

Figure 8-2 Fuel Economy Due to Air Preheating

c. Utilization as heat source for others

In case the sensible heat of the waste gas has heat quantity and temperature range suitable as the heat source for other equipment, and the gas source is located rather close to such equipment, the utilization should be considered. In addition, if there is demand for steam in the factory, it is recommendable to install a waste heat boiler, and consider the utilization of waste gas sensible heat for the generation of steam.

C) Sensible heat utilization of heated materials

The temperature of the heated materials that come out of the combustion equipment is too high as it is, and with the exception of the case in which it is used in the following process, generally speaking, it is cooled to ordinary temperature, or in order to prevent side reactions, in many cases it is quenched.

In such a case, the sensible heat of the heated materials should be recovered and utilized effectively. For instance, the utilization of clinker cooling air in the cement manufacturing plant as primary combustion air, and waste heat boiler for quenching of cracking furnace outlet gas in the ethylene plant are good examples.

8.2.2 Heat Transfer Equipment

(1) Basic calculations of heat transfer

In case there is temperature difference between objects, the transfer of heat (Heat Transfer) will occur, and the mechanism can be divided into the following three.

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

The actual heat transfer will be done by complicated combination of the above three mechanisms, and if the calculation is done accurately, it will become extremely complicated, but in many cases, the calculation can be simplified by the approximation and the

simplification of the phenomena. In the following paragraphs, calculation formulas based on the respective mechanisms are described.

A) Heat transfer by conduction

I will describe the case of the steady state where each part shows no changes in temperature with the elapse of time.

a. In case of flat surface

In case n sheets of flat plates are laminated, the Heat Quantity Q that will pass through them would be as follows:

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

where

A<sub>o</sub>: Area of the surface perpendicular to the direction of the heat transfer (m<sup>2</sup>)

Δt: Temperature difference between the low temperature portion and the high temperature portion (°C)

ℓ: Thickness of the flat plate (m)

Sometimes  $\Sigma (\ell_j / \lambda_j) = R$

is referred to as the heat resistance.

b. In case of cylindrical surface

By using the same symbols as those for the Flat Plates,

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

where

L: Length of cylinder (m)

r<sub>j</sub>, r<sub>j+1</sub>: Inside diameter and outside diameter of No. j layer (from the inside) plate (m)

B) Heat transfer by convection

Various conditions such as fluid specifications, flow conditions, shape of object, conditions of phase changes in the fluid, etc. are related to this, and a number of empirical formulas have been announced.

In this guideline, typical empirical formulas which normally have high usage frequency will be described.

a. The average heat transfer coefficient α<sub>m</sub> in case the fluid is air, and natural convection is taking place.

i) In case of flat plate

Heat release from bottom surface

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

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

Note: Refer to Table 8-4

where

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

$\ell$ : Representative length of flat plate (m)

Gr: Grashof number

Pr: Prandtl number

Heat release from top surface

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

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

Heat release from vertical surface

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

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

where H: Height of vertical surface

ii) In case of horizontal tubes

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

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

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

where D: Diameter of tube (m)

Table 8-2 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	$h(\nu^2/g)^{1/3}/k$	$Co, N_{Co}$
Reynolds number	$DG/\mu, D\bar{u}/\nu$	$Re, N_{Re}$
Prandtl number	$C_p \mu/k$	$Pr, N_{Pr}$
Péclet number	$C_p DG/k$	$Pe, N_{Pe} = (Re)(Pr)$
Grashof number	$(D^3 g/\nu^2)/(\beta \Delta t)$	$Gr, N_{Gr}$
Gractz number	$wC_p/k$	$Gz, N_{Gz} = \frac{\pi}{4} (Re)(Pr)(D/l)$

Note:  $D^3 g/\nu^2$  is referred to as Galilei number.  
 $D^3 g/\nu^2 = (Re)^2 / (\bar{u}^2/gD)$ ,  $\bar{u}^2/gD$  are referred to as Froude number.  
 $C_p$ : Specific heat at constant pressure  
 $D$ : Diameter or representative length  
 $\Delta t$ : Temperature difference  
 $G = \bar{u}p$ : Mass velocity  
 $\bar{u}$ : Average velocity of flow  
 $w = \frac{\pi}{4} D^2 G$ : Mass flow  
 $g$ : Gravitational acceleration  
 $k$ : Heat conductivity  
 $\mu$ : Viscosity       $\rho$ : Density       $\nu = \mu/\rho$ : Kinetic viscosity  
 $\beta$ : Coefficient of thermal expansion     $l$ : Tube length

b. Heat transfer coefficient  $\alpha$  in case of forced convection

i) Heat transfer coefficient inside of tube

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

where

D: Inside diameter of tube (m)

$\eta$ : Viscosity of fluid

$\eta_w$ : Fluid viscosity at tube wall temperature

ii) Heat transfer coefficient outside of tube

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

where

D: Outside diameter of tube (m)

C and m are as follows depending on Re.

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

C) Heat transfer by radiation

The Heat quantity Q radiated to the surrounding from an object having a temperature T ( $^{\circ}$ K) can be expressed by the following formula.

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

where

$\epsilon$ : Emissivity of object.

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

The heat quantity Q emitted and received between two objects (1, 2) with different temperatures can be expressed by the following formula.

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

where

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

$F_{12}$ : Coefficient determined by the relative positions of the objects (geometrical coefficient)

$T_1, T_2$ : Respective temperatures (K)

$\epsilon_1, \epsilon_2$ : Respective emissivities

By using the above formula, heat radiation to broad space can be approximated to the following formula.

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

where

$T_1, T_0$ : Temperature of respective objects and the atmosphere (K)

D) Calculation examples of heat transfer composed of 3 types of heat transfer mechanisms

An explanation will be given about heat release to atmosphere from the bottom surface of a flat equipment as an example.

$$\begin{aligned} & \text{Quantity of heat release } Q \\ & = \text{Heat quantity transferred from equipment walls } (Q_k) \\ & = \text{Convection heat transfer quantity } Q_c + \text{Radiation heat transfer quantity } Q_r \\ & \dots\dots\dots (1) \end{aligned}$$

If the inside temperature of the equipment, surface temperature of the equipment, and the atmosphere temperature are represented by  $t_i$  ( $^{\circ}\text{C}$ ),  $t_w$  ( $^{\circ}\text{C}$ ), and  $t_o$  ( $^{\circ}\text{C}$ ), respectively:

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

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

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

If we substitute equations (2) – (4) into equation (1), and obtain  $t_w$ , quantity of heat release can be obtained.

Since this equation is very complicated, normally the equation is solved by diagram method or trial and error method. However, if computers are used, needless to say, they can be solved rather easily.

(2) Heat transfer calculation of heat exchangers

A) Overall heat transfer coefficient

As for the heat transfer of a single tube where fluid is flowing inside and outside, by the composition of heat resistance of the pipe wall and the soiling attached to it, and the convection heat transfer of the tube inside and outside, it can be expressed by the overall heat transfer coefficient  $U_o$  of the following equation using outside diameter as the standard.

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

where

- $h_i$ : Convection heat transfer coefficient inside of the tube
- $h_o$ : Convection heat transfer coefficient outside of the tube
- $D_i$ : Inside diameter of the tube
- $D_o$ : Outside diameter of the tube
- $D_m$ : Mean diameter of the tube
- $x$ : Tube wall thickness
- $\lambda$ : Thermal conductivity of tube wall
- $R_i$ : Coefficient of scale inside of the tube
- $R_o$ : Coefficient of scale outside of the tube

Since the coefficient of scale is influenced by type of fluid, temperature, flow velocity, and the degree of cleaning, it is difficult to argue in general. As reference, in Table 8–3, examples of various scale coefficients are shown.

Even if the heat exchangers are cleaned thoroughly, the R will never return to 0. Furthermore, the influence of the degree of cleaning and the cleaning period on the heat transfer is quite significant, so the maintenance of the heat exchangers will have great influence on energy saving.

Next, in case of the multi-tube heat exchangers, the value of overall heat transfer coefficient calculated as single tube cannot be used as it is, and another formula slightly modified is necessary, and in addition, compensation will also be required. Since the compensation is determined by the layout number and the flow direction, it is extremely complicated, and explanation will be omitted here. Actual examples are shown in Table 8-4.

Table 8-3 Scale Coefficient of Water and Various Fluids

(a) Scale coefficient of water

Temperature of high temperature fluid (°C)	Up to 115		115~205	
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) Scale coefficient of various fluids

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

Table 8-4 Overall Coefficient of Heat Transfer of Multi-Tube Heat Exchangers

Service condition	High temperature fluid	Low temperature fluid	Overall coefficient of heat transfer (kcal/m <sup>2</sup> ·hr·°C)
Cooler	Water	Water	1,200~2,500* <sup>1</sup>
	Methanol	"	1,200~2,500* <sup>1</sup>
	Ammonia	"	1,200~2,500* <sup>1</sup>
	Water solution	"	1,200~2,500* <sup>2</sup>
	Organic matter viscosity 0.5cP or below**	"	350~ 750
	Organic matter viscosity 0.5~1.0cP** <sup>3</sup>	"	250~ 600
	Organic matter viscosity 1.0cP or below**	"	25~ 400* <sup>3</sup>
	Gas	"	16~ 250* <sup>3</sup>
Heater	Water	Brine	500~1,000
	Organic matter viscosity 0.5cP or below**	Brine	200~ 500
	Steam	Water	1,000~3,500* <sup>1</sup>
	"	Methanol	1,000~3,500* <sup>2</sup>
	"	Ammonia	1,000~3,500* <sup>3</sup>
	"	Water solution viscosity 2.0cP or below	1,000~3,500
	"	Water solution viscosity 2.0cP or above	500~2,500* <sup>1</sup>
	"	Organic matter viscosity 0.5cP or below	500~1,000
Heat exchanger	"	Organic matter viscosity 0.5~1.0cP**	250~ 500
	"	Organic matter viscosity 1.0cP or above	30~ 300
	"	Gas	25~ 250* <sup>3</sup>
	Water	Water	1,200~2,500* <sup>1</sup>
	Water solution	Water solution	1,200~2,500* <sup>1</sup>
	Organic matter viscosity 0.5cP or below**	Organic matter viscosity 0.5cP or below**	200~ 400
Organic matter viscosity 0.5~1.0cP**	Organic matter viscosity 0.5~1.0cP** <sup>3</sup>	100~ 300	
Organic matter viscosity 1.0cP or above**	Organic matter viscosity 1.0cP or above**	50~ 200	
Organic matter viscosity 1.0cP or above**	Organic matter viscosity 0.5cP or below**	150~ 300	
Organic matter viscosity 0.5cP or below**	Organic matter viscosity 1.0cP or above**	50~ 200	
Note 1:	Overall coefficient 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 m <sup>2</sup> ·hr·°C/kcal and 0.35 to 0.7 kg/cm <sup>2</sup> respectively.		
Note 2:	*1 to *6 on the above table are as follows: *1. When scale coefficient is 0.0002 m <sup>2</sup> ·hr·°C/kcal. *2. When pressure loss is 1.4 to 2.1 kg/cm <sup>2</sup> . *3. Greatly varies with service pressure of the gas. *4. Organic matters such as benzene, toluene, acetone, ethanol, methyl ethyl ketone, gasoline, light kerosene, naphtha, etc. *5. Organic matters such as kerosene, hot gas oil, heat 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

The heat transfer quantity Q in a heat exchanger can be expressed as follows:

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

where

A<sub>o</sub>: Heat transfer surface area based on outside diameter as standard

Δt<sub>m</sub>: Mean temperature difference between both fluids.

In most cases, the mean temperature difference between both fluids have different values for different points of the heat exchanger.

If a solution for differential equation of heat balance using A<sub>o</sub> and Δt as variables is obtained in case of one passage type heat exchanger for both high temperature and low temperature fluids, the following relation is obtained.

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

where subscripts for Δt indicate the inlet and outlet of the heat exchanger.

If equation (1) and equation (2) are placed as equal, we obtain

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

and this is called logarithmic mean temperature difference. In most cases, the heat

exchangers in actual use have very complicated fluid passages as shown in Fig. 8-3, so the temperature difference obtained by equation (3) cannot be used as it is, and correction will be required.

If we show the correction factor (coefficient) as  $F_T$ , the mean temperature difference  $\Delta t_m$  can be calculated as follows:

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

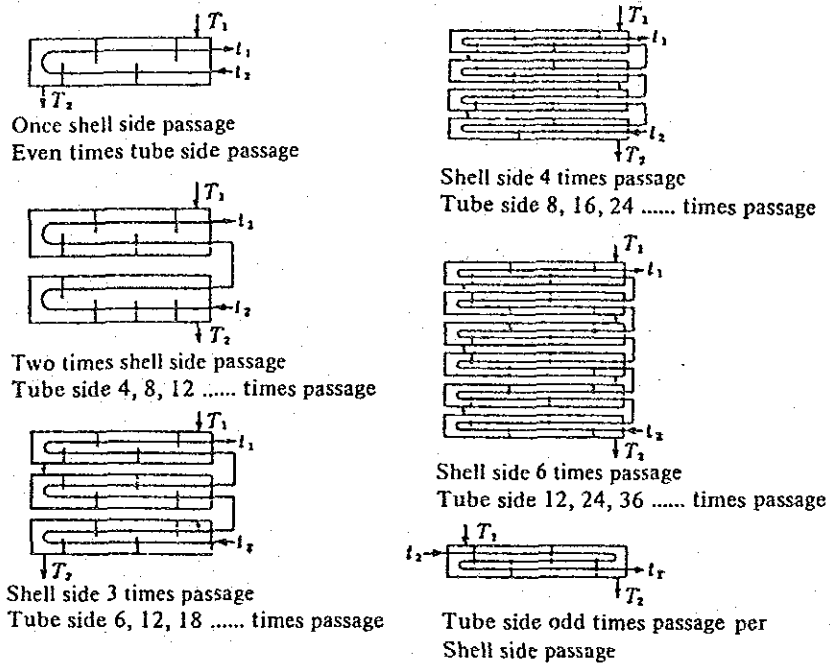


Figure 8-3 Shell/Tube Type Heat Exchanger

Correction Factors  $F_T$  based on various types of flows are shown in Fig. 8-4 (a) ~ (f).



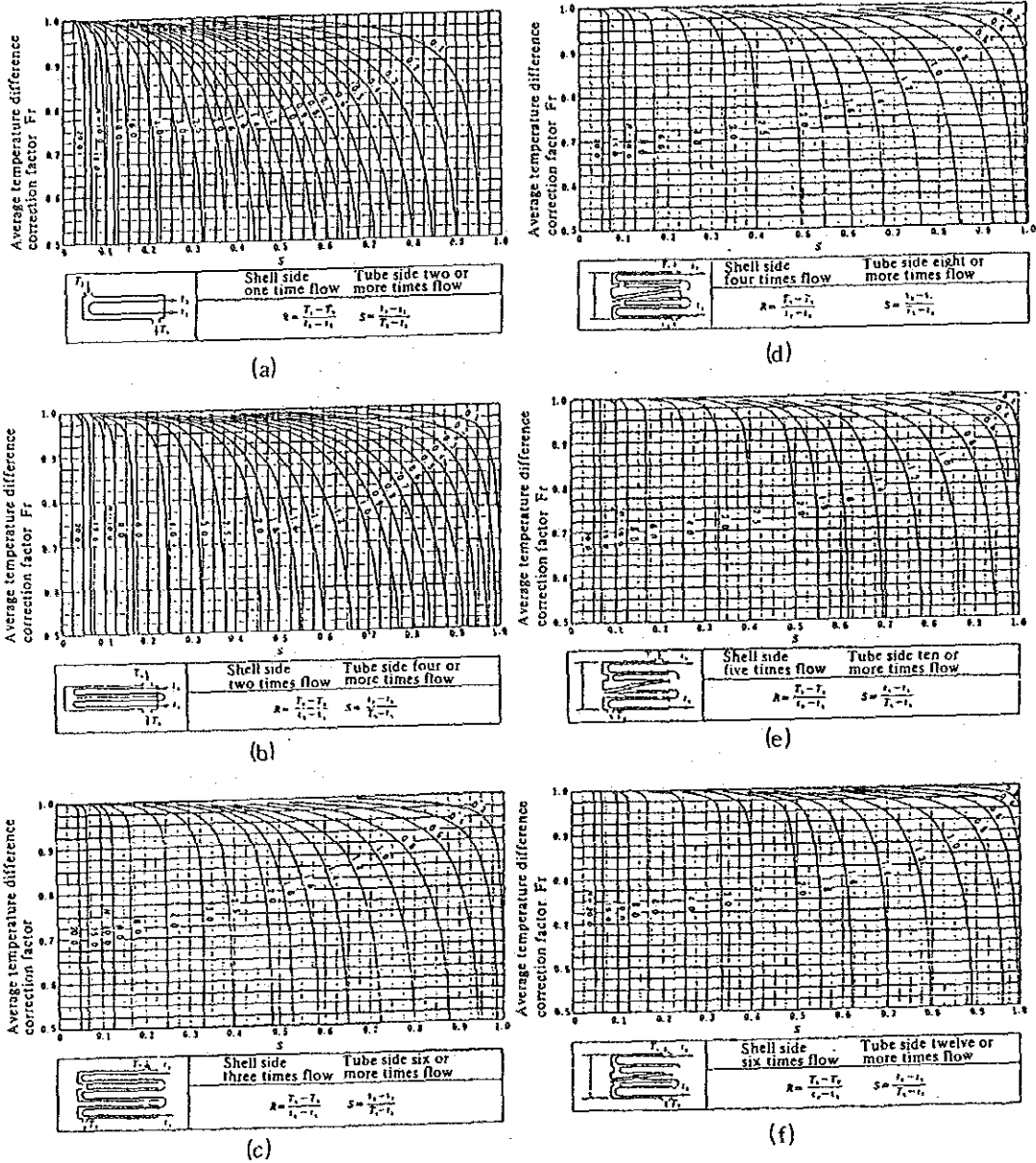


Figure 8-4 Correction Factor Ft

(3) Types of recuperator type heat exchanger

This is roughly divided by the structure of the heat transfer portion, then subdivided by the container which keeps the heat transfer portion.

The structural classifications are as shown below.

A) Tube types (Refer to Fig. 8-5 ~ Fig. 8-8)

- a. Coil type heat exchanger
- b. Trombone type (cooler)
- c. Double tube type heat exchanger
- d. Multi-tube type heat exchanger
  - (1) Fixed tube sheet type heat exchanger
  - (2) Floating head type heat exchanger
  - (3) U-tube type heat exchanger

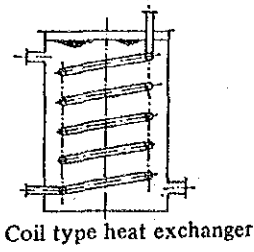


Figure 8-5 Coil Type Heat Exchanger

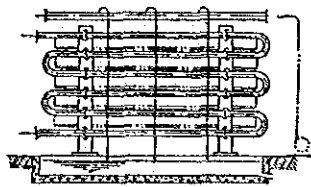


Figure 8-6 Trombone cooler

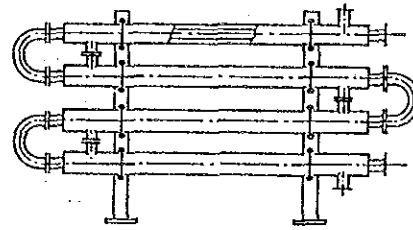
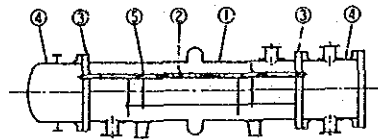
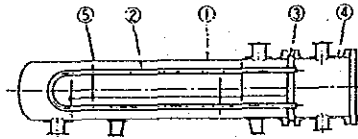


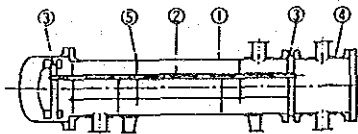
Figure 8-7 Double tube type heat exchanger



(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

Figure 8-8 Multi-Tube Type Heat Exchanger

- B) Plate type (Refer to Fig. 8-9 ~ Fig. 8-10)
  - a. Jacket type heat exchanger
  - b. Plate type heat exchanger
  - c. Spiral type heat exchanger

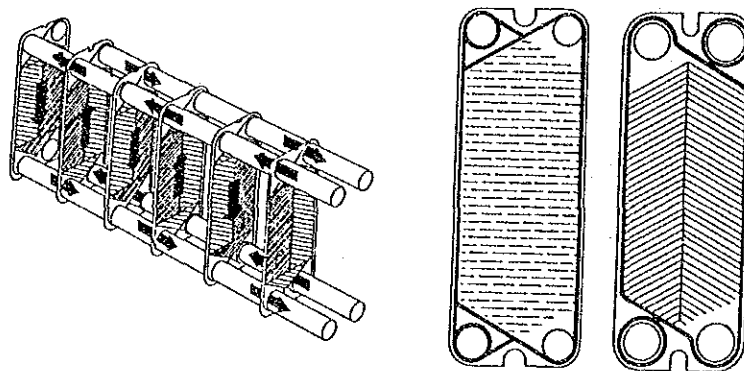


Figure 8-9 Plate Type Heat Exchanger

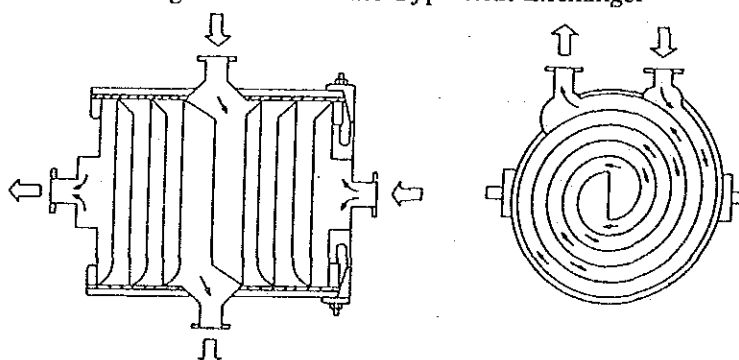


Figure 8-10 Spiral Type Heat Exchanger

Among the heat exchangers mentioned above, an explanation will be given on the characteristics of the typical ones.

