1.3.1 Electric Arc Furnace

(1) Steel-making process by an electric furnace

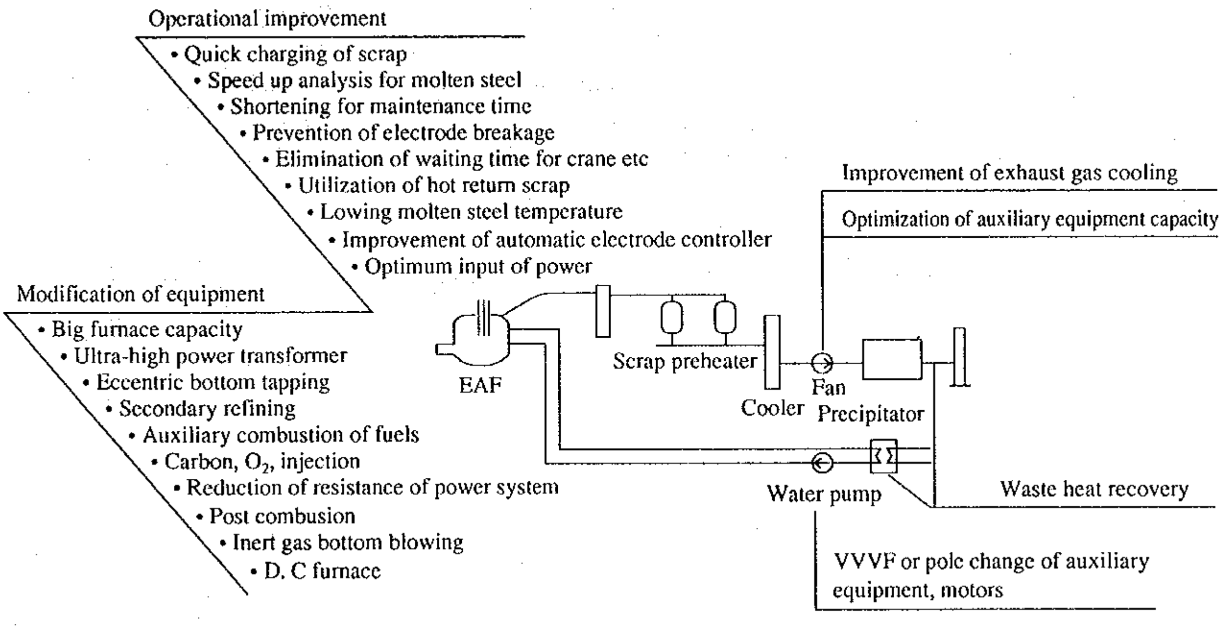
In the steel making process, scrap is heated, melted, reduced in an electric arc furnace (if necessary, degassing and other processes can be carried out with a secondary smelter), and the molten steel is then transferred to a continuous caster (CC), or to a conventional caster to produce slabs or ingots.

The steel-making process uses approximately 75 % of the total amount of energy consumed at an electric arc furnace plant, and most of the energy in the steel-making process is consumed by the electric arc furnace.

Scrap is heated and melted inside the arc furnace by the arc heat generated between the scrap and the electrodes, and by the electric resistance generated within the scrap. Normally, three-phase alternating currents are the principal energy source for this process.

Figure 1.27 shows a flow diagram of the process of an electric arc furnace and energy conservation measures thereof.

Figure 1.27 Flow and Energy Conservation Measures for Arc Furnaces



(2) Energy conservation by improvement of the operation and equipment

The substantial effect of energy conservation achieved in the steel-making process is owed greatly to a rise in the continuous casting ratio, improved productivity of the electric arc furnace due to feeding of auxiliary fuels such as fuel oil and carbon, and injeciton of oxygen. An explanation of energy conservation measures for auxiliary machinery at electric arc furnaces, such as dust collectors and cooling water pumps, etc., will be omitted here since these technologies are common to other facilities as well. The main emphasis will be placed rather on how to improve the energy intensity of the electric arc furnace itself.

Electric arc furnaces consume a large amount of electricity. Assuming that fuel is converted into electricity by a power generation plant at a net thermal efficiency of 35.1 %, 1 kWh of that electric power should be equivalent to 10,258 kJ (2,450 kcal).

The measures for reduction of electricity intensity, as described below, are taken in order to decrease the cost for manufacturing molten steel by an electric furnace. The effect evaluated based on 1 kWh = 10,258 kJ (2,450 kcal) shows that cost reduction measures constitutes energy conservation measures as well.

Generally, electric arc furnaces have fixed energy losses such as heat loss due to cooling water loss, radiated and dispersed heat losses of the furnace body. If the tap-to-tap time can be reduced by increasing the amount of energy input to the electric arc furnace; in other words, if productivity (quantity of steel tapped per unit of time) can be raised by increasing the amount of energy input, the rate of fixed losses will fall, and the energy intensity can be lowered. In view of the above, improving productivity has always been considered to be an effective energy conservation method. An example of a heat balance sheet for an electric arc furnace is shown in Table 1.2.

Here, however, 1 kWh of electricity should be treated as the equivalent of approx. 3600 kJ (860 kcal) in a theoretical analysis of the energy balance of an electric arc furnace.

Table 1.2 Heat Balance of an Arc Furnace (Example)

Mcal/t tapping

Heat input			Heat output		
	10^3 kcal/t	%		10^3 kcal/t	%
Heat by electric power	302	50.2	Sensible heat of molten steel	342	56.8
Combustion heat (Fuel)	41	6.8	Sensible heat of slag	52	8.6
Oxidation heat of electrode	20	3.3	Heat loss by exhaust gas	71	11.8
Oxidation heat of charged raw materials	197	32.7	Heat loss by cooling water	62	10.3
Heat of slag formation	12	2.0	Heat loss of transformer and secondary conductor	22	3.7
Heat recovered by preheater	15	2.5			
Others	15	2.5	Others	53	8.8
Heat input total	602	100	Heat output total	602	100

Heat input			Heat output		
	10^3 kcal/t	%		10^3 kcal/t	%
Heat by electric power	373	59.1	Sensible heat of molten steel	340	53.9
Combustion heat (Fuel)	25	4.0	Sensible heat of slag	47	7.4
Oxidation heat of electrode	26	4.1	Heat loss by exhaust gas	111	17.6
Oxidation heat of charged raw materials	192	30.4	Heat loss by cooling water	30	4.8
Heat of slag formation	11	1.8	Heat loss of transformer and secondary conductor	28	4.4
Heat recovered by preheater	–				
Others	4	0.6	Others	75	11.9
Heat input total	631	100	Heat output total	631	100

The following measures can be considered in order to improve the productivity of arc furnaces.

- Increasing the transformer capacity
- Improving the electricity intensity by utilizing a supporting burner, implementing oxygen injection, carbon injections, and preheating scrap
- Reducing the amount of power-off time
- Improving thermal efficiency
- Improving secondary smelting technology

Next, each of these measures is explained in further detail.

1) Increasing the transformer capacity

Transformer capacity of arc furnaces has exhibited a trend of steady growth in recent years, as the transition of RP → HP → UHP has been carried out. Table 1.3 shows the relationship between arc furnace capacity and transformer capacity.

As shown in the table, it has become possible to increase the size of transformers and input a greater amount of electric power owing to 4 kinds of technologies: ① the technology to manufacture electrodes for UHP, ② technologies to water-cool furnace walls and ceiling, technology related to refractory, ③ slag forming technology, and ④ stabilization of electric arcs during the initial melting period using residual molten metal.

Table 1.3 Relationship between Furnace Capacity, Required Size and Electrical Equipment

Nominal capacity of furnace	Outside diameter of furnace core	Metal bath depth	Diameter of electrode	Capacity of transformaer [MV·A]			Secondary voltage (RP furnace)
[10^3 kg]	[m]	[mm]	[mm]	RP	HP	UHP	[V]
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	430/140
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	

Notes: RP: regular power, HP: high power, UHP: ultra-high power
Source: Cast Product Handbook, 4th Edition, edited by Japan Cast Product Association

2) Reducing the electricity intensity

① Supporting burner

The temperature rise and melting of scrap is facilitated by installing a supporting burner and utilizing kerosene, fuel oil, and natural gas, etc., while simultaneously supplying the necessary amount of oxygen. The burner is normally installed facing the cold spot.

An example of a supporting burner installation is shown in Figure 1.28, and the effect of reduction in electricity intensity by using a fuel oil burner is shown in Figure 1.29.

Figure 1.28 Example of Combustion Supporting Burner Installation

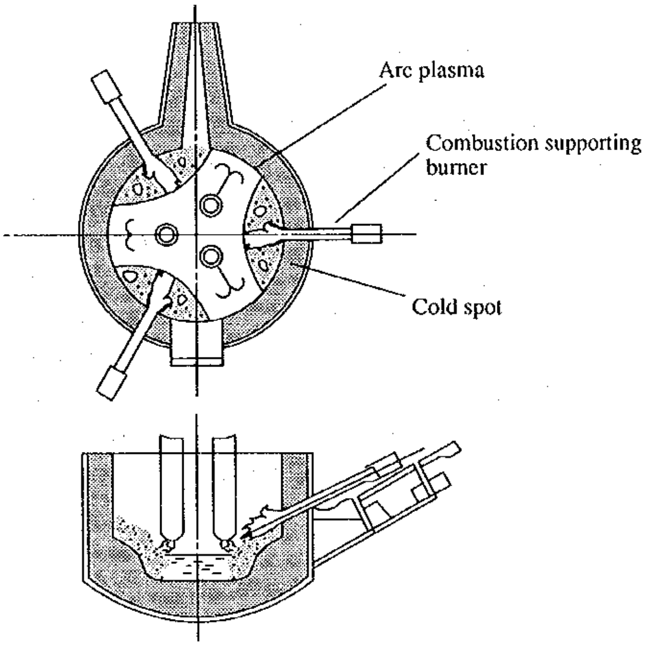
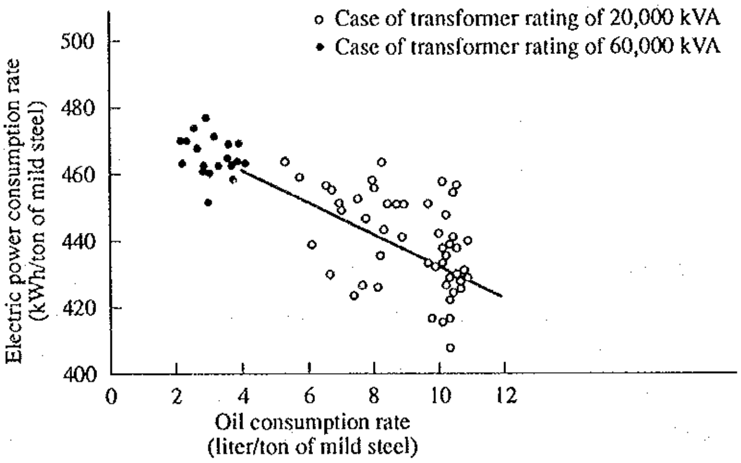


Figure 1.29 Effect of Combustion Burner

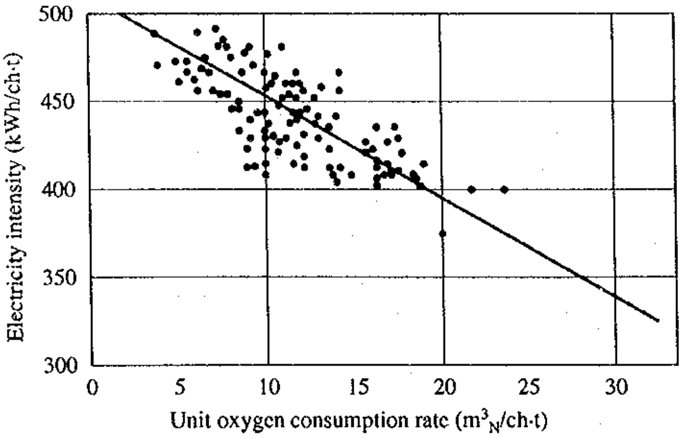


② Oxygen injection operation

Oxygen injection operations, in which oxygen is directly blown against scrap and molten steel, has the effect of enhancing scrap cutting and Fe oxidation reactions as well as improving heating and melting times on the one hand, while on the other hand they exhibit a shortcoming in terms of decreased yield in the tapped steel. The carbon injection process was developed to solve this deficiency, and at present, the electricity intensity is reduced by effectively combining ① the supporting burner, ② oxygen injection operations, and ③ carbon injections. While this has the effect of reducing the rate by 5.5 kWh of electric power per 1 m^3_N/t of oxygen, the effect is halved for 20 m^3_N/t, and further oxygen injection will increase oxidization loss, thus producing an adverse effect.

The effect of an oxygen injection operation is shown in Figure 1.30.

Figure 1.30 Effect of Oxygen Injection



③ Injection of carbon and aluminum dross

In addition to the melting of scrap by electric power, when oxygen and coke powder are blown into the furnace, the melting operation is further facilitated by the heat generation that accompanies oxidation of Fe and C, a slag forming phenomenon is triggered by the CO gas generated by the reaction between the FeO and C contained in the slag after meltdown, and radiation heat is prevented from being transmitted to the walls by the action of the resulting submerged arc. As a result, the electric power input efficiency is increased.

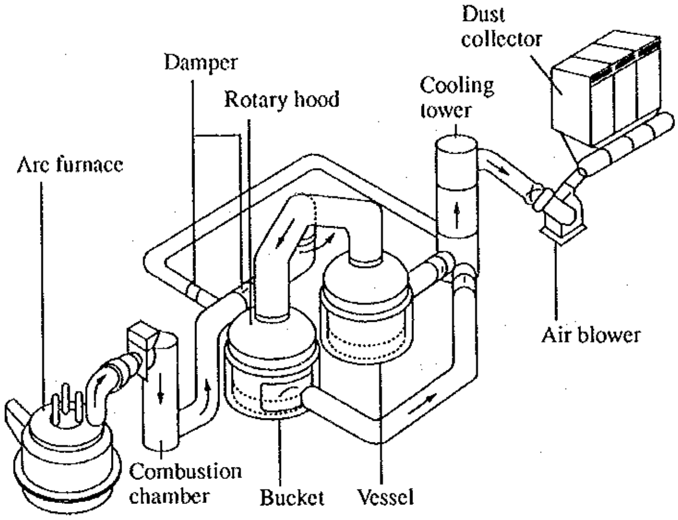
Due to this formation of a submerged arc, a high power factor operation and input of large amounts of electricity have become possible, and an improved electricity intensity, increased furnace wall life, and improved yield of steel output are achieved.

Recently, aluminum dross has come into use as a part of combustion supporting materials. The metal aluminum content in aluminum dross is 30 to 40 %, and the effect of reduced electricity intensity due to the reaction heat of oxidizing aluminum dross is 4 to 6 kWh /kg of aluminum; also, addition of aluminum dross has the effect of preventing a sudden reaction between the C and oxygen contained in the steel as well as preventing sudden boiling.

④ Preheating of scrap

A conceptional drawing of a device that recovers sensible heat from exhaust gas, which is the principle source of loss in arc furnaces and uses it to preheat scrap, is shown in Figure 1.31. Special emphasis is placed on the ease of operation in its design, in which the charging bucket that charges scrap is normally placed in one of a number of preheating baths installed in the exhaust gas system, subjected to drying/preheating and then can be taken out before the next charging of scrap. In order to prevent thermal deformation of the bucket, the pre-heating temperature of the exhaust gas used is limited to a maximum of 600 °C.

Figure 1.31 Conceptional Drawing of Scrap Preheating Equipment



These effects of electricity intensity reductions are summarized in Table 1.4.

Table 1.4 Effect of Alternative Energy on Electricity Conservation

Oxygen	0 to 20 m^3_N/t	5.5 kWh/m^3_N
	> 20 m^3_N/t	2.7 kWh/m^3_N
Oil	0 to 5 L/t	9.0 kWh/L
Natural gas		8.5 kWh/m^3_N
Coke		3.0 ~ 8.3 kWh/kg
Aluminium dross		5.0 kWh/kg-Aluminum
Scrap preheater		20 to 40 kWh/t

3) Reduction of power-off time

In order to reduce the tap-to-tap time, it is also necessary to reduce power-off time as shown in the following items. An actual investigation conducted on the tap-to-tap time and power off time is shown in Figure 1.32.

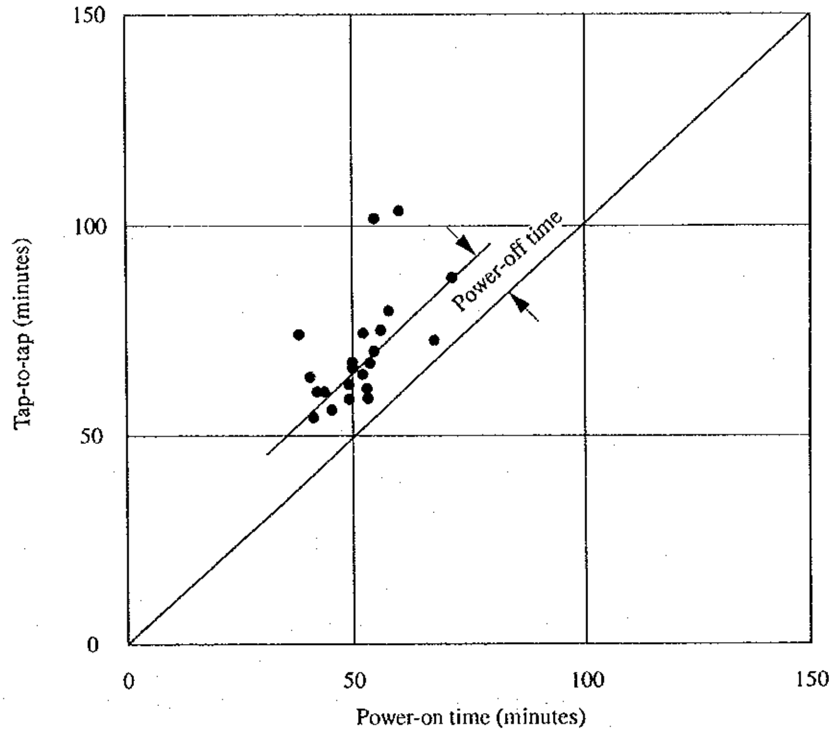
① Reduction of scrap charge time by accelerating the speed of raising, lowering, and rotating the furnace lid, as well as raising and lowering the electrodes.

② Reduction of the connection time for electrodes, etc.

③ Improvement of furnace heat resistance by introducing water cooling to the furnace walls

④ Reduction of tapping time by introducing eccentric bottom tapping (EBT) furnaces and a method of receiving steel in carts

Figure 1.32 Relationship between Tap-to-tap Time and Power-Off Time in Arc Furnace Operation



4) Improvement of thermal efficiency

The adoption of EBT furnaces, computerized control of electric power inputs, slag forming technology, gas bottom blowing, and deploying the secondary combustion method inside the furnace, etc. are all said to contribute to improving thermal efficiency. The thermal efficiency of DC furnaces is raised by the molten steel made by a direct current arc and electromagnetic forces (the electricity intensity is better than that of alternating current arc furnaces).

5) Improvement of secondary smelting technology

Adding facilities that smelt scrap inside the ladle, such as a ladle furnace (LF), not only improves targeting accuracy for temperature and composition, but also produces effects such as stabilization of CC operations, and improvements in the quality of slabs and steel ingots.

Especially when the functions of the electric arc furnace and ladle furnace are separated, a reduction in temperatures for tapping from the electric furnace, reduced tap-to-tap time, and improved CC ratio, etc. are observed. It should be noted, however, that the use of LF for the type of steel not requiring LF will bring about rather demerits.

6) Reductions in tapping temperature and the number of operating arc furnaces

By accelerating downstream processes (principally CC) and increasing the furnace size, the radiation heat from the ladle and the molten steel in the ladle will be relatively reduced. The tapping temperature equivalent to this radiation heat can be lowered, thus allowing the electricity intensity of an electric furnace to be reduced. A 10 °C reduction in tapping temperature results in a 3 kWh/t reduction in the electricity intensity.

If the time between completion of tapping at the arc furnace and completion of CC casting can be shortened from 150 minutes to 100 minutes, the electricity intensity can decrease by 50 kWh/t; therefore accelerating CC should lead to both an increase in productivity and a reduction in the electricity intensity.

If the number of electric furnaces in operation can be reduced by one unit with the productivity kept unchanged, a substantial energy conservation effect will be achieved. Hence, when a plural number of electric furnaces are used, the number of operating furnaces should always be kept in mind. In order to reduce the number of operating units, it is necessary to obtain the length of tap-to-tap time and implement various improvements for putting it into practice. Since reducing the number of operating furnaces leads to a substantial cost reduction (energy reduction), the reduction of the number of operating units is one of the measures which are widely used for achieving energy conservation.

7) Computerized control of electric power input (Optimization of electric power input)

Needless to say, automatic control of voltage and current contributes to energy conservation, but it is also effective in reducing costs such as the consumption rate of electrodes, which is why almost all furnaces have adopted it.

8) Reduction of cooling water heat loss

Heat loss due to cooling water loss occupies over 10 % of the heat entering the arc furnace, making the reduction of this loss an important energy conservation goal for arc furnaces.

