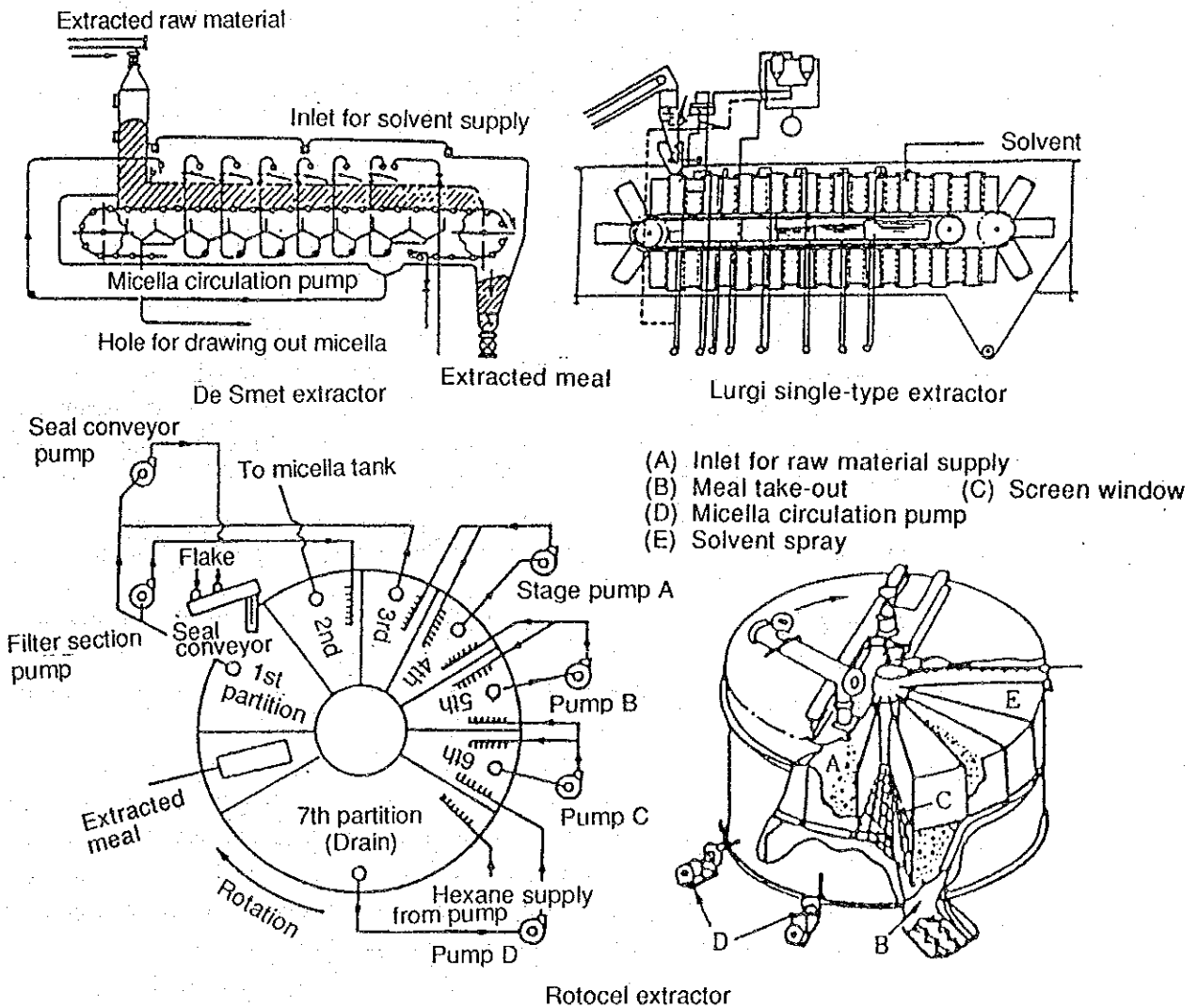


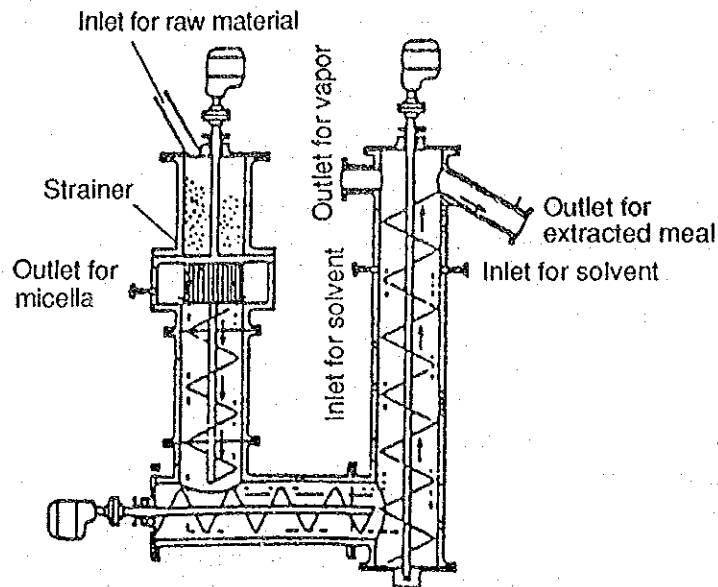
1) Extraction

The extractor can be broadly classified into the percolation process and the soaking process. De Smet (Belgium), Lurgi (Germany) and Rotocel (the United States) processes which are often used in the United States and Europe belong to the former process, while the Hildebrandt process (Germany) introduced in many Bulgarian plants in the 1980s belong to the latter process. Figure 5.5 illustrates these extractors.

Generally, the soaking process is more compact than the percolation process, however separation between extracted meal and micella is said to be more difficult. So the soaking process requires the filtering process before evaporation of the micella. Hexane is usually used as the solvent for extraction. Since the boiling point of the hexane is 69 °C, about 60 °C is said to be the optimum extraction temperature. Hexane will start boiling at the higher temperature, and the extraction efficiency will be reduced; furthermore, the pressure in the extractor will rise, resulting in much hexane loss. The extraction time is about 1 to 2 hours, though it depends on the type of the extractor.