Coil type heat exchanger: This heat exchanger is mainly installed to the inside of the storage tanks and the reactors.

The overall heat transfer coefficient is influenced greatly by the heat transfer coefficient outside of the tube. Its structure is simple, its cost is low, and cleaning and replacement can be done easily in general.

From the standpoint of design, in case condensation occurs in the fluid inside of the tube, it is necessary to give consideration so that discharging of the condensate is easy.

Trombone type cooler: This is composed of 180° bends and straight tubes. The replacement or addition of tubes can be done easily, and since the possibility of leakage is less, it is used for special processes such as coolers for sulfuric acid and the cooling of fluids.

Since the water side of heat transfer surface often comes into contact with air, the propagation of aerobic vegetation and attachment of scales caused by the evaporation of water, are likely to occur. Thus, cleaning should never be neglected.

Double tube type heat exchanger: This is used in case of small models having a heat transfer surface area of about 15 – 20 m<sup>2</sup>. It is necessary to pay attention to the cleaning of the ring shaped portion between the inner tube and the outer tube, and the leakage from the gland couplings.

Multi-tube type heat exchanger: This type is the most broadly utilized type in the chemical industry. It has high reliability from a practical viewpoint, and design and manu-

facture based on various specifications ranging to high temperature and high pressure, to large capacity ones are possible.

Although the fixed tube plate type ones are low cost and easy to manufacture, the shell side fluid is restricted to non-corrosive fluid which is not so dirty. The floating head type heat exchanger allows the tube bundle to be pulled out. Thus, inspection of the heat transfer tube and cleaning can be done easily.

In addition, it absorbs the thermal expansion caused by the temperature difference of the fluids, and it has advantage of preventing the occurrence of thermal stress. However, the structure is complex, and the cost is high. In the case of U-shaped tube type heat exchanger, you do not have to worry about thermal stress, and the tube bundle can be easily pulled out for cleaning. However, its drawback is that the bent portion of the tube is difficult to clean.

Since the Multi-tube heat exchangers are manufactured by employing the tube expansion method for the attachment of tube and plate, loosening of this portion and leakage of fluid owing to corrosion of this portion is likely to occur. Consequently, at the time of maintenance, this is a portion in which special attention should be paid to inspection.

Plate type heat exchanger: The heat transfer area can be freely increased or decreased by the number of plates to be used, and the assembly and cleaning are simple. Since turbulence can be added to the flow, the heat transfer coefficient is large, but from the standpoint of structure, the upper limit of pressure is about 10 kg/cm<sup>2</sup>, and the upper limit of temperature is about 150°C.

Use in pharmaceutical and foodstuff industries is high, but it is beginning to be used in general chemical factories also.

Spiral type heat exchanger: Since the fluid revolves, the heat transfer coefficient increases because of the turbulence. Similar to the plate type, designing of small models is possible. Since flange structures are adopted, disassembly is easy, but since the gap is small, it is difficult to inspect the condition between the plates at the far end.

As heat exchangers, besides the abovementioned recuperator type, there is also the heat storage type, but in this guideline it is omitted.

### 8.2.3 Reactors

Among the equipment used in the chemical industry, the reactors play the center role, and in many cases, they occupy an important position in the field of thermal energy also. There are a variety of types of reactors used in various chemical industries, and even for the same chemical reaction, several different reactors are used. The writer would like to explain the characteristics of each reactor in accordance with the general classification.

#### (1) Structural classification

##### A) Vessel type reactor

This is a reactor which is most broadly utilized in the chemical industry. Generally speaking, the reactors are equipped with agitators as well as jackets and coils as heat exchangers. This type of reactor is used in broad temperature and pressure range, and they can be utilized in batch operation as well as continuous flow operation.

B) Tube type reactor

This reactor is laid out as single tube reactor as well as parallel multi-tube reactor.

There are many reactors that perform heat exchange between the inside and outside of the tube, and in case catalysts are filled into them, the heat transfer will also be promoted. It is used in the synthesis of ammonia, oxidation of naphthalene, decomposition of hydrocarbons, etc.

C) Tower type reactor

In comparison with the tube type, these reactors are vertical cylinder type with large diameters. There are towers filled with catalyst particles, towers which have baffle boards attached to them, and also simple hollow ones. They are used in the production of formalin, hydrogenation and desulfurization of crude oil fractions, etc.

(2) Classification by temperature control

A) Isothermal operation

This operation is done in case the reaction heat is small, or the reaction amount is small, or when there is introduction of inert gas having large heat quantity, or heat exchange with the outside is done sufficiently and the inside of the reactor is deemed to be isothermal.

B) Adiabatic operation

In this case, heat exchange between the reaction system and the outside is not done at all, and the reaction is conducted adiabatically.

The heat generated or the heat absorbed by the reaction, will be an increase or decrease in the enthalpy of the reaction system.

In case the reaction heat is large, in certain cases, a method in which the reaction layer is divided into several layers is taken, and between each layer, a heat exchanger (or heater or cooler) is inserted, or low temperature (or high temperature) reactive fluid is introduced, and by adjusting the inlet temperature of each adiabatic reaction layer, the temperature distribution within the reactor is made to approach the optimum temperature distribution. This is called multi-layer adiabatic operation, and such examples can be seen in the  $\text{SO}_3$  converter of sulfuric acid manufacturing plant or ammonia synthesis tower.

C) Heat exchanger operation

This is a system which is broadly used to process reaction heat, and the emitting and receiving of reaction heat with the outside system are done from the walls of the reactor, and it is called heat exchanger operation. This operation can be divided into the self-heat-exchanging type in which the reactive portion is cooled (or heated) by the reactive fluid itself, and simultaneously, the fluid itself is pre-heated (or cooled) and enters the reaction portion, and the external heat-exchanging type in which the reaction portion is cooled or heated by other heat media.

(3) Rationalization of heat energy utilization

Generally speaking, in the case of industrial chemical reactions, the number of exothermic reactions is great. Thus, an explanation will be given on this reaction.

For the pre-heating of the raw materials, the heat is obtained by heat exchange from the high temperature product after the reaction, or by heat exchange performed inside of the reactor or intermediate cooling.

Heating which depends on fuel or steam should be kept at a minimum.

In the case of cooling for temperature control of the intermediate reaction layers or cooling for the high temperature products at the outlet of the reactor, besides pre-heating of the raw materials, it is desirable to recover the reaction heat effectively, and utilize this both inside and outside of the system by methods mentioned below.

- a. Lead to the outside of the system by heating water supply to boiler, or generating steam.
- b. Lead to the outside of the system by letting air or other fluid absorb the heat.

[Execution example 1]

In the sulfuric acid plant which uses sulfur as the raw material as shown in Fig. 8-11, the heat generated by sulfur burner is utilized for the generation of steam, and the reaction heat of the  $\text{SO}_3$  converter is utilized for the pre-heating of raw material air in the case of intermediate cooling, and for the pre-heating of the water supply in the case of cooling at the outlet. As a result, for every 1 ton of 100% sulfuric acid, 1 ton of high pressure steam is generated. (Example of the USA)

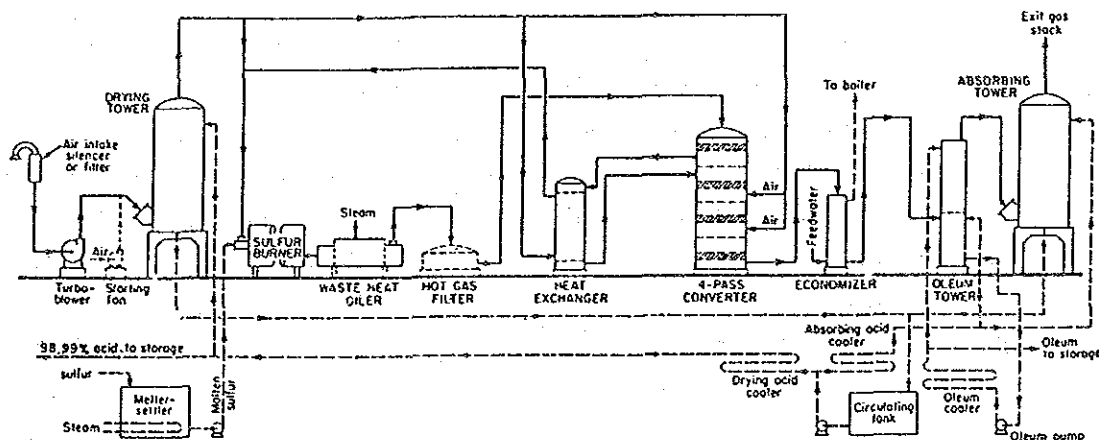


Figure 8-11 Typical Flowchart for a Sulfur-Burning Contact Sulfuric Acid Factory

[Execution example 2]

In a reactor which produces formalin by oxidizing methanol with air, the reaction heat is recovered as low pressure steam by quenching at the boiler, the high temperature ( $600 - 630^\circ\text{C}$ ) gas which is generated after the reaction. For every 1 ton of 38% formalin, the amount of recovered steam will be about 400 kg.

The total amount of recovered steam is consumed inside of the plant, and steam which is supplied from the outside of the system is merely about 100 kg. (Example of Japan).

## 8.2.4 Distillation Equipment

### (1) Principle of distillation

When a mixed solution consisting of 2 or more volatile matters is evaporated, the vapor generated will have a high concentration of low boiling point component in comparison with the original solution. On the other hand, the remaining liquid will have high concentration of high boiling point component. By the utilization of this principle, the process of separating a high concentration solution of specific component from a mixed solution is the distillation operation, and distillation facilities used for this purpose are broadly adopted in chemical plants.

If vapor that has been generated is condensed, then vaporized again, by the same principle mentioned above, the concentration of low boiling point component in the vapor generated will be heightened, and the remaining liquid will abound in high boiling point component all the more.

If this operation is repeated, gradually, it will be possible to obtain high concentration of low boiling point fractions. However, the amount of fraction will become extremely small, and it would not be practical. Thus, the so-called reflux in which a portion of the fraction is returned to the overhead, is conducted.

In order to think of distillation, the concept of equilibrium shown in Fig. 8-12 is necessary.

If solution having composition of Point I boils at  $92^{\circ}\text{C}$ , and generates vapor of composition J, I and J will have a relation of equilibrium.

If the vapor of J is cooled, the composition will not change, and only the temperature will lower, and become liquid at  $86^{\circ}\text{C}$ . Solution having composition K will boil at  $86^{\circ}\text{C}$ , and vapor having composition L will be generated. Point B is where the low boiling point component is 0%, and the boiling point of the high boiling point component is  $112^{\circ}\text{C}$ . Point A is where low boiling point component is 100%, and the boiling point at that point is  $80^{\circ}\text{C}$ . Let us now consider a facility like the one shown in Fig. 8-13.

If the bottom portion of the tower, I, is heated, vapor having composition J will be generated. Since this is the same composition as K, if vaporization latent heat is added to K and made to condense, vapor having composition of L will be generated. If we assume that mol vaporization latent heat within the tower is constant for all compositions, L and J will be the same mol number.

If such a procedure is continued, the low boiling point component in the lowest stage will gradually decrease. Consequently, the concentration in the generated vapor will also decrease. At this point, let us make improvements in the distillation facility as shown in Fig. 8-14.

Let us install a downcomer so that the liquid which overflows in the upper stage will flow to the lower stage, and let us return the condensed liquid to the uppermost stage.

This operation is called reflux, and if all is returned, it is called total reflux.

If such a total reflux is executed, the liquid composition will not change. The reason is that the liquid which overflows from the top stage will have the same composition and quantity as the vapor that is generated. Since this will be merely repeating vaporization and condensation, from condensate M extract a portion D, and from the tower bottom E extract a portion W, and replenish liquid F which will have the same composition as stage I.

Such a tower is referred to as a distillation tower which has composition F supplied, and which fractionates it into W and D.

In this case, the ratio of the reflux amount of condensate R, and D, that is,  $R/D$  is called the reflux ratio. This concept of reflux is a unique idea for conducting the separation operation called distillation, continuously. Normally,  $R/D = r$  is a value of 3 ~.

In order to get 1 part of fraction D, vaporization of 4 or above will be required, and it is an energy consuming operation. If the  $r$  is made small, the energy consumption will decrease, but the number of required stages will increase, and the construction cost will be very high.

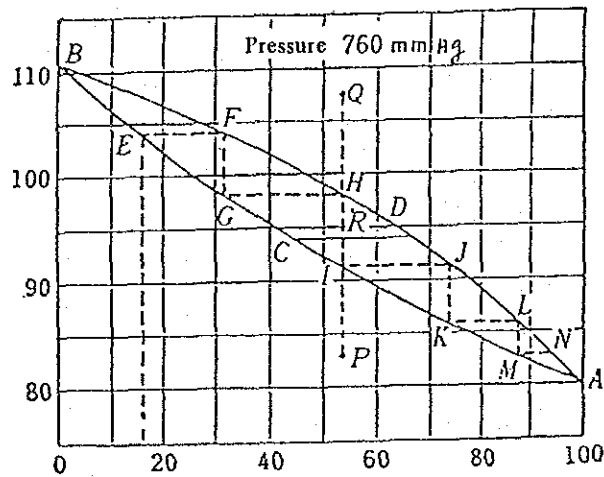


Figure 8-12

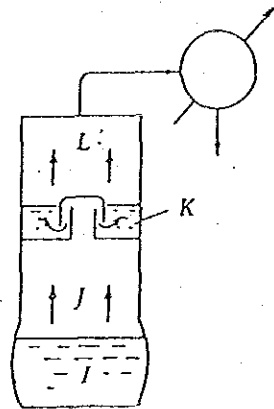


Figure 8-13

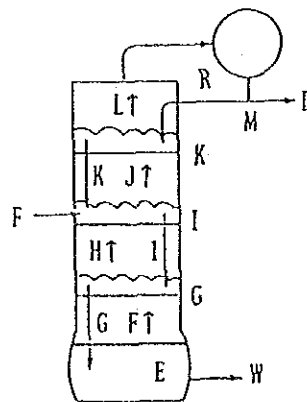


Figure 8-14



If we put the above mentioned relation in order and summarize them, they will be as follows:

« Reflux »

In order to maintain the composition of the overhead product constant (in case of continuous operation) or in order to make the separation with the high boiling point component even better (for both batch operation and continuous operation), a part of the overhead effluent shall be returned to the overhead. This is called reflux, and the ratio of reflux amount and flow of the overhead product [(reflux amount)/(overhead product amount)] is called the reflux ratio. This is one of the factors that has important significance in distillation operation.

« Relation between reflux ratio and the number of stages of the tower »

The relation between the number of stages necessary to separate the product of set concentration from raw fluid in a tower (called theoretical stage number)  $N$ , and the reflux ratio  $R$  is as shown in Fig. 8-15.

$R$  cannot be made smaller than  $R_m$ . At the time  $R$  equals  $R_m$ , the required number of stages for the tower will become infinite. If  $R$  is increased, the required number of stages will decrease but even if  $R$  is made infinite, the number of stages cannot be less than  $N_m$ .

$R_m$  is called the minimum reflux ratio, and  $N_m$  is called the minimum theoretical stage number. They are important indexes related to the designing and operating of the distillation facilities.

« Relation between reflux ratio and thermal energy »

The amount of vapor that rises inside of a tower will be the same at any stage within the tower unless cooling or heat emission is done inside of the tower. This amount can be expressed as

$(1 + R) \times (\text{product flow amount at overhead}) \times (\text{latent heat of vaporization})$  and it is given by the heater at the bottom of the tower\*.

Thus, in case of the distillation facilities, the decrease in  $R$  will be directly related to the energy saving.

Note: \* This is the case in which the raw material to be charged is at boiling point.

In cases other than this, correction based on raw material state will be required.

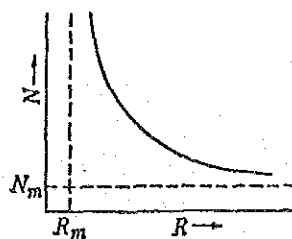


Figure 8-15 Relation between the Reflux Ratio and the Number of Steps of Tower

(2) Classification of distillation tower

A) Tray stage tower

In order to accumulate the liquid inside of the tower, multi-stages of trays (plates) are installed. With the purpose of making the contact between the vapor rising from the lower stages and the liquid on the tray better, the tray itself is perforated or large number of bubble caps are made.

Furthermore, a certain amount of liquid is accumulated on the tray, and various contrivances are made so that the flow of liquid to the lower stages will be done smoothly.

B) Packed tower

Packings having a structure to make the contact between gas and liquid efficient, are put into the tower, and instead of conducting vaporization and condensation in steps, it is done continuously.

The performance as a distillation tower is inferior to A) but the cost of the facilities, is cheaper, and there is the advantage that the pressure loss inside of the tower is small. Recently, although they are very expensive, there are packings sold on the market which outperforms the tray stage tower.

(3) Rationalization of energy usage

A) Optimization of reflux ratio

As mentioned previously, to decrease  $R$  means to save energy. However, this will cause an increase in high boiling point component in the overhead product, and an increase in the low boiling point component in the bottom product. As a result, this will lower the separation performance of the distillation facilities. Generally speaking, by putting into consideration the bad influence caused by the changes in raw material composition, and steam pressure fluctuation in the heating system, for safety's sake, operation is done at an  $R$  value which is larger than necessary.

In most cases,  $R$  is determined empirically, but it is advisable to make efforts to make the variations in various conditions as small as possible, then gradually decrease the  $R$  and find the minimum level which will not hinder the product.

In addition, since the raw material charging stage will also have influence on  $R$ , to change the charging stage by trial and error is another way of approaching this matter.

B) Cleaning of tray (plate) stage or packings

Actually, the vapor which is generated from each stage does not have equilibrium composition with the liquid.

The actual facilities are manufactured by putting this difference into consideration. That is, stage efficiency is considered, and the actual number of stages is obtained by dividing the theoretically calculated number of stages by this stage efficiency. When the tray or packings become soiled by foreign matters contained in the liquid during use, the stage efficiency will become lower than the calculated value, and in order to maintain the performance, the  $R$  will have to be increased.

In order to prevent such a matter, it is important to open the tower periodically and have the interior inspected and cleaned.

C) Prevention of channeling

The effect of the distillation tower is determined by how effectively the vapor and liquid come into contact. In case the liquid or vapor flows through only a certain portion of the tower, the contact efficiency will drop significantly. This phenomenon is called channeling. This is caused by the vertical degree of the tower, the horizontal degree of the trays, the state of the packings and their degree of soiling. Thus, these matters shall be inspected so that a condition in which it will function normally can be maintained.

D) Recovery of waste heat by heat exchangers

Since the overhead vapor possesses a large amount of latent heat, this is utilized for the heater of low temperature tower, or the sensible heat possessed by the bottom product is utilized for the pre-heating of raw material. (Fig. 8-16)

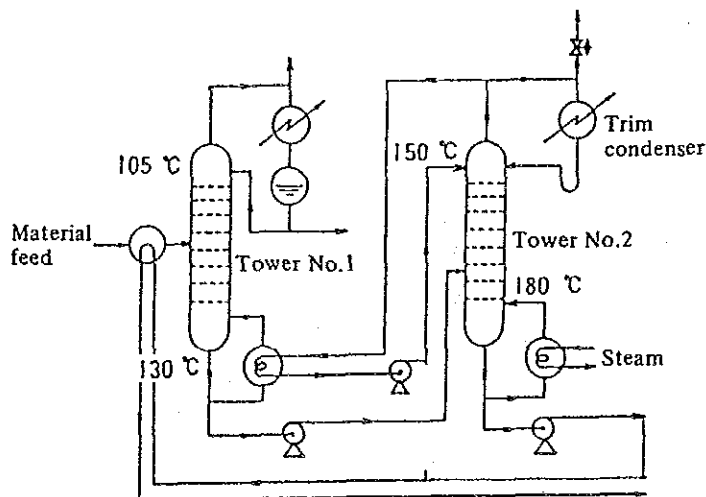


Figure 8-16 Use of Waste Heat for Distilling Equipment

Furthermore, the heat of the overhead condenser can be utilized for the generation of low pressure steam in case the temperature of the vapor is high. (Fig. 8-17)

Although the facilities will become slightly more expensive, there is a method in which the temperature of the vapor of the overhead product is raised by compression type or absorption type heat pump, and utilized in the power bottom heater (Refer to Fig. 8-18).