Introducing water cooling to the furnace body contributes greatly to the enlargement of the furnace size and to the promotion of UHP, thus serving as a more useful means for energy conservation than the water-cooling method for heat loss. However, there are examples in which water cooling loss was increased because the water cooling coefficient was raised too much, resulting in a deterioration of the electricity intensity and making it impossible to reduce tap-to-tap time. Thus it is believed that reexamination of the cooling water coefficient will become an important energy conservation issue in the future.

9) Relationship between the tap-to-tap time and electricity intensity

The relationship between the tap-to-tap time of an arc furnace and electricity intensity exhibits a trend as shown in Table 1.5.

Table 1.5 Relationship between Tap-to-Tap Time and Electricity Intensity

Tap-to-tap time	Electricity intensity
180 minutes	550 to 600 kWh/t
120 minutes	480 to 520 kWh/t
90 minutes	430 to 470 kWh/t
70 minutes	380 to 420 kWh/t
60 minutes	360 to 400 kWh/t

(3) Recovery of exhaust heat and modernization of process

a. Modified arc furnace

A few models using a new process which is aimed at preheating all scraps before heating and melting in order to improve electricity intensity by 20 %, such as the twin-shell furnace in which 2 electric furnaces are installed to perform alternate functions between heating/melting and scrap preheating, and the shaft furnace which continuously heats scrap, have been proposed and already in operation at some plants.

Although the results have not been presented yet, the day is close when an arc furnace that performs at 250 kWh/t or less will appear.

b. Recovery of exhaust heat

Heat can be recovered from the cooling water and exhaust heat of arc furnaces. In electric arc furnace plants in Japan, the exhaust heat from a reheating furnace is recovered but the exhaust heat from an arc furnace is not yet recovered because of no necessity of steam demand.

1.3.2 Reheating Furnace in Rolling mill

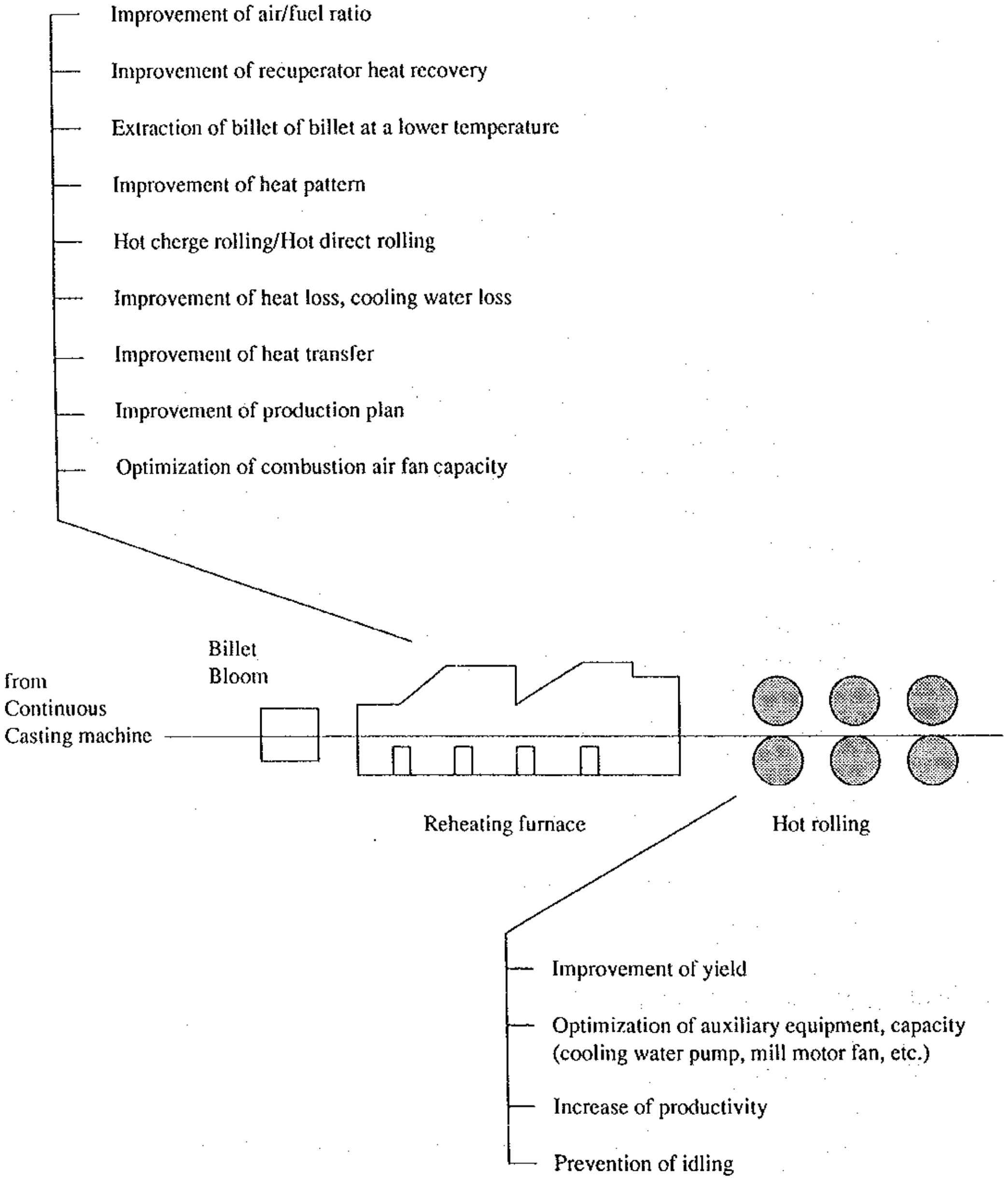
(1) Rolling process

In the rolling process, a semi-finished steel product (slab, bloom or billet) is heated to a specified temperature with a reheating furnace, rolled with a rolling mill, and then fabricated into the desired shape and size.

Usually, the main products that come out of the rolling mill at an arc furnace plant are almost all primary rolled products such as shape steels, bar steels, and wire rods. Energy conservation measures for the primary rolling process are described below.

The flow chart and energy conservation measures for primary rolling processes are shown in Figure 1.33.

Figure 1.33 Flow and Energy Conservation Measures for Rolling Process



- Improvement of air/fuel ratio
- Improvement of recuperator heat recovery
- Extraction of billet of billet at a lower temperature
- Improvement of heat pattern
- Hot cherge rolling/Hot direct rolling
- Improvement of heat loss, cooling water loss
- Improvement of heat transfer
- Improvement of production plan
- Optimization of combustion air fan capacity

- Improvement of yield
- Optimization of auxiliary equipment, capacity (cooling water pump, mill motor fan, etc.)
- Increase of productivity
- Prevention of idling

Energy conservation measures for reheating furnaces consuming the largest amount of energy in the primary process will be described below.

(2) Energy conservation by improvement of operations and equipment

While fuel takes up 60 % of the energy used in the primary rolling process, and electricity and steam occupy the rest, it is the reduction in fuel intensity of reheating furnaces that has achieved outstanding energy conservation results. There were many reheating furnaces with a fuel intensity exceeding 450 Mcal/t before the oil crisis; today, however, furnaces with intensity levels of 200 Mcal/t or less are emerging.

An example of heat balance at a reheating furnace is shown in Table 1.6.

Table 1.6 Heat Balance of a Reheating Furnace

Charged slab temperature : cold Example 1
Charged billet temperature: hot Example 2

(Example 1)

Heat Input	Mcal/t	(%)	Heat Output	Mcal/t	(%)
Combustion heat of fuel	318.7	(97.6)	Heat content of extracted slab	194.8	(59.7)
Sensible heat of fuel	0	(0)	Sensible heat of scale	2.1	(0.6)
Heat content of charged slab	0	(0)	Sensible heat of exhaust gas	33.3	(10.2)
Scale formation heat	8.0	(2.4)	Heat of cooling water	43.8	(13.4)
			Heat loss	52.7	(16.1)
Heat recovered by recuperator	(62.7)	((19.2))	Heat recovered by recuperator	(62.7)	((19.2))
Total	326.7	100	Total	326.7	100

Overall heat efficiency = {194.8/(318.7 + 8.0)} × 100 = 59.6 %

(Example 2)

Heat Input	Mcal/t	(%)	Heat Output	Mcal/t	(%)
Combustion heat of fuel	168.8	(65.6)	Heat content of extracted billet	174.9	(67.9)
Sensible heat of fuel	0.3	(0.1)	Sensible heat of scale	3.1	(1.2)
Heat content of charged billet	73.9	(28.7)	Sensible heat of exhaust gas	30.7	(11.9)
Scale formation heat	13.2	(5.1)	Heat of cooling water	41.9	(16.3)
Sensible heat of atomizer	1.3	(0.5)	Heat loss	6.9	(2.7)
Heat recovered by recuperator	(16.7)	((6.5))	Heat recovered by recuperator	(16.7)	((6.5))
Total	326.7	100	Total	257.5	100

Overall heat efficiency = {174.9/(168.8 + 0.3 + 73.9 + 13.2 + 1.3)} × 100 = 67.9 %

Reheating furnaces are roughly categorized into batch type and continuous type. The batch type is principally a furnace for reheating specially shaped items, while the continuous type is mainstream for mass production. The pusher type, walking beam type, and walking hearth type are representative types of continuous reheating furnaces. The pusher type has a low construction cost and is adopted as small scale furnaces of 150 t/h or less, while the walking beam type is used as large scale furnaces. The walking hearth type is used for reheating and heat treating special shapes like round steel members.

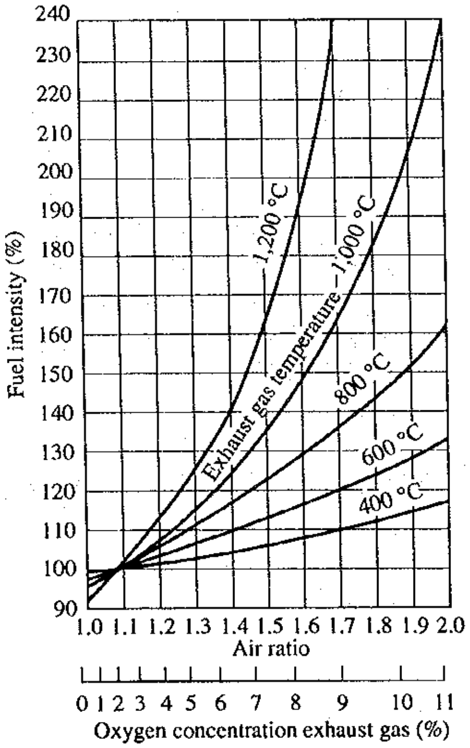
Besides the heat losses that occur during regular operations of a furnace, such as exhaust gas loss, other factors that reduce the thermal efficiency of a furnace, such as waiting time and rolling speed (load factor of reheating furnace), have unexpectedly large impacts. This is because a large amount of heat is required to retain and raise temperatures. This requires due consideration. Other factors not to be neglected include the effect that the rolling speed (load factor) of a reheating furnace, etc. have on the heat loss.

Next, energy conservation measures will be explained.

1) Improvement of the air ratio

While maintaining the air/fuel ratio at a proper level, the amount of air entering from outside is reduced by adjusting the furnace pressure controller. The relationship between air/fuel ratio and fuel intensity is shown in Figure 1.34. For example, if the exhaust gas temperature is 500 °C, and the air ratio is reduced from 1.5 to 1.2, the amount of fuel can be lowered by 9 %.

Figure 1.34 Relationship between Air/Fuel Ratio and Fuel Intensity



2) Reinforcing waste heat recovery

Since the performance of the air preheater (recuperator) deteriorates substantially and worsens fuel intensity when its heating surface gets dirty, the temperature efficiency it had when it was newly installed should be maintained by periodical simple heat balancing. If performance is not restored, the recuperator should be reinforced or replaced.

3) Low temperature discharge

When a slab, billet or bloom is discharged from the reheating furnace at lower temperatures, the fuel intensity goes down, but the electricity intensity tends to rise, and therefore these materials should be extracted as much as possible at low temperatures with ample considerations to both (electricity and fuel) intensity conditions as well as to skid marks. If the extraction at low temperatures is possible, fuel intensity is expected to decrease by about 3 to 5 Mcal/t for every 10 °C drop in discharge temperature.

4) Improvement of hot charge ratio

The design fuel intensity of reheating furnaces that reheat only cold slabs is 300 Mcal/t to 400 Mcal/t. There are many rolling reheating furnaces operating at fuel intensities of 200 Mcal/t or below at electric arc furnace plants that produce only deformed steel bars. High temperature slabs produced in continuous casting (CC) facilities are charged directly into rolling reheating furnaces (called HCR), or rolled as is with rolling mills (called HDR).

While it is obviously desirable to have the CC and reheating furnace slab charger close to each other for the conduction of hot charges, it is difficult to carry out a 100 % hot charge as there will be a discrepancy between the production capability of the CC and that of the rolling process. Therefore, a heat retaining box that temporarily stores hot continuous cast billets is normally installed as a buffer. The heat retaining box has a steel plate structure lined with insulating material, with a movable cover to allow billets to move in and out.

The amount of energy conservation achieved by hot charging is approximately 20 Mcal/t per charge temperature of 100 °C.

5) Prevention of heat loss due to radiation, and heat conduction, etc.

Furnaces installed recently have furnace walls made of ceramic fibers that are lightweight and have small specific heat, giving them superior heat insulation as well as small structural heat losses. Heat loss through the furnace walls is thus improved.

Existing furnaces which have walls made of bricks can have both the amount of radiation heat and structural heat losses reduced by 30 to 40 % if 50 mm thick ceramic fiber is added on their inside walls.

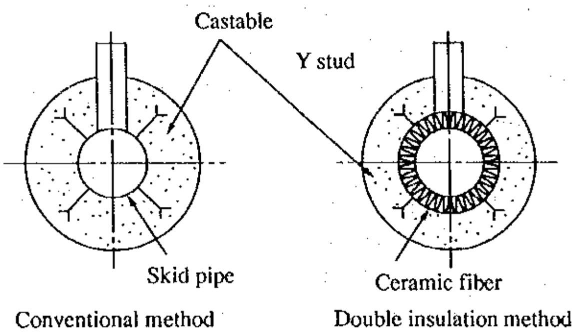
6) Prevention of heat loss from openings

The presence of openings causes heat to escape outside as radiation heat, resulting in a leak of combustion gas and heat loss. Therefore, modifications should be made to minimize the size of any opening (The presence of openings also causes combustion gas to leak outside, resulting in heat loss).

7) Prevention of heat loss from cooling water

Heat loss stemming from water cool skid pipes constituted 10 to 15 % of the fuel intensity in continuous reheating furnaces. In order to reduce the heat loss due to this cooling, methods to provide skid double insulation have been developed and adopted not only for newly installed furnaces, but also at existing ones, resulting in reduction of heat loss by half. An example of such an improvement is shown in Figure 1.35.

Figure 1.35 Double Insulation Method for Skid Pipe



8) More efficient heat conduction inside furnaces

The steel product inside a furnace is mainly (about in 95 % or more) heated by the heat radiated from combustion gas (gas radiation from CO_2 and H_2O, and solid radiation from hot carbon particle groups contained in the flame). Therefore, a sufficiently large furnace volume is required to obtain the so-called "optimal thickness of gas."

It is thus necessary to study whether or not the required furnace volume is obtained. If the volume is insufficient, innovations such as installing barrier walls to enhance heat-conduction inside the furnace and slightly changing the furnace configuration will be required. Also, if the hot gas is only flowing to the top end of the furnace and the gas temperature at its bottom end is lowered, there can be a drop in the amount of radiated heat conduction. Therefore, measures must be taken to make the temperature inside the furnace uniform in the direction of its height.

9) Prevention of heat loss due to external factors

If the air/fuel ratio of the reheating furnace is managed properly, its fuel intensity can be kept at a level that is quite high, provided that continuous operations at a heating speed (t/h) within a given range is possible.

In actual operation, however, circumstances of the preceding or subsequent processes sometimes make the heating speed high or sometimes low, or there may be a need to retain heat for prolonged periods. These fluctuations lead to a noticeably unfavorable fuel intensity on an annual average.

When such situations occur, it becomes imperative to remove the factors involved, sometimes making it necessary to change or improve the production plan itself.

For example, if criteria for retaining or raising the temperature in the reheating furnace can be specified by adjusting the production speed to the preceding or subsequent process, and by resolving problems during the process that comes before or after the furnace, the heat intensity can be improved substantially. Or, if there are multiple rolling lines (and therefore multiple reheating furnaces as well) making various types of products, some rolling lines may have to stop at times because the production capacity of the continuous casting facility cannot keep up with that of the rolling line. If such a situation occurs on a regular basis and readjustment of production plan and work procedure alone cannot cope with such situation, it is indispensable to take measures for reducing the heat loss due to radiation and regenerative loss.

(3) Energy conservation through waste heat recovery

a. Regenerative burner

When an air preheater is old and needs to be replaced, the installation of a regenerative burner should be studied. See Section 1.3.3 on forging furnaces for more details about regenerative burners.

b. Recovery of skid cooling water sensible heat

This type of sensible heat can be recovered for a feedwater preheater if a reheating furnace boiler is installed.

c. Reheating furnace boiler

The boiler installation should be studied after considering ways to reduce the amount of exhaust gas through ways to reduce fuel intensity such as the hot charge method.

The exhaust gas temperature becomes 200 to 300 °C when a regenerative burner is installed, reducing the benefits that can be derived from investing in the installation of a waste heat boiler.

(4) Improvement of yield, and reduction of troubles

Improving yield not only results in energy conservation for the roll process, but also contributes to energy conservation in the processes that follow. It is thus important to improve the product yield by taking measures to reduce scale loss, crop loss, and miss roll. Troubles occurring at the roll line worsens the fuel intensity at the reheating furnace, and the rate of miss roll increases, which in turn worsens yield. Reducing the frequency of facility troubles produces an immediate energy conservation effect.

1.3.3 Forge-Heating Furnaces

(1) Forging process

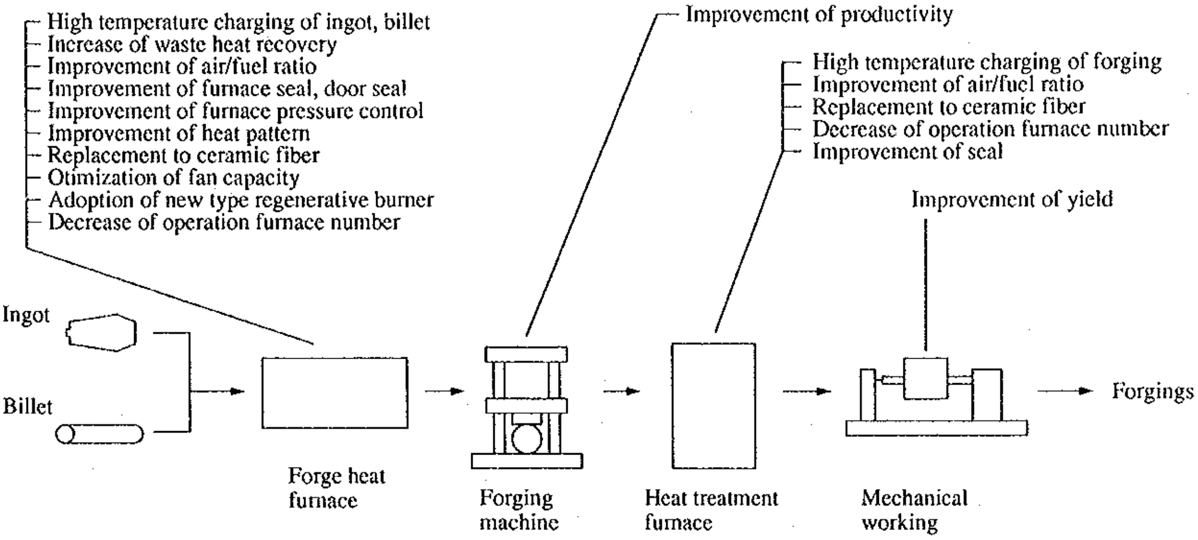
The forging process is used to heat steel ingots and semi-finished steel products (slab, bloom, or billet) in a forge-heating furnace to a specified temperature and then fabricate the steel into the desired shape and size by forging it in forging machines (press, hammer, forging roll). After forging in forging machines, heat treatment is carried out in order to remove internal stress and to instill the required material characteristics. Thereafter, the steel is machined, inspected, and shipped.

The roll process is used to fabricate a product in a two dimensional manner by means of a rolling mill, whereas the forging process is characterized by its capacity to fabricate raw materials three dimensionally and bringing it close to the shape of the final product. Thus the forging process is often installed as an integral part of the operation of a machine manufacturer such as an automotive component factory.

The three dimensional aspect of fabrication in a forging process can be involved in the manufacture of a diverse range of products, and its energy intensity fluctuates greatly depending on the size of the product, the degree of fabrication that takes place and on the presence or absence of heat treatment. The intensity level for forging processes overall is between 2,000 Mcal/t to 5,000 Mcal/t.

A flow chart and energy conservation measures for a forging process are shown in Figure 1.36.

Figure 1.36 Flow and Energy Conservation Measures for Forging Process



Fuel occupies most of the energy used in a forging process, and is especially used in great quantities by forge heating furnaces.