Figure 5.5 Extractor





Hildebrandt Extractor

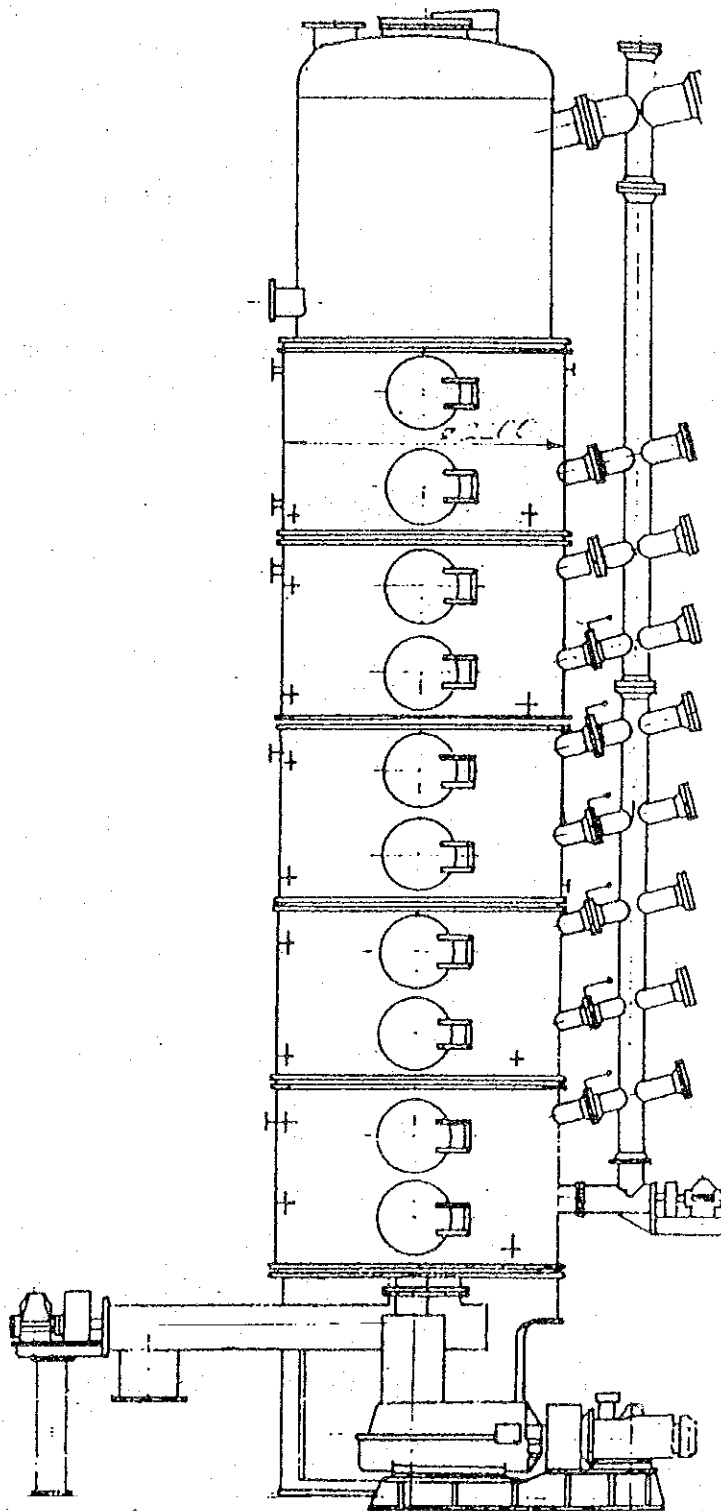
2) Meal treatment

The extracted meal contains about 30 % solvent, so the desolventizer is used to remove the solvent and to toast the meal. Solvent is removed directly or indirectly by steam in the upper stage of the 8- to 10-stage tower, and the meal is toasted indirectly by steam in the lower stage of the tower. The amount of the steam used by the desolventizer is close to 50 % of the total consumption in the extraction process. Especially a great amount of the direct steam is used. Figure 5.6 illustrates the desolventizer. The desolventizer output has a temperature of about 100 °C and 8 to 15 % water content, depending on the operating conditions.

When the water content at the desolventizer outlet is greater than that specified in the water content standard, water is removed by the dryer after the desolventizer. To prevent bridging in the product silo, it is cooled to the appropriate by the cooler.

The water content is stipulated at 9 % or less according to the water content standard for the sunflower meal in the plant of our study. The water content at the desolventizer outlet is 7 to 8 %, and does not require use of the dryer. The water content of the product is low, and bridging does not occur even if the product is put into the silo without being cooled. So no cooler is not installed.

Figure 5.6 Desolventizer



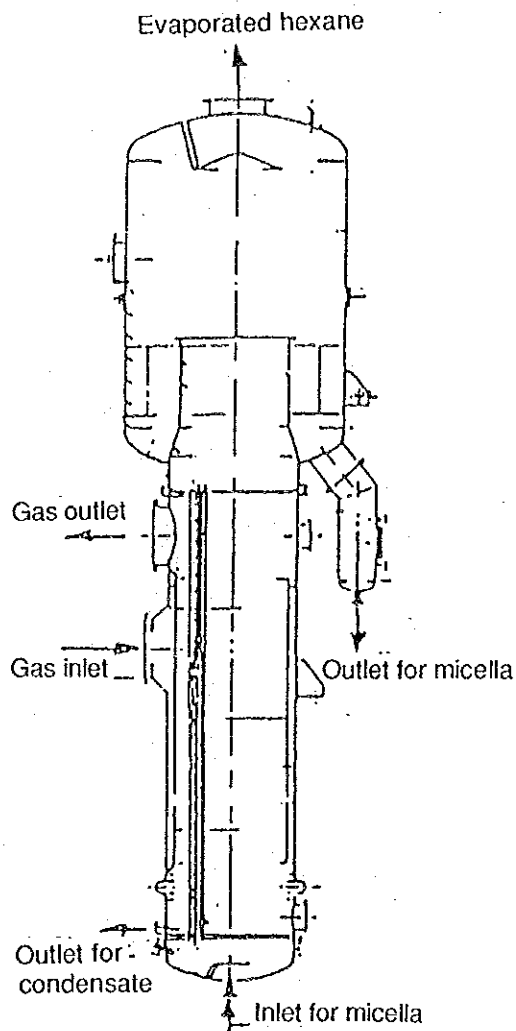
3) Micella treatment

The concentration of oil in the micella is 20 to 25 % according to the percolation process and is 15 to 20 % according to the soaking process. Hexane is removed by the two-stage evaporator and oil stripper until the residual hexane is reduced to 100 ppm. Since the micella or oil deteriorates if heated at a high temperature for a long time, solvent must be evaporated under vacuum conditions in a short time. The concentration of oil in the micella is 60 % at the evaporator output in the first stage, and is about 95 % at the evaporator output in the second stage.

