3. ENERGY CONSERVATION IN STEELMAKING INDUSTRY

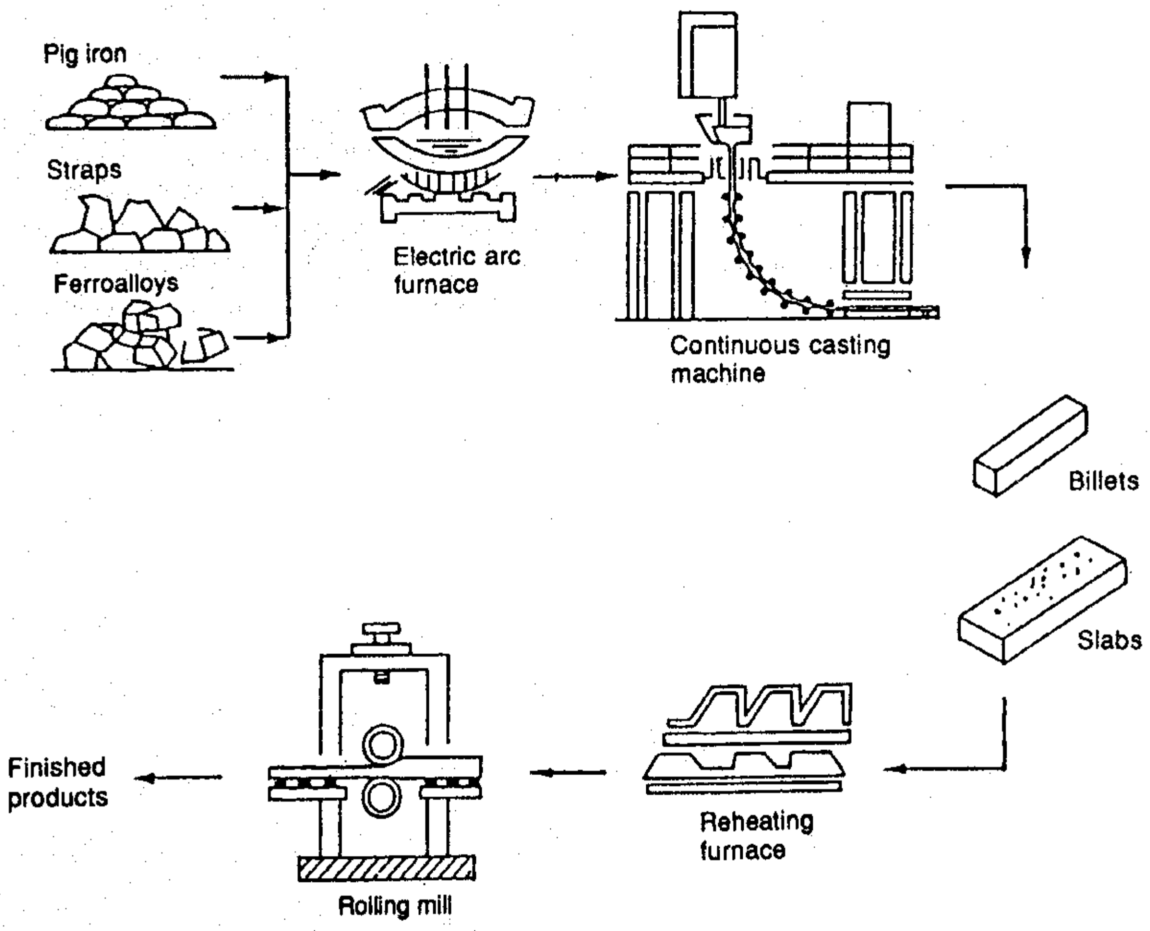
3. ENERGY CONSERVATION IN STEELMAKING INDUSTRY

3.1 Characteristics of Energy Situation in the Steelmaking Industry

3.1.1 Production process and principal equipment

Figure 3.1 shows the production process by the arc furnace steelmaking method. The arc furnace steelmaking method uses scraps as its raw material, thus making effective use of waste resources. Moreover, this method requires less energy than the blast furnace-converter method to produce one ton of crude steel, which may be said to be an energy-saving steelmaking method.