Heating and heat treatment in the forging process is similar to that of the previously mentioned roll process since batch type furnaces carry out almost all of these tasks in the forging process. Energy conservation measures for batch type furnaces are given the main emphasis here. Continuous heating furnaces such as rotary furnaces, walking beam type furnaces, and pusher type furnaces, etc. are also used in the forging process, but the energy conservation measures for these are similar to those of continuous heating furnaces in the rolling process.

(2) Batch heating furnace for forging

The thermal efficiency of most batch heating furnaces for forging is very low, usually around 10 to 20 %. The reasons for this are as follows.

1) The temperature inside the furnace is high, while the exhaust gas temperature is also high

2) Because the mass of the refractory in the furnace is much greater in comparison to the object to be heated, there is a large amount of heat loss due to its structural heat.

3) Air enters from doors and other sealed areas

4) The amount of oxygen fed into a forging furnace changes largely depending on whether it is reheating, soaking, heat-retaining, or idle. It is difficult to make adjustments in a manner that maintains low O_2 combustion during all of these periods, and in many cases, this adjustment is not implemented.

5) For example, bogie type heating furnaces with low operation rates because of maintenance requirements such as repairing the refractory surrounding the bogie, repairing the bogie frame, and repairing the refractory of the furnace.

(3) Energy conservation through improvement of operations and equipment

A heat balance example of a batch furnace is shown in Table 1.7.

Table 1.7 Heat Balance Example of Forge Heating Furnace

Unit of heating value [MJ]

Item	Before modification				After modification			
	Heat input	%	Heat output	%	Heat input	%	Heat output	%
Fuel combustion heat	167,708	86.5			65,406	70.1		
Heat recovered from preheated air	26,175	13.5			27,908	29.9		
Work absorption heat			16,196	8.4			16,196	17.4
Pier absorption heat			3,571	1.8			3,571	3.8
Heat loss from furnace wall			12,797	6.6			7,673	8.2
Furnace material structural heat loss			37,745	19.5			15,836	17.0
Water cooling heat loss			10,155	5.2			6,861	7.4
Exhaust gas heat loss			101,594	52.4			37,984	40.7
Miscellaneous losses			11,825	6.1			5,193	5.5
Total	193,883	100.0	193,883	100.0	93,314	100.0	93,314	100.0
Comparison of fuel economy		100.0				39.0		

a. Reduction of exhaust gas heat loss

In order to reduce exhaust gas heat loss, which is the largest among various heat losses in forge heating furnaces, it is necessary to reduce the amount of exhaust gas (control the concentration of oxygen in exhaust gas), and reduce the exhaust gas temperature (increase the amount of heat recovered using a recuperator). To this end, besides controlling the air/fuel ratio to a proper level, maintaining pressure inside the furnace to a proper level and preventing air from entering and exhaust gas from blowing out, the concentration of oxygen contained in the exhaust gas must be kept low by preventing air from entering through the contact surface of the door and from the periphery surrounding the bogie.

b. Reduction of structural heat loss

The second largest contributor to heat loss in forge heating furnaces is structural heat loss, which is why ceramic fibers (or aluminum fiber) are increasingly replacing the original material. Because a batch type forge heating furnace loses more heat in the form of structural heat loss on the inside of the furnace wall than it does from the outer wall of the furnace as radiation heat, it is necessary to make the furnace wall refractory brick lighter in weight and thereby reduce the amount of structural heat. Moreover, there is the additional advantage of reduced repair periods since maintenance of the frunace wall refractory brick becomes easier when it is converted to ceramic fiber.

Raising the operation rate of the furnace is another effective way of reducing structual heat loss, which can be achieved by planning production so that only the necessary minimum number of forging furnaces operate, and which will simultaneously reduce its maintenance cost.

c. Reinforcing heat recovery

Simple heat balances should be compiled periodically while making efforts to maintain the initial temperature efficiency that was attainable when the equipment was newly installed. It the performance is not restored, the air preheater should be reinforced or replaced. Consideration should be given to the installation of other more efficient equipment, for example, a regenerative burner described later, depending on the situation.

d. Raising the hot ingot charge rate

When a hot slab (or hot steel ingot) from the ingot-making process or continuous casting process is hot charged into the reheating furnace, the fuel intensity of the reheating furnace can be reduced by the amount equivalent to the fuel required to reheat up to the temperature of the hot slab.

(4) Energy conservation by waste heat recovery and reinforcing equipment

a. Regenerative burner system

By alternating combustion and heat recovery in intervals of a few tens of seconds by means of a "pair" of burners A and B that have a heat storage incorporated, a temperature efficiency of 85 % or more (preheated air temperature exceeds 1000 °C) can be obtained despite the compact structure. This is because burner B becomes an exhaust outlet while burner A burns and exchanges heat with the heat storage of burner B. The heat storage and air exchange heat to supply clean hot air to burner A which is burning.

This system uses alumina-based refractory brick for the heat storage, its high temperature part consisting only of the burner and heat storage. Its exhaust gas system and air tube system operate in low temperature, thus allowing the whole system to be compact. Because the switch valve for switching between heat recovery and combustion is set at a low temperature, there is little wear to the system, enabling a fuel saving of 30 to 50 %. This system has another excellent characteristic that NOx is 150 ppm or lower although the air preheating temperature is high. The flow diagram of this system is shown in Figure 1.37, and the effect of the increase in preheated air temperature is shown in Figure 1.38.

Figure 1.37 Conceptional Flow of Regenerative Burner

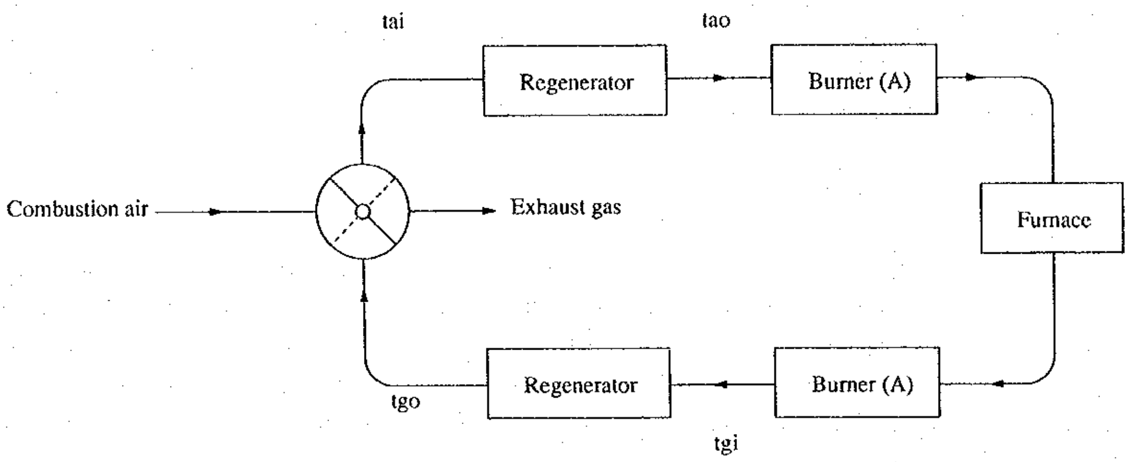
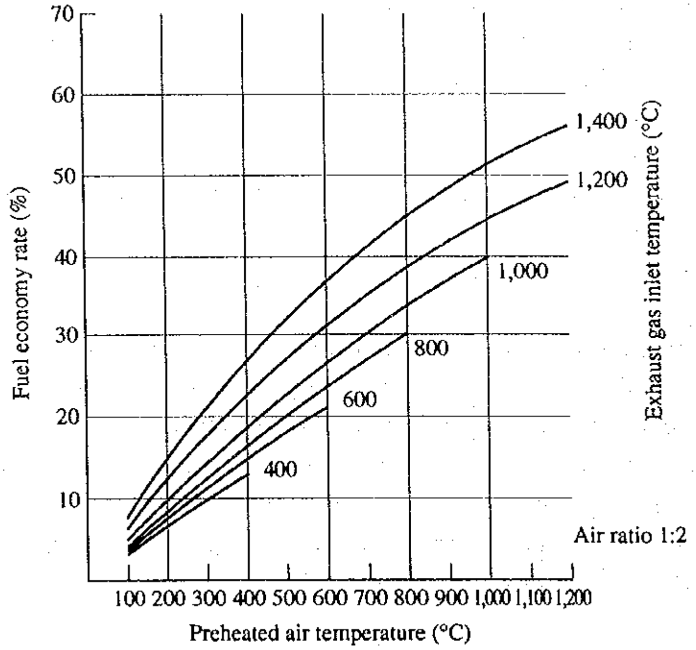


Figure 1.38 Effect of Air Preheater



b. Material preheating furnace

The furnace provides a twin-furnace arrangement in which the exhaust gas from one forge heating furnace is guided to the other furnace, and that furnace is used as a material preheating furnace. However, the regenerative burner mentioned in section "a" is usually more economic than newly installing a preheating furnace.

1.3.4 Melting Furnace at Foundries

The melting and casting processes are the largest consumers of energy at foundries, using about 50 % of total factory energy consumption.

(1) Melting and Casting Process

In the melting and casting processes, a raw ferrous material is melted in a melting furnace, subjected to refinements such as adjustment of composition and removal of impurities in order to obtain the desired type of material, and after its temperature raised to the necessary casting temperature, the molten metal is poured into a cast mould and solidified.

Although the melting temperature of cast iron differs from one type of material to another, it is normally between 1,400 and 1500 °C, and the higher the grade of casting, the higher the temperature of its molten output. The temperature at which cast material is poured into the mould differs greatly depending on the material and the product involved. There is a large variation to this temperature as some casting materials are poured into moulds at their molten output temperature, while others are poured at close to their solidifying temperature of 1,200 to 1,250 °C. Cupola furnaces, induction furnaces, and electric arc furnaces are used as melting furnaces.

In addition to these, a double melting method which combines cupolas with low frequency furnaces, or other furnace types, is often adopted in order to maximize the advantage of cupola characteristics (low cost and continuous tapping of molten metal).

Cast steel is usually melted in electric arc furnaces or induction furnaces. Since cast steel is used in machine parts that require high mechanical strength, removal of harmful components like phosphor (P), sulfur (S), hydrogen (H), and oxygen (O), as well as fine readjustments to the composition of various ingredients such as carbon (C), silicon (Si), and manganese (Mn) are required. Since its melting temperature and elasticity are high, its molten steel tapping is generally at a high temperature of approximately 1,600 °C in order to obtain cast steel casting products that possess high integrity.

(2) Selection of Melting Furnace and Energy Conservation

a. Cupola

Melting furnaces come in many forms, with each exhibiting its own advantage. However, when considering the quality and type of product, production quantity, and arrangement of operation (8-hour operation or 3-shift operation, for example), etc., the first step towards energy conservation is to select a furnace that is optimally suited for the foundry when taking these factors into account. Making the wrong choice can result in chronic energy loss, and run up manufacturing cost beyond anticipation.

Additionally, utilizing the full capacity of the melting furnace on a constant basis is an important element in energy conservation. Fixed heat loss, such as radiation heat loss and heat loss caused by cooling water, etc., become greater as the capacity of the furnace gets larger, and the number of melting furnaces used is larger. It is therefore desirable to keep the number of melting furnaces and their capacity as small as possible.

(3) Energy Conservation by Improvement of Operaton and Equipment

a. Cupola Furnace

① Cupola Furnace

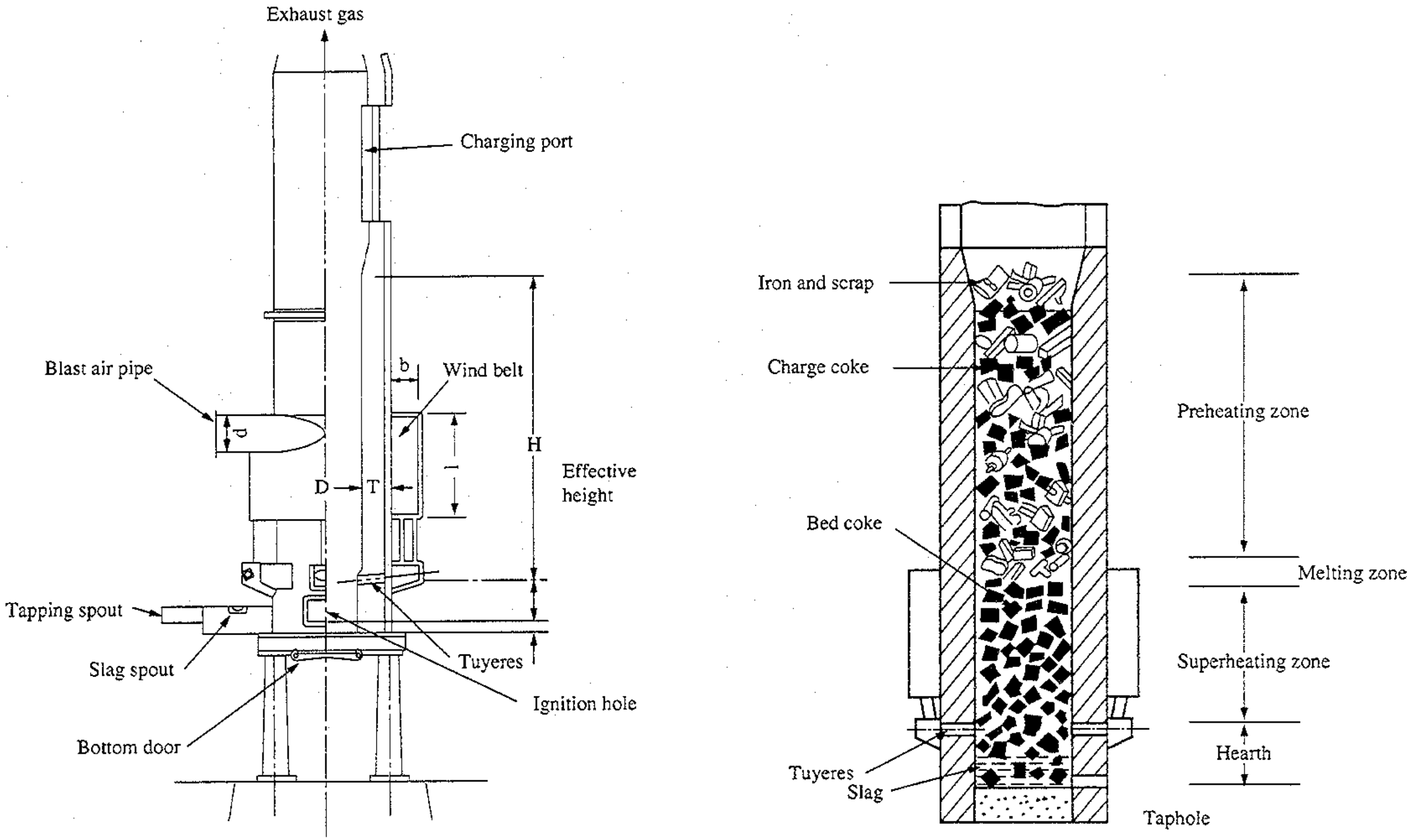
The cupola furnace is a melting furnace consisting of a cylindrical steel plate with fireproof bricks laid inside, and is suited for continuous melting operations. The furnace is filled with coke from the furnace's bottom to above its tuyere (this coke is called the bed coke), and onto this bed coke, coke and raw ferrous materials such as pig iron, scrap, and return scrap are charged into the furnace from the charging port in their correct ratios. Oxygen contained in the air blown in from the tuyere react with the carbon contained in the coke, and becomes carbon dioxide (CO_2) gas. The raw ferrous materials charged into the furnace are melted by this coke combustion heat.

$$C + O_2 = CO_2 + 97.8 \text{ Mcal/k-mol}$$

The spent coke that was burned is replaced by the coke that is charged from above, and the height of the bed coke is kept at a proper level. A section diagram of a cupola is shown in Figure 1.39.

The ratio of the mass between the charge coke that is charged from above, and that of the raw ferrous material, is called the coke ratio, and keeping this coke ratio as low as possible is an important energy conservation activity for cupola furnaces.

Figure 1.39 Conceptional Drawing of Cupola



② Measures to Reduce the Coke Ratio

The coke ratio of a cupola is intricately related to melting speed (productivity) and molten metal tapping temperature, in other words, the quality of the cast iron. Thus, a cupola's coke ratio is usually set to a level that minimizes manufacturing cost.
Cupola furnaces at foundries in Japan are operated with a coke ratio of 100 to 110 kg/t, and thermal efficiency of 35 to 45 %, when molten metal is output at 1,500 °C. The following energy conservation measures are implemented, and many of them are related to the combustion air of cupolas.

- Hot Blast

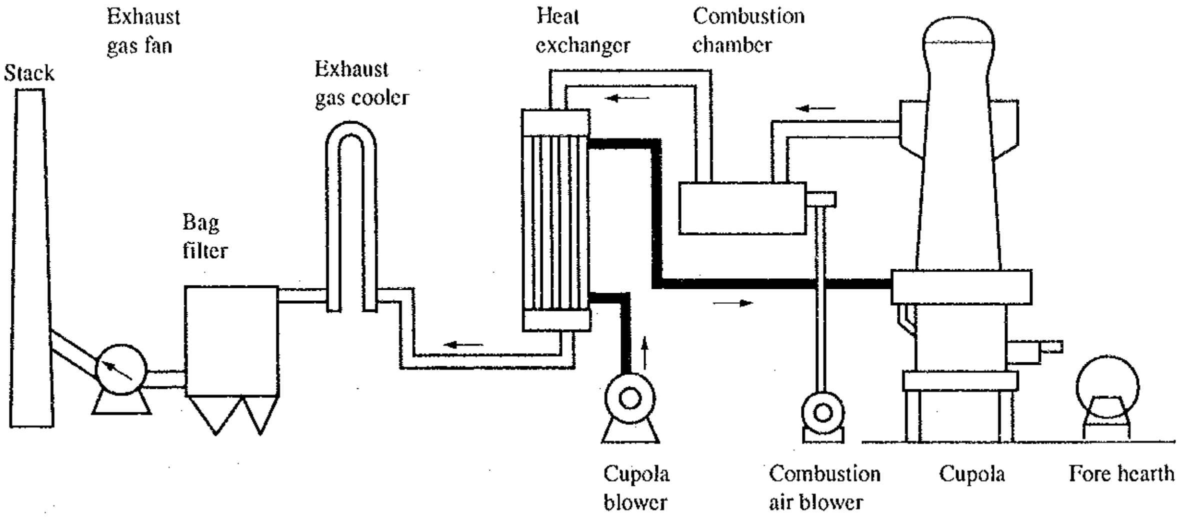
By preheating the blast, the amount of heat input into the cupola is increased, while combustion of coke is improved, and the thermal efficiency of the cupola is improved. In other words, there are the following advantages compared to cold blast.

- The coke ratio is reduced.
- The molten metal tapping temperature is raised, resulting in improved material quality and reduction in the foundry defect
- Melting speed increases
- Si and Mn losses are reduced

The ratio of scrap can be increased (since carbon pickup increases when the molten metal output temperature rises, the amount of pig iron can be reduced)
These effects are also interrelated. For example, if the molten metal temperature is already maintained at the target temperature when cold blast is used, implementing hot blast can reduce the coke ratio.

While the sensible heat of the cupola's exhaust gas and the latent heat of the CO contained in the exhaust gas are usually used to preheat the blast, other fuels are also used at times (overall efficiency will improve even when another fuel is used).
Many types of heat exchangers, such as a double-tube radiation type, muti-tube type and U-shape convection type, etc. are available, and the blast temperature is between 300 and 600 °C. A hot blast system diagram (example) is shown in Figure 1.40.

Figure 1.40 Hot Blast Cupola Process Flow Diagram



- Oxygen Enrichment Blasting

Oxygen enrichment during blasting enhances combustion reaction of the coke, and also reduces exhaust heat loss, and thus, improves the thermal efficiency of the cupola. When oxygen enrichment blasting is carried out alone (without auxiliary fuel charge), the coke ratio will go down by 2.5 % (25kg/t) for a 3 % enrichment of oxygen.
It is also reported that the amount of coke used was reduced by 9.6 %, and melting capacity improved by 16.3 %, and the molten metal tapping temperature raisded by 15 °C by an oxygen enrichment of 1.5 % during hot blast.

Other than this, there are also foundries that implement oxygen enrichment from start of blasting to initial molten metal tapping to reduce the amount of time it takes till initial molten metal is made, while also enhancing the rise of molten cast metal temperature, in order to obtain as stable a molten metal quality from the initial stage as possible.

- Blast Dehumidification

Moisture contained in the blast entering the cupola results in water gas reaction with the coke that is in red hot state, which wastes coke as well as generates heat loss due to endothermic reaction.

$H_2O + C \rightarrow CO + H_2 - 123$ MJ/kmol

For this reason, operation that is stable throughout the year can be obtained by installing a blast dehumidifier, and cutting moisture content to a level of 5 to 7 g/m^3_N.

While adsorption (using silica gel, etc.), absorption (using calcium chloride), and freezing methods are available as blast dehumidification methods, the freezing method is generally used.

- Split Blasting (2-stage blast)

This is a blasting method that has an extra tuyere besides the regular one installed to raise thermal efficiency and increase melting speed in order to reduce the coke ratio.