The evaporator used is the Kestner evaporator which is a liquid film rise type. As shown in Figure 5.7, the micella is fed through the tube side of the vertical shell and tube type heat exchanger, and heat source such as steam is fed to the shell side. The miscella enters from the bottom and rises inside the tube by evaporation; then, the liquid and gas are separated at the top dome.

The oil stripper causes the micella and steam to contact in counter current to evaporate the solvent.

Figure 5.7 Kestner Evaporator



4) Solvent recovery

The solvent evaporated in the desolventizer process and the evaporation process is condensed by the condenser and is recovered; it is then fed back to the extractor to be used again. The solvent equivalent to the amount lost during the treatment is added.

The residual oil of the extracted meal and solvent loss are used to determine the results in the extraction process. In the plant placed under effective management, the residual oil of the extracted meal is below 1 % and solvent loss per ton of the material is below 1 liter.

The following shows an example of the energy unit consumption in the soybeans and rape seeds extraction process in Japan.

Energy unit consumption in the extraction process in Japan

Steam : 200 to 240 kg/t (material: in tons)

Electric power: 15 to 20 kWh/t (material: in tons)

The steam unit consumption in particular depends heavily on ambient temperature. Generally, the steam unit consumption tends to increase as the micella concentration is lowered and the residual oil of the meal is reduced. The unit consumption differs according to whether the steam ejector or vacuum pump is installed on the vacuum generator.

The dryer or cooler of the extracted meal often uses a large-sized fan to feed hot air or cold air. So the unit consumption depends heavily on whether or not such equipment is installed.

5) Characteristics and handling of solvent

Hexane is extensively used as solvent. Table 5.1 illustrates the properties.

Table 5.1 Properties of n-Hexane

Item	Properties
Name	Normal hexane
Molecular weight	86
Molecular formula	C_6H_{12}
Structural formula	$ \begin{array}{cccccccc} & H & & H & & H & & H & & H & & H & & H \\ & & & & & & & & & & & & & \\ H & - C & - & C & - & C & - & C & - & C & - & C & - & H \\ & & & & & & & & & & & & & \\ & H & & H & & H & & H & & H & & H & & H \end{array} $
External appearance	Colorless transparent volatile liquid
Specific gravity	0.66 (20 °C), 0.64 (40 °C), 0.62 (60 °C)
Water solvency	Insoluble in water
Specific heat	0.54 cal/(g·°C) at 20 °C
Latent heat for evaporation	80 cal/g at 60 °C
Boiling point	69 °C under the normal pressure
Flash point	-26 °C
Explosion range	1.2 ~ 7.5 vol %

The following describes the cautions to be noted when handling the hexane:

1. Hexane has an extremely low flash point, and easily catches fire.
2. Evaporated hexane gas has a density three times that of air, and will spread far away along the floor and ground, possibly causing fire accident.
3. When the evaporated hexane gas mixes with air and catches fire with its concentration within the range of explosion, it will be burnt in explosion.

To prevent this, the gas detector must be so set that it will give alarm sound at 1.2 vol%.

4. The electric equipment in the plant should be provided with explosion prevention measures according to the hazard probability.
5. For fire fighting, use air interruption measures. Use foam, powder and carbon dioxide gas as fire extinguishing agent.
6. When the steam is not purged, power driven tools, tools likely to cause sparks or hose to be easily charged electrically should not be brought in the plant.

c. Refining process

The refining process can be divided into the degumming, neutralization, decoloring, dewaxing, and deodorization processes. The batch refining process is currently the mainstay in Bulgaria, but will be switched over to the continuous process. Some of the plants in Bulgaria have no decolorization process, but the decolorization process is considered to be adopted as products are required to have high quality.

Table 5.2 shows the impurities to be removed in each process:

Table 5.2 Impurities Removed at Refining Process

Process	Components
Degumming	Water soluble phospholipid
Neutralization	Oil soluble phospholipid, free fatty acid (FFA)
Water washing	Soap
Decoloring	Coloring matter (carotene, chlorophyll, pheophytin)
Dewaxing	Wax, sterol
Deodorization	Free fatty acid, odorant components

1) Degumming

The degumming process is intended to remove water soluble phospholipid contained in the oil. Add the amount of water required for hydration of gummy matters, and stir it. Separate and remove the gummy matter by hydration. Generally, set the oil temperature at 70 to 80 °C, and add cold or hot water 1 through 3 percent of the oil. Stir it about 30 to 60 minutes, and separate the gummy matter by sedimentation or centrifugal separation. Phospholipid in the oil changes according to the materials and oil expression conditions, so the water addition ratio also changes. The temperature, water addition rate and agitation time are different in the batch and continuous processes. If the water soluble phospholipid is not completely eliminated in the degumming process, soap separation will become difficult in the next (alkali) refining process, resulting in a great refining loss and deteriorated product quality.

In the plant of our study, degumming was performed at the oil temperature of 60 °C and added water temperature of 60 °C with agitation time of two hours. The removed gummy matters are discarded.

2. Neutralization (Alkali Refining)

The neutralization (alkali refining) process is intended mainly to eliminate free fatty acid (FFA) from the oil. The amount of FFA is represented as acid value (AV). The value provides a guideline to check the quality of the material seed or the adequacy of oil expression process. This process removes the oil soluble phospholipid, protein, and coloring matter which could not be removed in the degumming process. FFA can be also removed by the deodorization process. The amount of FFA can be expressed in the following equation:

$$\text{FFA (\%)} = \text{AV}/2$$

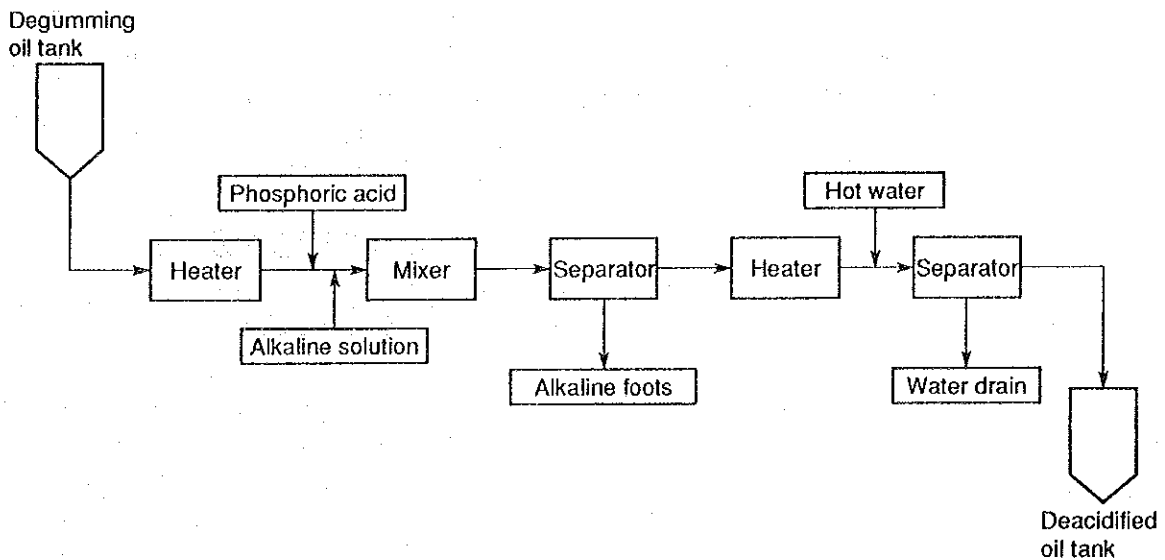
The representative process is the neutralization process where alkali aqueous solution is mixed with oil sufficiently to be made into contact with each other and FFA is separated from the oil in the form of alkali soaps. Alkali refining generally uses caustic soda aqueous solution of 10 to 24 °Be (6.55 to 17.7 %).

The following shows an example of the batch type neutralization process for cotton seed meal: Degummed oil is heated to 50 °C, and caustic soda aqueous solution of 18 °Be (12%) is added 100 % of the neutralization equivalent in excess. Then it is stirred for 20 to 30 minutes. Stop stirring when breaking has occurred, and add 10 % water preheated to 50 °C. Settle it for about one hour. After removing the alkali foots from the lower layer, add 10 % alkali aqueous solution of 0.4 % concentration to oil; then wash it at 100 °C. After removing the lower layer, wash it again with alkali water of 95 °C, and wash it finally with 8 to 10 % boiling water two or three times. The entire process requires 10 to 12 hours. The plant of our study uses the former Soviet-made refiner; the principle is the same although the operation method is different. The oil temperature is set at 68 to 72 °C.

According to the batch type neutralization, the contact time for alkali aqueous solution and oil is 10 to 60 minutes, and 1 to 10 hours are required for separation of alkali foots. Furthermore, sedimentated alkali foots contain much neutral oil, indicating a great loss of oil. The continuous alkali refining process provides a method of preventing the loss of neutral oil by reduction of treatment time and separation of the alkali foots by centrifugal separator.

The following describes an example of short mix process of Alfa-Laval Inc. as a representative case of the continuous neutralization process. Caustic soda aqueous solution is used as alkali aqueous solution. Figure 5.8 illustrates the flow sheet of the Continuous Neutralization Process.

Figure 5.8 Continuous Neutralization Process



The amount of alkali aqueous solution can be expressed in the following equation:

$$\text{Amount of alkali aqueous solution to be used (\%)} = \frac{\text{FFA (\%)} \times \text{Factor} \times \text{Excess}}{\text{Concentration of alkali aqueous solution (\%)}} \times 100$$

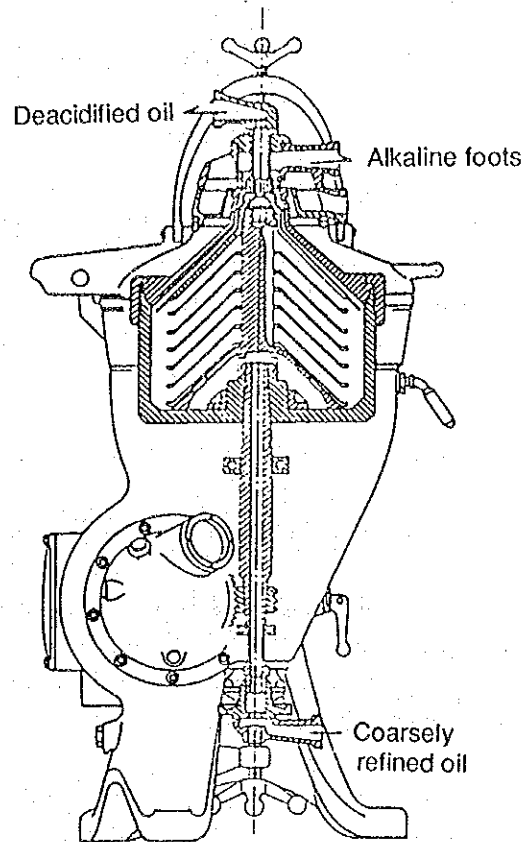
The factor can be calculated in the following equation:

$$\begin{aligned} \text{Factor} &= \text{Caustic soda molecular weight/oleic acid molecular weight} \\ &= 40/282 \\ &= 0.142 \end{aligned}$$

Excess is normally 0.1 to 1.13 % in the case of soybeans. Add about 0.1 % phosphate to the degummed oil pre-heated to 75 to 82 °C, and add a specified volume of alkali aqueous solution to the mixture oil; then make them contact with each other after mixing carefully with the line mixer or paddle mixer. During the short-term contact, hydration of oil soluble phospholipid, neutralization of FFA and reaction with coloring component take place. Alkali foots generated by using the enclosed type rotary disk centrifugal separator (6,000 rpm) is separated from the neutral oil. The back pressure at the outlet of the oil from the centrifugal separator is adjusted to shift the separation zone for heavy liquid and light liquid inside the centrifugal separator. Increase of the back pressure will reduce the amount of soap remaining in oil, and will increase the amount of the neutral oil enclosed in the alkali foots, resulting in greater alkali refining loss. On the contrary, reduction of the back pressure will reduce the alkali refining loss, but will increase the amount of soap content in oil. Normally, adjustment is made so that the soap content in the neutralized oil will be below 300 ppm. Of the refining loss, the neutralization loss accounts for the greatest percentage, 65 %.