Figure 3.1 Production Process by Arc Furnace Steel-Making Method



(1) Arc furnace

The arc furnace for steelmaking uses three-phase alternating current to melt scrap iron in the furnace by means of the arc heat generated between scrap iron charged into the furnace and the electrode and the resistance heat occurring in the scrap iron. The features are described below:

a. High temperature can be obtained and temperature control is easy.

b. Either oxidization or reduction refining is easily carried out.

c. There is less restriction in the quality of the steel materials to be used.

d. Both of special steel and ordinary steel can be produced.

e. High thermal efficiency

Structurally, an arc furnace is roughly divided into the furnace body and electrical equipment. Figure 3.2 shows the body structure of an arc furnace, and Figure 3.3 its electrical machinery and apparatuses. The furnace body consists of a furnace shell, a furnace tilting device, electrode devices, a furnace lid opening/closing device, a transformer secondary side bus bar and a flexible conduit tube. Electrical equipment are composed of main electrical devices including a breaker, a furnace transformer and an automatic electrode control device.

Figure 3.2 Body Structure of Arc Furnace

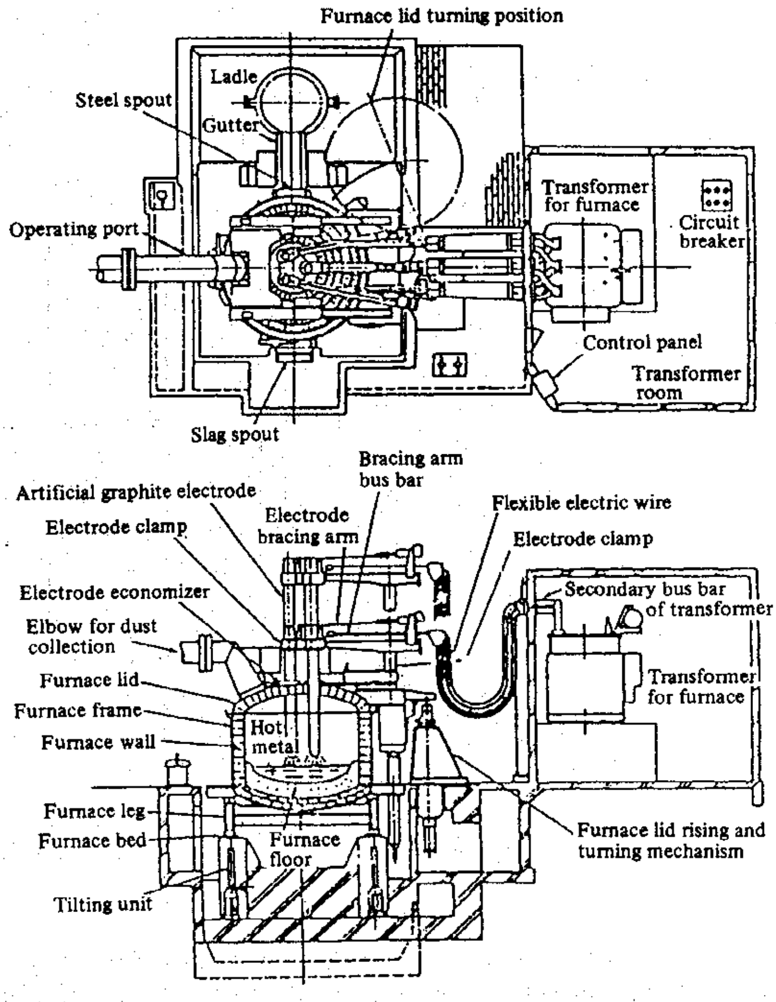
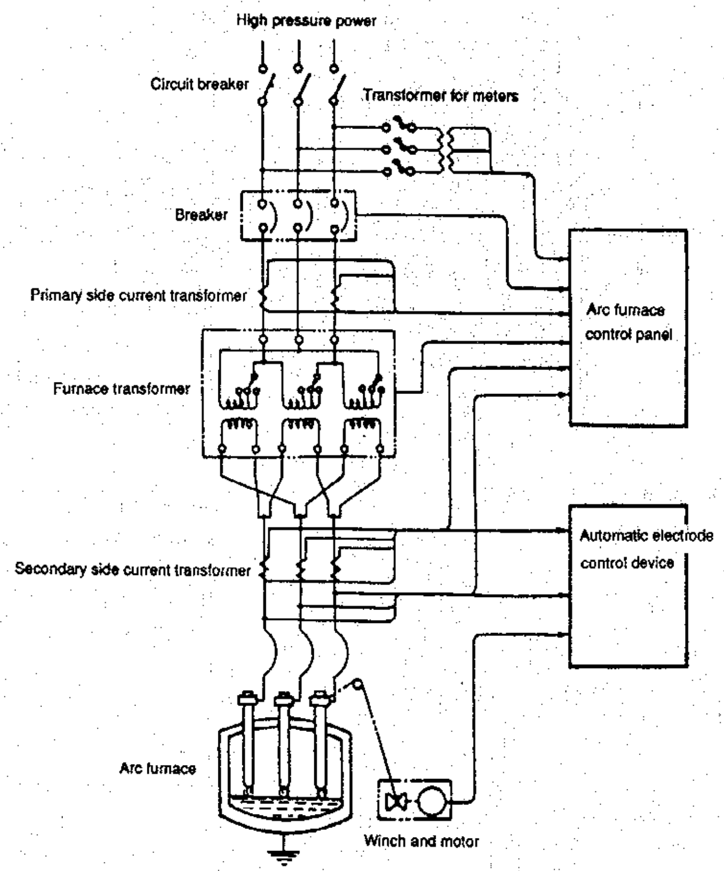