Depending on the purpose of installation, either the preheating zone or the over heating zone is chosen for the site of the additional tuyere. It is said that implementing the 2-stage blast will increase thermal efficiency by 2 %. The non-reacting CO inside the furnace is combusted, and CO_2 gas concentration increases, which is advantageous in terms of thermal efficiency, but can also lead to increased loss due to Si and Mn oxidized by the oxygen contained in the blast. Adequate operational controls are therefore needed.

- Coke Breeze Injection

Besides reducing the coke ratio, injecting coke breeze from the tuyere also has the following effects.

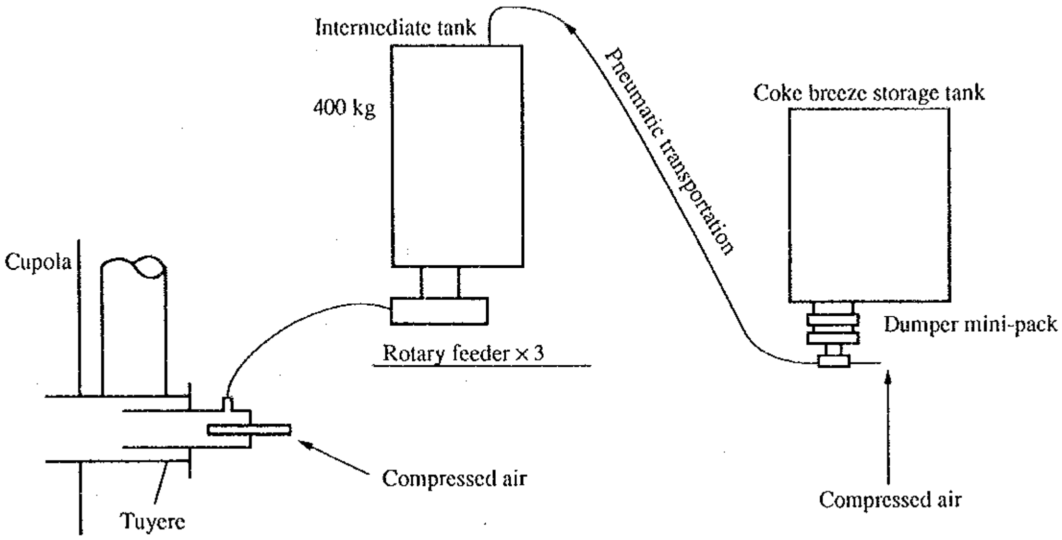
- According to actual results in Japan, operation will be stabilized, thus leading to the stabilization of carbon in the metal.

- Melting speed will increase

By injecting 1 % coke breeze, the coke ratio will go down by 1.5 %, and melting capacity will go up by 4 %. The flow of injecting coke breeze is depicted in Figure 1.41.

- Enhancement of Coke Moisture Control

Figure 1.41 Coke Breeze Injection System Flow Diagram



When the water content of coke increases by 1 %, the coke ratio changes by about 10 kg/t hot metal, which becomes a large factor of fluctuation for the furnace. Thus, coke should be stored inside the building.

- Increased Life of Molten Metal Tap Hole

Exchanging the cupola once a week will generate a loss of bed coke of 2 to 3 kg/t hot metal. Thus, it is desirable to lengthen the interval of cupola replacement as much as possible. In Japan, while the need to replace a furnace is influenced by operational conditions, those with short lives are exchanged once every few weeks, while some with long endurance are exchanged in spans of several weeks. Thus efforts to achieve long life are made such as changing the structure of the molten metal tap hole, and replacing the firebrick used for the furnace body and furnace bottom with higher grade materials.

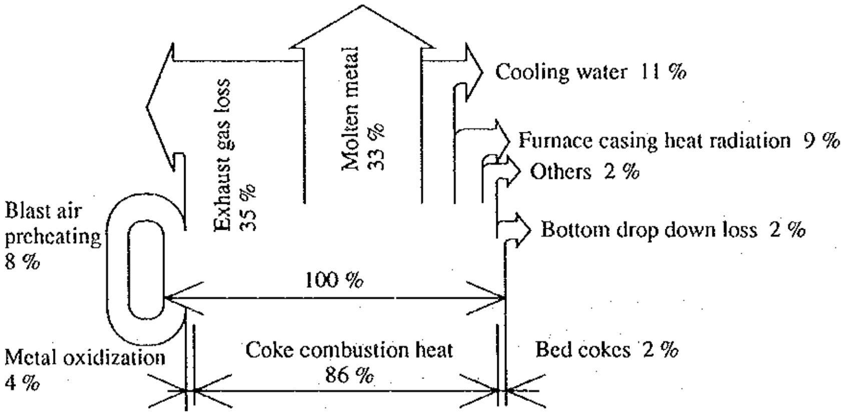
- Double Melting

In this double melting method, melting in the cupola is economized to the maximum, and then the temperature is raised and composition adjusted, using a low frequency induction furnace or a high frequency induction furnace. This method is used in the manufacture of metals that require high temperature molten metal tapping such as white cast iron and ductile iron.

- Reinforcing Operation Control

Utilizing information on the cupola's Si loss, CO and CO_2 contained in the exhaust gas, the exhaust gas temperature, and blast volume, efforts are made to operate the furnace keeping its coke ratio as low as possible while judging the state of the cupola in a comprehensive manner.
An example of a cupola's heat balance is shown in Figure 1.42.

Figure 1.42 Heat Balance of Cupola (Example)



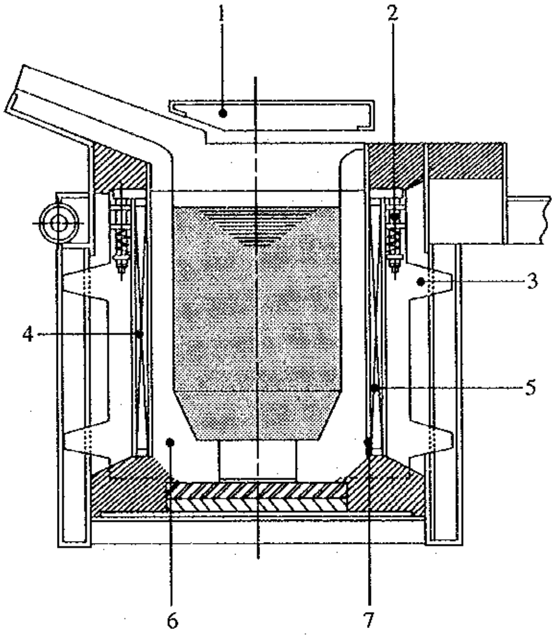
b. Induction Furnace

The use of induction furnaces is on a rising trend because of the following advantages:

Induction furnaces are more efficient in spite of their higher cost than cupolas;
They can produce higher quality products as they are less prone to impurities entering while melting is in progress;
Easy adjustment of molten material composition;
Energy conservation;
Elimination of workers possessing special skills to operate;
Almost no pollution emission;
Improvement of work environment

As induction furnaces for cast iron, there are high frequency crucible induction furnaces (referred to as "high frequency induction furnace" hereafter), low frequency induction furnaces of the same type, and channel induction furnaces. Examples of induction furnace structures are given in Figure 1.43.

Figure 1.43 Induction Furnace Sectional Drawing



1. Furnace cover
2. Compression device for coil
3. Yoke
4. Coil
5. Coil insulation
6. Lining
7. Detector of metal leakage

① High Frequency Induction Furnace

With its relatively small size and large melting capacity (t/h), it is suited for batch operations, and is the furnace of choice especially when the types of materials to be produced are numerous.

A chart comparing high frequency furnaces with low frequency furnaces is shown in Table 1.8, the energy loss distribution diagram in Figure 1.44, and the electricity intensity in Table 1.9.

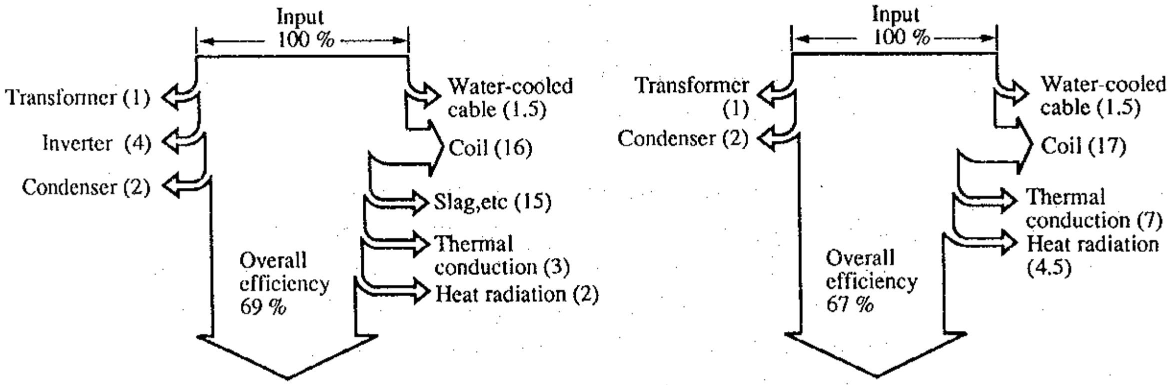
The thermal efficiency of an induction furnace is almost entirely determined by the furnace's structure. In other words, its thermal efficiency is determined when the manufacture designs and manufactures. Therefore, the following cautions pertaining to energy conservation should be taken.

- Select a furnace type, capability, number of units, and manufacturer that suits the mode of operation and product manufactured.
- Do not overheat the molten metal (high frequency induction furnaces can raise molten metal temperature in a short amount of time after scrap is melted, capable of raising the temperature by 100 °C in 2 to 4 minutes)
- Keep the heat retaining time of induction furnaces as short as possible

Table 1.8 Comparison between a High-frequency Induction Furnace and a Low-frequency Induction Furnace

	High-frequency induction furnace	Low-frequency induction furnace	Confer: Channel induction furnace
Operation pattern	Suitable for batch operation	Suitable for continuous operation	Suitable for continuous operation
Furnace capacity	Suitable for small-size furnaces (50 kg to 6 t)	Suitable for medium/large capacity furnaces (~ 50 t)	Suitable for medium/large-capacity furnaces
Use	Melting (Rasing of temperature is also available)	Temperature-holding/raising, melting and duplex melting with a cupola	Temperature holding/raising
Kinds of melting materials	No problem even with more kinds of material	Inferior to a high-frequency furnace	–
Starting from the cold furnace	Starting is available even with small scraps.	A starting block is required.	Operation cannot be started without molten metal.
Melting	Residual molten metal is not required.	Residual molten metal is required (1/3 or more).	–
Thermal efficiency	67 to 73 %	65 to 71 %	75 to 85 %
Halt	A furnace can be made empty	A furnace can be made empty	A furnace cannot be made empty.
Equipment cost	Expensive	Rather inexpensive	Inexpensive
Power capacity (kW)	1,200 kW is available for 500 Hz 1 t	350 kW per ton	–
Frequency (Hz)	150 to 10,000 Hz	50/60 Hz	50/60 Hz
Countermeasure for the higher harmonics	Necessary	Not necessary	Not necessary
Mixing power	Medium	Strong	Weak
Melting speed (t/h)	Fast	Slow	–

Figure 1.44 Heat Balance of Induction Furnace



(a) Heat loss distribuftion for a high-frequency furnace
The values in parenthesis indicate heat loss [%]

(b) Heat loss distribuftion for a low-frequency furnace
The values in parenthesis indicate heat loss [%]

Table 1.9 Electricity Consumption of Induction Furnace (Example)

High frequency furnace

Furnace capacity [kg]	Frequency [kHz]	Furnace input [kW]	Cast iron (1,500 °C)			Cast steel (1,600 °C)		
			Melting time [minimum]	Melting rate [t/h]	Power consumption [kWh/t]	Melting time [minimum]	Melting rate [t/h]	Power consumption [kWh/t]
30	3	60	22	0.081	749	26	0.069	886
50	2	80	27	0.113	721	31	0.097	833
100	2	200	18	0.332	611	19	0.311	652
200	1	200	38	0.318	638	41	0.292	696
300	1	200	58	0.309	657	65	0.277	732
300	1	450	23	0.792	576	24	0.753	606
500	0.5	500	33	0.908	533	35	0.862	562
500	0.5	500	27	1.109	524	26	1.060	548
1000	0.5	1200	26	2.292	507	26	2.214	525
1500	0.5	600	85	1.065	545	90	0.997	583
1500	0.5	900	54	1.669	522	57	1.592	548
1500	0.5	1500	31	2.877	505	32	2.781	522
2000	0.5	900	72	1.660	525	76	1.574	554
2000	0.5	1200	53	2.264	513	55	2.169	536
2000	0.5	1800	35	3.472	502	36	3.358	519
3000	0.5	1200	80	2.244	518	84	2.137	544
3000	0.5	1500	83	2.848	510	66	2.731	532
3000	0.5	2400	39	4.659	499	40	4.514	515
5000	0.5	1800	88	3.399	513	92	3.274	532

Note 1: The capacity in this table does not include the necessary time for holding.
2: Actual electricity consumption will be about 100 kWh/t higher than these data if the necessary time for holding is included.

Low frequency induction furnace

Furnace			Cast iron melting						Cast steel melting		
Capacity [t]	Transformer [kVA]	Power input [kW]	1,450 °C melting		1,550 °C melting		100 °C temperature rise		Power input [kW]	1,600 °C melting	
			[t/h]	[kWh/t]	[t/h]	[kWh/t]	[t/h]	[kWh/t]		[t/h]	[kWh/t]
1	400	350	0.57	590	0.53	630	7.8	45	300	0.34	860
1.5	600	500	0.85	570	0.79	610	11.9	42	450	0.56	775
2	700	600	1.05	550	0.98	590	14.8	40.5	550	0.72	735
3	1000	800	1.46	530	1.36	570	20.3	39.3	700	0.96	710
4	1200	1000	1.86	520	1.73	560	25.9	38.7	850	1.16	710
5	1450	1200	2.28	510	2.11	550	31.6	38	1000	1.4	690
6	1650	1400	2.66	510	2.46	550	37	37.6	1200	1.7	685
8	2150	1800	3.49	500	3.23	540	48.6	37	1550	2.27	665
10	2500	2100	4.08	500	3.77	540	56.9	36.9	1800	2.66	660
12	2800	2400	4.7	495	4.39	535	65	36.9			
15	3300	2800	5.5	490	5.13	530	72	36.9			
16	3800	3200	6.3	490	5.8	530	87.6	36.5			
18	4800	4000	8.0	485	7.4	520	110	36.1			
20	5800	4800	9.7	480	9.3	505	133	36			
25	7200	5000	12.3	475	11.3	510	169	35.5			
30	9000	7500	15.4	470	14.3	510	212	35.5			
40	12000	10000	20.7	470	19.1	510	283	35.5			

Note 1: The capacity in the table is for 1/2 remaining molten metal operation and does not include the necessary time for holding (ex. removing slag, measuring temperature, adjustment of composition and pouring-out).
The practical melting rate becomes 80 to 60 % of the rate indicated in this table.
2: Actual electricity consumption will be about 100 kWh/t higher than these data if the necessary time for holding is included.

② Low Frequency Induction Furnaces

Compared to a high frequency induction furnace with identical melting capacity (t/h), a low frequency furnace requires a 3 times greater furnace size (if the melting capacity is identical, power source capacity is about the same). Thus, since its radiation heat loss is greater than that in a high frequency induction furnace, its power consumption for holding and melting also become greater.

For this reason, high frequency furnaces characterized by small size and largecapacitance are becoming the mainstream while low frequency crucible induction furnaces are diminishing in number. Although high frequency furnaces are considered better in terms of energy conservation, low frequency furnaces can stir molten metal with greater force, which enables them to be made in furnace sizes of greater scale, thus, depending on production conditions, such as the manufacture of large scale products, they are still widely used.

On the other hand, there are examples in which low frequency induction furnaces are used for double melting in conjunction with cupolas, and as retaining furnaces, and from the standpoint of reducing running cost, they are chosen as replacement furnaces for channel furnaces.

③ Channel Induction Furnace

While they are highly efficient, and have better furnace holding power consumption rates than low frequency induction furnaces, they have the disadvantage of having to always have molten metal in the furnace, which requires them to always be charged with electric power. Usually, they are used as retaining furnaces (especially large capacity retaining furnaces), but they suffer deficiencies in terms of difficulties in changing molten metal material, and long furnace repair periods.

On the other hand, although low frequency induction furnaces usually have high holding power consumption rates, their furnaces can be emptied when operation is halted for several days, so depending on the mode of operation, the running cost of low frequency induction furnaces may be lower.

Further, the holding power of a channel furnace is 125 kwh/ht (retaining 1,500 °C) for a 10 t furnace, while that figure for a low frequency induction furnace of 10 t (effective capacity; 7 t furnace) is about 165 kwh/ht (retaining 1,500 °C).

2. ENERGY CONSERVATION IN THE CHEMICAL INDUSTRY

2. ENERGY CONSERVATION IN THE CHEMICAL INDUSTRY

2.1 Characteristics of Energy Consumption in the Chemical Industry

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

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

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

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

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

2.2 Rationalization in the Use of Thermal Energy

2.2.1 Combustion Equipment

(1) Fuel

a. Gaseous fuel

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

b. Solid fuel

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

c. Liquid fuel

Liquid fuel is generally of petroleum fuel, and represented by diesel oil or gas oil, and fuel oils. Since fuel oil contains sulfur, the combustion gas usually contains 0.1 to 0.25 % SO_2 and further 1 to 5 % of such SO_2 is converted into SO_3, causing corrosion.

d. Calorific value

1) Solid and liquid fuels

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

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

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

Lower calorific value, $H\ell = Hh - 600\ (9h + w)$ kcal/kg

2) Calorific value of gaseous fuel

When combustible components contained in 1 m^3_N fuel for example, CH_4 and H_2 are represented by ch_4 and h_2 (m^3_N) respectively,

$$\text{Higher calorific value, Hh} = (3{,}055 \cdot co + 3{,}036 \cdot h_2 + 9{,}498 \cdot ch_4 + 14{,}982 \cdot c_2h_2 + 35{,}702 \cdot c_6h_6 + \cdots)\ \text{kcal/m}^3_N$$

$$\text{Lower calorific value, Hl} = Hh - 600\ (18/22.4)\ (h_2 + 2\ ch_4 + c_2h_2 + 3\ c_6h_6 + \cdots)\ \text{kcal/m}^3_N$$

e. Air ratio and volume of combustion gas

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

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

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

Figure 2.1 to Figure 2.3 show relations between calorific values of solid, liquid and gaseous fuels against volume of air and combustion gas at various air ratios.

Figure 2.1 Relation between Low Calorific Value of Solid Fuel and Combustion Gas Amount, and Theoretical Air Amount

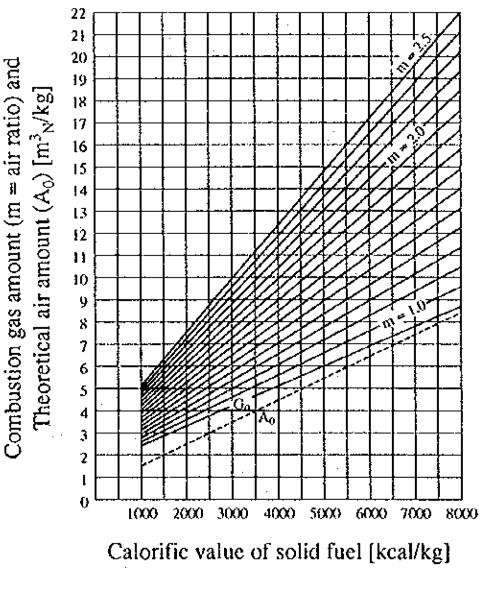


Figure 2.2 Relation between Low Calorific Value of Liquid Fuel and Combustion Gas Amount, and Theoretical Air Amount

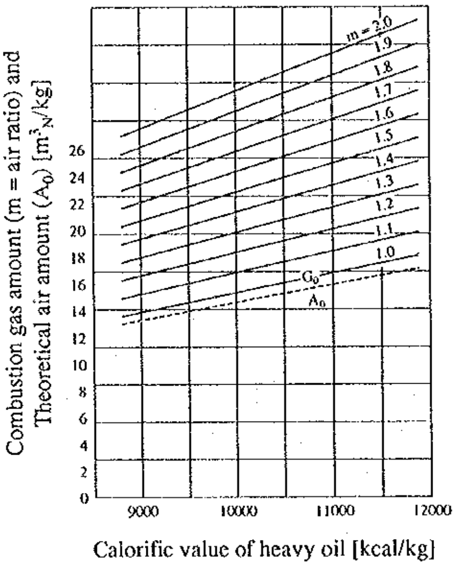
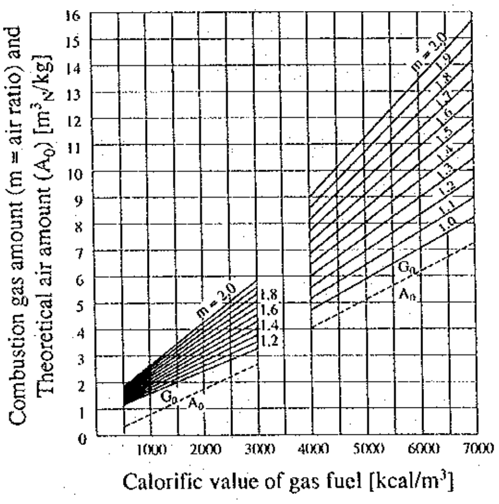


Figure 2.3 Relation between Low Calorific Value of Gas Fuel and Combustion Gas Amount, and Theoretical Air Amount



(2) Heat Balance and Thermal Efficiency

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

To calculate the heat balance,

① Properties of the used fuel

② Fuel consumption

③ Temperature of air

④ Composition of combustion products

⑤ Temperature of flue gas

⑥ Amount and temperature of heated matters

⑦ Amount and composition of unburnt matters

⑧ Chemical reaction in heated matters, etc. on a basis of which the following calculations are made:

- Heat input

  Heat content retained by fuel
  $(Q \times F) + (F \times Cpf \times \Delta t)$

  Sensible heat of air
  $V \times Cpv \times \Delta t$

  Heat content carried in by heated matters
  $M \times Cpm \times \Delta t$

  Heat input due to chemical changes
  $H \times M$

- Heat output

  Heat content carried out by heated matters
  $M \times Cpm \times \Delta t$

  Heat content carried out by combustion exhaust gas
  $(E \times Cpe \times \Delta t) + (S \times Cps \times \Delta t) + 600\ S$ (when based on higher calorific value)

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

Heat loss due to unburnt matters in combustion residue

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

Heat loss due to radiation, conduction, etc.