Neutralized oil is fed to the washing process. After the oil is heated up to about 90 °C by the heat exchanger, it is mixed with 10 to 20 % hot water of 95 °C and is made to contact; then it is separated by the centrifugal separator. Figure 5.9 illustrates the centrifugal separator.

Figure 5.9 Centrifugal Separator



Theoretical loss in the alkali refining process is called "Wesson loss", and can be calculated in the following equation:

$$\text{Wesson loss (\%)} = AV/2 + \text{phospholipid (\%)} + \text{water content (\%)}$$

If FFA, phospholipid and water content can be removed completely in the alkali refining process, the alkali refining loss will become equal to Wesson loss.

3) Decolorization

The decolorization process is not introduced in many of the Bulgarian Plants. In the plant of our study decolorization is not currently performed. Since this is a process essential to improve the product quality, its use is considered to be spread gradually.

The decolorization process is literally a process to remove the coloring component contained in the oil to refine the oil into the light-colored product. At the same time, it removes coloring matter (carotene, chlorophyll and pheophytin), peroxides (POV), soap, unsaponifiable materials and metallic compounds. Adsorbent such as activated clay is used as general decoloring agent.

About 10 to 100 ppm of soap content is normally in the oil after neutralization, and promotes deterioration during heating. Chlorophyll and pheophytin much contained in rape seeds and immature seeds promote oxidation of oil, and their elimination will contribute to stabilization of the oil. Tocopherol, carotene and phospholipid working as natural antioxidant, however, are also removed by adsorption.

Clay is a mineral mainly comprising montmorillonite ($\text{Al}_4\text{Si}_8\text{O}_{20}(\text{OH})_4 \cdot n\text{H}_2\text{O}$) which is formed of volcanic ashes exposed to efflorescence for a long time and is produced by thermochemical reaction through geothermal energy. Adsorption is increased as more aluminum ion is replaced by hydrogen. Adsorption will be deteriorated when water content is excessive or insufficient; water content of 8 to 16% is said to be appropriate. The amount of the activated clay to be used should be 0.3 to 2.0 %. A greater amount of clay is required as more coloring matter and products decomposed by oxidation are contained.

Decolorization under the normal pressure accelerates oil oxidation and deteriorates the decolorization effect of the activated clay, so decolorization is performed under the reduced pressure in recent years. To minimize contact with air and to ensure effective operation, continuous decolorization process is often adopted.

The following describes an example of the continuous decolorization process, and Figure 5.10 illustrates the flowchart. 0.3 to 2.0 % activated clay is added to neutralized oil which has been pre-heated to 54 °C, to be made into slurry. It is then led to the deaeration tank on the upper stage of the decolorization tower whose pressure is reduced to 380 Torr, and is dehydrated and deaerated. Then it is heated by the heat exchanger and is maintained at 110 °C under the reduced pressure for seven minutes. After that, it is separated from the clay. The horizontal or vertical pressure type leaf filter accommodated in the enclosed vessel is generally used as the filter, in addition to the filter press.

The waste clay separated from the oil and fat is discarded or is washed by elution by such solvent as hexane, in order to recover the oil adsorbed by the waste clay.

Figure 5.10 Continuous Vacuum Decolorization Process

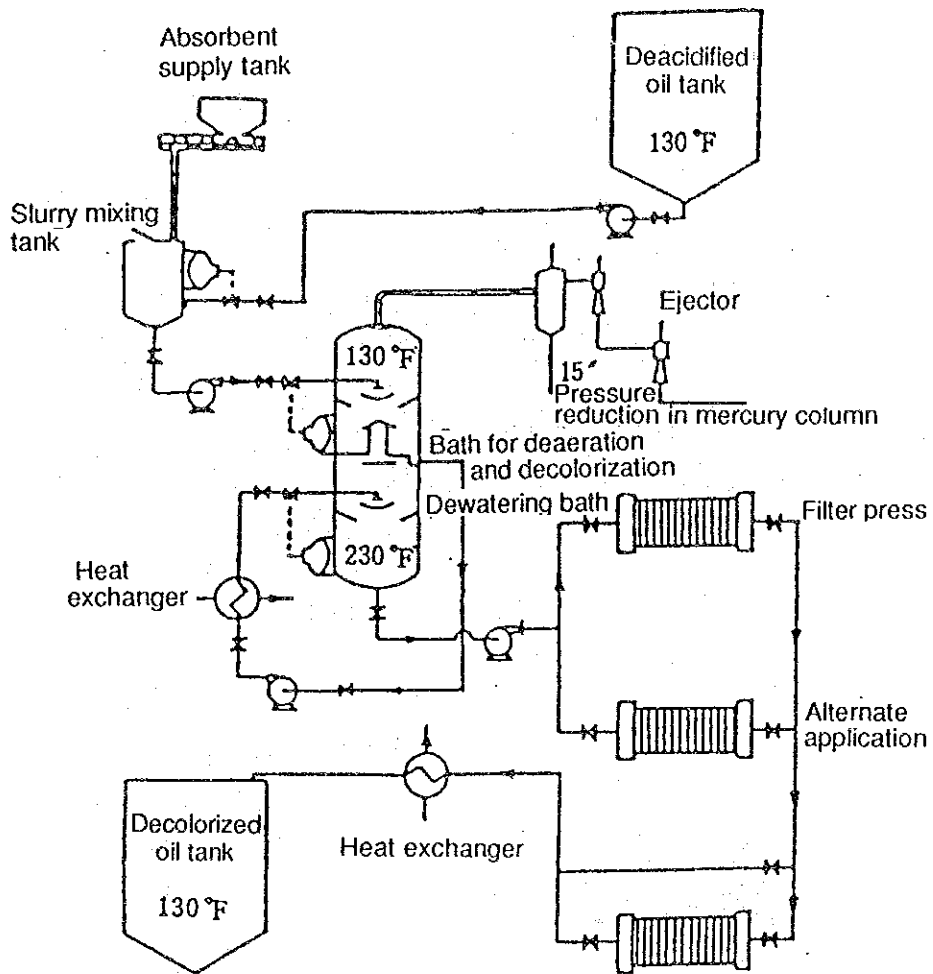


Figure 5.11 shows the filter press, while Figure 5.12 shows the pressurized type leaf filter.