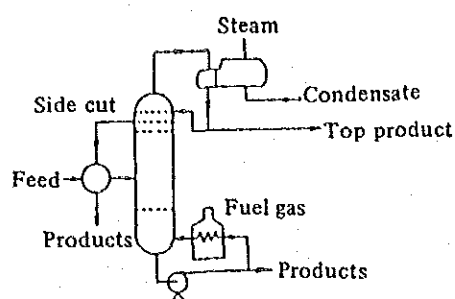


Figure 8-17 Steam Generated by Tower Top Vapor

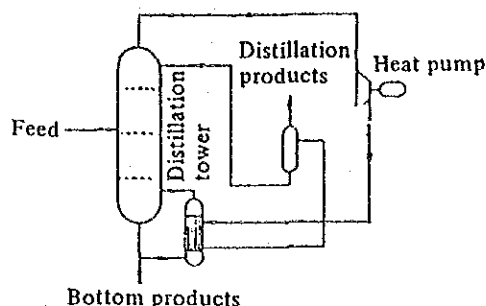


Figure 8-18 Use of Heat Pump

#### E) Precautions related to insulation

In case the main body of the distillation tower is not insulated, or even if it is insulated, in case the thermal insulation effect is not so good, by the heat emission from the walls of the tower portion, the vapor rising in the tower will be condensed (this is called partial condensation).

When partial condensation occurs, the reflux  $R$  will decrease from the point above such partial condensation, and the separation performance of distillation tower will drop. In order to prevent this, if you try to maintain  $R$ , the thermal loss from the tower walls will have to be compensated by the tower bottom heater.

#### 8.2.5 Evaporation

Among chemical facilities, many use evaporators for concentration, and crystallization of the solution. Generally speaking, the solvent of the solution is water, and since the latent heat for evaporation is large, it is an important equipment from the standpoint of energy saving. As heat source, besides steam, burnt gas, direct firing, electrical heat, thermal media, etc. are used.

As for the types of evaporators, and rationalization of energy use, please refer to 5.4 Foodstuff Industry.

#### 8.2.6 Drying Equipment (Dryers)

In this Section, we will restrict our discussion to drying equipment having a mechanism in which the moisture in the material is vaporized by making hot air and wet material come into contact with each other. The shape as well as the physical and chemical properties of the materials to be dried abound in variety, and in addition, the moisture content will also be different. Thus, the drying operation will vary for each.

Consequently, various types of drying equipment models which comply with the characteristics of each material and each operation are sold on the market.

The types of equipment are numerous, and the selection of equipment is important.

However, in this Section, we will discuss only the general problems, and describe the general energy saving of the drying equipment.

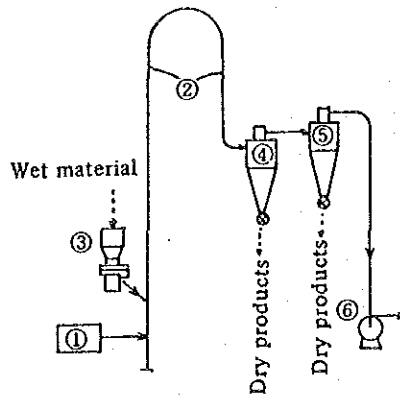
##### (1) Types of drying equipment

Depending on the moving system of the material to be dried and heat transfer system, the dryers can be divided as follows:

A) Hot air drying equipment (hot air dryer)

a. Hot air carrier type

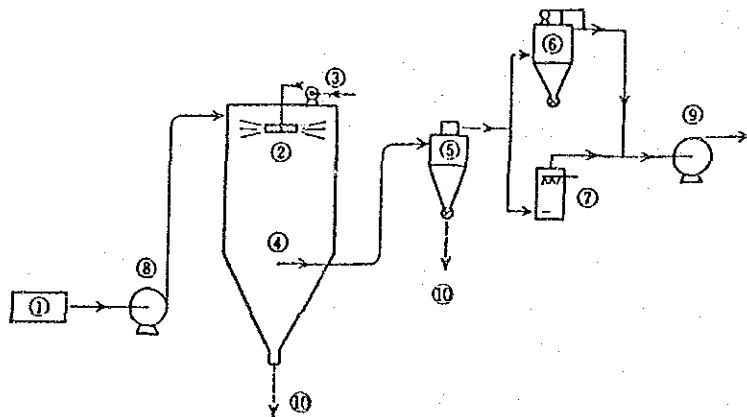
(1) Flash dryer (Fig. 8-19)



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

Figure 8-19 Distribution Diagram of Flash Dryer  
 (Direct Feed System)

(2) Spray drying equipment (Refer to Fig. 8-20)



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

Figure 8-20 Distribution Diagram of Spray Drying

b. Material agitation type

Single cylinder direct firing type

(1) Rotary dryer Double cylinder direct/indirect heating type

External fire type (Refer to Fig. 8-21)

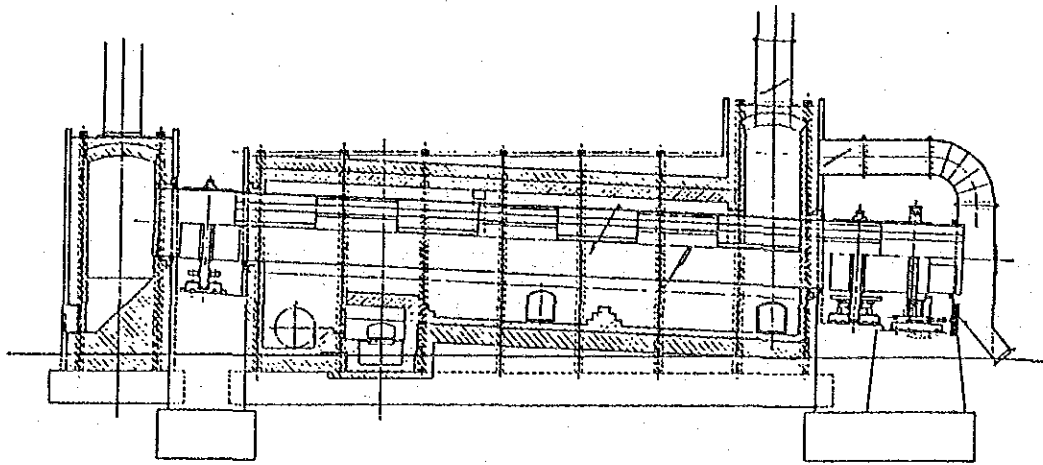


Figure 8-21 External Fire Type Rotary Dryer

- (2) Multiple stage disc hot air dryer (Fig. 8-22)
  - (3) Groove type agitation dryer (Fig. 8-23)
  - (4) Fluidized bed dryer
- Multi-stage continuous type  
 Horizontal multi-chamber continuous type  
 One stage continuous flow type (Fig. 8-24)  
 Batch type

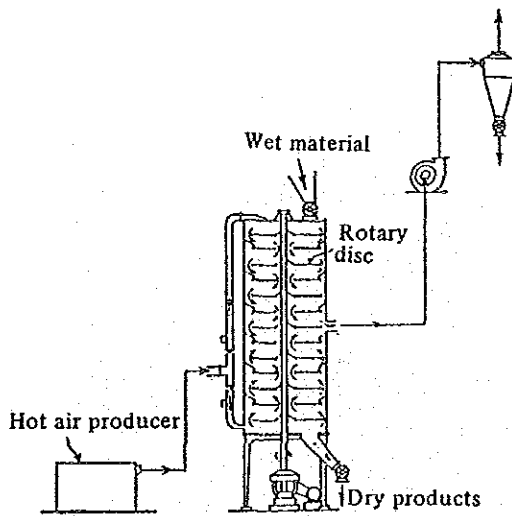


Figure 8-22  
 Multiple-Stage Disc Hot Air Dryer

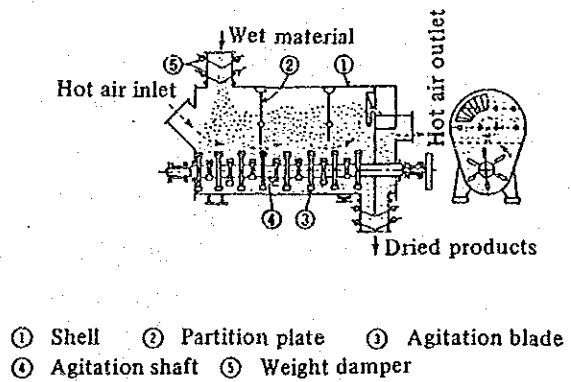


Figure 8-23  
 Hot Air Groove Type Agitation Dryer

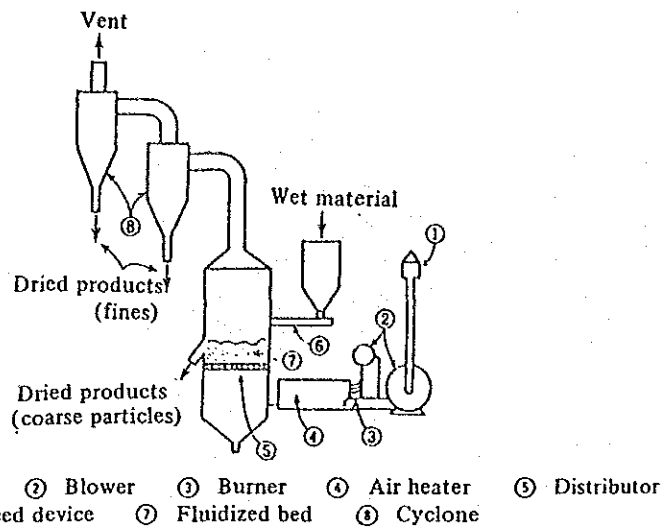


Figure 8-24 One Stage Continuous Flow Dryer

c. Material conveying type and stationary type

- (1) Through-circulation dryer
  - Band type (Fig. 8-25)
  - Rotary type (Fig. 8-26)
  - Vertical type moving bed (Fig. 8-27)
  - Box type batch system (Fig. 8-28)
- (2) Tunnel dryer (Refer to Fig. 8-29)

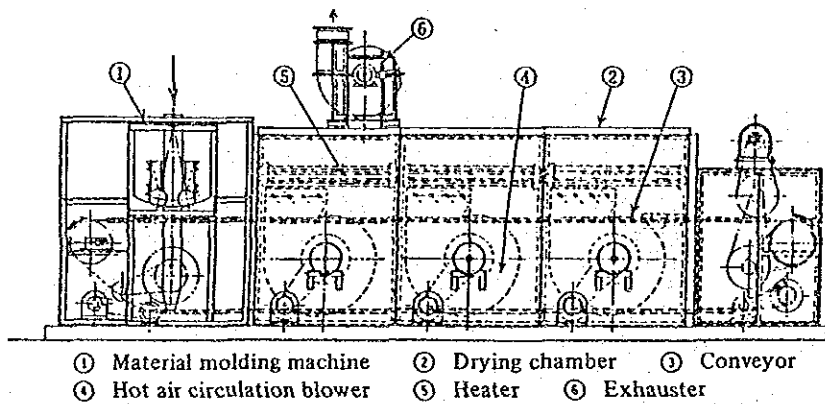


Figure 8-25 Band Type Continuous Through-Circulation Dryer

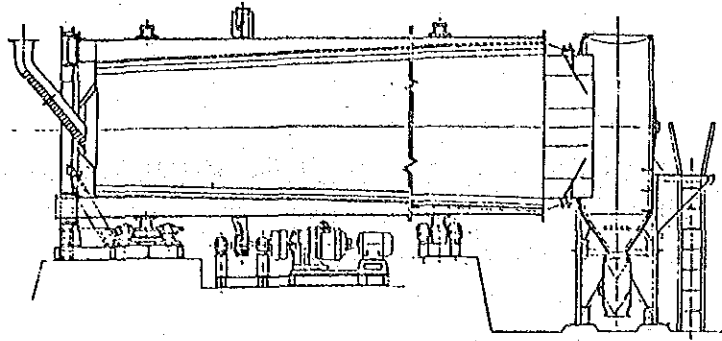


Figure 8-26 Rotary Type Continuous Through-Circulation Dryer

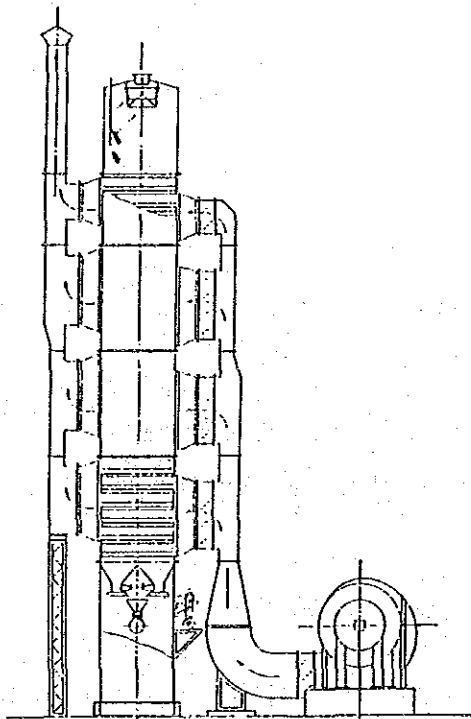


Figure 8-27 Vertical Type Continuous Moving Bed Through-Circulation Drying System

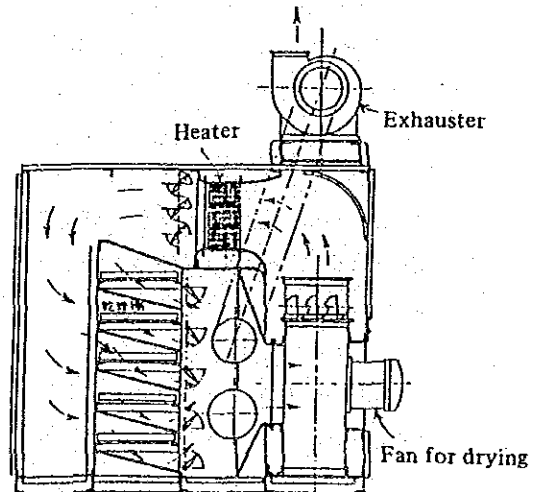


Figure 8-28 Box Batch Type Through-Circulation Dryer

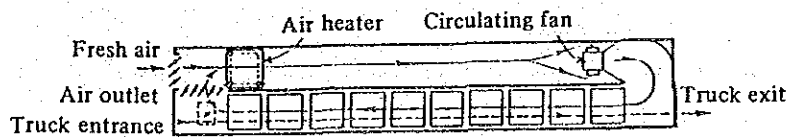


Figure 8-29 Distribution Diagram of Counter-Current Tunnel Dryer



- B) Heat conductive dryer
  - a. Material agitation type
    - (1) Hot air groove type agitation dryer
    - (2) Cylindrical agitation dryer – Ordinary pressure type/vacuum type
    - (3) Flat plate agitation type dryer
    - (4) Rotary dryer with steam heating tube
    - (5) Multi stage agitation dryer
    - (6) Vacuum rotary dryer
  - b. Stationary material type
    - (1) Vacuum dryer
    - (2) Freeze drying equipment
  - c. Drum dryer
    - (1) Normal pressure type
    - (2) Vacuum type

(2) Rationalization of thermal energy use

A) Pre-treatment of material

In the process of the preceding stage, remove as much moisture as possible. In the case of soluble components, concentrate it as much as possible. In the case of insoluble materials, it is desirable to dewater them by mechanical dewatering as much as possible, then charge it into the drying process. Although the capital cost of dewatering equipment is rather expensive, if it is compared with the drying method in which the moisture is removed by thermal evaporation, the energy consumption will be much less.

B) Prevention of heat loss

Generally speaking, in case of small dryers, the specific area is large, and the radiation loss is liable to become big. In certain cases, it exceeds 10% of the heat quantity supplied. Thus, it is necessary to do sufficient thermal insulation. Next, the loss owing to leakage of hot air is in many cases much larger than expected. Sealings corresponding to the internal pressure are required around the flanges, junctions of the rotary portion and fixed portion as well as inlet of raw materials, outlet of products, etc.

C) Circulation of exhaust gas

In the case of hot air dryers, the sensible heat quantity taken away by exhaust gas is very large.

In order to lower this, besides lowering the temperature, it is important to decrease the amount of exhaust gas. If a portion of the exhaust gas is re-circulated and re-used, the heat efficiency will be improved.

In the case of band through-circulation dryers where a large amount of hot air is blown perpendicular to the direction in which the materials move, the exhaust gas temperature is high, and the humidity is low. Thus, if the hot air blowing portion is divided into several sections, and starting from the rear end stage, if the exhaust gas is utilized for the preceding stage in succession, the efficiency will be improved. In

case drying is done at high temperature, the drop in drying speed caused by the increase in humidity is small, so in many cases the exhaust gas recirculation can be applied.

D) Recovery of sensible heat from the exhaust gas

The sensible heat taken away by the exhaust gas is recovered, and utilized for the preheating of air used for drying. In this case, plate type heat exchangers or heat pipe type heat exchangers are suitable as heat exchangers. However, in the latter case, there is the drawback that the capital investment will be high.

Point to pay attention to when adopting the heat exchanger system are that the heat transfer surface will be soiled by dust and moisture contained in the exhaust gas, and in certain cases, corrosion may occur. So periodical cleaning and inspection are necessary.

Next, a method in which the heat possessed by the exhaust gas is recovered directly instead of through the heat exchangers should be studied.

For instance, in case of the spray dryer, if the exhaust gas is made to come into direct contact with the liquid to be dried, and consequently the liquid is concentrated the exhaust gas sensible heat can be utilized to almost saturation point.

E) Recovery of latent heat from exhaust gas

Of the heat quantity consumed for the drying operation, the heat quantity rate used for the evaporation of water is great. This evaporated steam is accompanied by exhaust gas. If this latent heat can be recovered, the heat efficiency will be improved remarkably.

As for the method of recovery, it may be used as heat source for the concentrator, or be recovered by heat pump. The portion of utilization in the plant should be studied by putting into consideration of the temperature and the humidity of the exhaust gas.

F) Recovery of sensible heat of the dried product

In case the temperature of the dried products is rather high, cool them by air, then recover the heat possessed by the product and utilize it by pre-heating the air used for drying. Since the temperature of the dried product is not so high, if cooling and pre-heating of air is done by fluidized bed, the efficiency becomes sometimes very good.

G) Others

In chemical facilities, we often use air for the cooling of reaction products, and cooling of condensers in the distillation tower and the refrigeration units. In such cases, although the temperature of the air exhausted is not so high, since the amount of air is great, in many cases, it may be used as air for drying. In case if a certain exhausted air temperature may be sent to the dryer as it is, the effect of saving energy is significant.

Recently, a unique type of dryer which uses compression type refrigeration unit as a heat pump has been contrived. In this case, wet air which has taken moisture from the object to be dried in the dryer is introduced to the evaporator of the refri-

generation unit, and after condensing and separating the moisture, it will be heated and its temperature will be raised in the condenser portion of the refrigeration unit, and returned to the dryer again. In other words, the thermal energy that is used for drying the object to be dried, is recovered as condensation latent heat of water at the evaporator of the refrigeration unit, 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 object to be dried.

### 8.2.7 Heat Pump, 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 equipments, 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.

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 Fig. 8-30.

The operating media which have become high temperature and high 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.

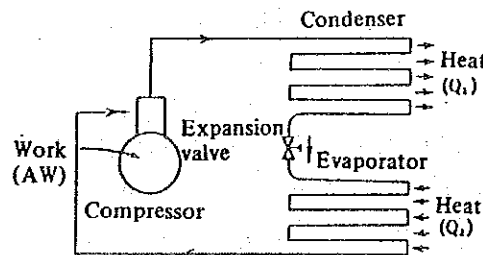


Figure 8-30 Refrigeration Cycle

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 quantity absorbed by the evaporation by  $Q_2$  kcal, and the heat quantity emitted at the condenser by  $Q_1$  kcal, the following relation exists.

$$AW = Q_1 - Q_2$$

where

$$A = 1/427 \text{ kcal/kg-m}$$

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

- 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.

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

Chart which indicates the cycle on the P – i Chart is Fig. 8–31. 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 (kg-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/kg-m)

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

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

where

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

The ratio between the refrigeration effect and the compression workload is called the 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 work load.

$$\begin{aligned} E_n &= (i_B - i_C)/(i_B - i_A) \\ &= 1 + E \end{aligned}$$

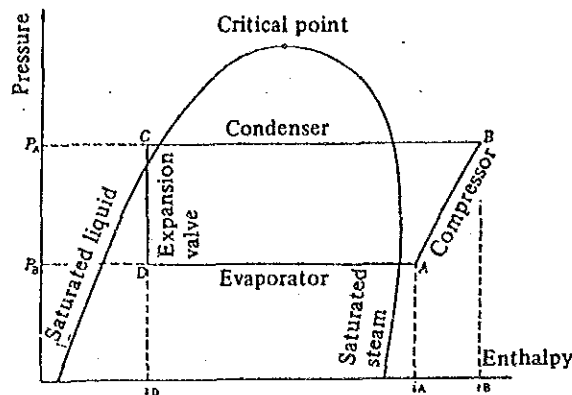


Figure 8-31 P-i Diagram

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  $40 \text{ m}^3/\text{min.}$  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 compressors 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 8-4 and 8-5. Furthermore, the P - i Charts of the refrigerants are shown in Figure 8-32 and Figure 8-33.