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

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

$$hr = 4.88\ [(To/100)^4 - (Ta/100)^4],\ \varepsilon/\Delta t\ \frac{\lambda\,(Ti-To)}{\ell}\cdot A$$

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

(Symbols)

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

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

a. Reduction in air ratio

Heat carried out by combustion exhaust gas is greatly influenced by the volume of exhaust gas as mentioned in item (2), which is directly related to the air ratio. Heat loss due to the exhaust gas increases linearly with increase in the air ratio as shown in Figure 2.4 and Figure 2.5. Therefore, the less the air ratio is, the less heat loss ought to be. Since, however, heat loss due to incomplete combustion takes place when the air ratio is less than 1.01, the maximum value for thermal efficiency exists while the air ratio is between 1.02 and 1.10 (Figure 2.5)

Figure 2.4 Relation between Air Ratio and Waste Gas Loss

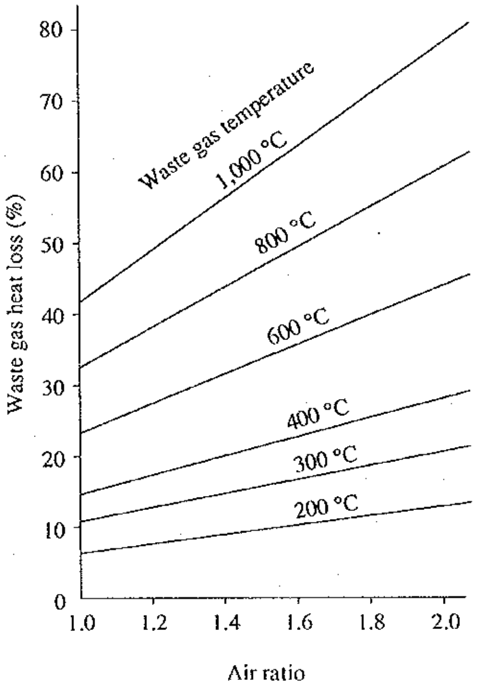
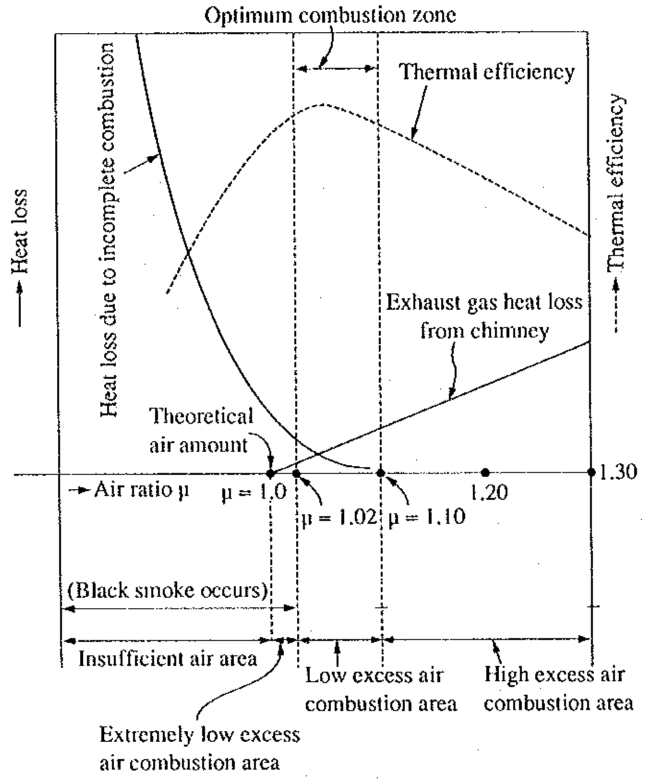


Figure 2.5 Relation between Air Ratio and Thermal Efficiency



However, at the general combustion equipment, the load usually fluctuates and, incomplete combustion may generate black smoke due to a low air ratio in the process of changes in the fuel amount. Therefore, the equipment should be, in fact, operated at an air ratio of approximately1.2 to 1.3, including some allowance. (Table 2.1)

Table 2.1 Standard Air Ratio

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

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

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

b. Recovery of Waste Heat

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

1) Preheating of raw material

Since raw material is usually charged at normal temperatures, a preheating chamber is provided at the material charging place and exhaust gas is introduced here to heat the raw material. Suspension preheater systems in cement plants are a good example of this method. (Figure 2.6)

2) Preheating of combustion air

When temperature of combustion air is raised by the use of a heat exchanger, the used amount of fuel will decrease as can be seen from the heat balance . As one example, air preheating temperature and fuel economy rate at air ratio of 1.3 are shown in Figure 2.7. Here, corrosion due to sulfur contained in fuel should be paid attention to. Sulfur is in the form of SO_2 in the exhaust gas, and a portion of such SO_2 is converted into SO_3. SO_3 further combines with water vapor in the combustion gas into sulfuric acid vapor, which reaches the dew point at low temperature walls to liquefy, corroding the heat exchanger. The dew point temperature, which is influenced by the concentration of S content in the fuel, is difficult to clarify theoretically and determined empirically. It is generally said to be 110 to 160 °C for fuel oil combustion. (Refer to the item for Boiler in a later section.)

Figure 2.6 New Suspension Preheater System Cement Plant

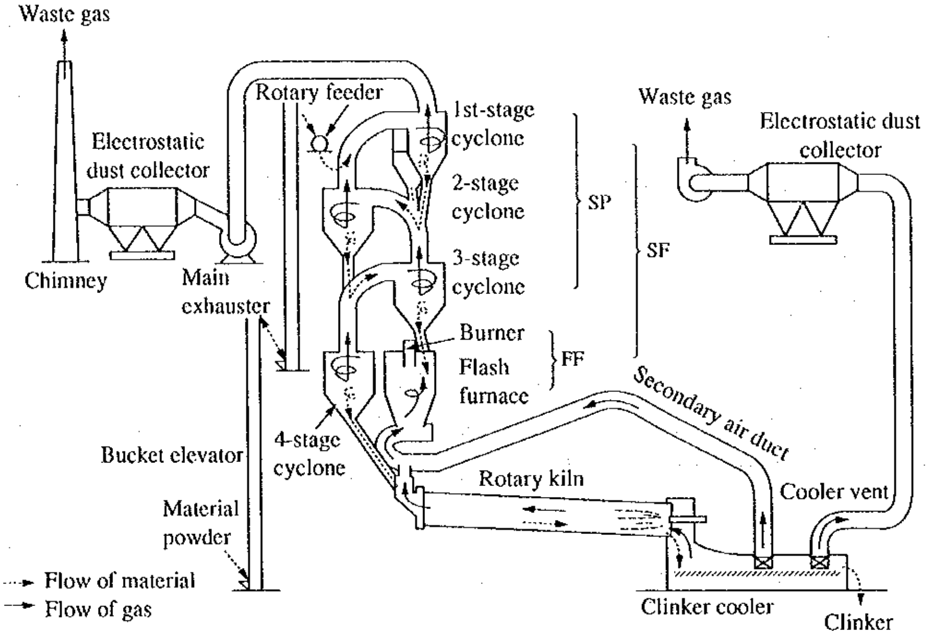
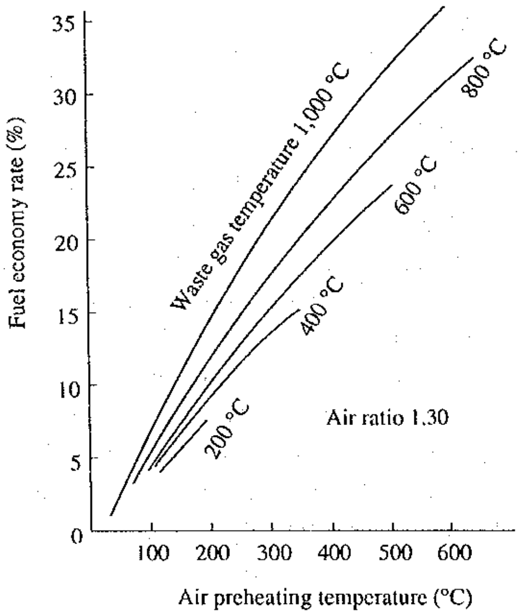


Figure 2.7 Fuel Economy due to Air Preheating



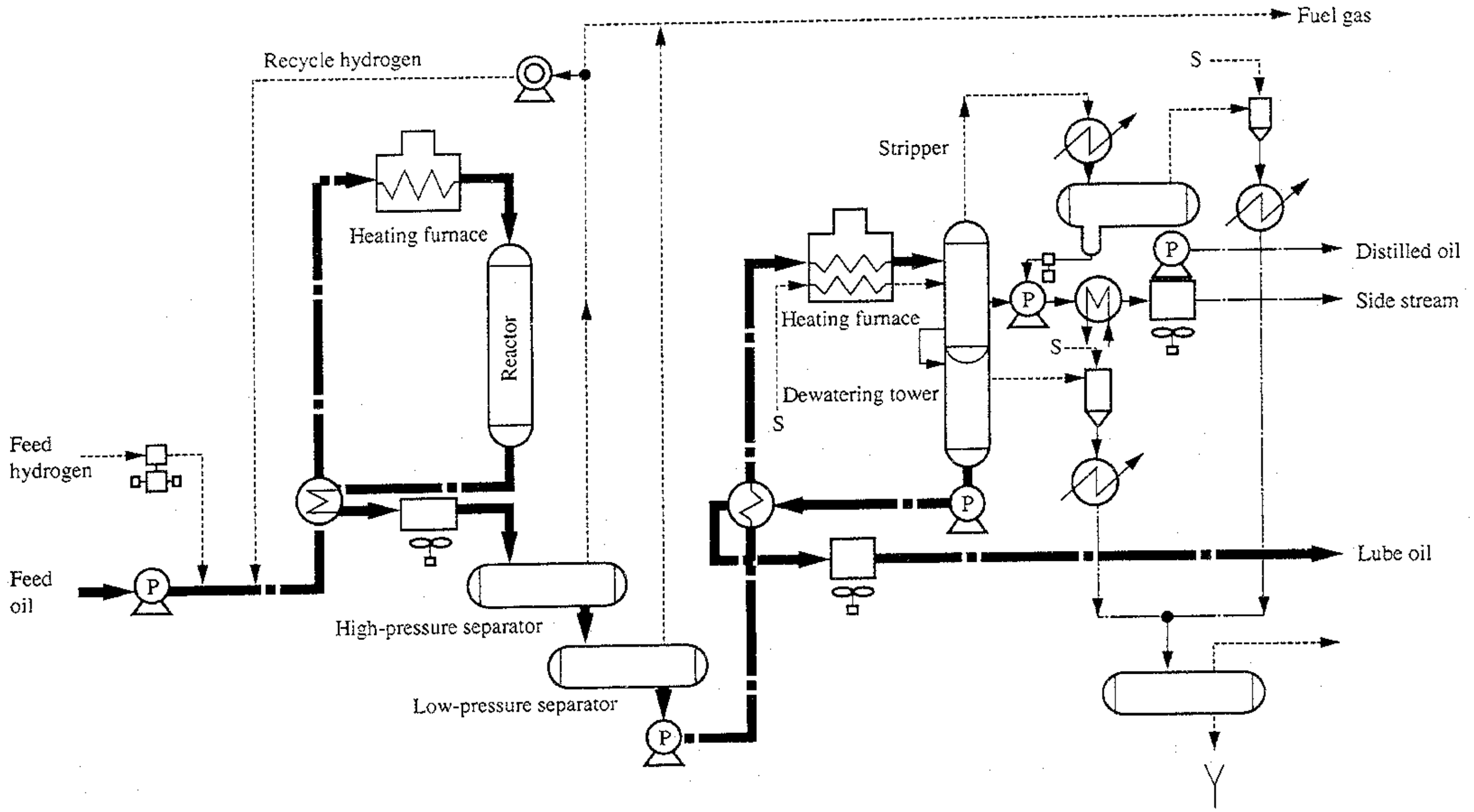
3) Utilization as other heating source

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

c. Utilization of Sensible Heat of Heated Matters

Heated matters from combustion equipment are at high temperature, and as such they, except as subsequently treated in the next process, generally are cooled to ambient temperature or mostly quenched to prevent side reaction. In such a case, the sensible heat of heated matters should be recovered for effective utilization. Good examples of use include utilization of clinker cooling air as primary combustion air in cement plants (see Figure 2.6); a waste heat boiler for quenching gas at the outlet of the cracking furnace in ethylene plants; heat recovery to the fuel oil for the reheating furnace in the lubricating oil manufacturing process (Gulfinning process; hydro-refining process) (see Figure 2.8).

Figure 2.8 Lube Oil Manufacturing Process (Gulfinning Process)



2.2.2 Heat Transfer Equipment

(1) Basic Calculation of Heat Transfer

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

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

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

a. Heat transfer by conduction

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

1) In the case of plane

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

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

where A_o: Area of a surface perpendicular to the direction of heat transfer (m^2)
Δt: Temperature difference between low and high temperature surfaces (°C)
l : Thickness of plate (m)
λ : Heat conductivity of plate (kcal /mh°C)

Assuming $(lj/\lambda j) = R$, R may be called heat resistance.

2) In the case of cylindrical surface

Using the same symbols as item a.

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

where L : length of cylinder (m)
r_j, r_{j+1}: Inside and outside diameters of jth layer (from inside) (m)

b. Heat transfer by convection

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

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

i) In the case of plate

Convection from lower surface

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

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

Note: Refer to Table 2.2.

where Δt : Temperature difference (°C)
ℓ : Representative length of plane (m)
Gr: Grashof number
Pr : Prandtl number

Convection from upper surface

$$\alpha_m = 2.27\ (\Delta t/l)^{1/4} \qquad (\text{kcal/m}^2\text{h}^\circ\text{C}) \qquad 10^5 < Gr \cdot Pr < 2 \times 10^7$$
$$\alpha_m = 0.831\ (\Delta t)^{1/3} \qquad (\text{kcal/m}^2\text{h}^\circ\text{C}) \qquad 2 \times 10^7 < Gr \cdot Pr < 3 \times 10^{10}$$

Convection from vertical surface

$$\alpha_m = 1.22\ (\Delta t/H)^{1/4} \qquad (\text{kcal/m}^2\text{h}^\circ\text{C}) \qquad 10^4 < Gr \cdot Pr < 10^9$$
$$\alpha_m = 1.13\ (\Delta t)^{1/3} \qquad (\text{kcal/m}^2\text{h}^\circ\text{C}) \qquad 10^9 < Gr \cdot Pr < 10^{12}$$

where H: Height of vertical surface

In addition, more simplified value equations may be employed.

Convection from the lower surface

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

Convection from the upper surface

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

Convection from the vertical surface

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

ii) In the case of horizontal pipe

$\alpha_m = 1.14\ (\Delta t/D)^{1/4}$ (kcal/m²h°C) $10^4 < Gr\cdot Pr < 10^9$
$\alpha_m = 1.07\ (\Delta t)^{1/3}$ (kcal/m²h°C) $10^9 < Gr\cdot Pr < 10^{12}$
$\alpha_m = 0.4\ (\lambda D)$ (When D is small) (kcal/m²h°C) $Gr\cdot Pr < 10^{-5}$

when D: Outside diameter of pipe (m)

Table 2.2 Dimensionless Terms Related to Heat Transfer

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

Note: Cp: Specific heat at constant pressure
D : Diameter or representative length
Δt : Temperature difference
u : Average velocity of flow
g : Gravitational acceleration
λ : Heat conductivity
μ : Viscosity ρ: Density $\nu = \mu/\rho$: Kinetic viscosity
β : Coefficient of thermal expansion

2) Heat transfer coefficient, a in forced convection

i) Inside heat transfer coefficient

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

where D : Inside diameter of pipe (m)
η : Viscosity of fluid
η_w: Viscosity of fluid at tube wall temperature

ii) Outside heat transfer coefficient

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

where D: Outside diameter of pipe (m)

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

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

c. Heat transfer by radiation

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

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

where ε : Emissivity of object
A: Surface area of object (m^2)

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

$$Q = A_1F_{12}\left(\frac{4.88}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}\right)[(T_1/100)^4-(T_2/100)^4] \qquad \text{(kcal/h)}$$

where A_1 : Radiation area of object 1 (m^2)
F_{12} : Coefficient determined by relative position of object (View factor)
T_1, T_2: Respective temperatures (K)
ε_1, ε_2 : Respective emissivity

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

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

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

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

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

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

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

$$Q_k = A \cdot (t_i - t_w) / \sum_{j=1}^{n} (\ell j / \lambda j) \quad \cdots\cdots (2)$$

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

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

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

(2) Heat Transfer Calculation of Heat Exchanger

a. Overall heat transfer coefficient

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

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

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

Since the fouling factor depends on type of fluid, temperature, fluid velocity, and the degree of cleaning, it is difficult to discuss generally. For reference, an example of various fouling factor is shown in Table 2.3. Heat transfer is greatly influenced by the degree and frequency of cleaning of the heat exchanger. Therefore, maintenance of the heat exchanger has a great influence on energy conservation.

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

The correction is determined by the layout of tubes, the number of arrangements, the flow direction, etc. and is complicated. Here, the description is omitted and actual examples of overall heat transfer coefficient are shown in Table 2.4.