Figure 3.3 Electrical Machinery and Apparatuses of Arc Furnace



Accessory facilities include dust collecting equipment which remove the generated gas and the aerial dust in the house by means of a bag filter or by the electrostatic method, and a scrap preheater which preheats scraps by use of sensible heat of the generated gas.

The size of the furnace is usually expressed in terms of furnace capacity (melting volume), the inner diameter of furnace shell and transformer capacity. Table 3.1 shows the relationship between furnace capacity and transformer capacity.

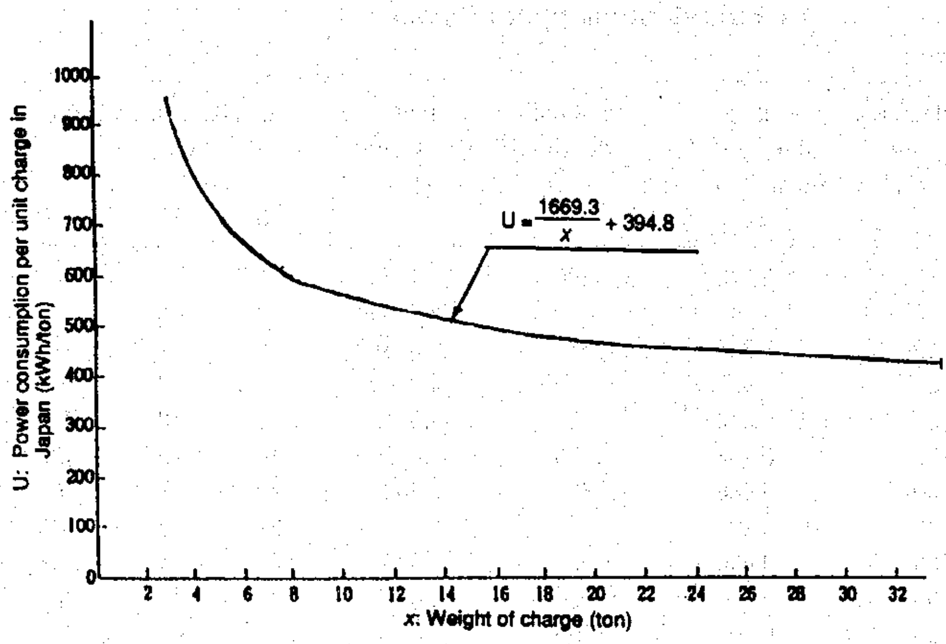
Figure 3.4 shows a regression curve for actual power consumption per unit charge in Japan.