Table 8-5 Refrigerant properties (for High temperature)

Classification of refrigerants		Ammonia	Freon R-22	Propane	Propylene	n-butane	i-butane
Chemical formula		NH <sub>3</sub>	CHClF <sub>2</sub>	C <sub>3</sub> H <sub>8</sub>	C <sub>3</sub> H <sub>6</sub>	C <sub>4</sub> H <sub>10</sub>	C <sub>4</sub> H <sub>8</sub>
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 <sup>2</sup> (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 <sub>e</sub> = -15°C and T <sub>c</sub> = 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	kcal/kg	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 <sup>3</sup> /kg	0.5087	0.0778	0.1548	0.142	0.623	0.400
Specific volume of saturated liquid at 25°C	g/kg	1.6588	0.8384	2.0253	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 <sup>3</sup> /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 5-8-6 Refrigerant properties (for Low temperature)

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

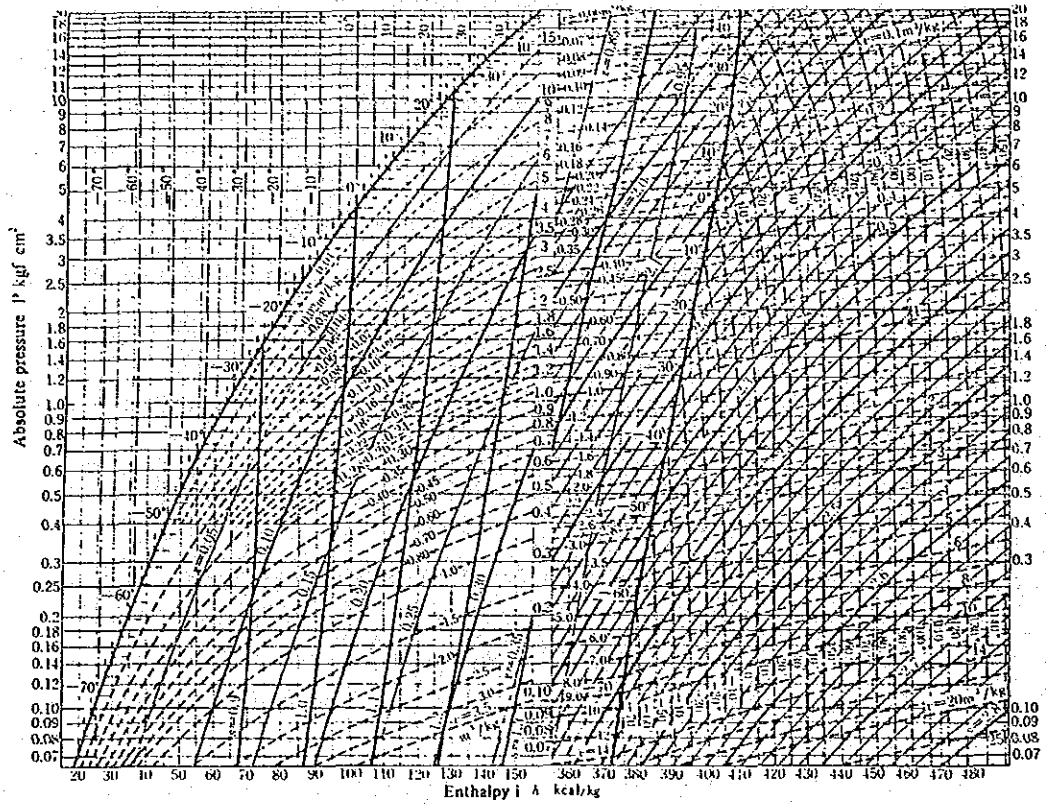


Figure 8-32 P-i Diagram of Ammonia

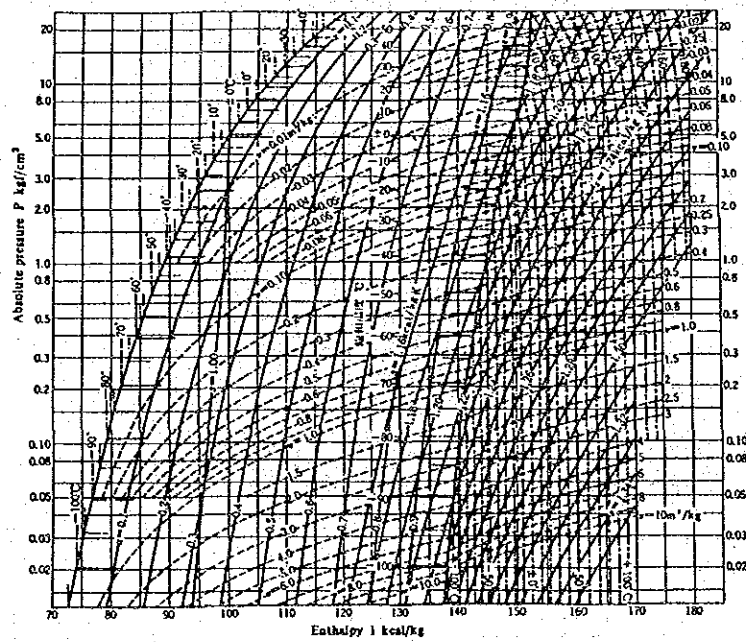


Figure 8-33 P-i Diagram of R-22



If refrigerants for high temperature use such as R-22 or ammonia are used when the vaporization temperature becomes below  $-80^{\circ}\text{C}$ , 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 Fig. 8-34. At the evaporator, the operating media which gained heat from the brine and were vaporized, are absorbed by 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 8-35 and Figure 8-36.

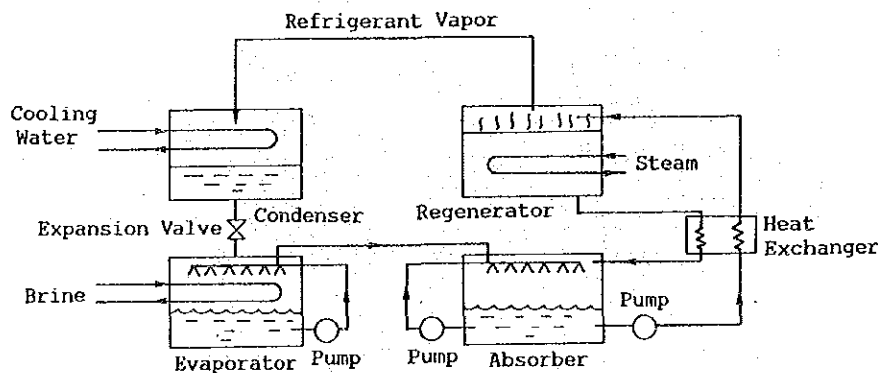


Figure 8 -34

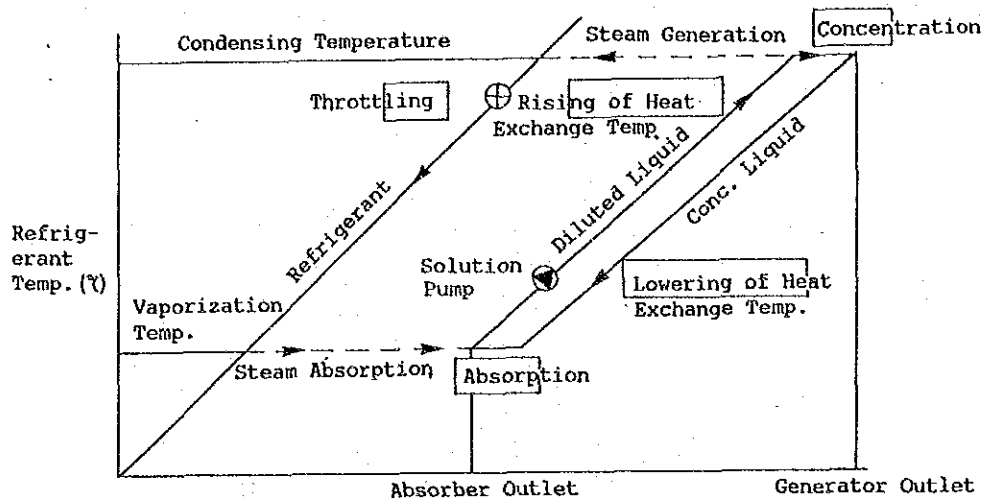


Figure 8-35

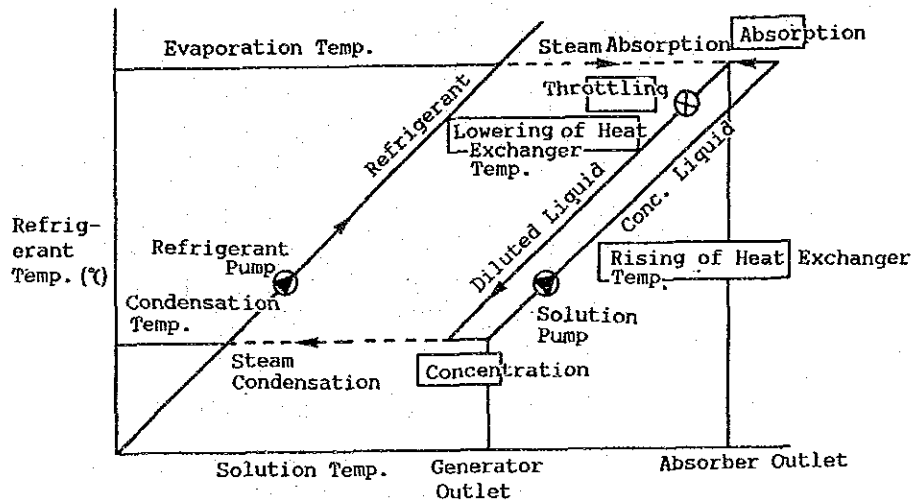


Figure 8-36

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,  $H_2SO_4$  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 ( $\text{NaCl}$ ), magnesium chloride ( $\text{MgCl}_2$ ), methanol, ethanol, ethylene glycol, glycerine, etc. In Fig. 8-37, the specific heat of brine is shown, and in Fig. 8-38, the specific gravity and freezing temperature are shown.

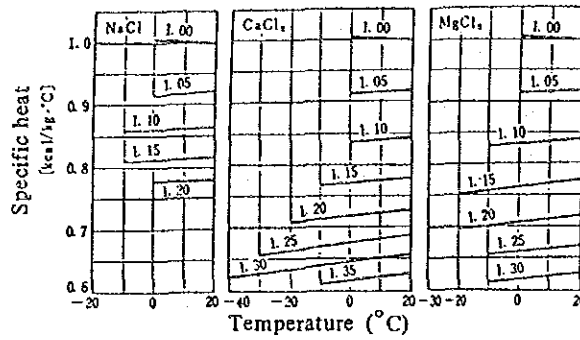


Figure 8-37 Specific Heat of Brine

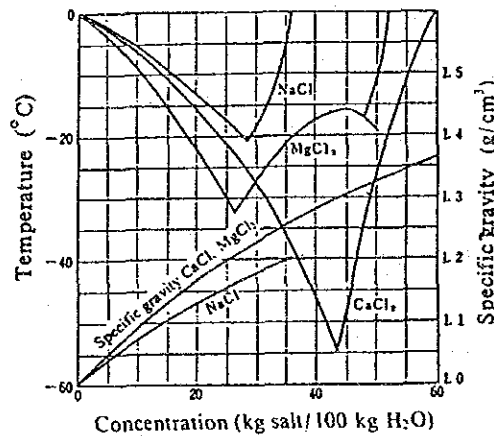


Figure 8-38 Freezing Temperature and Specific Gravity of Brine

(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  $0^\circ\text{C}$  water into  $0^\circ\text{C}$  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  $32^\circ\text{F}$  ice in 24 hours.

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

(8) Rationalization of the use of refrigerating energy

In Table 8-7, the energy saving method of refrigerator and heat pump equipment is shown.

Table 8-7 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 8.20	
	Decrease in Conveying System Drive	○	○	○	Refer to Table 8.20	
Improvement of Efficiency	Cycle Improvement	Adoption of Supercooling · Economizer	○	—	○	High Heat Transfer Pipe High Heat Transfer Pipe Mixed Refrigerant, etc. High Heat Transfer Pipe
		Steam Temperature Rise	○	○	○	
		Condensation Temp. Drop	○	○	○	
		Selection of Optimum Refrigerant	○	△	○	
		Heat Transfer Promotion in Solution Heat Exchanger	—	○	—	
		Decrease in Solution Circulation	—	○	—	
	Others	Decrease in Auxiliary Equipment Power	○	○	○	Direct Firing
Waste Gas Heat Recovery	—	○	—			
Partial Load Efficiency Increase	Division into Number of Units complying with Annual Load Conditions	○	○	○	Direct Firing	
	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	—	○	—		
Load Change Response Improv	Optimum Operation by Microcomputer	○	○	○	For miniatures	
	Electronically Controlled Expansion Valve	○	—	—		
	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 is 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 make 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  $10^\circ C$ , it is said that during actual operation, the condensation temperature will rise by about  $20^\circ C$  ~

25°C. The purging of the non-condensable gases are 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 (Fig. 8-39). Consequently, the power consumption of the compressor will increase. (Fig. 8-40)

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 Fig. 8-41). 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.

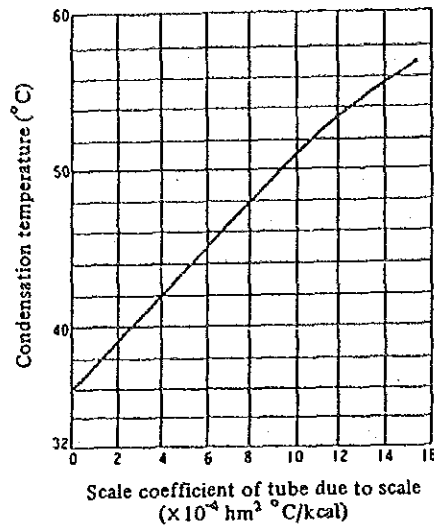


Figure 8-39 Heat Transfer Surface Staining and Condensation Temperature

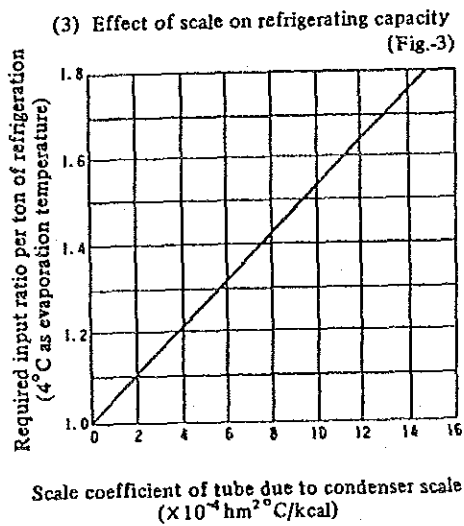


Figure 8-40 Effect of Scale on Refrigerating Capacity

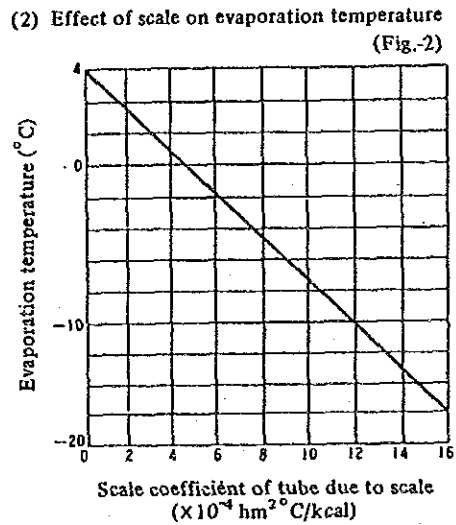


Figure 8-41 Effect of Scale on Evaporation Temperature

### 8.2.8 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  $100^\circ\text{C}$  to  $1,000^\circ\text{C}$  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  
Herschoff'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.

Fig. 8-42 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.



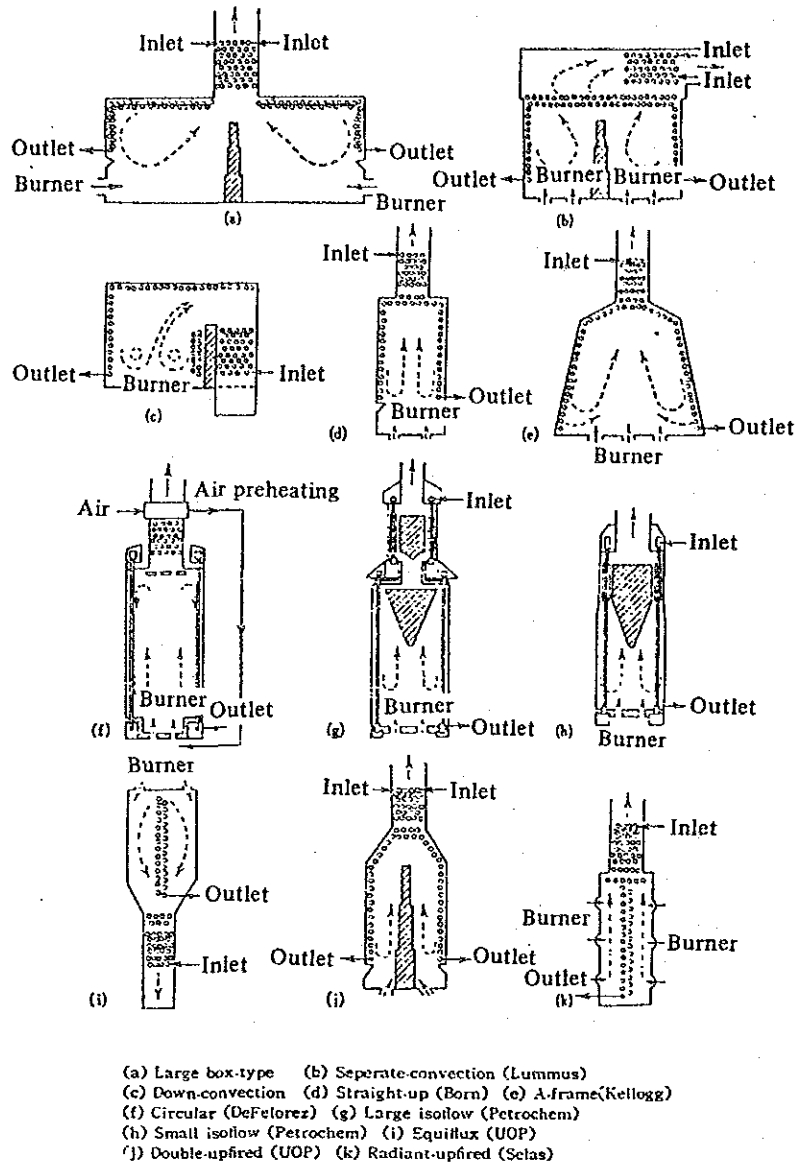


Figure 8-42 Various Furnace Types of Pipe-Still

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 amount 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  $290^{\circ}\text{C}$ , Fig. 8-43) 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

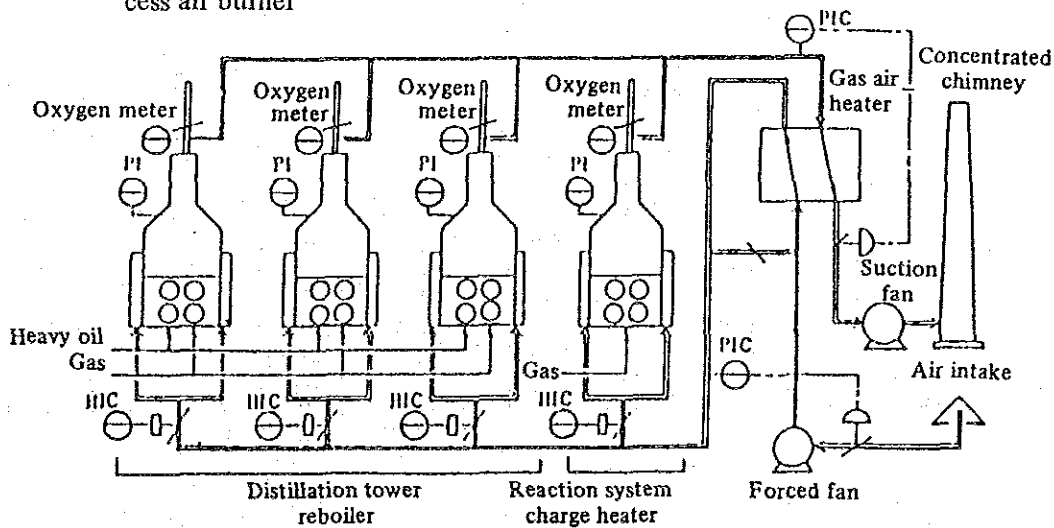


Figure 8-43 Energy Conservation Measures for Pipe Steel

(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 8-8. 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<sub>3</sub> and NaNO<sub>2</sub> 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 8-8 Physical properties of thermal fluids

Property	Dowtherm A*	Dowtherm E*	Fixed salt Hi Tec †	Oil Mobiltherm 600 †	Oil Mobiltherm light †	Hydrotherm ‡ 750-200	Hydrotherm § 700-160	Thermalol ¶ FR-2	Mercury	NaK
Chemical formula	(C <sub>6</sub> H <sub>5</sub> ) <sub>2</sub> O (C <sub>6</sub> H <sub>5</sub> ) <sub>2</sub>	C, H, Cl,	NaNO <sub>3</sub> NaNO <sub>2</sub> KNO <sub>3</sub>						Hg	44 wt. NaK
Molecular weight	165	147	92						200	
Specific gravity at 212°F	0.997	1.181	1.98(300°F)	0.90	0.935	1.11	1.88	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	>600	>600			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(495°F.)	0.412(352°F.)	0.373(300°F.)	0.380(500°F.)	0.33(300°F.)	0.56(600°F.)	0.64(500°F.)	0.33(500°F.)	0.13(112°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	0.00035			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.)	0.608(500°F.)	0.63(500°F.)	1.23(700°F.)	0.24(600°F.)
Surface tension (on contact with air), dynes/cm	43	37				37			487	105
Thermal conductivity liquid, B.t.u./(hr.)(sq ft.)(°F./ft.)	0.076	0.064	0.35	0.067	0.0652	0.0590	0.072	0.057	4.83	15.6

\* The Dow Chemical Company.