Table 2.3 Fouling Factor ($m^2h\cdot c/kcal$)

(a) Fouling factor for water

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

(b) Fouling factor for various fluids

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

Table 2.4 Overall Coefficient of Heat Transfer of Multi-tube Heat Exchangers

Service condition	High temperature fluid	Low temperature fluid	Overall coefficient of heat transfer (kcal/m^2·hr·°C)
Cooler	Water	Water	1,200~2,500 *1
	Methanol	"	1,200~2,500 *1
	Ammonia	"	1,200~2,500 *1
	Water solution	"	1,200~2,500 *1
	Organic matter viscosity 0.5cP or below*4	"	350~ 750
	Organic matter viscosity 0.5 to 1.0CP*5	"	250~ 600
	Organic matter viscosity 1.0cP or below*4	"	25~ 400 *2
	Gas	"	16~ 250 *3
	Water	Brine	500~1,000
	Organic matter viscosity 0.5cP or below*4	Brine	200~ 500
Heater	Steam	Water	1,000~3,500 *1
	"	Methanol	1,000~3,500 *1
	"	Ammonia	1,000~3,500 *1
	"	Water solution viscosity 2.0cP or below	1,000~3,500
	"	Water solution viscosity 2.0cP or above	500~2,500 *1
	"	Organic matter viscosity 0.5cP or below	500~1,000
	"	Organic matter viscosity 0.5 to 1.0cP*5	250~ 500
	"	Organic matter viscosity 1.0cP or above	30~ 300
	"	Gas	25~ 250 *3
Heat exchanger	Water	Water	1,200~2,500 *1
	Water solution	Water solution	1,200~2,500 *1
	Organic matter viscosity 0.5cP or below*4	Organic matter viscosity 0.5cP or below*4	200~ 400
	Organic matter viscosity 0.5 to 1.0cP*5	Organic matter viscosity 0.5 to 1.0cP*3	100~ 300
	Organic matter viscosity 1.0cP or above*6	Organic matter viscosity 1.0cP or above*6	50~ 200
	Organic matter viscosity 1.0cP or above*6	Organic matter viscosity 0.5cP or below*4	150~ 300
	Organic matter viscosity 0.5cP or below*4	Organic matter viscosity 1.0cP or above*6	50~ 200

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

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

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

b. Mean temperature difference

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

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

where A_o : Heating surface based on outside tube

Δt_m: Mean temperature difference between both fluids

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

$$Q = A_o \cdot U_o \cdot (\Delta t_1 - \Delta t_2) / \ell n (\Delta t_1 / \Delta t_2) \qquad (2)$$

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

Equispacing equations (1) and (2),

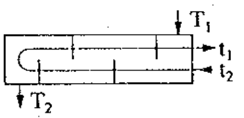
$$\Delta t\ell_m = (\Delta t_1 - \Delta t_2) / \ell n (\Delta t_1 / \Delta t_2) \qquad (3)$$

This is called logarithmic mean temperature difference ($\Delta t\ell m$). In many of the heat exchangers in practical use, the fluid channel is complicated as shown in Figure 2.9 and, as such, the temperature difference value calculated from equation (3) cannot be used as-is but needs some correction. Treating the correction factor as F_T, mean temperature difference Δt_m is calculated by the following equation:

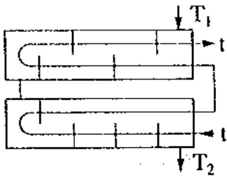
$$\Delta t_m = F_T \cdot \Delta t\ell_m = (\Delta t_1 - \Delta t_2) / \ell n (\Delta t_1 / \Delta t_2) \qquad (4)$$

Values F_T due to each channel configuration are shown in Figure 2.10

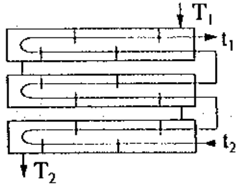
Figure 2.9 Shell/Tube Type Heat Exchanger



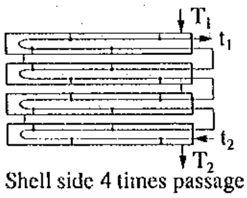
Once shell side passage
Even 2 times tube side passage



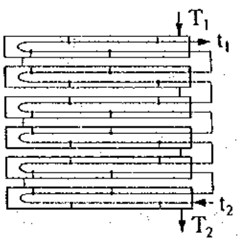
Two times shell side passage
Tube side 4, 8, 12 ...... times passage



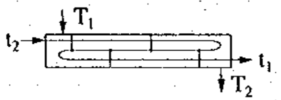
Shell side 3 times passage
Tube side 6, 12, 18 ...... times passage



Shell side 4 times passage
Tube side 8, 16, 24 ...... times passage

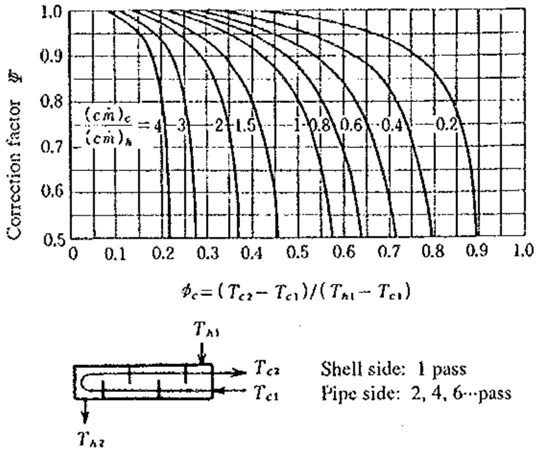


Shell side 6 times passage
Tube side 12, 24, 36 ...... times passage

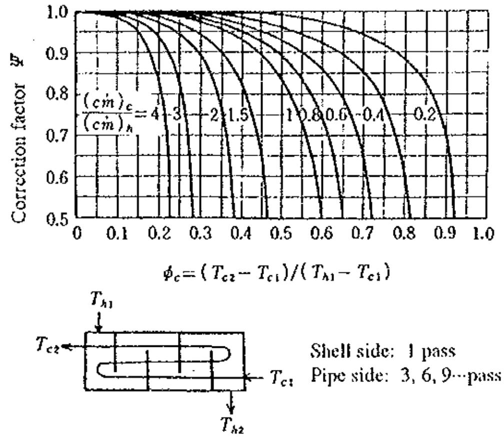


Tube side odd times passage per
Shell side passage

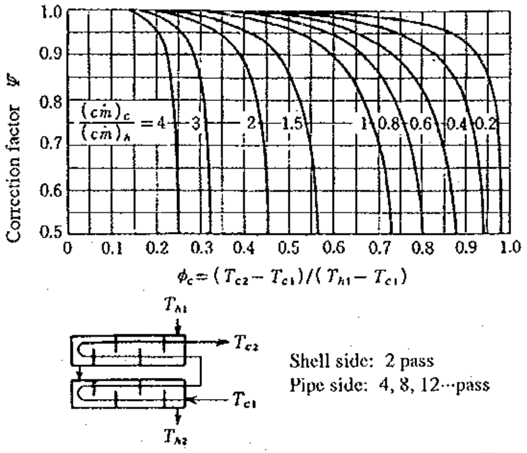
Figure 2.10 Correction Factor F_T



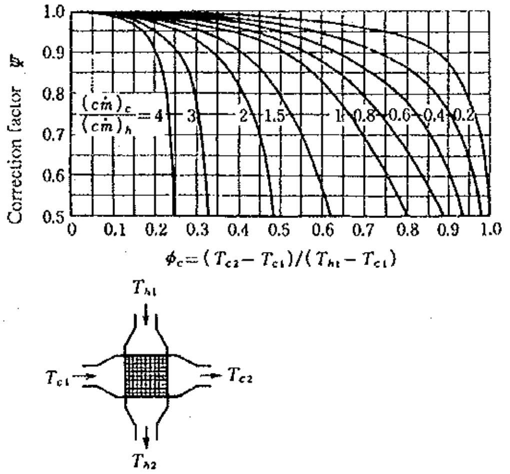
(a) Correction factor for 1-2 pass heat exchanger ψ (2)



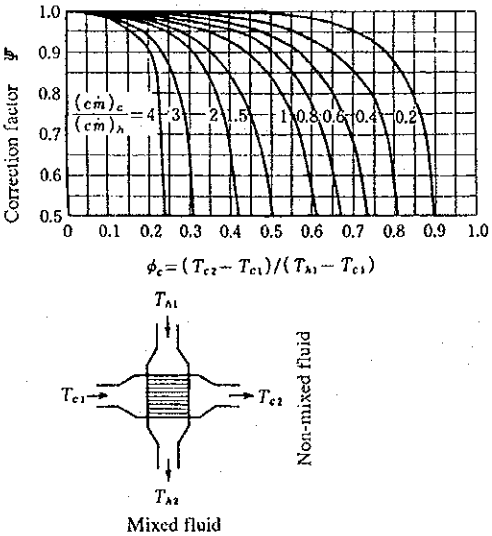
(b) Correction factor for 1-3 pass heat exchanger ψ (2)



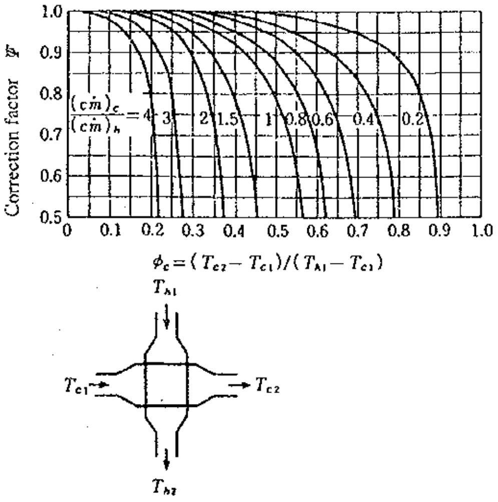
(c) Correction factor for 2-4 pass heat exchanger ψ (2)



(d) Correction factor for DC/AC heat exchanger where neither of the fluids mix ψ (2)



(e) Correction factor for DC/AC heat exchanger where only one fluid mixes ψ (2)



(f) Correction factor for DC/AC heat exchanger where both fluids mix ψ (2)

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

(3) Types of heat exchangers

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

a. Tubular type (Figure 2.11 to Figure 2.14)

1) Coil type heat exchanger

2) Trombone type (Cooler)

3) Double tube type heat exchanger

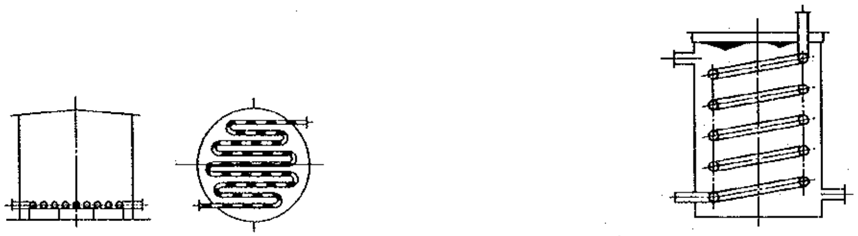
4) Multitubular heat exchanger

① Fixed tube plate type

② Floating head type

③ U-tube type

Figure 2.11 Coil Type Heat Exchanger



(a) Tank heater

(b) Coil type heat exchanger

Figure 2.12 Trombone Cooler Exchanger

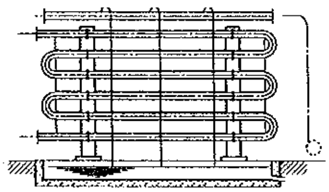


Figure 2.13 Double Tube Type Heat Exchanger

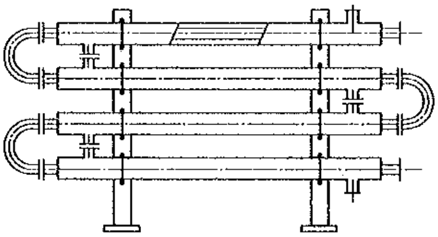
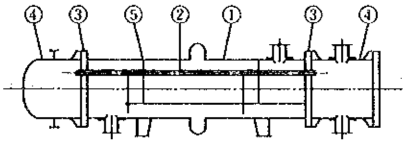
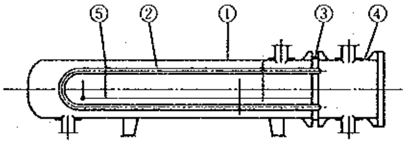


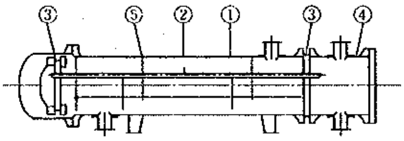
Figure 2.14 Multi-Tube Type Heat Exchanger



(a) Fixed tube plate type heat exchanger



(b) U-tube type heat exchanger



(c) Floating head type heat exchanger

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

b. Plate type (Figure 2.15 to Figure 2.16)

1) Jacket type heat exchanger

2) Plate type heat exchanger

3) Spiral type heat exchanger

Figure 2.15 Plate Type Heat Exchanger

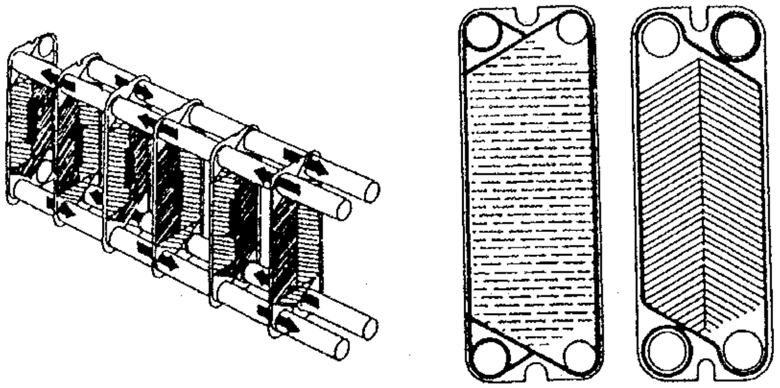
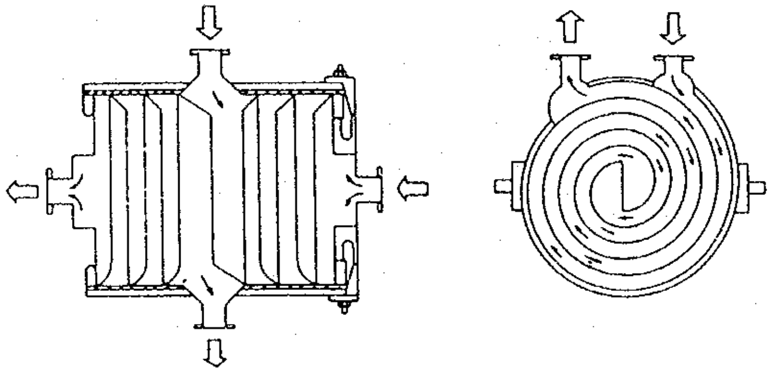


Figure 2.16 Spiral Type Heat Exchanger



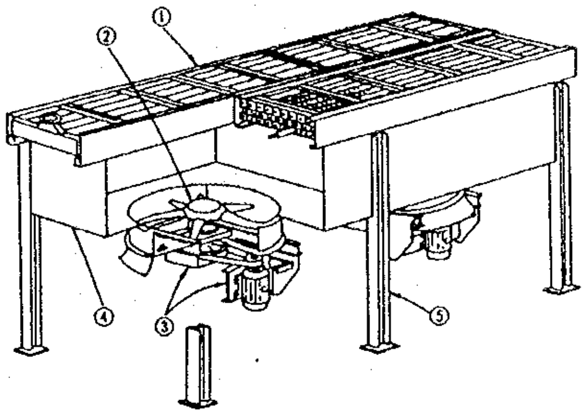
c. Special type (Figure 2.17)

1) Air cooling type heat exchanger

2) Bayonet heat exchanger

3) Compact heat exchanger

Figure 2.17 Air Cooling Type Heat Exchanger



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

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

Coil type heat exchangers:

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

Trombone type cooler:

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

Double tube type heat exchangers:

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

Multitubular heat exchangers:

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

Plate type heat exchanger:

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

Spiral heat exchangers:

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

Air cooling type heat exchangers:

Air cooling type heat exchangers consist of finned tubes, header, fan and its drive. Since the cooling medium is air, it is convenient when cooling water is dirty or in short supply. At their use, the installation place should be taken into due consideration so that cool fresh air can be introduced. Table 2.5 shows approximate values of overall heat transfer coefficients for heat exchangers.

Table 2.5 Approximate Values of Overall Heat Transfer Coefficients for Various Heat Exchangers (1/2)

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

Table 2.5 Approximate Values of Overall Heat Transfer Coefficients for Various Heat Exchangers (2/2)

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

(4) Rational use of heat energy

When heat exchangers are used for recovery of waste heat, a heat exchanger suitable for the temperature conditions and the fluid should be selected. It is equally important to maintain the main body of the heat exchanger and reinforce the heat insulation of piping.

2.2.3 Reactors

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

We follow their general classification and describe the respective characteristics:

(1) Classification by construction and form

a. Vessel type reactors

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

b. Tubular type reactors

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

c. Tower type reactors

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

(2) Classification by temperature control

a. Isothermal operation

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

b. Adiabatic operation

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

When heat of the reaction is great, some factories use a method to bring temperature distribution in the reactor close to optimum temperature distribution, in which the reaction layer is divided into several stages, a heat exchanger (or heater or cooler) is inserted between each stage, or reaction fluid at low temperature (or high temperature) is introduced to adjust temperature at inlet of each adiabatic reaction layer. This is called multiple adiabatic operation and is used for an SO_3 converter in a sulfuric acid plant and ammonia synthesis converter.

c. Heat exchange operation

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

(3) Rationalization in the use of thermal energy

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

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

For cooling for temperature control in the intermediate reaction layer or cooling of high temperature products at the reactor outlet, together with or separately from the raw material preheating method shown by Figure 2.8, it is desirable to effectively recover the heat of reaction and utilize it both outside and inside of the system by the following methods:

a. Heating of boiler feed water or steam generation.

b. Heating of air or of other fluids.

In the manufacture of dyestuff, when reaction such as diazo reaction generates a large amount of heat, it is necessary to control the amount of ice and chemicals for reaction depending on the reaction temperature so as to maintain the prescribed reaction temperature and thereby improve the yield.

2.2.4 Distilling plants

(1) Principle of distillation

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

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

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

<Reflux>

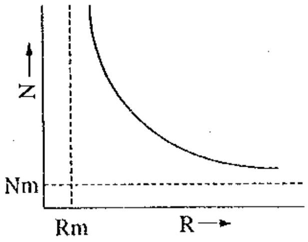
To keep the composition of the overhead product constant (in the case of continuous operation), or to improve separation from the high-boiling point component (for both batch and continuous operation), a portion of the overhead distillate is returned to the top, which is reflux. Ratio (Flow rate of reflux)/(Flow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

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

Relation between a number of plates (called "Theoretical number of plate"), N required to separate product at a specified concentration from original solution and the reflux ratio, R is shown in Figure 2.18.

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

Figure 2.18 Reflux Ratio vs Theoretical Number of Plates



<Relation between reflux ratio and thermal energy>

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

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

(2) Classification of distillation towers

a. Plate tower

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

b. Packed tower

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

(3) Rationalization in the Use of Energy

a. Optimization of reflux ratio

Although reduction in R leads to energy conservation as mentioned above, increase in the high-boiling point component in the overhead product and increase in the low-boiling point component in the bottom product occur, resulting in lowered performance of separation in the distilling plant. In general, taking into consideration adverse effects which may be caused by fluctuations in feed composition, fluctuations in pressure of heating steam, etc., it is, in most cases, seen that the operation is made at a larger value of R than required with margin. Although R is generally determined empirically, it is advisable to first endeavor to minimize the range of fluctuation in various fluctuating conditions and to determine the lowest value of R which will not affect the product by analyzing the composition and decreasing R gradually. Also, since value R is influenced by feed plates number, it is also a method to change the feed plates according to a method of trial and error.

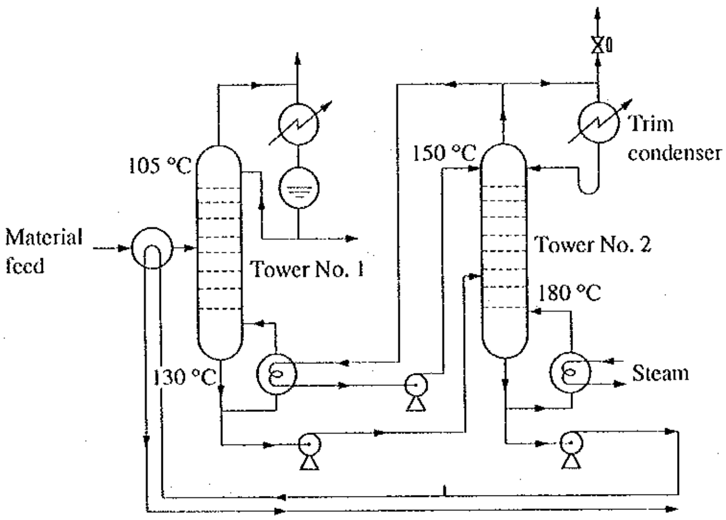
b. Cleaning of plates or packings

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

c. Recovery of waste heat due to heat exchanger

Since overhead vapor has latent heat, utilize this for the heater in another tower at low temperatures and preheat feed with sensible heat retained in the bottom product. (See Figure 2.19)

Figure 2.19 Heat Recovery of Distillate



Also, heat in the overhead condenser can be utilized to generate low pressure steam when the vapor is at high temperature. (See Figure 2.20)

There is a method to utilize vapor in the overhead product for the bottom heater by pressurizing the vapor to raise the condensation temperature, though it may be a somewhat expensive plant. (See Figure 2.21)

Figure 2.20 Steam Generation by Heat of Distillate

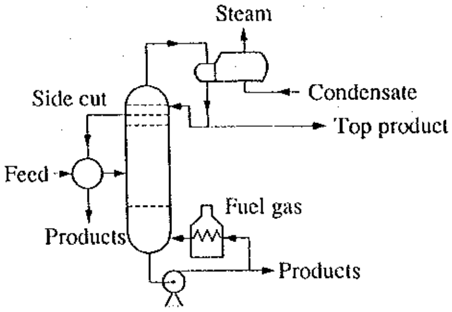
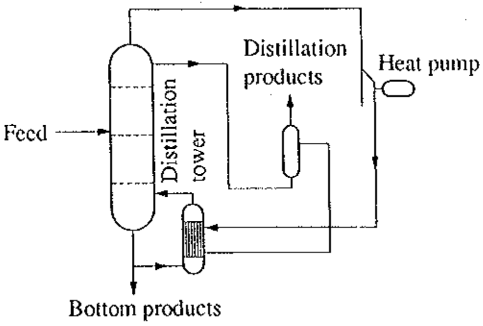


Figure 2.21 Use of Distillate Heat to Reboiler



d. Maintenance for and reinforcement of heat insulation

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

2.2.5 Evaporators

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

(1) Types of evaporators

Construction of typical evaporators is shown in Figure 2.22.

(a) is often used for batch type.

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

(c) is used in cases where liquid is naturally circulated, being heated while it falls down along a central large tube (called downtake), and rises within small tubes and this type is most widely used.

(d) is used in cases where solution becomes a vapor-liquid mixture in heating tubes and rises at a high rate in jet, and the efficiency is high.

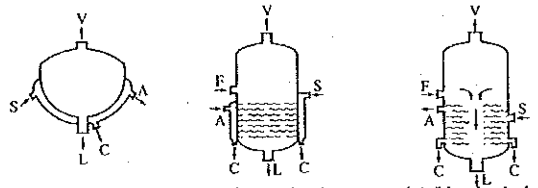
(e) is used in cases where heating and evaporation areas are separated and it is easy to replace and clean tubes and convenient to operate.