Table 3.1 Relation between Furnace Capacity, Required Dimensions and Electric Equipment of Furnace

Nominal furnace capacity (10^3 kg)	Outside diameter of furnace core (m)	Metal bath depth (mm)	Diameter of electrode (mm)	Capacity of transformer (MV · A)			Secondary voltage (RP furnace) (V)
				RP	HP	UHP	
2	2.178	300	175	1.5	–	–	180/80
5	2.743	400	200~250	3	5	–	200/100
10	3.353	400	300~350	5	7.5	–	220/100
20	3.962	450	350~400	7.5	12	15	240/100
30	4.572	650	400~450	12	18	22	270/120
50	5.182	750	450~500	18	25	30	330/130
60	5.486	850	500	20	27	35	400/130
70	5.791	850	500	22	30	40	400/130
80	6.096	900	500	25	35	45	430/140
100	6.400	950	500~550	27	40	50	460/160
120	6.706	1000	550~600	30	45	60	500/200
150	7.010	1000	600	30	50	70	500/200
170	7.315	1050	600	35	60	80	500/200
200	7.620	1100	600	40	70	100	560/200
400	9.754	1,200	700	–	–	150	

Note: RP: Regular power, HP: High power, UHP: Ultra-high power
Source: Cast Product Handbook, 4th Ed., ed. Japan Cast Product Association

Figure 3.4 Power Consumption Per Unit Charge in Japan



Source: 1977 Japan Cast and Forged Steel Association Report of Analysis Results on Unit Steel Production in Different Electric Arc Furnaces