Figure 5.11 Filter Press

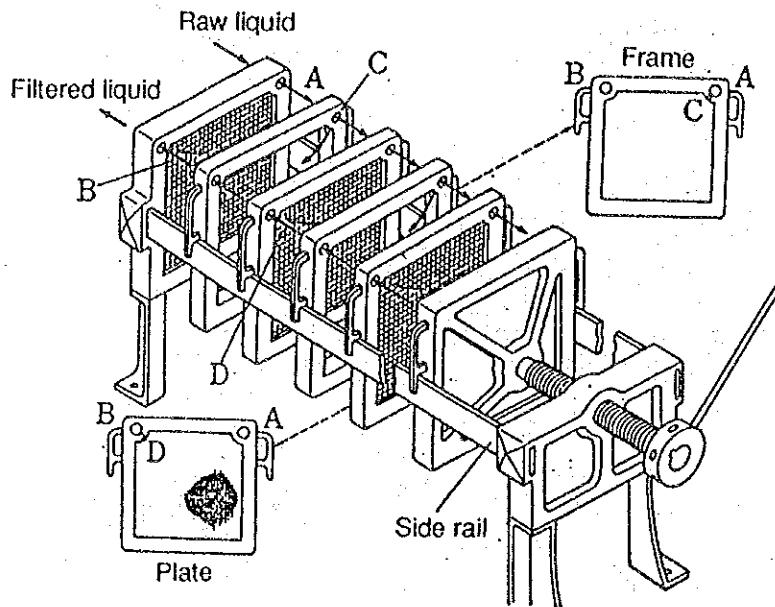
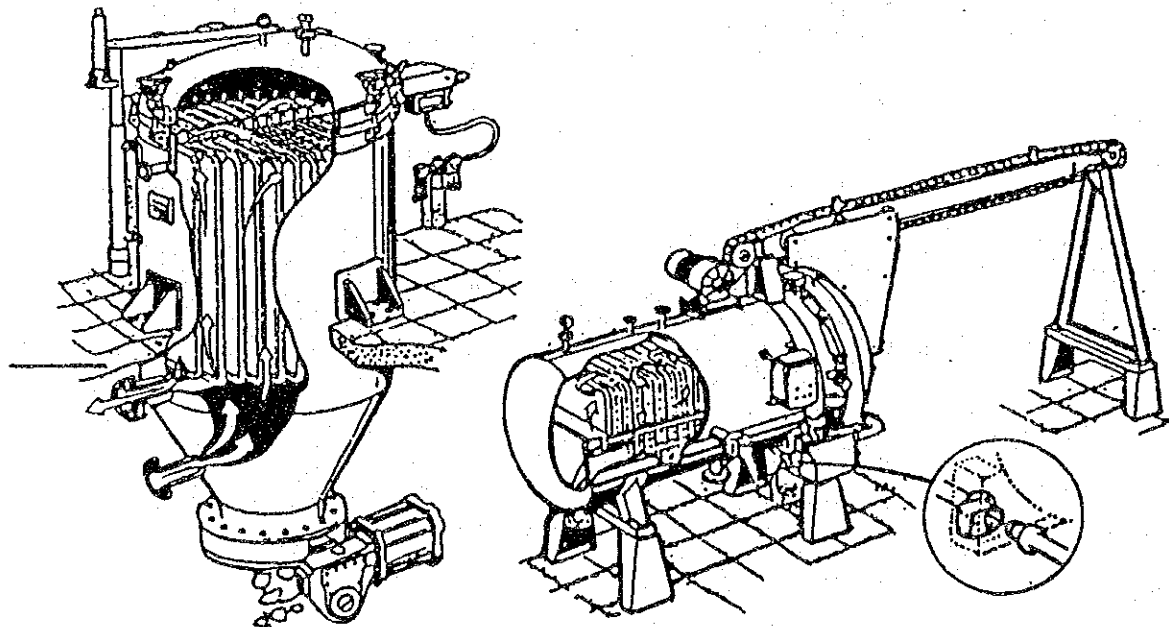


Figure 5.12 Leaf Filter



4) Dewaxing

Much wax is contained in the plant seeds, husk and embryos. The seed coat of the bred sunflower seeds accounts for 22 to 28 % of the entire seed, and up to 3 % of the 5 % oil contained in the husk is occupied by wax. As much as 0.02 to 0.35 % wax is contained in the oil obtained without removing the husk, while 0.011 to 0.015 % wax is included in the oil taken after removing of the husk.

The oil which contains very little wax such as sunflower seeds, safflower seeds and rape seeds is normally cooled to about 7 to 14 °C and is left at that temperature; then the deposited crystal is separated by the pressure-filtered by the filter press or leaf filter.

5) Deodorization

The deodorization process is a final stage of the edible oil production. It is a process to remove the offensive odor unsuited for the food and to ensure refined oil of excellent stability and preservative quality. The product is heated to a high temperature under the vacuum conditions, and most of the volatile components such as odorant, fatty oil and unsaponifiable materials are removed in this process.

In the plant of our study, the deodorization process is followed by the dewaxing process, but the deodorization process should be placed at the final stage in order to ensure excellent refined oil quality.

The deodorizer is available in batch process, semi-continuous process and continuous process. The batch process is used for small lot production, and the semi-continuous process is used in the case of a great variety of oils, while the continuous process is effectively used for mass production of a single type of products.

The batch process deodorizer is currently used in the plant of our study. It is limited mainly for refining of the sunflower seed oil, so use of a continuous process is recommended. If the plant is to handle olive oil and other many types of oils in future, semi-continuous process will be effective.

The organic heating medium such as Dowtherm is generally used as heating medium. To prevent the possibility of heating medium entering the oil, it is going to be replaced by high pressure steam in recent years. The steam jetting device such as ejector and booster is used for vacuum generation. A high degree of vacuum below 6 Torr is normally used.

Deodorization uses the principle of steam distillation method where steam is blown into the oil heated to a high temperature under a high degree of vacuum to distill the volatile matters. The lower the absolute pressure of the system, the lower will be the heating temperature, though the situation may depend on the amount of the steam to be blown inside. Table 5.3 shows the vapor pressure of the palmitin acid and oleic acid which are representative free fat acids contained in the oil.

Table 5.3 Vapor Pressure of Fatty Acid

mmHg	Palmitin acid	Oleic acid
1	153.6 °C	176.5 °C
5	188.1	208.5
10	205.8	223.0
20	223.8	240.0
40	244.4	257.2

The blown-in steam serves to stir the oil during deodorization to facilitate evaporation of volatile matters. The amount of the steam to be used is 3 to 4.5 % in the case of the continuous and semi-continuous processes, and is 20 to 30 % in the case of the batch process.