(f) and (f') are used in cases where solution evaporates while it is flowing down in the form of a film on the heating surface, and it is suitable for concentration of the solution with high viscosity and sensitivity to heat. Heat transfer portion has two types: one is vertical, long tube type (f), and the other is plate type (f'). The former is not suitable for solution which forms scale and crystal because of inside tube flow down system. Uniform distribution of solution on the heating surface is one of the important operating conditions for both types.

(g) is used in cases where evaporation is performed by blowing out hot gas in a liquid, or by installing a burner in the liquid, allowing it to burn directly and blowing out combustion gas at high temperatures in the liquid. Since evaporation is performed by direct liquid-gas contact in the presence of inert gas, concentration is performed at low temperatures, and the heat transfer capacity is great.

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

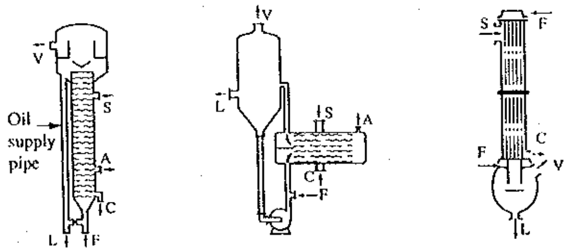
Figure 2.22 Example of Evaporators



(a) Jacketed evaporator

(b) Horizontal tube system (inside tube: steam)

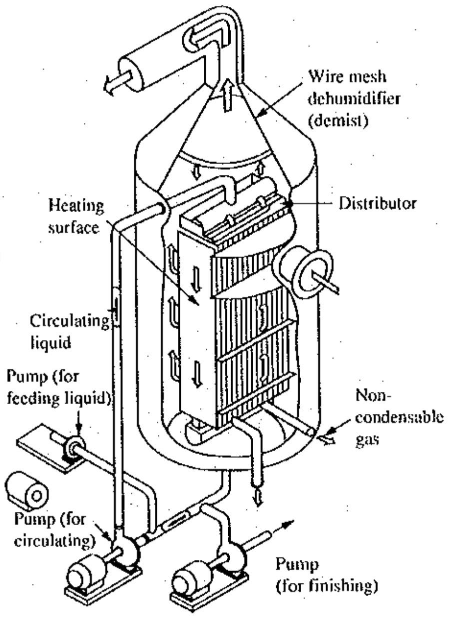
(c) Vertical short tube system (inside tube: liquid) (standard type)



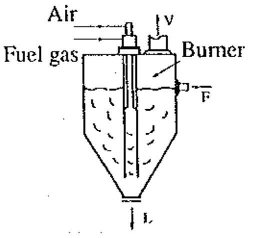
(d) L.T.V. type (Natural circulation system)

(e) External heating forced circulation system

(f) Falling-film evaporator



(f') Falling-film evaporator



(g) Submerged-combustion evaporator

A: Non-condensable gas outlet (vent)
C: Condensate outlet (drain)
F: Dilute liquor inlet
L: Thick liquor
S: Inlet of steam for heating
V: Evaporated vapor outlet

(2) Effective utilization of energy

Since evaporation requires a lot of energy, several methods shown in Figure 2.23 are adopted from an energy economy standpoint.

a. Vapor recovery method

Vapor is utilized as-is; (a)

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

b. Vapor compression method

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

c. Back pressure utilization method

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

d. Multiple effects method

Discussion later; (e)

e. Combination of above methods

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

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

(3) Rationalization in the use of thermal energy

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

a. Effect of scale

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

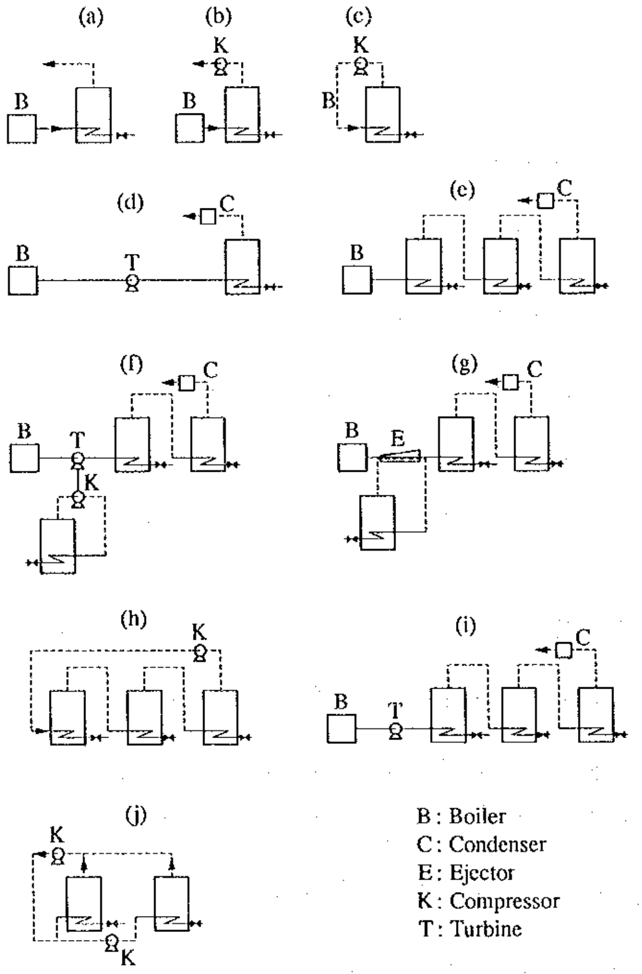
1) Remove scale formation ingredients beforehand.

2) Select pH, concentration, temperature, etc. of the liquid.

3) Introduce suitable chemicals.

4) Select the type of evaporator to which it is difficult for scale to stick, and clean thoroughly.

Figure 2.23 Classification of Evaporations Systems



b. Steam consumption in steam ejectors

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

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

*Note: Representing saturated pressure corresponding to water temperature in the barometric condenser as Pt_1, Pt_2, and ejector driving steam pressure corresponding to each of them as P_1, P_2 respectively,

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

(Unit) Pt_1, Pt_2: Torr
P_1, P_2 : kg/cm^2 (G)

c. Air purge in steam heating chamber

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

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

(4) Multi-effect method

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

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

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

where $P = Wy \cdot Cs/K$

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

Wy: Annual amount of evaporation (kg/y)

Cs : Unit price of steam

F_E : Fixed cost of evaporator

2.2.6 Dryers

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

(1) Types of dryers

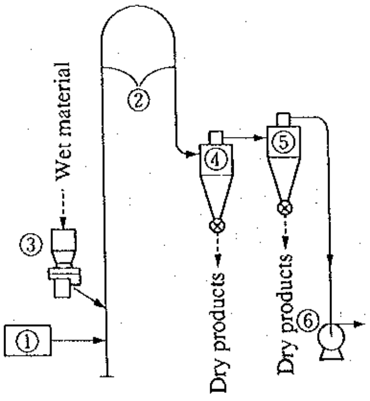
Dryers are classified by the relation between material moving system and heat transfer as follows:

a. Hot air dryers

1) Hot air conveying types

① Pneumatic dryer (See Figure 2.24)

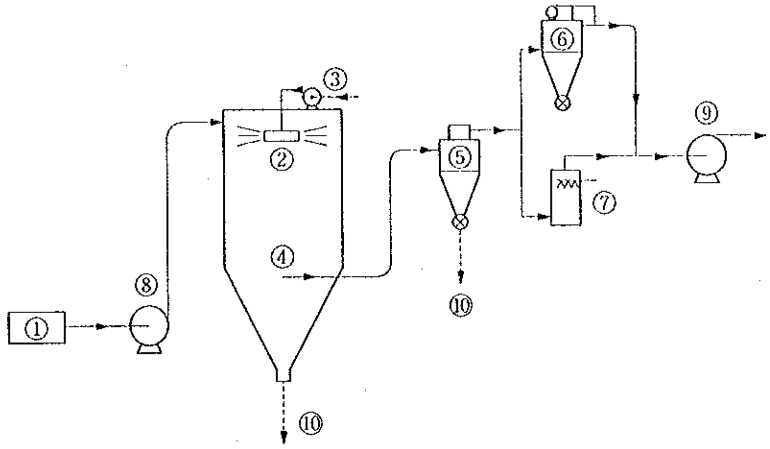
Figure 2.24 Pneumatic Dryer (Direct Feed System)



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

② Spray dryer (See Figure 2.25)

Figure 2.25 Spray Dryer

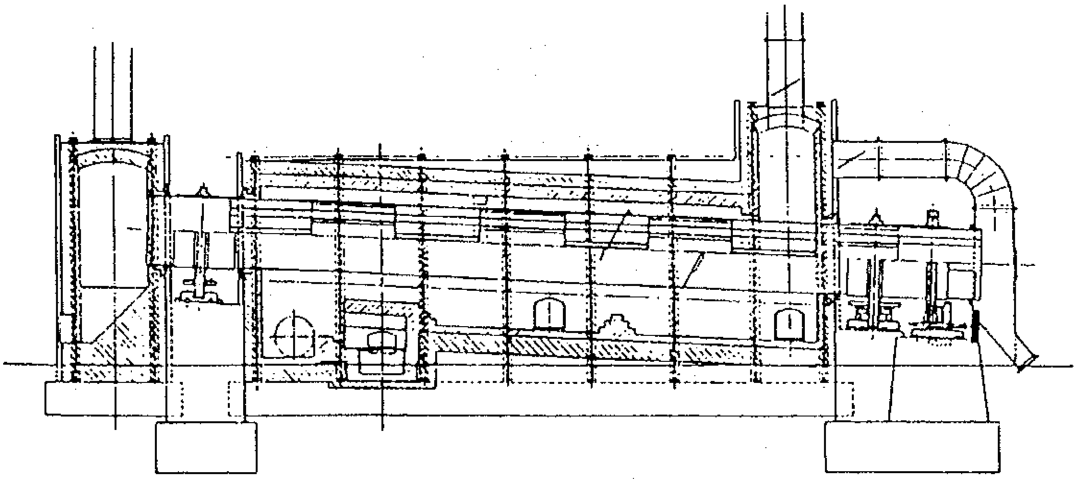


① Hot air producer ② Sprayer ③ Feed liquid pump ④ Drying tower
⑤ Cyclone collector ⑥ Bag filter ⑦ Scrubber ⑧ Blower ⑨ Exhauster
⑩ Dried products

2) Material agitation types

① Rotary dryers
- Single cylindrical direct heating type
- Double cylindrical indirect heating type
- External fire type (See Figure 2.26)

Figure 2.26 External Fire Type Rotary Dryer



② Muliple-stage disk dryer (See Figure 2.27)

③ Agitator trough dryer (See Figure 2.28)

④ Fluidized bed dryers
- Multi-stage continuous type
- One-stage continuous type (See Figure 2.29)
- Batch type

Figure 2.27 Multiple-Stage Disc Hot Air Dryer

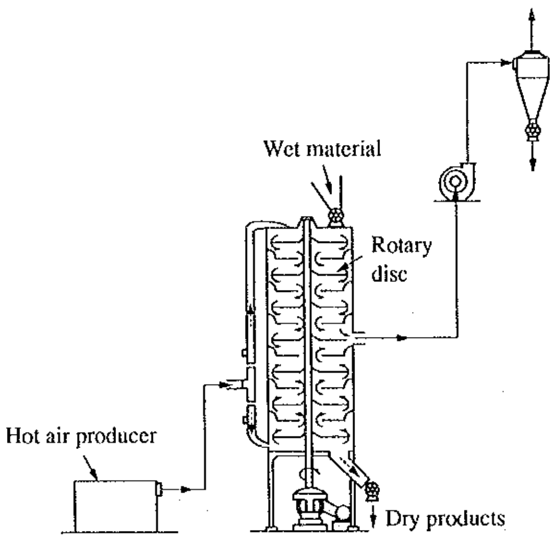
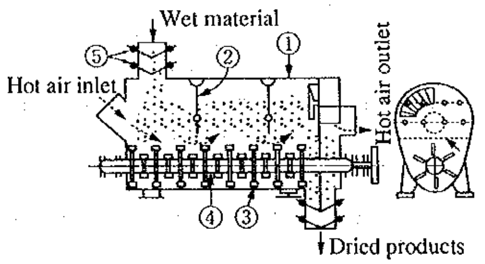
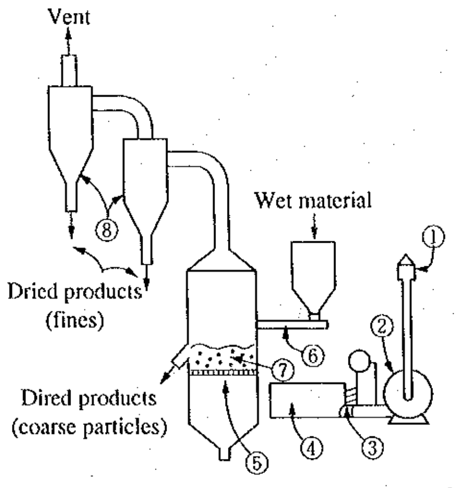


Figure 2.28 Agitator Trough Dryer



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

Figure 2.29 Continuous Fluidized Bed Dryer



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

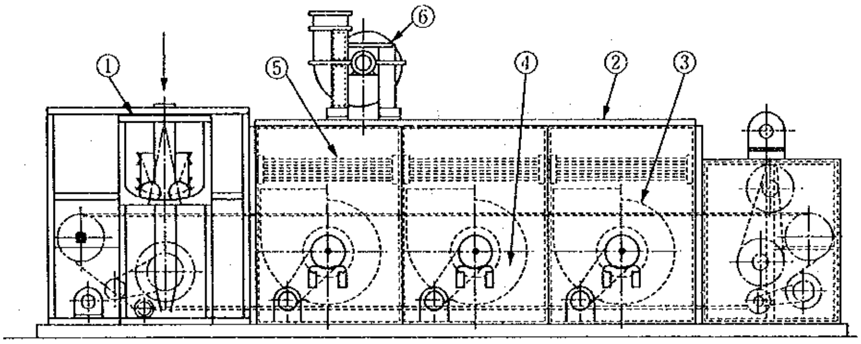
3) Material conveying types and stationary types

①	Through-circulation dryers	Band type (See Figure 2.30) Rotary type (See Figure 2.31) Vertical moving bed type (See Figure 2.32) Box batch type (Figure 2.33, Figure 2.34)

② Tunnel dryer (See Figure 2.35)

③ Verical nozzle jet dryer (See Figure 2.36)

Figure 2.30 Band Type Continuous Dryer



① Material molding machine ② Drying chamber ③ Conveyor
④ Hot air circulation blower ⑤ Heater ⑥ Exhauster

Figure 2.31 Rotary Type Continuous Dryer

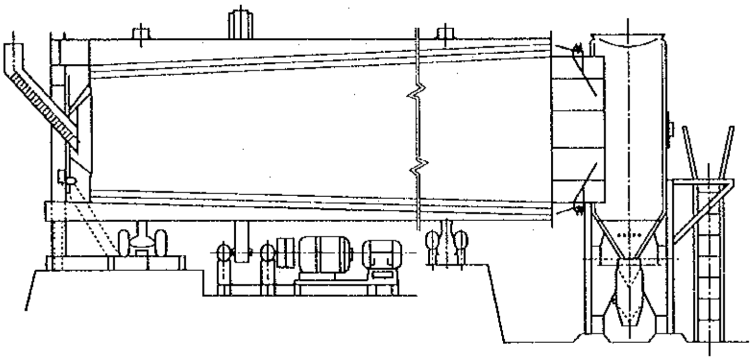


Figure 2.32 Vertical Moving Bed Dryer

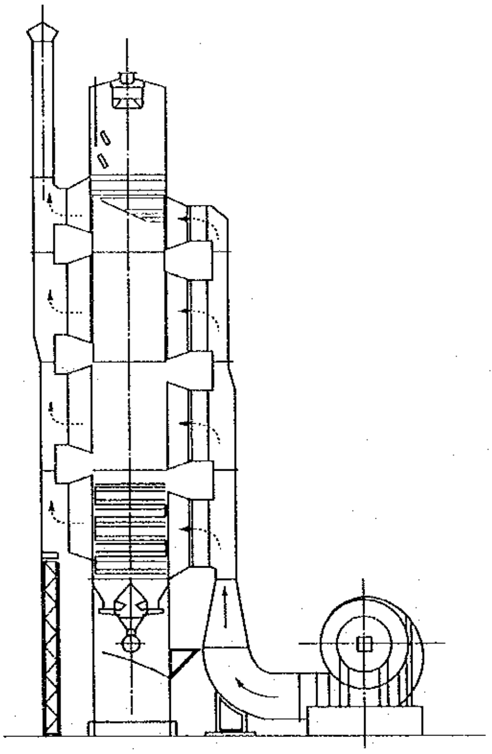


Figure 2.33 Box Type Dryer

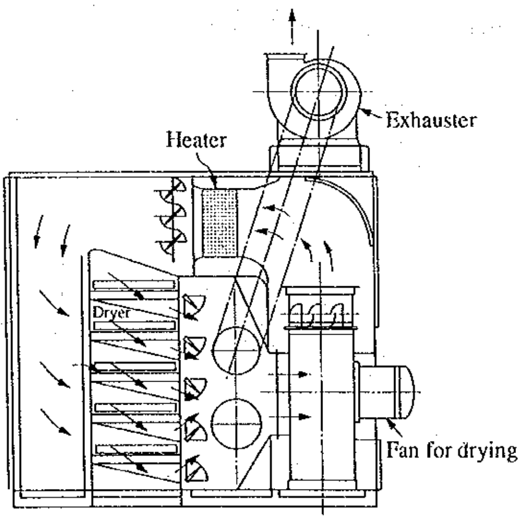
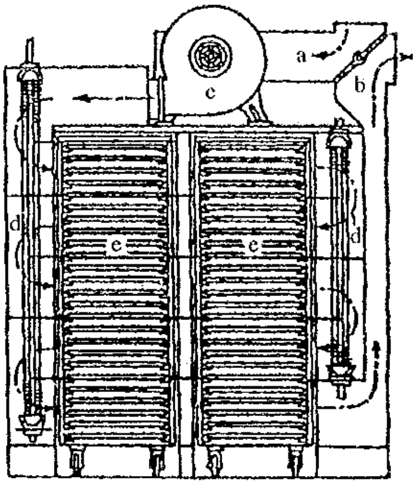


Figure 2.34 Batch System Parallel Flow Box Type Dryer



a: Air inlet, b: Air outlet, c: Blower
d: Air heater, e: Dryer trays

Figure 2.35 Tunnel Dryer

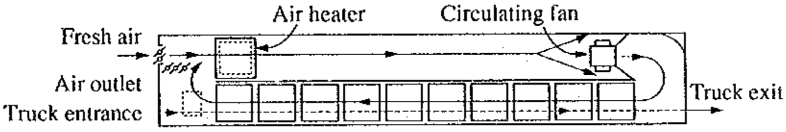
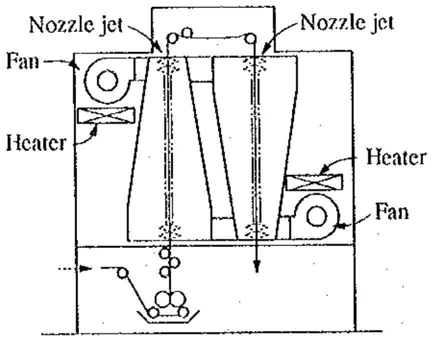


Figure 2.36 Vertical Nozzle Jet Dryer



b. Heat conduction dryers

1) Material agitation types

① Agitator trough dryer

② Cylindrical agitation dryers
  - Atmospheric pressure type
  - Vacuum type

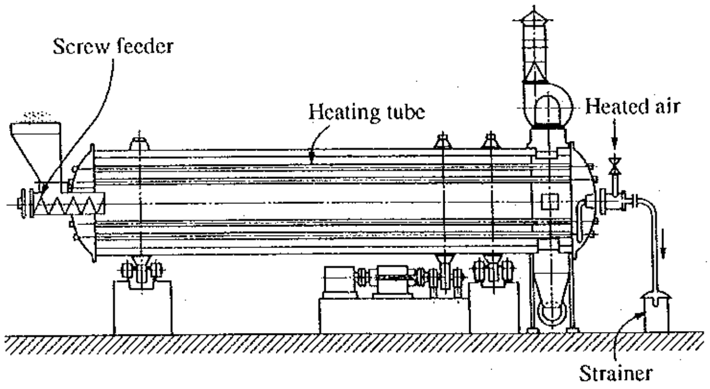
③ Plate agitation dryer

④ Steam tube rotary dryer (See Figure 2.37)

⑤ Multi-stage agitation dryer

⑥ Vacuum rotary dryer

Figure 2.37 Steam Tube Rotary Dryer



2) Material stationary types

① Vacuum tray dryer

② Freeze dryer

3) Cylindrical types

① Drum dryers { Atmospheric pressure type
                         Vacuum type

② Cylindrical dryer

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

Table 2.6 List of Dryers (1/2)

Name of Dryer			Dryer Mechanism and Main Characteristics	Heating capacity	①Heat capacity coefficient *ha* (kcal/m³hr°C) or heat transfer coefficient *U* (kcal/m²hr°C) ②Hot air temperature [°C] ③Thermal efficiency [%] ④Critical moisture content [%]	Properties of materials to be heated ①Forms ②Treatable moisture content	Application	Others
Hot air dring	Hot air carrying	Pneumatic dryer	To dry materials while making them float in the hot air current and conveying them in parallel ①Drying time is short (1 ~ 10 seconds) ②Even the use of high temp., air will do no damage to the material, thus allowing a safety operation. ③Simple structure and easy operation ④High thermal efficiency	Continuous large-scale treatmeat is possible. Example: Ammonium sulfate 15 t/hr Coal 10 t/h	① *ha* =2000 ~ 6000 ②300 ~ 600 ③50 ~ 75 ④1 ~ 3	①Muddy, cakey, powder particle, lump ②20 ~ 75 % (W.B)	①Suitable for removing absorbed moisture ②To dry coal, clay, synthetic resin, inorganic chemicals	①Moisture evaporation 1 ~ 1.5 kg/kg-gas ②Low construction cost
		Spray dryer	To spray fluid to be distributed and carried in concurrent, or countercurrent ①Such processes as grinding, classification and filtering can be omitted. ②Powder particle products can be obtained in short process.	Evaporated moisture Maximum 6 t/hr Example Powder milk 1.2 t/h Dyestuff 0.1 t/h	① *ha* = 20 ~ 80 ②Countercurrent 200 ~ 300 ③Concurrent 250 ~ 400 ④20 ~ 30	①Solution Suspension ②90 ~ 50 % (W.B)	①To dry milk, dyestuff, detergent, coffee, synthetic resin, etc. ②Spray granulation in which the molten material is sprayed to be hardened in cold air.	①Evaporated moisture should be 100 kg/hr or more; otherwise, it will be uneconomical. ②Large thermal consumption ③Rotary disk spraying involves high maintenance cost. ④Unsuitable for materials with high viscosity and large wearability
	Material agitation	Rotary dryer	Drying methods available are: direct contact method where the material agitated inside the cylinder and hot air are directly contacted; the method where the material and hot air are directly/indirectly contacted; external fire method in which the material inside the cylinder is indirectly heated from outside the cylinder. ①High operation safety ②Large-scale treatment ③Wide-ranging material to be treatable	Continuous, large-scale drying is possible. Example: Clay 70 t/hr Limestone 60 t/hr Chemical fertilizer 120 t/h	① *ha* = 100 ~ 200 ②countercurrent 250 ~ 800 concurrent 300 ~ 600 ③40 ~ 50 ④2	①Powder particle ②Lump ③40 ~ 50 (W.B or less)	①Rather rough drying where large-scale treatment is required ②Drying where material staying time will extend from 2 to 3 hours is possible. ③To dry limestone, clay, fertilizer, lime, synthetic resin, inorganic chemicals, etc.	①High construction cost
		Multi-stage disc dryer	Annular discs are placed on multiple stages, the material on each of which is agitated by rotation of the arm extending from the central shaft, and falls successively on the lower stage, while being contacted with hot air and dried. ①Smaller amount of dust ②Saving of floor space	Continuous and large-scale processing is possible.		①Powdered and granular	①Active carbon, medicines, ore, etc.	①Construction and operation costs are high.