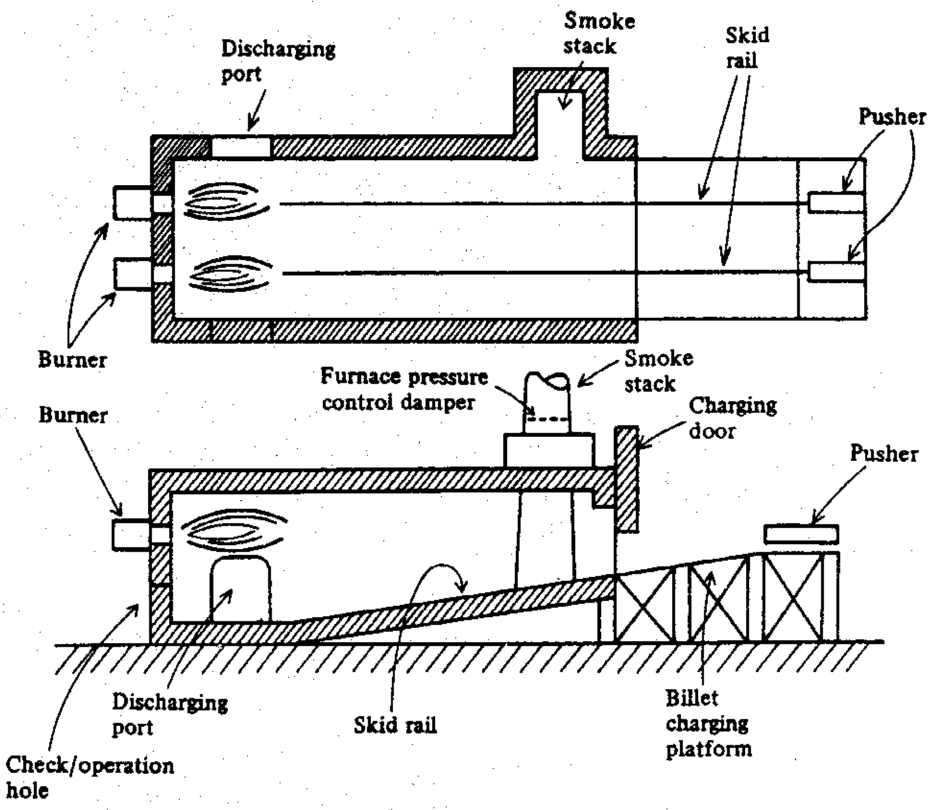
(2) Reheating furnace

The reheating furnace is used for reheating the billets roughly rolled at a blooming mill or produced by continuous casting up to a given temperature according to their purpose in order to roll them into finished products. Reheating furnaces are broadly classified into the batch type and the continuous type. The batch type furnaces are mainly used for reheating materials of special forms, while the continuous type furnaces are generally used for mass production.

Continuous heating furnaces include the pusher type, the walking-beam type, the walking-hearth type, etc. The walking hearth furnaces were used for reheating or heat treatment of special materials, such as thin materials, round billets, steel pipes and so forth. Although in the past the pusher type reheating furnaces were mainly employed, along with an increase in the size of the equipment and their automatization, etc. the furnace type has changed from the pusher type single zone furnace to the multi-zone type, and further to the walking beam type.

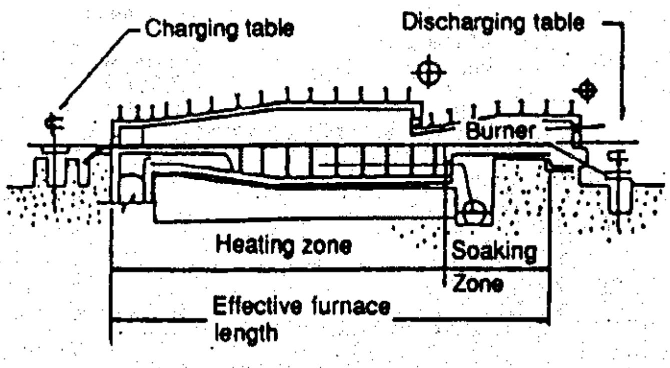
The oldest and most elementary types of furnace include the pusher-type single zone reheating furnace as shown in Figure 3.5. Since this type of furnace has a heating capacity of not more than 50 t/h, billets are heated only from the top side. This causes a large difference between the top and bottom side temperatures. Moreover, this type of furnace employs single-zone control of furnace temperature; therefore, it has little flexibility in operation.

Figure 3.5 Pusher-Type Single Zone Reheating Furnace



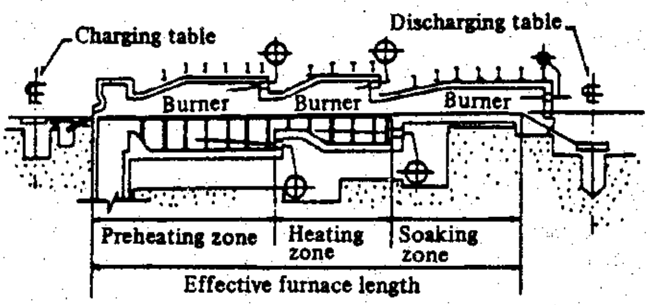
As a furnace with a heating capacity of 60~120 t/h, there is a pusher-type 3-zone reheating furnace, which is shown in Figure 3.6. The pusher-type 3-zone reheating furnace has a heating zone and a soaking zone clearly divided. In the heating zone, billets are heated up to the specified temperature from both top and bottom sides, while in the soaking zone, the number of skid marks is made to decrease in order to make the billet temperature uniform. This type of furnace allows controlling the furnace temperature in each of the three zones, thus providing flexibility in operation.