Deodorization temperature is usually 230 to 250 °C and the degree of vacuum is 3 to 6 Torr for the continuous and semi-continuous processes. In the batch process, both the temperature and degree of vacuum are lower than those in the case of the continuous and semi-continuous processes, though they may depend on the type of the oil. The deodorization conditions in the plant comprise temperature of 160 °C, vacuum of 40 Torr and one cyclic operation time of five hours.

Figure 5.13 illustrates the flowchart of the batch process, and Figure 5.14 illustrates the flowchart of the continuous process according to the Gardner method.

Figure 5.13 Batch Type Deodorization Process

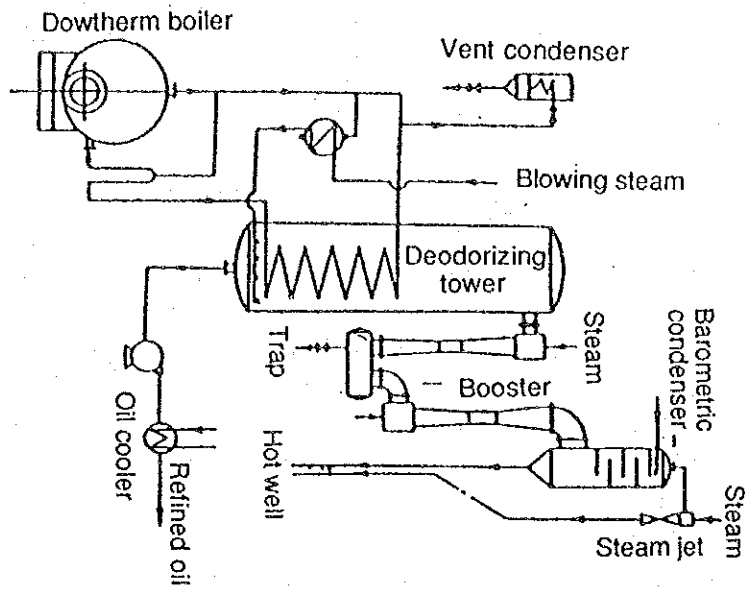
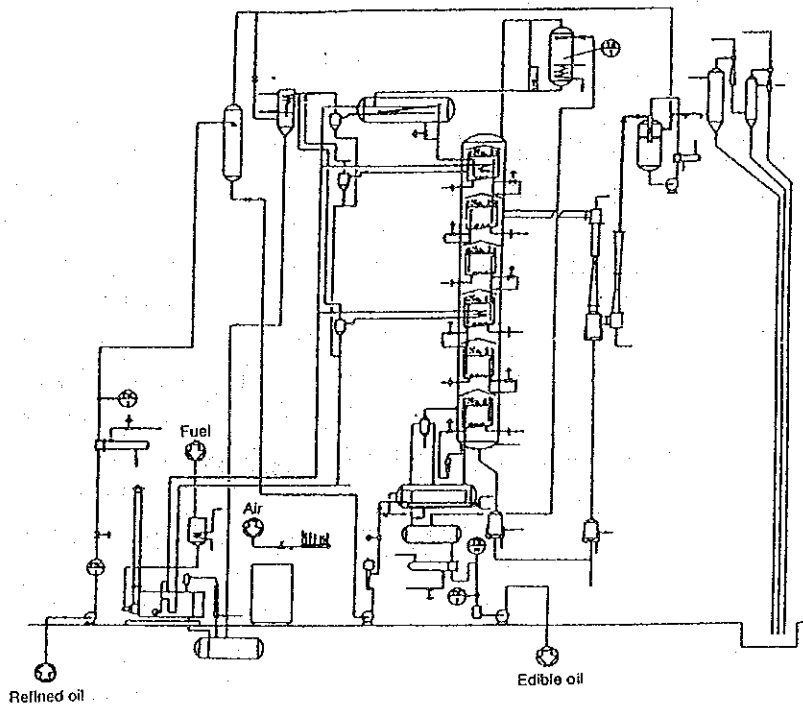


Figure 5.14 Continuous Deodorization Process



In the process of Gardner method, 5 to 6 trays are suspended in one vertical cylindrical vacuum tower (shell). Inside the shell, almost constant vacuum is maintained by the operating of the ejector and booster, and the dewaxed oil is fed inside, passing from the first tray to the next one downward sequentially. In the 5-stage tray structure, each tray is assigned with different functions; deaeration for the first tray, heating for the second tray, deodorization for the third and fourth trays and cooling for the fifth tray.

In the semi-continuous process oil is fed to the lower tray in the specified time by the operation of the inter-stage valves which are located between trays. In the case of the continuous process, oil is fed continuously to the first tray and is fed to the next lower tray after it has overflowed the first one, so the inter-stage valve is not provided. Energy unit consumption differs according to the water content of the material, ambient temperature, required product quality as well as according to the process.

The following shows the energy unit consumption of continuous and semi-continuous deodorizers in Japan:

Energy unit consumption in Japanese deodorization process

Steam	: 80 to 120 kg/t	(product oil, in tons)
Electric power	: 30 to 50 kWh/t	(product oil, in tons)

(2) Rationalization in energy use

Before taking rationalization measures for energy use, it is necessary to check the amount of energy currently used. In the case of steam, it is possible to get steam consumption by the orifice for direct steam, and by measuring the amount of condensate generated for indirect steam. It is possible to get it by calculating the heat balance.

After that, in the case of direct steam, try to reduce the amount of steam to be used, with consideration given to the position of steam blowing, nozzle shape, steam pressure, material contact time and use of exhaust gas. In the case of indirect steam, study the steam pressure, reuse of the condensate and replacement of steam by alternative heat sources and such related matters. In the continuous process, the temperature is raised or lowered in order to ensure treatment under the optimum conditions, so it is needed to study the possibility of mutual heat exchange.

a. Expression process

The expression process must be considered with consideration given to extraction process. Expression and extraction should be combined to achieve energy conservation and improved yield. Expression process can be said to be a pre-treatment process to ensure the optimum extraction.

Extraction efficiency is affected by the thickness of the flake rolled by the flaking roller. The flake should be about 0.2 to 0.4 mm thick. If it is over 0.4 mm, breakage of the cell membrane will be insufficient, resulting in reduced extraction efficiency. If much powder is produced during flaking, extraction efficiency is also reduced. Flaking without generating powder requires control of the water content and temperature of the material before flaking, as well as daily roll management.