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

‡ Mobil Oil Corp.

§ American Hydrotherm Corp.

¶ Monsanto Co.

Table 8-9 Thermal fluids heaters

Type	Vertical type	Horizontal multi-tube type	Marine type	Water tube type
Heat capacity (kcal/hr)	50,000~200,000	50,000~15,000	100,000~600,000	600,000 or more
Thermal efficiency (%)	50~55	50~55	about 70	70~75
Radiant section thermal load (kcal/m <sup>2</sup> ·hr)	15,000	-	15,000	-
Convection section thermal load (kcal/m <sup>2</sup> ·hr)	8,000	8,000	1,000	15,000~20,000
Construction	Simple - Small	Simple - Large	Simple - Medium	Dual drum water tube type
Thermal fluid	Small quantities	Large quantities	Large quantities	1 m <sup>3</sup> /10,000 kcal
Natural circulation system	Unsuitable	Suitable	Suitable	Unsuitable
Burner	Short flame burner	Fore-fire burner	Short flame burner	Easily adjustable burner
Applications	for small capacity	for small capacity	for general purposes	for large capacity



## 9. Plastic



## 9 Plastics Molding (Extrusion Molding)

### 9.1. Plastics Molding Processing Technology

The processing technology of plastics molding materials consisting of polymers deal with technology related to preparation of molding materials, mixing, polymer modification, as well as modification operation such as surface treatment of molding material components, melting, forming, processing operation based on physical and chemical changes (blowing, stretching, crosslinking, setting, etc.), operations for improving physical properties of the molded goods in the processing stage, and secondary processing operations for deformation and surface treatment of the molded products.

The molding and processing technology of plastics first began with the thermosetting resins. At that time, the setting was done by heat, and simultaneously, a processing technology which matches the characteristics of the thermosetting resins which became a three-dimensional structure was advanced. In other words, processes such as compression molding, laminated molding, and casting were advanced. On the other hand, with the advent and propagation of thermoplastic resins, a processing method which takes advantage of the properties of becoming molten and flowable by heating has been developed one after another to this day. These processes are the extrusion molding, injection molding, stretching technology and blowing technology. A part of these processes are also applied to thermosetting technologies.

In Figure 9-1 the molding and processing methods used currently, and the objects of application are shown.



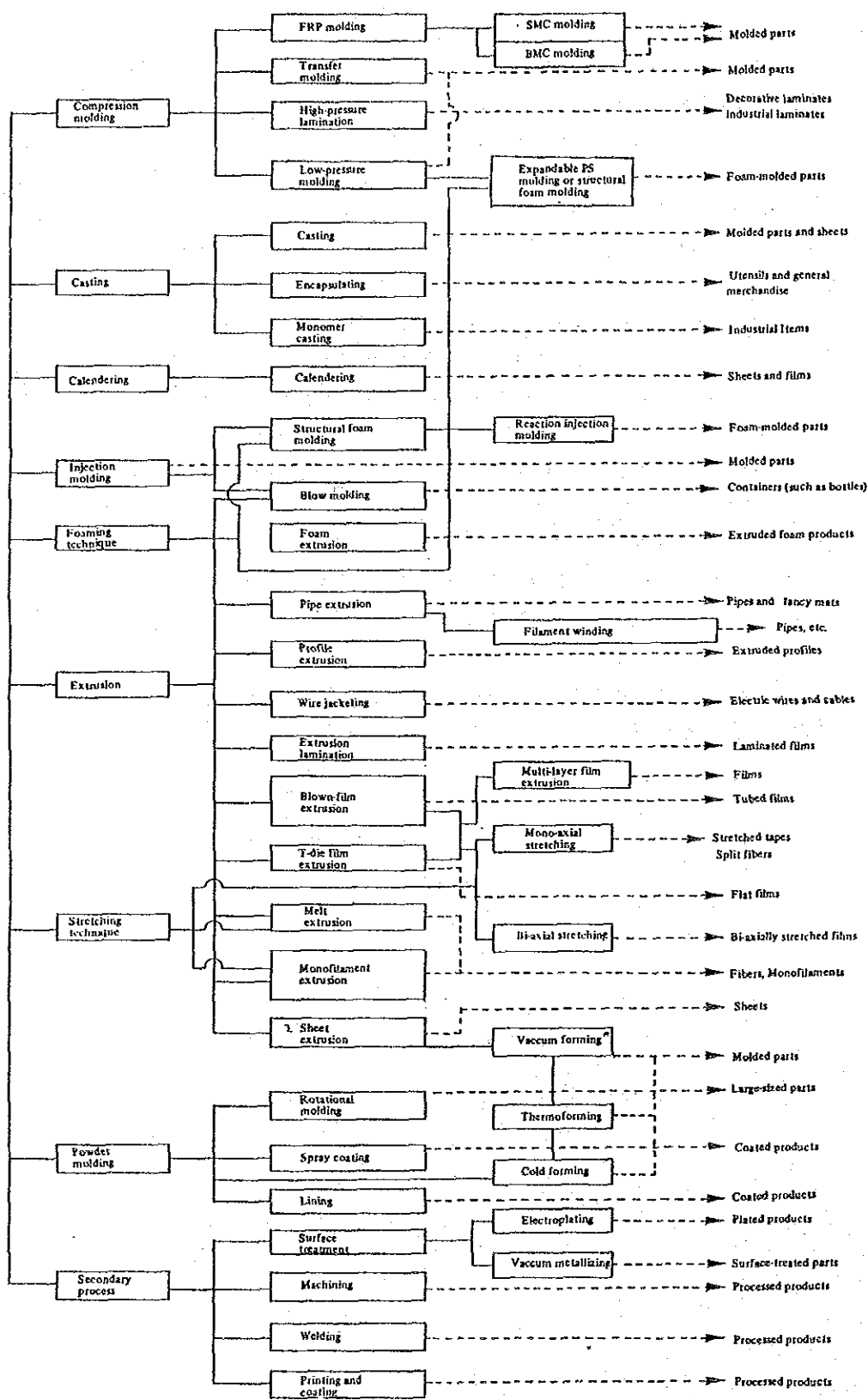


Figure 9-1 Plastics Processing Diagram

In the days when the thermosetting resins were the mainstay, the compression molding and casting were the main processing methods. However, with the advent of the thermoplastics, a conversion was made to more efficient injection molding and extrusion molding as the main processes.

The extrusion molding is a general term given to continuous processing of products using an extruder. Thus, there are the field of the melting and transferring using the extruder, and the application technology which perform the forming and the changes in physical properties. The development of the extrusion molding process was observed from the standpoint of changes and diversification in processing equipment, as illustrated in Figure 9-2. Furthermore, if we indicate the case of the injection molding development by the trend in injection molding machine, it will be as shown in Figure 9-3.

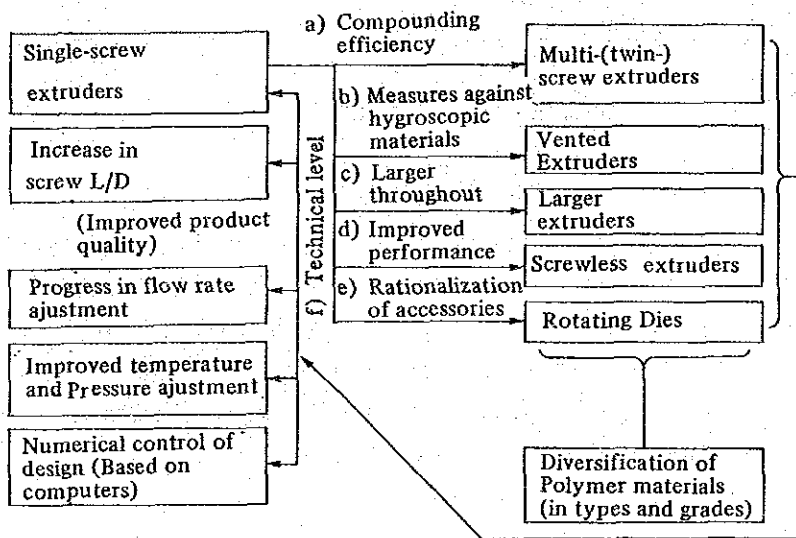


Figure 9-2 Progress in Extrusion Technology (or Extruders)

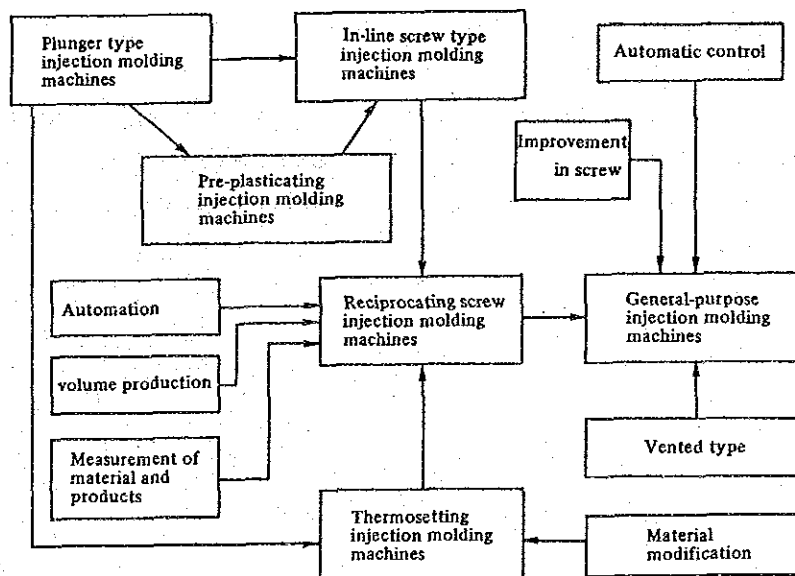


Figure 9-3 Progress of Injection Molding Machines

## 9.2 Extrusion Molding Equipment

Extrusion molding uses an extruder which has a built-in screw. It is a method in which the desired product is obtained by passing thermoplastic resins which have been softened by heating, through extrusion dies having various shapes, to form pipes, rods, profiles (irregular shaped), sheets, films, mono-filaments or products such as electric wires continuously, and cooling and hardening them in the sizer. As an example, a pipe and tube extruder molding line is shown in Figure 9-4.

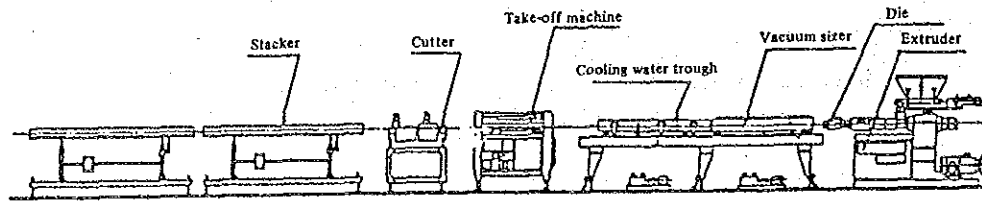


Figure 9-4 Pipe and Tube Extrusion System

Starting from this basic molding method, the blow extrusion technology for cushioning materials and synthetic wood, co-extrusion technology for multi-layer film sheets, composite technology for manufacturing hoses containing steel wires, or extrusion technology for non-continuous products such as flexible spiral tube and nets have been developed.

On the other hand, new technologies regarding continuous extrusion based on screw extruders such as the continuous extrusion molding of thermosetting resins such as phenols and epoxies as well as ceramics are being developed one after another.

In case of the extruders, there are the single axis screw type and the multi-axis screw type that uses two or more screws as well as the special raw material kneader. Among these extruders, the extruder having one screw called the single-screw type is mainly used, followed by the bi-axial screw type. The special kneader type extruder is mainly used for kneading, and there are various types depending on the application.

### (1) Single-screw extruder

The structure of the single screw extruder is very simple, and it is possible to extrude all kinds of plastics. In Figure 9-5, one of the examples is shown. It consists of the driving unit, cylinder, screw heating and cooling unit, temperature control equipment and pressure gauge.

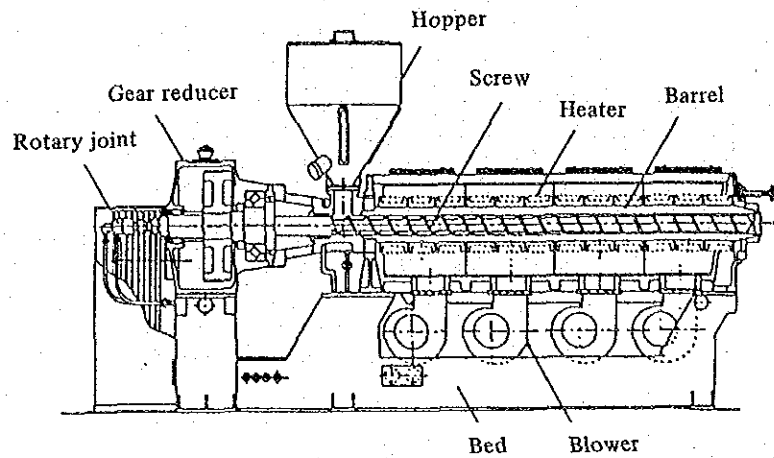
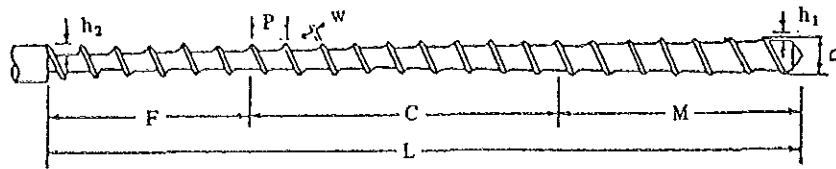


Figure 9-5 Single-Screw Extruder (Unvented)

In the case of single-screw extruder there is the vent type and the no-vent type. The extruder shown in Figure 9-5 is a no-vent type extruder, and the extruder which has a vent hole in the middle of the cylinder is the vent type extruder. In the case of the vent type, the air and volatile materials contained in the raw materials (pellet or powder) can be removed through this vent hole.

The model shown in Figure 9-6 is the fundamental structure of single-screw type extruder. It consists of the Feed Zone (F) which will be the portion for supplying the raw materials, the Compression Zone (C) where the resin is compressed and plasticization occurs, and the Metering Zone (M) where the completely molten raw materials are measured and extruded. Among these zones, the most important factors are the Compression Ratio (CR), the Effective Length (L/D) and the clearance between the screw crest and the cylinder walls.



$$P = D \cdot w = 1/10 \cdot P$$

Compression ratio  $CR = \frac{V_2}{V_1}$   $V_1$  : Volume of space provided by the flight depth at the end of the metering section,  $h_1$  and one screw pitch.  
 $V_2$  : Volume of space provided by the flight depth at the base of the screw,  $h_2$ , and one screw pitch.

(Note: In calculating the volume, take the round at flight base into account.)

$$\text{Screw length to screw diameter ratio} = \frac{L}{D}$$

L = Screw length  
D = Screw outside diameter  
F = Length of feed section  
C = Length of compression section  
M = Length of metering section  
P = Screw pitch  
w = Flight width  
 $h_1$  = Flight depth at the end of screw  
 $h_2$  = Flight depth at the base of screw  
As a simple method, compression ratio can be expressed frequently in the ratio of the flight depth — that is,  $CR = h_2/h_1$ .

Note: The allowance between the top of the screw flight and inside of the barrel is to be between 0.07 and 0.09 mm.

Figure 9-6 Basic Design of Mono-Axial Screw

In the case of single-screw extruder, generally speaking, the shearing strength is large, but the dispersion and mixing action is small, the resin will be heated by friction, and the resin temperature distribution is liable to become non-uniform. Consequently, in the case of rapid molding or in the case of different conditions, unless the most suitable screws are used, it is difficult to obtain molded goods having high precision. Thus, various improvements have been made on the screws.

## (2) Multi-screw extruder

Extruders which use two or more screws are called multi-axis extruders, but the majority of them are twin screws. As for the screws, there are the deep groove type, the shallow groove type, the intermeshing type and the non-intermeshing type. Furthermore, as for the direction of rotation, there are the co-rotating type and the counter rotating type.

The twin screw extruders excel in the kneading performance and the extrusion performance, but in most cases, the performance is determined by the limits of the mechanical strength of the driving system and the screw axis. As a result, conical twin screw extruders which have large driving part, and which have less restrictions on the thrust bearings and size of gears have also been developed.

## 9.3 Extrusion Molding and Energy Saving

### (1) Energy required for the extrusion molding

In the case of the extruders used for the extrusion molding, both the action to plasticize the resins and the action to feed the resins are required.

By plasticization of resin, we mean the process of change in condition in which the solid resin is heated and becomes molten body. Feeding means the process the sup-

plied resin being pressed from the material charging hopper of the extruder to the discharge orifice and conveyed.

Besides the above, it is necessary for the resins to be mixed or kneaded in the solid state, during the plasticization process, or in the molten state.

The energy required for the extrusion is as follows:

- (1) Heat energy equivalent to the enthalpy increment for melting the resin supplied to the hopper, and raising its temperature to the required level.
- (2) Mechanical energy required in the process of plasticizing the resin, and mechanical energy to add shear strength to the plasticized resin in order to knead it.
- (3) Mechanical energy required to raise the resin pressure from 1 atmospheric pressure to the required level, and mechanical energy required for pump action of extruding the resin out.

Among these energies, the energy of (1) where the resin is heated and the temperature is raised from the room temperature to the required temperature is done partially by heat conduction from the heater installed to the cylinders, however, the contribution of self-heating caused by the shearing strength added to the plasticizing process of (2) cannot be neglected.

The necessary mechanical energy of (3) where the pressure of the resin is raised from 1 atmospheric pressure to the pressure required for extruding the resin by pump action, is comparatively small when we calculate it.

Actually, a major part of the screw driving power is utilized for actions other than the pump action. In other words, it is mainly used as mechanical energy for plasticizing the resin and adding shearing strength to the plasticized resin for kneading. The mechanical energy used for the purpose of item (2) will be converted into heat as friction heat. Furthermore, as for the energy for pump action, at the time of flow in the die, the viscous friction is converted into heat.

As function of the extruder, the elements of (1) (2) and (3) are necessary, but as energy input two energy sources, namely, (4) cylinder heater, and (5) drive motor are also contributing to the energy.

From the standpoint of energy conservation, it is necessary to pay attention to these two points.

- 1) Improvement of power utilization rate of motor drive
  - 2) Decrease in mechanical loss from the power transfer system such as speed reduction gear and bearings.
  - 3) Decrease the shear amount that the resin receives in the extruder to a tolerable level, and prevent unnecessary self-heating.
  - 4) In temperature adjustment, prevent the repetition of heating and cooling, and keep the number of such adjustments to a minimum.
  - 5) Prevent radiation of heat.
- (2) Screw drive

Although there is considerable difference in the motor horsepower by the types of resin used and the shape of the screw, in general, for every 1 kg/h of extrusion, metha-

crylate resin 0.66 HP, low density polyethylene 0.44 HP, soft polyvinyl chloride 0.33 HP, heat resistant polystyrene 0.22 – 0.30 HP may be used, as a standard. The important point for a drive unit is speed stability under non-stage variable speed range and high load. The adjustment of speed is made by the following:

- (1) Mechanical gear box
- (2) Electrical non-stage variable speed motor (DC or AC)

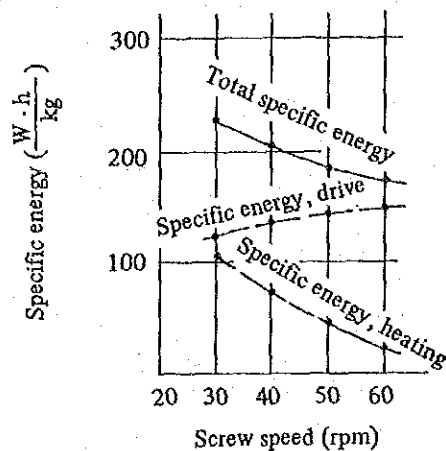
Recently, speed adjustment by (1) mechanical gear box has almost disappeared. For extrusion, variable speed motors are used. Those which are used broadly are motors with eddy current couplings, DC motors, variable frequency inverter motors, etc. Among these motors, the ones which have good power utilization efficiency are the latter two. The motor with eddy current couplings has large loss at the coupling portion in case of low speed region and is not recommendable from the standpoint of energy conservation.