Figure 3.6 Pusher-Type 3-Zone Reheating Furnace



As a furnace with a larger heating capacity of 200~250 t/h, there is a pusher-type 5-zone reheating furnace available. This type of furnace has been developed from the pusher-type 3-zone reheating furnace, and has the preheating zone, the reheating zone and the soaking zone clearly divided. (Refer to Figure 3.7)

Figure 3.7 Pusher-Type 5-Zone Reheating Furnace



Walking beam furnaces which have eliminated the disadvantages of the pusher-type furnace and are provided with a large heating capacity have recently been in wide use. (Refer to Figure 3.8)

Figur 3.8 Walking Beam-Type Reheating Furnace

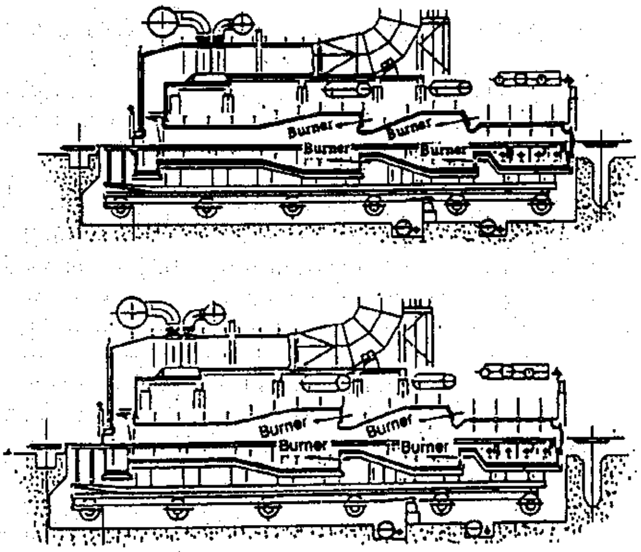


Table 3.2 shows a comparison between the pusher-type furnace and the walking-beam furnace.

Table 3.2 Comparison of Pusher Furnace & Walking-Beam Furnace

	Pusher furnace (PF)	Walking-beam furnace (WBF)
Application	1. Mass production	1. Mass production 2. Slabs of deformed sections to which PF is not applicable, and for quality products
Slab carrying method	The slab is pushed in with a pusher from the charge side and is caused to move as sliding forward on the water-cooled skid.	The slab on the water-cooled fixed beam is carried by the water-cooled moving beam, which makes back-forth motions.
Advantage	1. Equipment cost is less than that of WBF. 2. Cooling water loss heat is less than that of WBF.	1. There is no restriction in the furnace length. 2. Skid mark is minor, and no scratches are produced. 3. The furnace can be easily emptied because the slabs in the furnace can be freely carried by the own power. 4. Slabs can be carried in suitable intervals.
Disadvantage	1. Skid mark and scratches are easily produced. 2. Buckling of slabs tends to occur in the furnace and there are restrictions in the furnace length. 3. Charge of slabs of extremely different thickness levels cannot be made. 4. It is hard to empty the furnace. 5. The frequency of maintenance of the soaking hearth is large.	1. The equipment cost is higher than that of PF. 2. As the number of skids is large, the cooling water loss is larger than that of PF.

The burner arrangement for the heating furnace includes three methods; (1) axial-flow combustion, (2) side combustion and (3) roof combustion. Each of these methods has, however, its particular characteristic, and for actual furnaces, therefore, the most suitable one will be employed with consideration given to its characteristic, heating capacity, etc. Some furnaces also use a combination of these combustion methods. Table 3.3 shows a comparison of the combustion methods in terms of characteristics.

In addition, the furnace types differ depending on the billet conveying method.

Table 3.4 shows the layout of the reheating furnace according to the charging/extraction method.