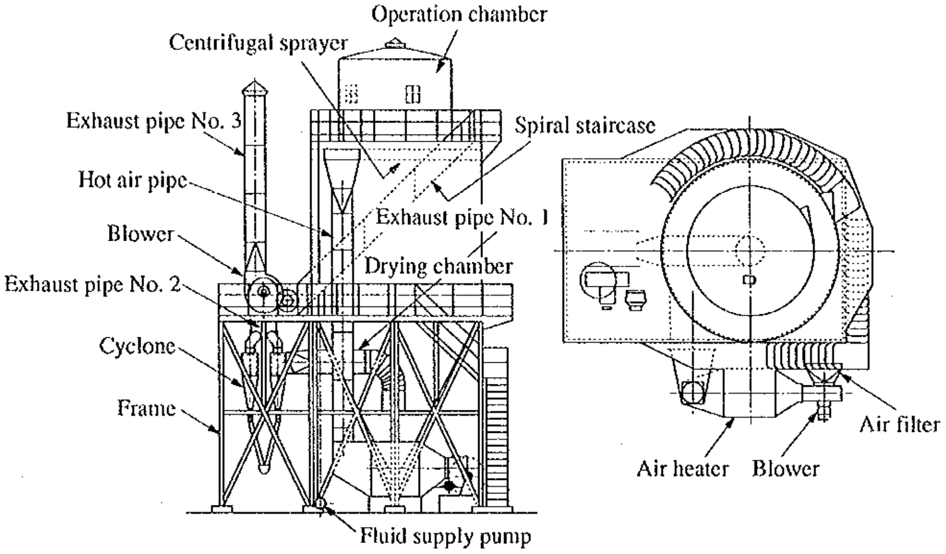
Table 2.6 List of Dryers (2/2)

Name of Dryer			Dryer Mechanism and Main Characteristics	Heating capacity	①Heat capacity coefficient ha (kcal/m^{3}hr°C) or heat transfer coefficient U (kcal/m^{2}hr°C) ②Hot air temperature [°C] ③Thermal efficiency [%] ④Critical moisture content [%]	Properties of materials to be heated ①Forms ②Treatable moisture content	Application	Others
Hot air drying	Stationary	Box type tray dryer	Trays are loaded on the trucks which are pushed into the dryer long drying time. Steam is the usual heating medium and a main heater is installed before the circulating fan.	Small batch	①Concurrent ha= 200 ~ 300 Through-ciculation ha= 3,000 ~ 8,000 ②100 ~ 150 °C ③20	①Pastes and sludges	①Dyestuff, chemical agents	At large capacity, investment and operating cost are high.

Table 2.7 Comparison of Spraying Methods

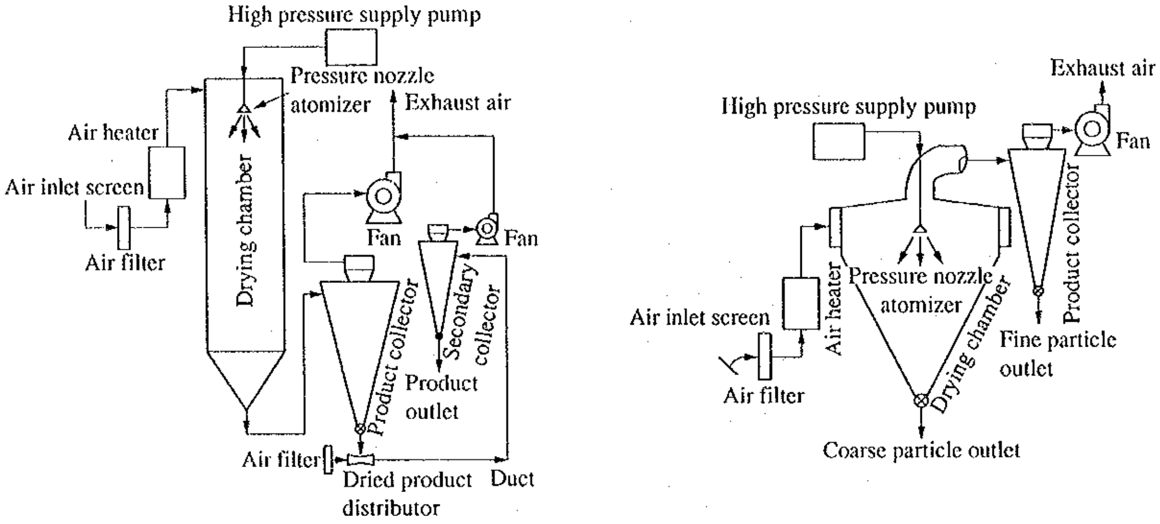
		Rotary disc type	Pressure nozzle type	Bi-fluid type
Properties of fluid	Solution	Suitable	Suitable	Suitable
	Slurry	Suitable	Suitable (Strainer is necessary)	Suitable (strainer is necessary)
	Easy to get sticky	Care should be taken.	Suitable	Suitable
	Highly viscous	Generally, 1 ~ 2 poise	Same as the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

Figure 2.38 An Example of Spray Dryer



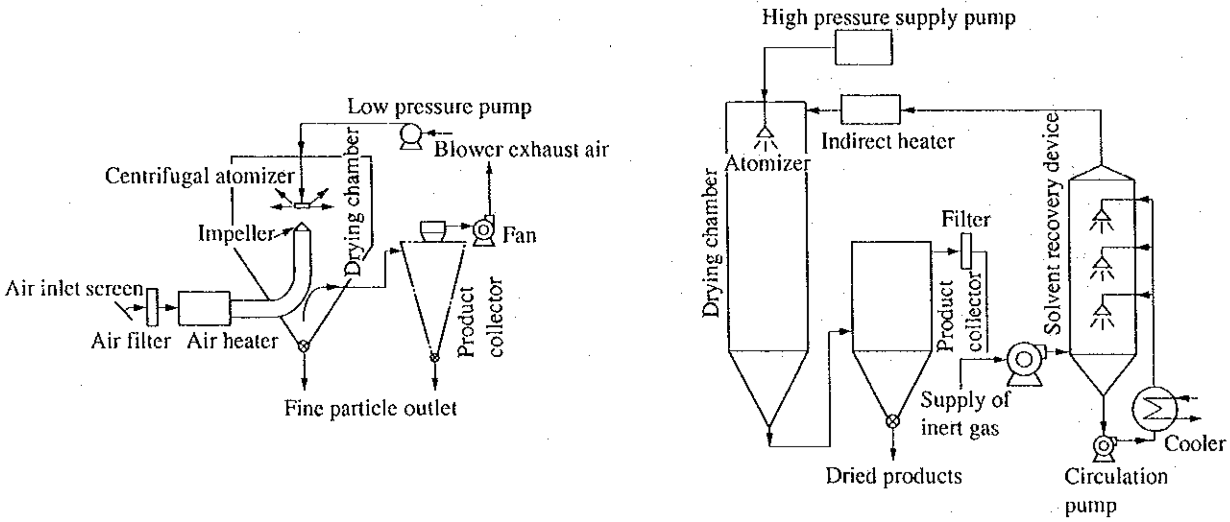
Undiluted solution (per hour)	Diameter and height of Drying chamber		No. of rotations of sprayer (each minute)	Diameter of Spraying Disc	Total Horsepower	Area of the building required for the equipment dot
Up to	Diameter	1,400	20,000	70 m/m	2	5.3 m^2
10 liter	Height	3,200				
Up to	Diameter	3,000	1,200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

Figure 2.39 Configuration Examples of Spray Dryers



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

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



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

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

Table 2.8 Application Examples of Spray Dryers

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

(2) Thermal efficiency of dryers

Heat balance and thermal efficiency are shown below mainly with regard to spray dyrers.

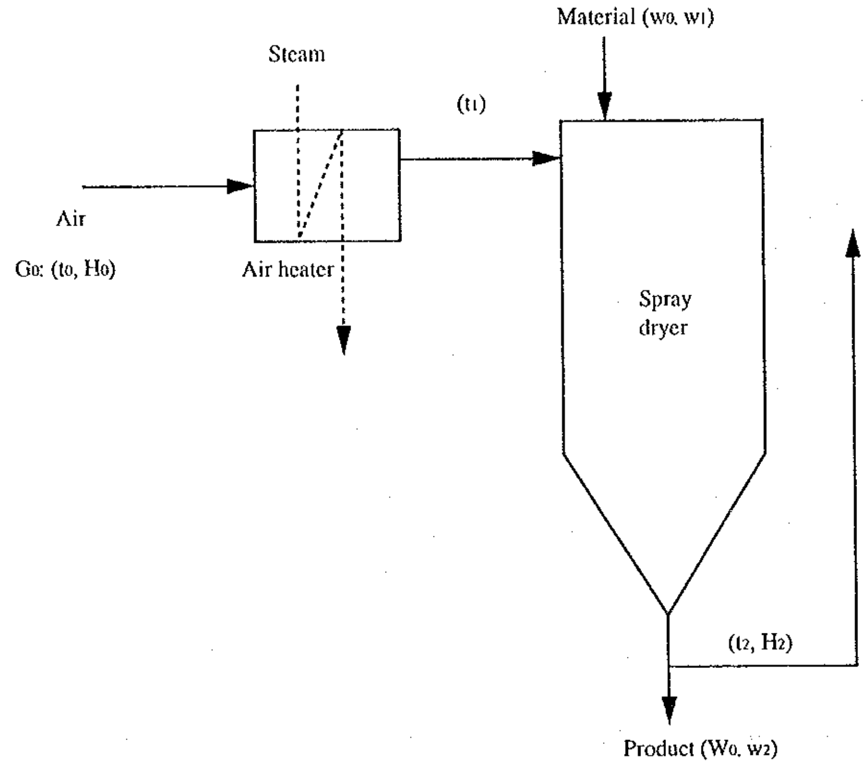
Material balance of a continuous hot air dryer is obtained from the following equation.

$$G_0 (H_2 - H_0) = W_0 (W_1 - W_2)$$

G_0 : Air volume blown in the dryer [kg/h-D.A]
H_2 : Exhaust gas humidity [kg-H_2O/kg-D.A.]
H_0 : Outdoor humidity [kg-H_2O/kg-D.A.]
W_0 : Anhydride material feeding speed [kg/h]
W_1 : Water content [kg/kg-anhydride material]
W_2 : Water content [kg/kg-anhydride material]
D.A.: Dry air

Thermal efficiency is as follows.

Figure 2.40 Spray Dryer



The heat balance inside the drier is as follows.

$Q' = G_{OI}C_{HI}\ (t_1 - t_2) = Q_0 + Q_n + Q_l$

Q' :	Heat value consumed inside dryer	[kcal/hr]
C_{HI}:	Moisture specific heat	[kcal/kg-D.A.·°C]
Q_0 :	Heat value due to moisture evaporation	[kcal/hr]
Q_n :	Heat value due to heating of material	[kcal/hr]
Q_l :	Heat loss	[kcal/hr]

Heat value Q_l [kcal/hr] given by the hot air generator is :

$Q_I = G_{OI}C_{HO}\ (t_1 - t_0)$

Thus, the thermal efficiency of the hot air generator becomes :

$\eta = (Q_O + Q_h)/Q1$

For those that require large sensible heat for heating materials, Q_h cannot be ignored. If no heat loss is considered, $\eta_{max} = (t_1 - t_2)/(t_1 - t_0)$, but $t_2 > t_0$ (t_2 is at least t_1, wet bulb temperature of H_0), and therefore, will not become substantially 100 %. Since t_2 is 60 to 120 °C, and t_0 is 0 to 30 °C, η gets larger as t_2 becomes lower. Thus, even though it becomes more cost efficient from a heat value standpoint, the temperature difference between the material and the exhaust becomes small, increasing equipment size. Therefore, an economically optimal temperature should exist for t_2.

This value is given for various drier types, empirically.

(3) Rationalization in the use of thermal energy

a. Pretreatment of material

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

b. Prevention of heat loss

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

c. Circulation of exhaust

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

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

d. Recovery of sensible heat from exhaust

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

Next, a method to directly recover heat retained in the exhaust without using heat exchangers should be studied. For example, when the liquid to be dried is concentrated by allowing it to come into direct contact with the exhaust in spray dryers, almost all sensible heat of the exhaust can be utilized. Figure 2.41 shows an example of waste heat recovery of exhaust gas.

e. Recovery of latent heat from exhaust

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

f. Recovery of sensible heat from dried products

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

g. Recovery of the sensible heat from condensate of steam for heating

When steam is used for heating the air for drying, condensate of high temperatures can be obtained. Energy conservation can be achieved by heat-exchanging of this condensate with the injected air before utilizing it as hot water for cleaning. Figure 2.42 shows an example of heat-exhange for a spray dryer.

Figure 2.41 Waste Heat Recovery of Exhaust Gas

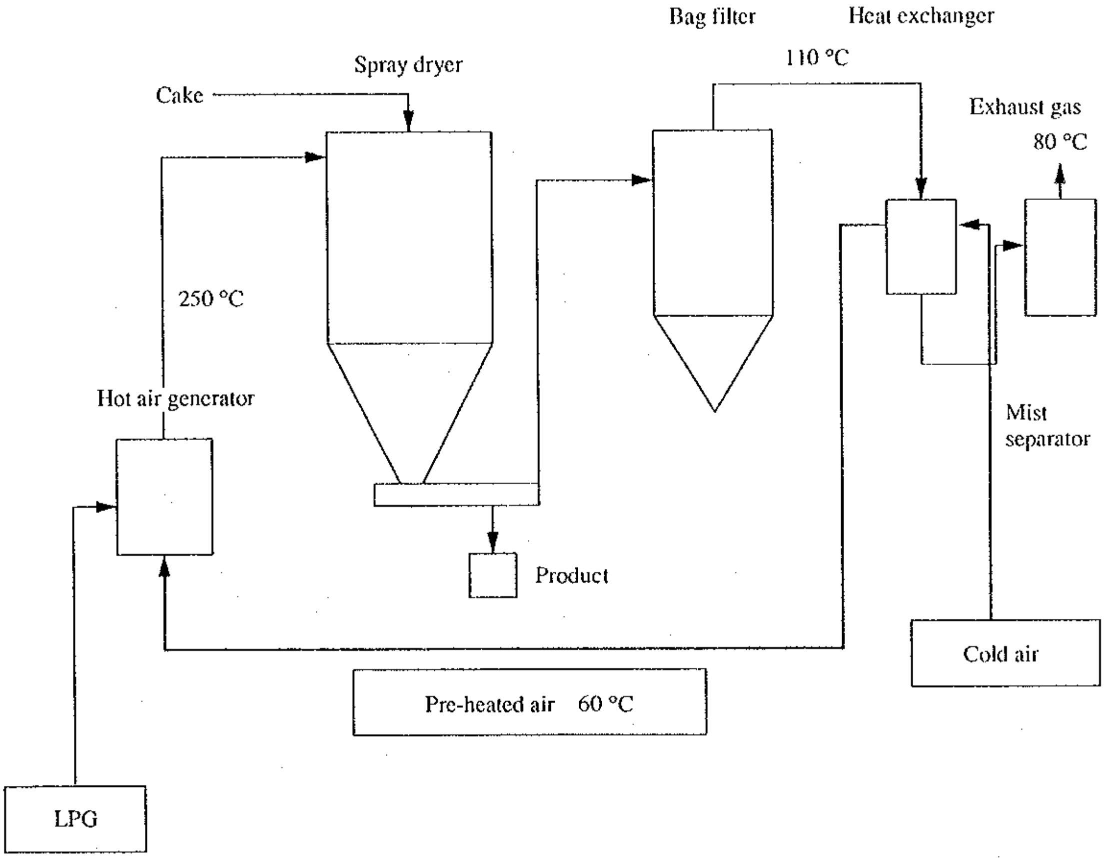
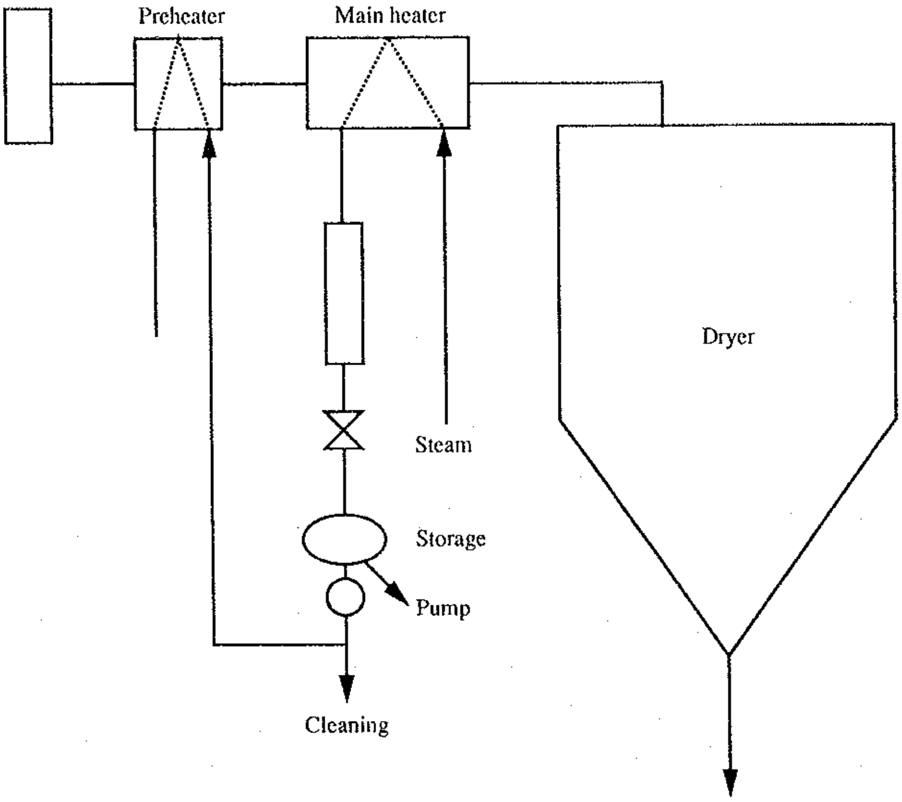


Figure 2.42 Waste Heat Recovery of Condensate



h. Others

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