DC motors can control the speed accurately, and they have high efficiency even at low speed, and the operation is simple. In the case of ordinary extrusion operation, they will be used in most cases at about half of the motor ratings. Thus, although they are rather expensive, DC motors having good efficiency at low speed are desirable from the standpoint of energy saving, and in general, they have been widely used, in recent years.

Although the AC motors will be influenced directly by the voltage variation inside of the plant, the DC motors will use the voltage after stabilizing it by the action of the constant voltage unit of the control board, so it has the effect of improving the dimensional precision of the extruded product.

- (3) Heating and cooling of cylinder barrel

The materials fed to the extruder will receive heat in the barrel and become molten, then extruded from the die as a product. Extruders of the early stages were used to add heat to the raw materials at the cylinder heated by heaters. However, as the performance of the extruders improved, internal heat generation caused by friction heat of the materials became large. In particular, in case of hard polyvinyl chloride resins and ABS resins, it becomes close to adiabatic extrusion operation where the melting is done by internal heat generation only. Consequently, it became necessary to develop a heating-cooling system in which the extruder can be heated from the outside as well as cooled at the same time. The heater is used to raise the temperature to the processing temperature at the beginning, and heat the material in the feed zone during operation. The heat for melting the material in the barrel is now being designed so that it will be given by the mechanical work of the screw. This current state is shown in Figure 9-7. In case the rpm is low, the rise in temperature of the material is mainly done by heaters. However, as the rpm increases, it is obvious that internal heat generated by the screw rotation is the main cause.



Extruder : Screw diameter = 90 mm  
 L/D = 20  
 Material used : Low-density polyethylene

Figure 9-7 Energy Balance of Extruder

The heating-cooling system of the extruder plays an important role in heating up the cold extruder to the desired operational temperature within a certain period of time, and maintaining the uniformity of temperature, pressure, and extrusion amount for the extrusion product through the maintenance of the desired operational temperature of the barrel and screw during the extrusion operation in minimum fluctuation. Unsuitable design or adjustment of the heating-cooling system will cause periodical temperature changes in the barrel or screw, and this will have bad influence on the uniformity of the extruded product. For the temperature adjustment of the cylinder barrel, the oil heating method and the electrical heating method (resistance heating and induction heating) are used. Among these methods, the resistance heating method is most broadly adopted.

In the resistance heating system, either a band heater or sheath wire aluminum cast-in heater is used. In case the operating temperature exceeds 350°C, the sheath wire brass cast-in heater or iron cast-in heater is used. Although the band heaters and the aluminum cast-in heaters are designed with a watt density of 2 ~ 5 W/cm<sup>2</sup>, in the case of brass or iron cast-in heaters, it can be 7 ~ 8 W/cm<sup>2</sup>.

In order to suppress the heating based on the friction heat of resin inside of the screw, and to control the cylinder temperature at the optimum temperature, the forced cooling of the cylinder is performed. As for the forced cooling system, there are the air cooling based on the blowers installed in each control zone, and the liquid cooling method in which water or oil is flowed through the stainless steel pipe cast-in together with the cast-in heater, or through the pipes wound to the grooved perimeter of the cylinder.

#### (4) Temperature control system

The control of heating and cooling is done by making inputs to the Temperature Indication Controller (TIC) regarding the outputs from the thermocouples inserted into the inner walls of the central cylinder of each control zone or the outputs from the resistance thermometer.



As for the initial heating and cooling control, the heating control was mainly done, and the cooling control was done additionally. The majority was controlled by the ON-OFF control.

When the heaters are heated, if the sensor installed to the cylinder senses that the fixed temperature is reached, the flow of electricity will be discontinued and the timer will actuate. Subsequently, when the timer time is up, the fan will begin to operate, and cooling will begin, in general. If cooling advances by the above mentioned method, electricity will be put on the heaters again, and heating and cooling will be repeated.

In case heating and cooling are repeated by the above mentioned method, the deviation correction operation will be done slightly more than the optimum value for both the heating and cooling, and since the compensation operation for the excessive amount will be made, the heating and cooling will be done alternately at a high frequency.

Since the temperature is liable to become non-uniform by this control method, it has disappeared almost completely, and P Control System (Proportional Control System) has become general.

Furthermore, recently, the PID operation (Proportional integrational differential control system) which excels from a functional standpoint has begun to prevail. From the viewpoint of improved control accuracy and less energy loss, the cooling control is being studied at the same level as the heating control.

As temperature control systems, hitherto, P Control Type was broadly used, but recently, a system called the dual PID which adopts PID for both heating process (input electricity through the heater) and cooling process (input electricity through the fans) are now being employed.

The outstanding feature of this H/C dual control system is that at the fixed point it will possess a function in which no heating or cooling is done (dead band function) and a function in which heating and cooling can be done simultaneously (i.e. overlap function).

In the dual PID system, since the temperature deviation or offset can be kept extremely small whether it is heating process or cooling process, a fixed point for heating (i.e. the upper limit fixed point) and a fixed point for cooling (the lower limit fixed point) are set separately, and a narrow dead band is made between the two. If operation is done at a temperature within this zone, the time in which no heating or cooling is done will increase, and the effect of energy conservation will be significant. The output operation chart of this unit is shown in Figure 9-8.

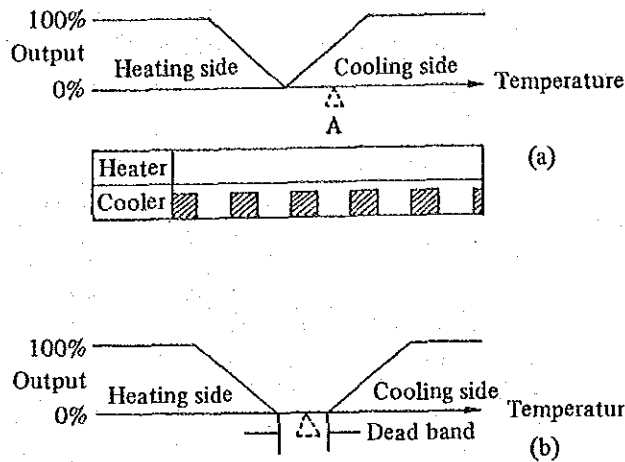


Figure 9-8 Diagram of Temperature Controller Output

In (a) of the same figure, at Point A, that is, if the cylinder temperature becomes on the cooling side, since only cooling control will suffice, the electric power for the heater will not be required. On the other hand, as shown in (b) of the same figure, by the dead band function, if it stabilizes at Point B, the electric power for both heating and cooling will become unnecessary. In Figure 9-9, the difference in temperature control accuracy based on the difference of the control system is shown.

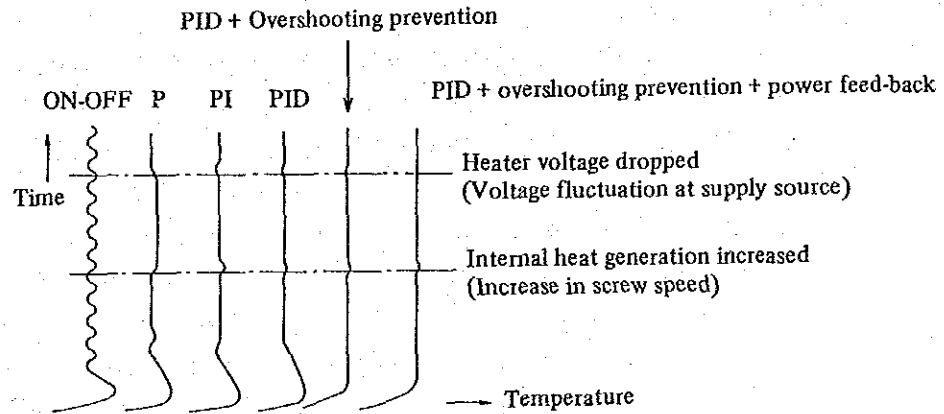


Figure 9-9 Comparison of Various Controlling Methods in Accuracy of Control

In Table 9-1, the comparison results of power consumption between the conventional proportional control system and the PID control system are shown.

**Table 9-1 Comparison of Electric Consumption between Proportional Control and PID Control**

Zone	Conventional Method (Proportional control)		Energy conscious method (PID control, with dead band)	
	Hours of heater energized and electric consumption	Hours of blower in action and electric consumption	Hours of heater energized and electric consumption	Hours of blower in action and electric consumption
C1	0.4h x10kW= 4kWh	0.6h x0.64kW=0.38kWh	0.22hx 10kW=2.2kWh	Not energized
C2	0.2h x10kW= 2kWh	0.8h x0.64kW=0.51kWh	Not energized	0.5h x0.64kW=0.32kWh
C3	0.26hx10kW=2.6kWh	0.74hx0.64kW=0.47kWh	Not energized	0.5h x0.64kW=0.32kWh
C4	0.29hx10kW=2.9kWh	0.71hx0.64kW=0.45kWh	0.04hx10kW=0.4kWh	0.01hx0.64kW=0.01kWh
Total	11.5kWh	1.81kWh	2.6kWh	0.65kWh
	13.31kWh		3.25kWh	
Comparison	100%		Equivalent to 24.4% (Saving by 75.6%)	

Note : Cylinder diameter 50mm  
 Heater 10kW x 4  
 Blower 0.64kW x 4

In the case of the conventional proportional control system, the power consumption of the heater was 11.5 kWh, the power consumption of the blower was 1.81 kWh, and the total power consumption was 13.31 kWh. Contrary to this, in the case of the PID control system, the power consumption for the heater was 2.6 kWh, the power consumption for the blower was 0.65 kWh, and the total power consumption was 3.25 kWh. In case the proportional control system is made 100, the PID control system will be 24.4, and it will be a saving of 75.6%.

Next, the specific energy (amount of electrical power for gaining unit extrusion amount) which is the total of power required for the driving as well as the heating and cooling at the time LDPE is extruded with an extruder having a screw diameter of 40 mmφ and L/D = 24. As it is clear by this table, in the case of DC motor and PID (Heating PID – Cooling PID), in comparison with the eddy current coupling motor and heating P control, it will be an energy saving of 26.96% in the high speed region, and an energy saving of 59.32% in the low speed region.

As theoretical critical energy a valve of 0.1595 kW-hr/kg was used. This valve was obtained dividing 3.898 kW by sum of heat quantity required to melt the resin 3.92 kW and energy required to discharge the resin by pump action 0.0691 kW by the discharge amount 25 kg/hr.

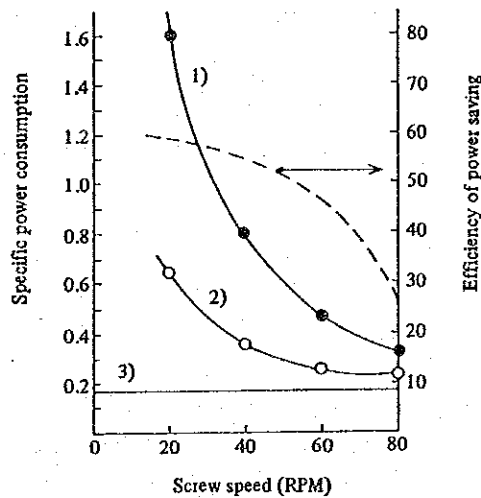
In order to make this table easier to see, it was illustrated as graphs which are shown in Figure 9-10. As it is evident from this Figure, just by replacing the drive motor and the temperature controller, an energy conservation of about 50% can be achieved.

**Table 9-2 Comparison of Total Electric Energy Consumption by Driving and Heating/Cooling**

Specific power consumption (kwh/kg)				
Screw speed (RPM)	20	40	60	80
DC motor + heater, PID controlled – cooler, PID controlled	0.644	0.357	0.248	0.233
Ideal critical specific power consumption/ Actual specific power consumption	(24.77%)	(44.68%)	(64.31%)	(68.45%)
Eddy current coupling motor + heater, P controlled	1.583	0.788	0.465	0.319
Ideal critical specific power consumption/ actual specific power consumption	(10.08%)	(20.24%)	(34.30%)	(50.00%)
Power saved by adopting: DC motor + heater, PID controlled – cooler, PID controlled	0.939	0.431	0.217	0.086
Power saved/eddy current motor + heater, p controlled	(59.32%)	(54.70%)	(46.67%)	(26.96%)

Note: The ideal critical specific power consumption was assumed to be 0.1595 kW-hr/kg. The saved power is equivalent to the difference in power consumption between eddy current coupling motor + P controlled heater combination and DC motor + PID controlled heater + PID controlled cooler combination.

- 1) Eddy current coupling motor + P controlled heater
- 2) DC motor + PID controlled heater – PID controlled cooler
- 3) Ideal critical specific power consumption



**Figure 9-10 Comparison of Total Electric Energy Required for Driving and Heating/Cooling**  
(Efficiency of power saving indicates: Saved Power consumption/Power required for eddy current motor + P controlled heater)

## 9.4. Extrusion Molding Materials and Pelletizing

### (1) PVC and compounding agents

Hitherto, for the hard irregular shaped extrusions, straight polymers of suspension polymerization having  $PI,000 \sim 1,300$  were used. For soft PVC, straight polymers of  $PI,300 \sim 1,500$  were used, and in case special rubber elasticity was required, straight polymers of  $P2,500 \sim 3,500$  were used.

As for PVC compounding agents, there are plasticizers, stabilizers, lubricants, fillers, and auxiliary reinforcing agents. By compounding these ingredients, various desired properties such as hardness, elasticity, abrasion resistance, chemical resistance, oil resistance, weather resistance, nonflammable properties and non-toxic features can be added to the polyvinyl chloride.

There are a large number of plasticizers that can be used for soft PVC, but among the ester phthalates, the typical one is DOP (di-2-ethyl hexyl phthalate).

As for the stabilizers and auxiliary stabilizers for PVC, there are lead soap, metallic soap, and organic tin.

Construction materials such as PVC window frames use various kinds of impact resistance improving agents in order to improve the impact resistance. Chlorinated polyethylene is one of the typical ones, and besides this, there are ethylene vinyl acetate (EVA) copolymers, PVC graftomers and acrylates. These materials must be uniform, well-dispersed, and sufficiently mixed and kneaded.

### (2) Blending and pelletizing of PVC

Compounding is the starting point of PVC processing. The good or bad of the compound will have direct influence on the extrusion processability.

Blending means to mix PVC, plasticizer, stabilizer, etc. in a blender. Compounding means to knead the blended materials on mixing rolls or in extruders and to make them into pellets.

Various methods can be taken from the compounding process to the pelletizing process or powder mixing process. These methods are illustrated in the flow sheet of Figure 9-11.

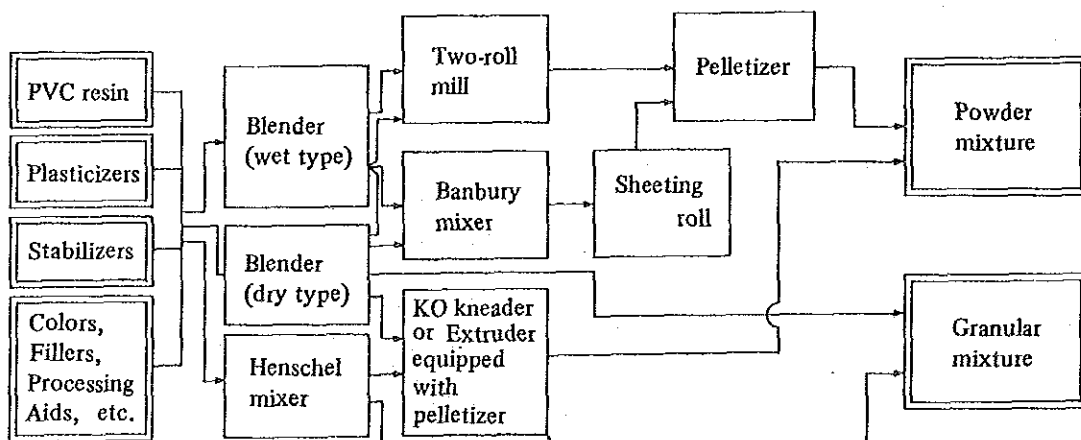


Figure 9-11 Compounding Process Flow Sheet

For the blending, generally speaking, Henschel Mixers are used.

The Henschel Mixer is slightly different from the ribbon blender, and by the high speed revolution of the blades, friction heat is generated. It makes the resins into semi-gels, and advances the compounding efficiently.

In Figure 9-12, the inside structure of the Henschel Mixer is shown.

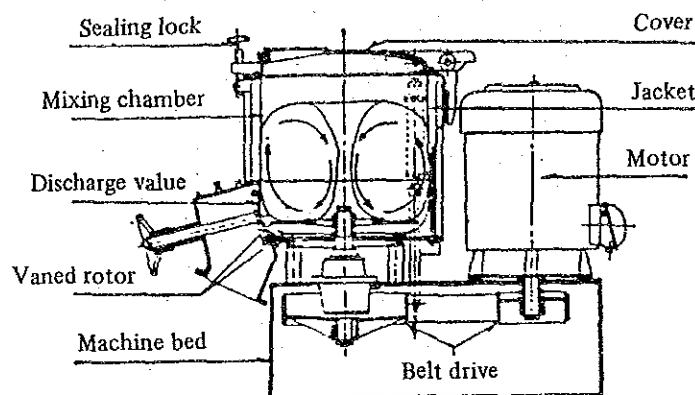


Figure 9-12 Construction of Henschel Mixer

This equipment consists of a container having heating unit and cooling unit, and agitator blades having special shapes for super high speed revolutions. By the revolution of high horsepower motor, the mixture inside will be driven in the direction of the arrow, mutually collide, and complete gellation within a short period of time by friction heat. In order to cool this, the content is introduced to the cooling mixer where it is cooled to almost ordinary temperature.

The cooled powder is made into pellets by using mixing rolls, Banbury mixers, or extruders. Generally speaking, the extruder system is mainly adopted.

As extruders, the general single screw and twin-screw extruders, ko-kneaders, etc. are widespread.

As cut systems which make pellets by using the above mentioned equipment, there are the cold cut method and the hot cut method.

Among these methods, the ones which are put to practical use the most, are the strand cut method and the hot cut in air method.

In Figure 9-13, an example of hot cut in air pelletizer is shown.

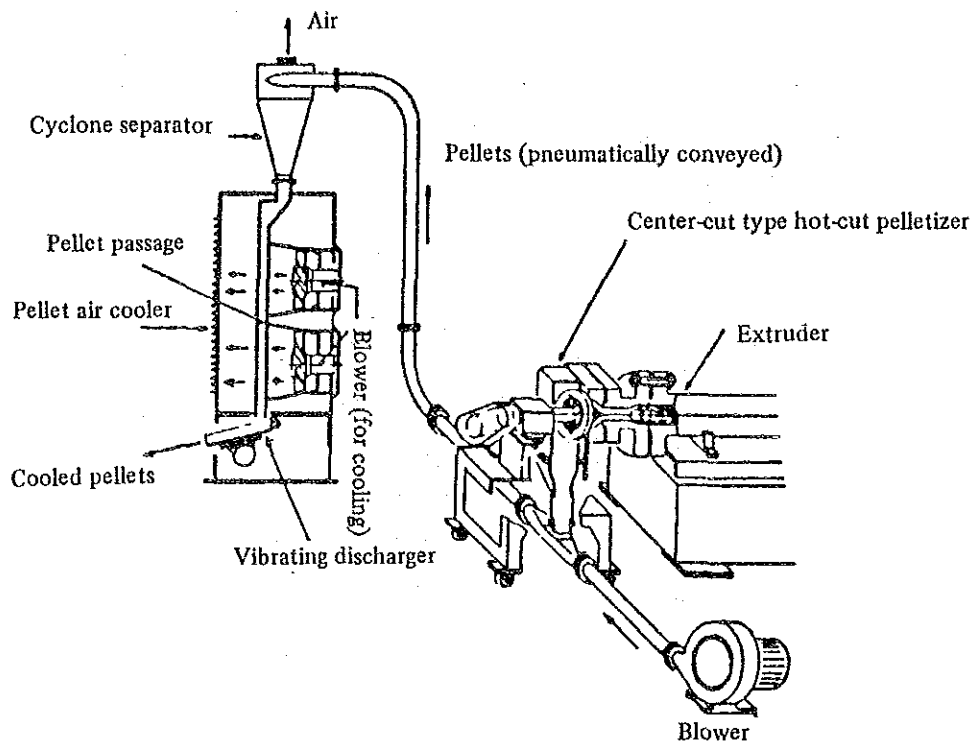


Figure 9-13 Hot-Cut Pelletizer (Cut-in-air Type)

#### 9.5 Automation Technology in Extrusion Molding

The automation of extrusion molding is lagging in comparison with the injection molding. The reason is that the molding method is very much diversified, and with the exception of a certain portion, small lot production of various grades is common. However, recently, as a worldwide trend, the automation of extrusion molding is making rapid progress.

##### (1) Multi-point measurement of pipe and hose thickness and dimensional control

The automation of extrusion molding begins from the dimensional measurements of the products. Measurement of simple objects such as thickness and width of general sheets and films, diameters of pipes, etc. has been done from olden times. However, continuous multi-point measurement of small diameter soft pipe is very difficult to conduct, and practical means had not been developed. In the case of recently developed supersonic measuring equipment, soft tube having a minimum outside diameter of 5mm $\phi$ , and a minimum thickness of 0.5mm, can be measured continuously at 8 different points on the perimeter at very high speed. This equipment makes the measurement in the cooling tank with supersonic waves, and it is made into a mechanism where feedback is made to the take-off machine or extruder so that each part of the tube will become the specification value within the preset minimum and maximum thickness. By combining it with the eccentricity automatic adjusting equipment, complete automation is possible. Since the measured values are recorded on the recorder, it will also be useful in quality control.