The press can take up oil until the residual oil contained in the meal is reduced to about 4 to 5 %. This, however, will require severe operating conditions and big power consumption, as well as severe wear and damage of the machine. When the material is fed to the extraction process, the residual oil contained in the meal should be kept to about 15 to 20 %; this will be more effective since it increases the amount treated.

Much steam is used by the material drier and cooker of the expression process. Since the water content of the material in dehulling, flaking and press processes of the expression process constitutes an important factor, the material containing much water should be passed through the material drier to reduce the water content. The material dryer may not be used for the material containing less water content such as sunflower, but in order to prevent pulverization in the flaking process and to ensure uniform flaking, it is recommended to pre-heat the material to about 40 to 60 °C by means of the pre-heater.

The cooker uses direct and indirect steam to heat the flaked material to 100 to 120 °C with the water content of 3 to 5 %. It is important to minimize the amount of direct steam by the optimum control of the material retention time and steam pressure.

Figures 5.15 and 5.16 illustrate the impact of the cooker outlet temperature and water content on the residual oil contained in the meal in the press machine:

Figure 5.15 Influence of Cooking Temperature

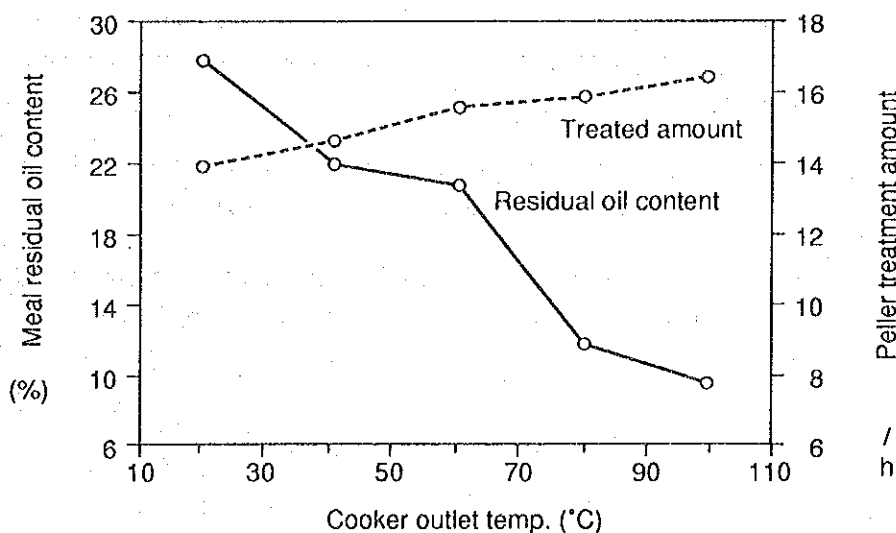
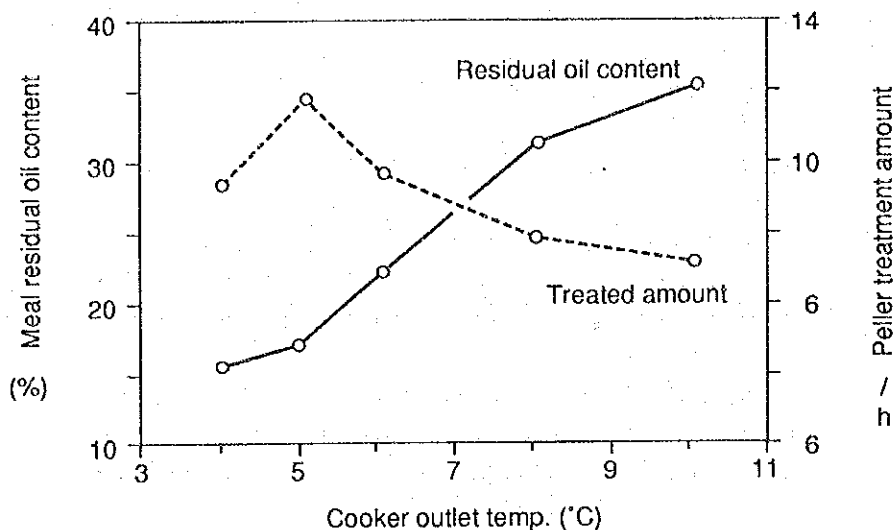


Figure 5.16 Influence of Water Content of Flake



The condensate generated in the expression process is difficult to reuse in the expression process, so it is usually fed back to the boiler.

b. Extraction process

The extraction process uses more steam than the expression process, and has a higher temperature in liquid state, making it easier to exchange heat. It is possible to expect a greater effect of energy conservation. It is important also for safety management to have correct information on the heat balance in the extraction process and to make effective control.

The exhaust gas of the desolventizer equipment is generally used as heat source for the distillation tower. The condensate of the indirect steam of the desolventizer equipment is used as heat source for the micella or used as heat source for the evaporator No.2 by producing flash vapor.

Direct and indirect steam is used in the oil stripper. Since it is less used than in the desolventizer equipment, its recovery is less rewarding.

The oil temperature at the oil stripper outlet is close to 100 °C. So the heat can be reused by heat exchange when oil is to be stored in the tank without being refined immediately.

If the micella and oil are heated for a long time at a high temperature, they will be deteriorated. They must be evaporated under vacuum conditions in a short time. Control of the degree of vacuum and temperature in the evaporation process is important for energy conservation as well as for quality and safety control. The condenser should be inspected and cleaned on a periodic basis.

c. Refining process

Deodorization of the refining process consumes the greatest amount of steam in both the batch and continuous processes. The amount of steam blown to the deodorization tower is 3 to 5 % of oil in the continuous process, and 20 to 30 % in the batch process.

Product quality heavily depends on such deodorization factors as temperature, degree of vacuum and the amount of blown steam. When introducing the continuous equipment, it is necessary to install the equipment which allows higher level of deodorization than the batch type equipment, without using the equipment having the same deodorization conditions as those of the batch system. This is because users' needs for high quality products will be coming earlier than anticipated.

The steam condensate and hot water produced in cooling the deodorized oil can be used for washing of neutralized oil or for preheating of the oil in the refining processes.

The continuous neutralization process uses the centrifugal separator to remove foots meal. The balance in separation is likely to be destroyed by temperature, flow rate, acid value of the oil and the amount of chemicals added. This requires severer operation management and installation of waste water treatment facilities.