##### (2) Control of resin feed and product weight control equipment

Dimensional control of the products in extrusion molding is generally done by measuring the dimensions of the products, and feeding this information back to the

extruder or take-off machine. However, recently, a new method has been developed to control the dimensions by controlling the raw material feed and the extrusion amount so that they will be constant.

The raw material feeding unit consists of the storage hopper, measuring hopper, flap, level sensor, and alarm devices. In order to maintain the extrusion amount of the resin constant at all times, it is designed to make a feedback to the screw revolution.

In this equipment, by setting the extrusion amount of the resin, that is, by setting the weight per 1m (g/m) and the extrusion amount per 1 hour (kg/h), it is possible to conduct extrusion molding of the products of the specified dimensions at the specified capacity.

(3) Line control system of the pipe extrusion

Figure 9-14 shows the overall process control unit of the extrusion molding line, and the monitor indicates the conditions such as temperature, number of screw revolutions, feeder rpm, resin pressure of the insurrounding equipment, that are drawing equipment, winder, cutter, etc. at a glance, and automatic temperature rise, automatic starting and automatic stopping are possible.

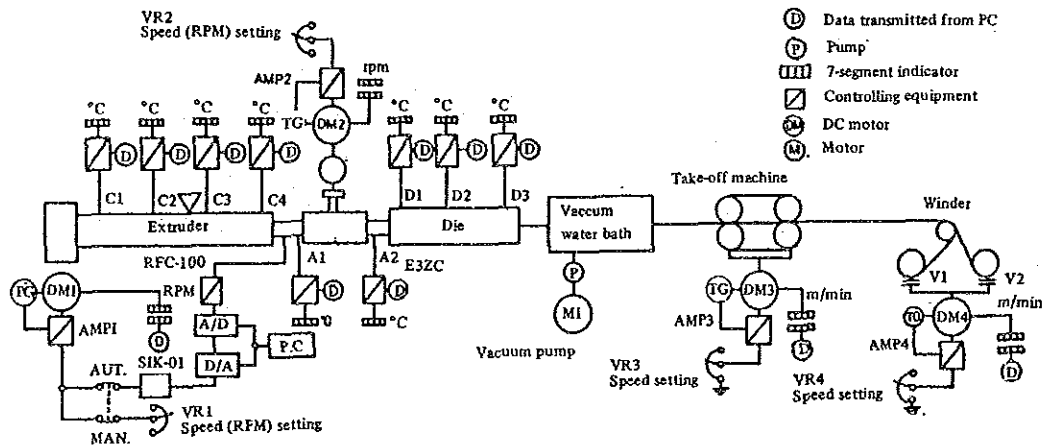


Figure 9-14 Automated Flexible Tube Production Line

As another example, there is also an unmanned pipe molding equipment in which the whole system is computer controlled by the integration of the following equipment with the automatically controlled extruder:

- (1) Supersonic thickness measuring equipment
- (2) Automatic pipe eccentricity control equipment
- (3) Automatic control system of material weighing, feeding, and extruding
- (4) Automatic vacuum control equipment of calibrator
- (5) Automatic controlling unit of resin pressure
- (6) Automatic control equipment of resin temperature, screw torque, etc.





## 10. Cast Steel



10. Cast Steel

10.1 Characteristics in the Use of Energy

10.1.1 Manufacturing Process and Major Equipment

Cast products are used in a wide range including daily necessities as well as the parts of machinery, equipment and vehicles. The materials used for casting are iron and steel, copper, aluminum, etc. The castings of iron system differ from each other in property depending upon carbon content, and are divided into cast steel for carbon content of 2% or less and cast iron for that of more than 2%.

In addition to ordinary cast steel, cast steel includes special cast steel containing alloy elements such as stainless steel with nickel or chromium added for improving corrosion resistance, high manganese steel with manganese added for improving abrasion resistance, etc. Cast iron differs from each other in property depending on the contents of carbon and silicon, and is used for each corresponding purpose according to the property. Also available is ductile cast iron having intensified strength by the addition of magnesium to spheroidize the contained graphite and decrease stress concentration, and malleable cast iron having intensified strength with semi-spherical graphite by heat treatment after casting.

The manufacturing process is illustrated in Figure 10-1.

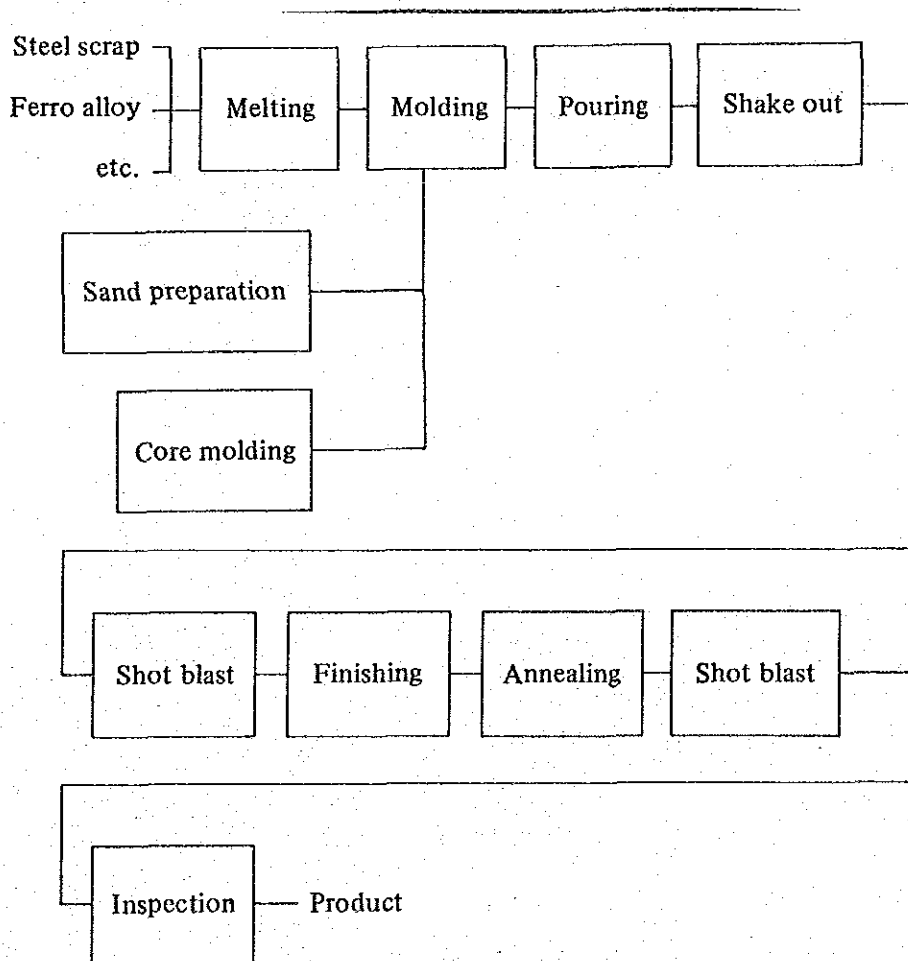


Figure 10-1 Manufacturing Process Chart for Cast Steel

The dissolution equipment currently used for the manufacture of cast steel are electric arc furnace and induction furnace. The classification of the dissolution furnaces is shown in Figure 10-2

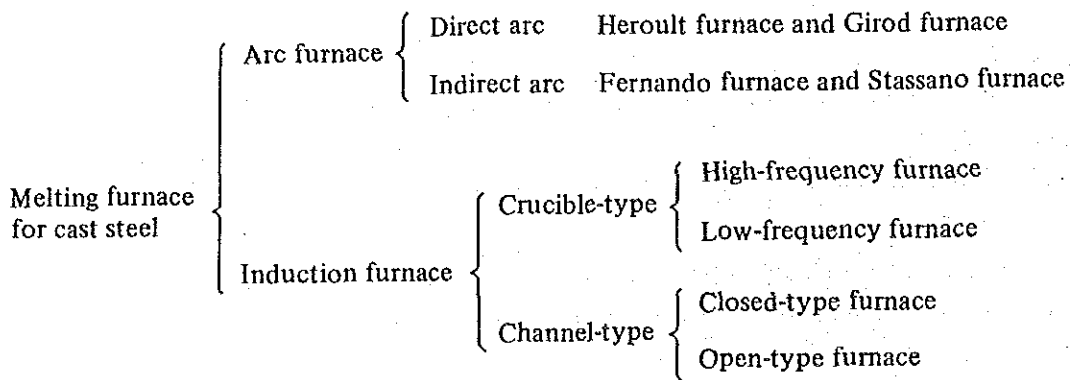


Figure 10-2 Melting Furnace for Cast Steel

(1) Electric arc furnace

Most popular electric arc furnace is Héroult electric arc furnace having the structure as shown in Figure 10-3, which melts iron scraps in the furnace with three-phase AC arc heat generated between three artificial graphite electrodes and charged iron scraps as well as the heat by resistance generated in the iron scraps.

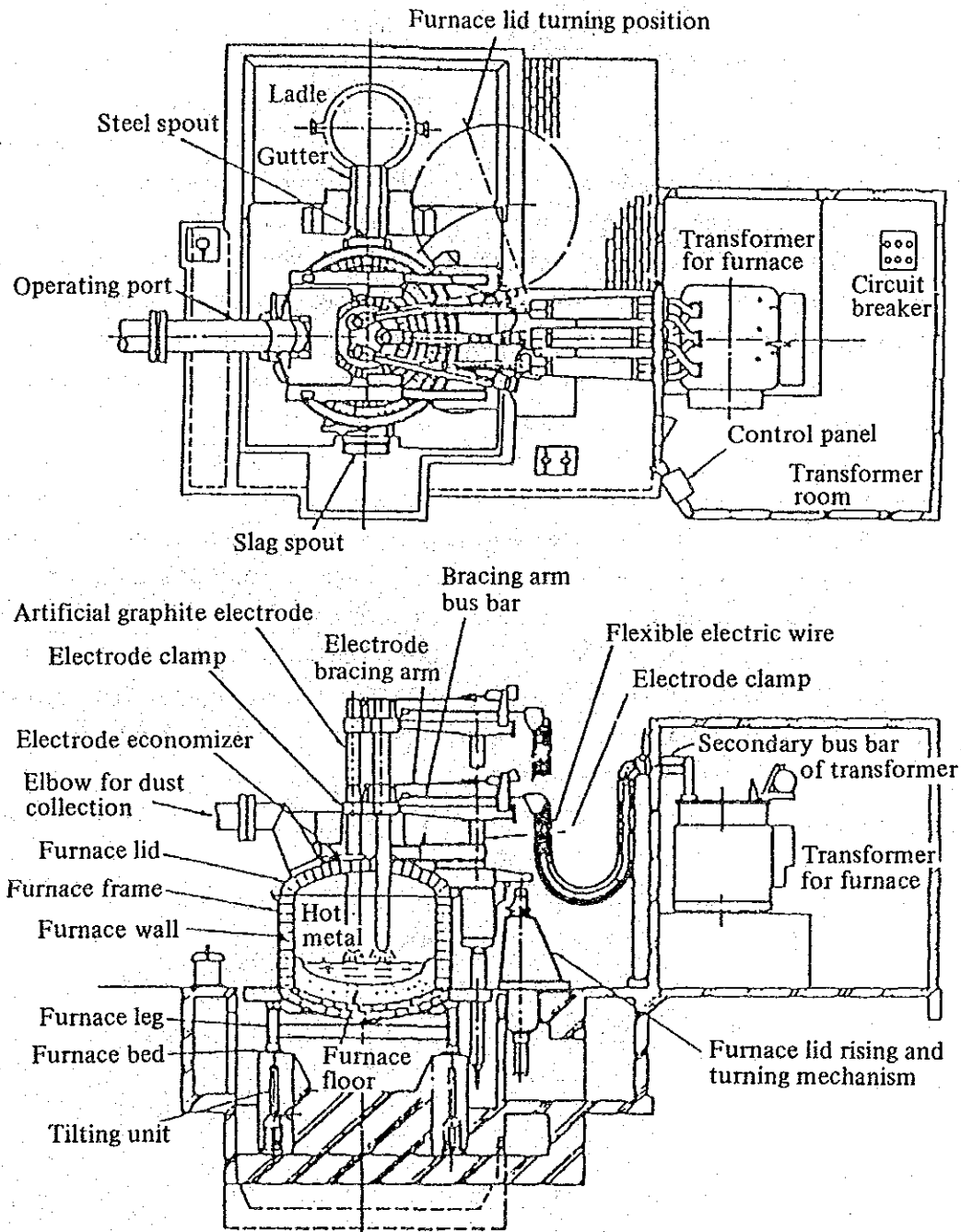


Figure 10-3 Body Structure of Arc Furnace for Steel Making

An electric arc furnace is featured by the followings:

- a. High temperature is attained, and charged power is easily controlled.
- b. Both oxidation refining and reduction refining are performed with ease.
- c. Restriction to the quality of iron raw materials is minimized.
- d. Both special and ordinary steel can be manufactured.

The furnace chamber consists of furnace walls and furnace floor, the steel shell of which is lined with refractory materials, and a furnace cover, the frame of which is brick-lined. Tilting tapping is possible with the furnace chamber.

In a basic furnace, refractory materials which constitute furnace walls are covered with magnesia brick, and furnace floor is stamped with magnesia clinker or dolomite clinker. On the contrary, in an acid furnace, silica brick is used. A basic furnace possesses the function of retaining arc heat and further, of steel production reaction by basic slag.

The electrodes are supported by the clamps that are attached to the support arms, and are automatically moved up and down by the electrode control device to keep a constant electric energy. Moreover, the electrodes are equipped with water cooling rings called "economizers" to prevent hot gas from spouting during operation from the clearance between the electrode and the furnace body and to prevent oxidative consumption of electrodes.

Since, the material is charged to the electric arc furnace usually at the top except a small furnace, the furnace cover and electrode equipment are arranged to enable movement.

The transformers are connected with large-capacity reactances to prevent impulse current flow through external transmission line even if a high current flows in the furnace.

In general, secondary bus bars are cooled with copper plates or water cooling steel pipes along with connecting cables to be cooled. The auxiliary equipment include a dust collector which removes dust in the gas generated or the air inside buildings using a bag filter or by electrostatic system, or a waste heat recovery unit which utilizes the sensible heat of generated gas for material preheating.

Table 10-1 indicates the general relation between furnace volume and transformer capacity.

Table 10-1 Relation between Furnace Capacity, Required Dimensions and Electric Equipment of Furnace

Nominal furnace capacity (10 <sup>3</sup> kg)	Outside diameter of furnace frame (m)	Depth of steel bath (mm)	Electrode diameter (mm)	Transformer capacity (MV · A)			Secondary voltage (RP furnace) (V)
				RP	HP	UHP	
2	2.178	300	175	1.5	—	—	180/80
5	2.743	400	200 ~ 250	3	5	—	200/100
10	3.353	400	300 ~ 350	5	7.5	—	220/100
20	3.962	450	350 ~ 400	7.5	12	15	240/100
30	4.572	650	400 ~ 450	12	18	22	270/120
50	5.182	750	450 ~ 500	18	25	30	330/130
60	5.486	850	500	20	27	35	400/130
70	5.791	850	500	22	30	40	400/130
80	6.096	900	500	25	35	45	430/130
100	6.400	950	500 ~ 550	27	40	50	460/160
120	6.706	1,000	550 ~ 600	30	45	60	500/200
150	7.010	1,000	600	30	50	70	500/200
170	7.315	1,050	600	35	60	80	500/200
200	7.620	1,100	600	40	70	100	560/200
400	9.754	1,200	700	—	—	150	—

Note: RP: Regular power HP: High power UHP: Ultra-high power

## (2) Induction furnace

Utilizing the principle of induction heating, an induction furnace melts special steel, cast iron, copper and other high-grade metals, alloys, etc., and is used also for retention, heating, deoxidation, component adjustment, etc. for molten steel, but different from electric arc furnace, has no function of refining with slag.

An induction furnace is featured by the followings:

- a. Because of direct exothermic material, the furnace is high in thermal efficiency and suitable for hot melting.
- b. Without the need of oxygen for heating, closed vacuum melting is possible.
- c. Automatically agitated molten steel by electromagnetic force facilitates adjustment of composition and temperature, and improves quality and yield.
- d. Exothermic reaction of the material alone minimizes hot portion and exhaust gas, and improves workshop environment.
- e. High and stable yield of alloying elements facilitates high-alloy steel melting.

An induction furnace is classified into the following three types according to the construction and frequency of power source:

High frequency furnace, crucible type 150 – 10,000 Hz

Low frequency furnace, crucible type 50, 60 Hz

Low frequency furnace, channel type 50, 60 Hz

Compared with a low frequency furnace, a high frequency furnace needs a frequency converter and hence, increases power-source loss, but is efficient in that starting block is unnecessary and power consumption at startup is minimized. Agitating power which is inversely proportional to the square root of frequency is mild, lessens furnace erosion, im-



proves the yields of alloying elements, and is effective in homogenizing composition, temperature, etc. and in desulfurizing reaction. Such energy conservation and easiness in handling are enhancing the adoption ratio of high frequency furnaces.

Table 10-2 exhibits the power-consumption comparison result between high and low frequency furnaces.

Table 10-2 Comparison Energy Saving-Type High-Frequency Furnace with Crucible-Type Low-Frequency Furnace

Equipment		Low-frequency furnace	High-frequency furnace	Remark
	Electric power (kW) – capacity ( t ) Frequency (Hz)	800--3 50	800--1 500	
Materials for melting Molten metal discharging temperature (°C) Operation		Ordinary cast iron 1,500 8 h/day, 22 days/month	same as left	
Initial Batch	Electric power consumption rate (kWh/t) Melting time (min) Number of batch	650 209 1	620 58 1	
Normal Operation	Electric power consumption rate (kWh/t) Melting time (min) Number of batch	580 73 min/1.5 t 3	565 45 8	
Holding	Holding electric power (kW) Holding time (min) Electric power consumption rate (kWh/t) Times	120 10 12.3 4	85 6 8.5 9	
Operating time (min) Total electric energy consumption (kWh)		468 (7.8 h) 4,640	472 (7.86 h) 5,216.5	
Production (t/day) Total melting capacity (t/h) Unit electric power consumption rate for total melting (kWh/t)		6.5* 0.84 714	9 1.14 579.6	
Installation space (X, Y, Z) (m) Total quantity of refractories used (kg) Tonnage of expected passage ( t ) Consumption (kg) of refractories per ton of molten metal		6 × 7.5 × 4h approx. 1,100 700 1.57	6 × 5.2 × 2.5h approx. 500 430 1.16	

\* Deduct 1/2 of residual molten metal quantity and 1 ton for Starting Block for low-frequency furnace.

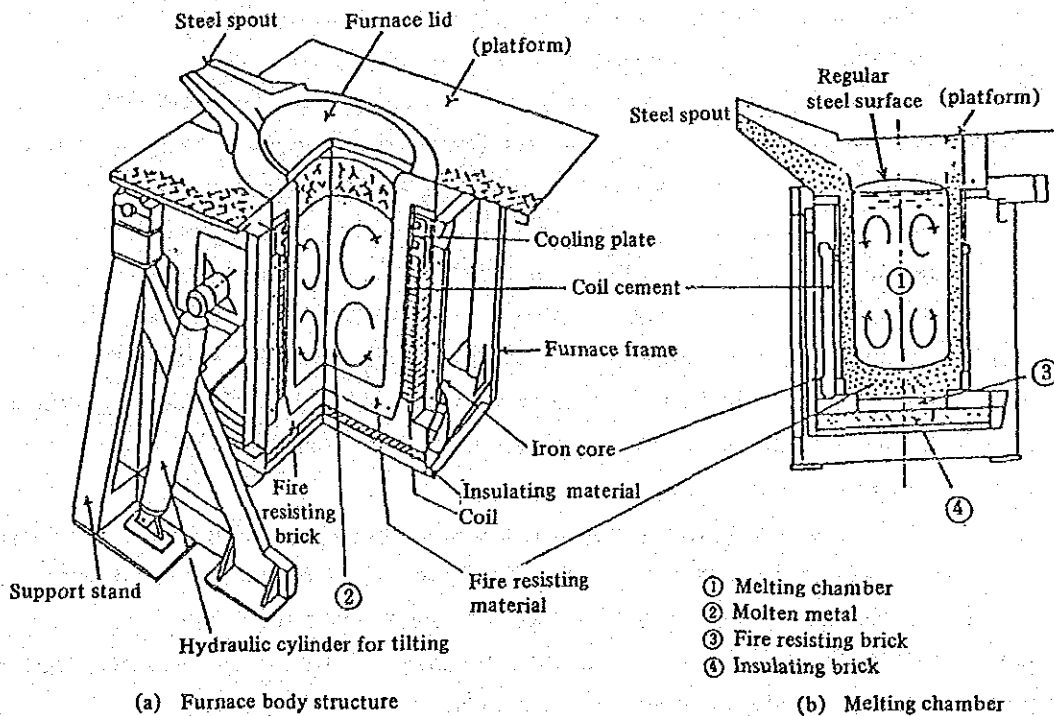
The secondary current generated in material is concentrated in the surface layer of the material with increase in frequency. Hence, the higher the furnace volume is, the lower the adopted frequency becomes. Table 10-3 shows a general relationship between furnace volume and frequency, input, melting hour and power consumption.

**Table 10-3 Example of the Capacity and Performance of Recent Thyristor Inverter Type High-Frequency Furnace**

Electric power (kw)	Frequency (Hz)	Furnace capacity (kg)	Cast iron melting		Steel melting	
			Melting time (min)	Power consumption rate (kwh/t)	Melting time (min)	Power consumption rate (kwh/t)
200	3,000	50	10	620	11	670
300	3,000	100	12	600	13	645
600	1,000	300	16	545	18	585
800	1,000	500	20	540	22	580
1,200	1,000	1,000	28	535	30	570
1,600	1,000	1,500	31	530	33	565
1,800	500	2,000	37	530	39	565
2,400	500	3,000	41	525	44	560

A channel type furnace which uses iron cores of closed circuit is high in power factor and efficiency and easy in heat insulation, but necessitates continuous retention of molten steel in the channel even during shutdown. Because of low electricity density, the channel type is suitable for temperature raising and retention rather than melting.

Figure 10-4 illustrates the structure of crucible type furnace.



**Figure 10-4 Cross Section of Crucible Induction Furnace (Example)**

When a conductor (metal blank) is placed inside a coil around with copper tubes and the coil is subjected to AC flow, then alternating field is generated inside the coil, eddy current flows in the metal by electromagnetic induction, and the metal is heated to melting by Joule heat.

As the direction of eddy current is opposite to that of coil current, repulsion force is generated between molten steel and the coil, resulting in molten steel agitation.

Figure 10-5 depicts the structure of a channel-type furnace.

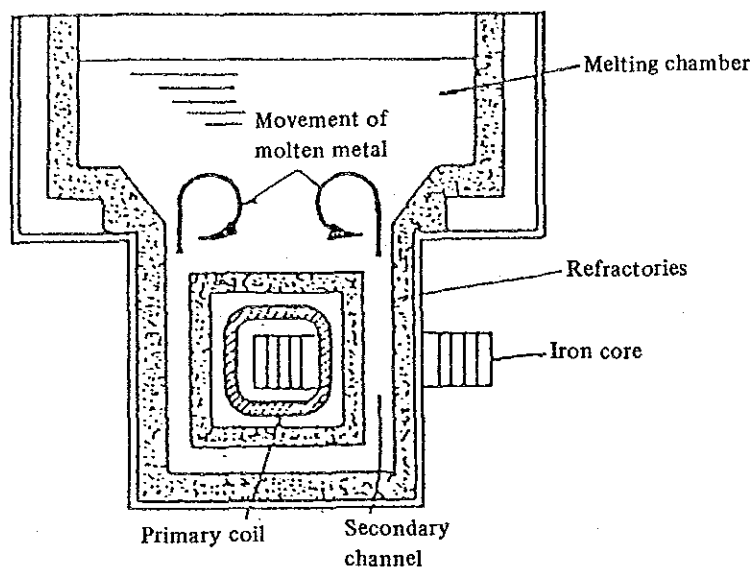


Figure 10-5 Cross-Section Chart for Channel-Type Furnace

The furnace consists of a melting chamber which retains molten steel and a secondary channel (exothermic chamber) which supplies molten steel with heat energy, the latter being composed of refractory, iron cores of closed circuit, primary coil, etc.

The coils and iron cores are forcedly cooled by water cooling or air cooling to prevent thermal damage due to heat conduction from furnace material, heat release of itself, etc.

Formerly, the combination of electric motors and generators was used for converting the frequency of commercial power source to the required frequency, but nowadays, thyristors are used in most cases. In this means, the commercial current is one converted to DC by use of a thyristor inverter, then converted to the required frequency, and charged to the furnace via a high-frequency matching transformer and a power-factor improving condenser. This system is characterized by the wide range of matching the variation in load impedance as well as the function of always supplying maximum electric energy by virtue of arbitrarily variable frequency.

The induction resistance of coil increases with increase in frequency. To compensate the phase lag of current caused by the above resistance, a lot of condensers are connected.

In the case of a large-capacity furnace with high electricity density, the iron cores are placed outside the coils as the return route for magnetic flux to prevent steel frame heat-int, mitigate coil vibration and reinforce the coils.

- (3) Heat treating furnace  
Refer to "Metal processing section".

### 10.1.2 Present Status of the Use of Energy

The transition of basic unit of electricity on the electric arc furnaces in Japan and basic unit of electricity by furnace volume are shown in Figure 10-6 and Table 10-4, respectively.

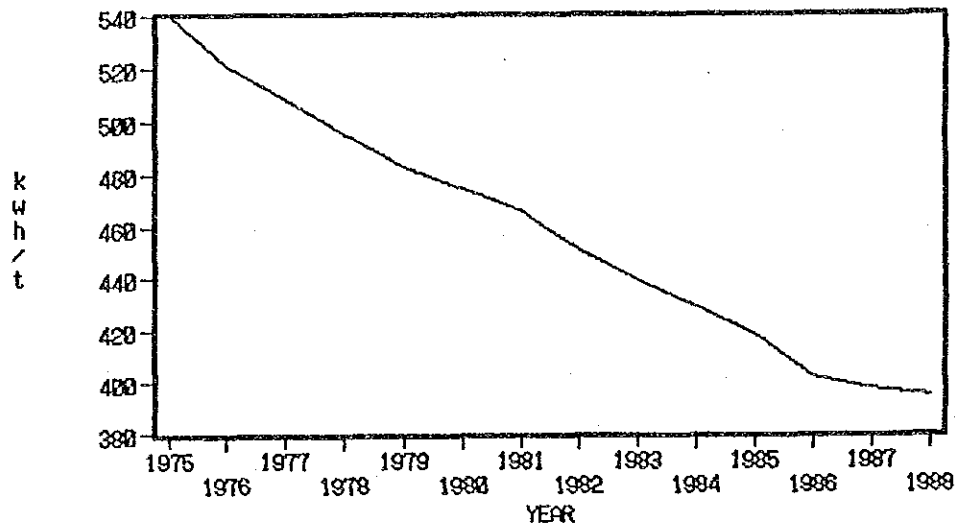


Figure 10-6 Electric Power Consumption Rate of Japanese Arc Furnace

Table 10-4 Average Electric Power Consumption Rate for Mild Steel

Furnace capacity	10 t	15 t	30 t	60 t	80 t
Electric power consumption rate kWh/ton of good-quality ingot	550	520	480	440	410

The regression equation for the result of basic unit of electricity (in 1977) concerning basic arc furnace in Japanese cast and forged steel industry is as follows:

$$\text{Basic unit of electricity} = \frac{399}{0.88 \times C + 2.44} + 574 \text{ kWh/t-charge}$$

where C: Furnace volume

An example of heat balance for an electric arc furnace is exhibited in Table 10-5.

The standard basic unit of electricity for melting with a high-frequency induction furnace is shown in Table 10-3.

Table 10-5 Heat Balance of Arc Furnace

Item		Kind of steel				Furnace capacity				Total	
		Mild steel (N = 7)		Special steel (N = 11)		30~50 t furnace (N = 7)		50t or more furnace (N = 11)			
		10 <sup>3</sup> kcal/ steel dis- charge t	%	10 <sup>3</sup> kcal/ steel dis- charge t	%	10 <sup>3</sup> kcal/ steel dis- charge t	%	10 <sup>3</sup> kcal/ steel dis- charge t	%	10 <sup>3</sup> kcal/ steel dis- charge t	%
Heat input	Heat quantity of electric power	373.0	59.1	438.3	61.5	437.6	62.2	398.2	59.8	412.9	60.6
	Calorific value of fuel	24.9	3.9	16.7	2.3	6.7	1.0	29.4	4.4	20.7	3.0
	Oxidation heat of electrode	25.7	4.1	34.3	4.8	35.9	5.1	28.9	4.3	32.1	4.7
	Oxidation heat of charged raw materials	192.4	30.5	208.4	29.2	204.5	29.0	199.5	30.0	201.5	29.6
	Heat of slag formation	11.2	1.8	12.6	1.8	15.0	2.1	10.2	1.5	12.1	1.8
	Others	3.6	0.6	2.7	0.4	4.4	0.6	-	-	1.7	0.3
	Total heat input	630.8	100	713.0	100	704.1	100	666.2	100	681.0	100
Heat output	Potential heat of molten steel	339.6	53.8	347.5	48.7	342.9	48.7	344.7	51.8	344.0	50.5
	Potential heat of slag	46.5	7.4	55.0	7.7	63.4	9.0	44.2	6.6	51.7	7.6
	Heat loss on transformer and secondary conductor	28.1	4.4	37.9	5.3	46.4	6.6	26.7	4.0	34.5	5.1
	Sensible heat of exhaust gas	111.0	17.6	115.9	16.3	115.1	16.3	112.2	16.8	112.4	16.5
	Heat carried out by cooling water	30.3	4.9	72.3	10.1	49.7	7.1	59.9	9.0	56.1	8.2
	Others (heat release from furnace body, radiant heat at time of additional charging, etc.)	75.3	11.9	84.4	11.8	86.6	12.3	78.5	11.8	82.3	12.1
	Total heat output	630.8	100	713.0	100	704.1	100	666.2	100	681.0	100

## 10.2 Rationalizing the Use of Energy

The fundamentals of energy conservation in steel production with electric furnace is to reduce ineffective heat output and formulate effective use of exhaust heat by improving thermal efficiency of a furnace, productivity and product yield.

### 10.2.1 Electric Arc Furnace

Table 10-6 lists the energy conservation items for an electric arc furnace. A few examples are described below:

**Table 10-6 Items on Energy Conservation for Arc Furnace**

Decrease of heat input	Substitution of heat input	Auxiliary combustion of oil Oxygen injection Preheating scrap by fuel
	Utilization of waste heat	Preheating scrap by exhaust gas Utilization of hot return scrap
	Lowering molten steel temperature	Increasing of ladle brick temperature Prevention of heat release by ladle lid
Reduction of heat loss	Improvement of facilities	Increasing of furnace capacity Adoption of high power system Improvement of automatic electrode controller Reduction of resistance of secondary conductor and electrode Reduction of openings on furnace body Insulation
	Improvement of operation	Removing impurities of charging scrap Quick charging of scrap and other raw material Optimum input of power Speeding up of analysis for molten steel Shortening time for maintenance Prevention of electrode breakage Elimination of waiting time for crane etc. Effective operation of dust collector
Improvement of product yield		Selection of good quality raw material Reduction of miscasting Decrease of residual molten metal
Utilization of waste heat		For scrap preheating Utilization of hot water for living, air conditioning, boiler feed water etc.

#### (1) Improving oil combustion

In order to promote scrap melting inside a large-capacity arc furnace, swing type burners are installed to burn oil at the furnace wall of the cold spot most distant from the arc by making holes in the wall.

Figure 10-7 and Figure 10-8 show the condition of burner installation and the relation between fuel consumption. Considering heat loss in power generation, the conversion of heat source from electric energy to fuel leads to energy conservation.

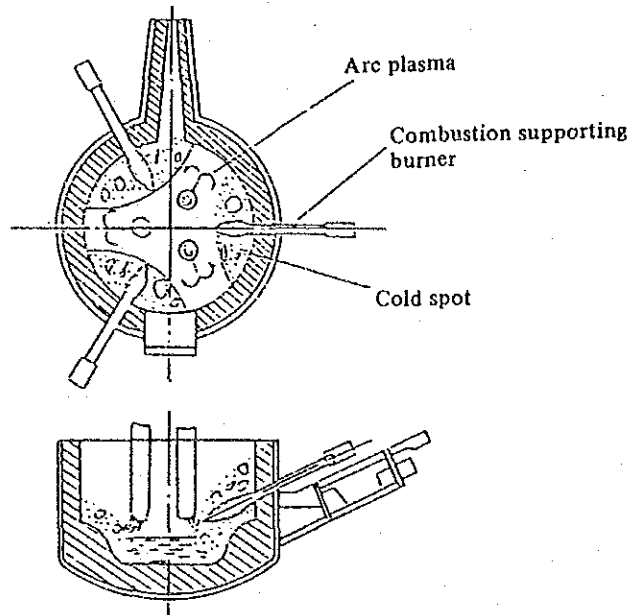


Figure 10-7 Example of Installation of Combustion Supporting Burner

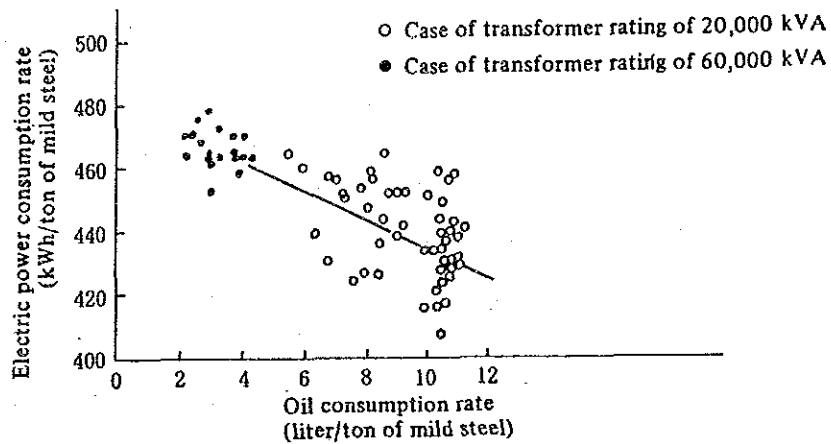


Figure 10-8 Oil Consumption Rate and Electric Power Consumption Rate Showing the Effect of Combustion Supporting (per ton of mild steel)

(2) Oxygen blowing

Oxygen is blown in during the initial stage of melting, scraps are cut to promote melting and blown to steelbath after melting out, and shortening of melting time is planned by use of oxidation heat of carbon, silicon, etc. Because of constantly high heat loss in electric arc furnace, shortening of melting hour leads to energy conservation.

Figure 10-9 indicates the relation between basic units of oxygen and electricity.

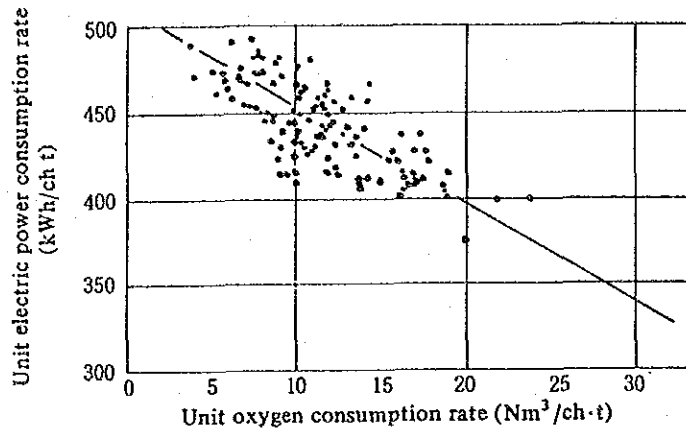


Figure 10-9 Relationship between Unit Oxygen Consumption Rate and Unit Electric Power Consumption Rate in Oxygen Enriching Operation

(3) Scrap preheating

Preheating of scraps before charging to an electric arc furnace can be made by fuel combustion and the use of exhaust gas of the arc furnace.

Figure 10-10 shows an example of scrap preheater that preheats scrap in charging bucket using the furnace exhaust gas.

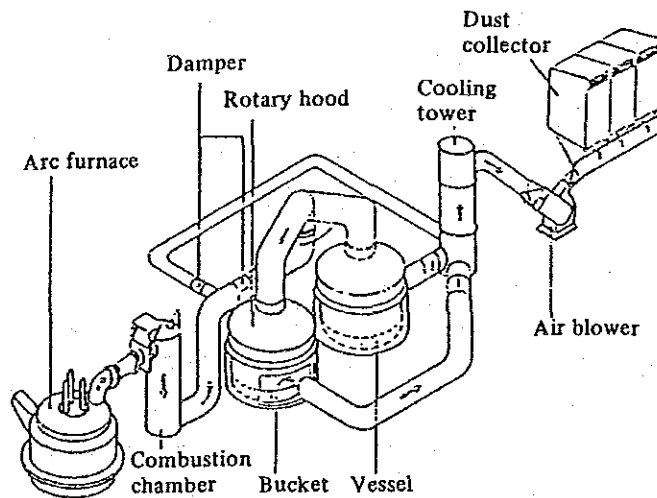


Figure 10-10 Scrap Preheater Using Arc Furnace Exhaust Gas for Heating Scrap in Charging Bucket

The scrap filled in the charged bucket is placed between the exhaust gas combustion chamber of the dust collector and the cooling tower. The exhaust gas is drawn by the blower for the dust collector and charged into the air through the dust collector after the scrap in the vessel is heated.

An example of the energy saving in scrap preheating by the arc furnace exhaust gas is shown in Table 10-7



Table 10-7 . Example of Energy Saving Effect in Scrap Preheating by Arc Furnace Exhaust Gas

Applicable furnace	Reduction of unit electric power consumption rate (kWh/t)	Reduction of electrode wear amount (kg/t)	Shortening of steel making time (min.)
30 t	30.6	0.17	10
30 t	36	0.7	8
50 t	40 ~ 50	0.2 ~ 0.4	5 ~ 8
60 t	40 ~ 45	0.2 ~ 0.3	5 ~ 7

In addition, energy can be saved by returning the scrap generated in the factory to the arc furnace while it is kept hot.

(4) Suppressing heat release from openings of furnace body

The electric arc furnace is equipped with openings in the side walls of the body such as slag opening, tapping opening, etc. The openings should be closed except during use. However, poor sealing or failure to close will cause heat loss due to incoming cold air in the furnace. An example shows a reduced basic unit of electric energy by 4% by means of closing the openings alone.

(5) Suppressing heat release during furnace repair

Inspection is made for the inside of the electric arc furnace at every time of tapping, followed by repairing the damaged portion, if any, such as furnace floor, etc. Since the accumulated heat in the furnace body is released, the repair work must be completed as early as possible. A large furnace is equipped with a furnace-material spraying repair machine to shorten the repair hour.

(6) Optimizing power charge

The shorter one-charge time is, the less power consumption becomes. During the initial stage when the furnace walls are shielded with scraps, the voltage and current are adjusted to maximize the electric arc power. It was a common practice that when the furnace walls were exposed with the proceeding of scrap melting, the short-arc operation was made with low voltage and high current to prevent the melting loss of the furnace walls. However, the adoption of water cooled furnace walls with a copper jacket in recent years has enabled long-arc operation.

In view of the above, the optimum electric input program must be found out to systematically optimize electric energy, loss of furnace walls and electrode consumption according to the form and shape of each furnace and scraps charging method.

### 10.2.2 Induction Furnace

Items of energy conservation for induction furnace are shown in Table 10-8.

Table 10-8 Items on Energy Conservation for Induction Furnace

Decrease of heat input	Lowering molten steel temperature	Preheating of ladle brick Prevention of heat release by ladle lid Avoiding overheating
Reduction of heat loss	Improvement of facilities	Selection of optimum frequency Reduction of resistance of cable and busbar Closing gap of cover Improvement power factor Increasing efficiency of frequency convertor
	Improvement of operation	Removing impurities of charging scrap Dense charging of scrap Optimum size of starting block Shortening idle time (temperature measurement, analysis, waiting ladle etc.) Optimum coil cooling Optimum hot metal remaining

(1) Condenser for improving power factor

The power factor of the induction furnace is about 20% for a crucible type low frequency furnace and 5 – 10 % for a high frequency furnace. Therefore, a large capacity condenser for improving the power factor is used.

As compared with a paper condenser containing mineral oil, the heat loss of a film-type condenser containing insulating oil is about one figure less than that of the paper condenser. For example,  $\tan \delta = 0.025$  for the film-type condenser containing special insulating oil to  $\tan \delta = 0.26$  for the paper condenser containing mineral oil in case the both are for 1,000 Hz.

Since a high frequency condenser of 600 kW, 1 t and 1,000 Hz is about 7,000 KVA, the difference of heat loss between the two condensers is about 16.4 kW.

(2) Frequency converter

An electromotive power generator was conventionally used as a frequency converter for a high frequency furnace. However, high frequency inverters of thyristor type are available nowadays at economical prices. The conversion efficiency of a thyristor at 1,000 Hz and 600 kW is about 95% as compared with that of an electromotive power generator under the same condition being about 85%, making a difference of about 10%.

In addition, a thyristor inverter matches the load impedance by automatically changing frequency, increasing the load factor and shortening melting hours as compared with an electromotive power generator. Therefore, replacement of an electromotive power generator with a thyristor inverter will lead to energy conservation of about 15%.

(3) Water-cooled cable and bus bar

Since the electrical circuit is of low voltage and high current, bus bars as conductors and water-cooled cables are used. In particular, the wiring loss of the water-cooled cables is high owing to the current density of 10 – 15 A/mm<sup>2</sup>.

As an example, two water-cooled cables of 400 mm<sup>2</sup> – 6 m are used for a crucible-