Table 3.3 Comparison of Combustion Method

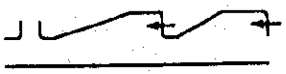
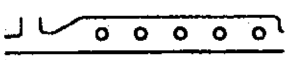
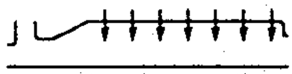
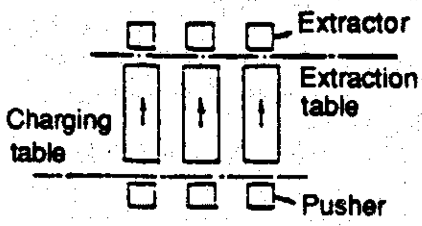
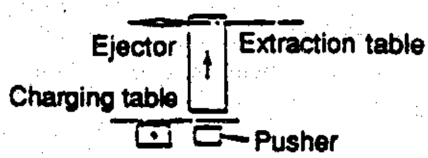
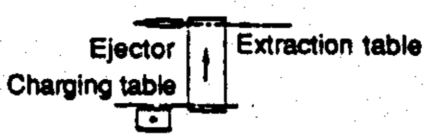
Item	Axial flow combustion	Side combustion	Roof combustion
Burner position			
Fuel	Fuel oil, C-gas, M-gas, natural gas	Fuel oil, C-gas, M-gas, natural gas	Fuel oil, C-gas, M-gas, natural gas
Burner type	External mixing type	External mixing type or variable flame burner	Roof burner
Flame form	Long flame	Short flame (variable flame)	Completion of combustion in ports
Combustion rate controllability	Broad control range	Narrow control range Thinning control is needed in correspondence to the combustion rate.	Relatively broad control range
Heating load	May be large with large capacity burner	May be large with large capacity burner	Not very large with small capacity burner
Restrictions by furnace internal dimensions	There are restrictions in the length per zone in the longitudinal direction.	There are restrictions in the widthwise direction.	None in particular. But lower combustion is not permitted.
Flow of combustion gas in the furnace	Flows without unnaturalness in the longitudinal direction.	Drift tends to occur because there is an angle between the burner direction and the longitudinal direction.	There is no unnaturalness in the flow because combustion is almost entirely completed in burner tiles.
Mounting of burners	Nose section is required, and the furnace structure is complicated.	The furnace structure is simple.	The furnace structure is simple. But the piping is complicated because the number of burners is large.
Heat pattern	Equalization of the temperature in the widthwise direction is easy. The temperature drops in the longitudinal direction. The temperature at the nose section drops.	Equalization of the temperature in the widthwise direction is inferior. Equalization of the temperature drops in the longitudinal direction is easy.	Equalization of the temperature is easy in both of the widthwise direction and the longitudinal direction.
Workability	Relatively good. But no good at the periphery of the lower burners because of high temperature environment.	The working environment is good.	The workability is inferior because the number of burners is large and because of high temperature environment.

Table 3.4 Layout of heating furnace

Charging/extraction method	Furnace layout	Characteristics
Back charging, front extraction		1. It is easy to charge and extract large billets. 2. The layout is easy when two or more furnaces are installed. Thus, this method is suitable for large-capacity facilities such as hot strip mills and slab mills. 3. The area of openings for charging and extracting is large. As a result, heat loss by thermal radiation or air intrusion is large. 4. Extraction is done by pushing or extractors.
Back charging, side extraction		1. Billets can be kept hot during the rolling, thanks to the closeness of the rolling mill and the reheating furnace. 2. Heat loss by thermal radiation from the extraction outlet is small. 3. Extraction is done by ejectors or rollers. However, when rollers are used, heat loss is large through cooling water for the rollers.
Side charging, side extraction		1. Heat loss is small at both the charging inlet and the extraction outlet. This method is most suitable to a reheating furnace for long billets.

3.1.2 Energy situation

(1) Arc furnace

Figure 3.9 shows the transition of the electric power consumption rate of Japanese arc furnace, and Table 3.5 shows the electric power consumption rate for each furnace capacity. A remarkable decline in the electric power consumption rate has resulted from a large-scale furnace, ultra-high power (UHP) operation, scrap preheating, use of oil burner for the saving of electric power, the developmant of optimum current control device, etc.

Figure 3.9 Electric Power Consumption Rate of Japanese Arc Furnace

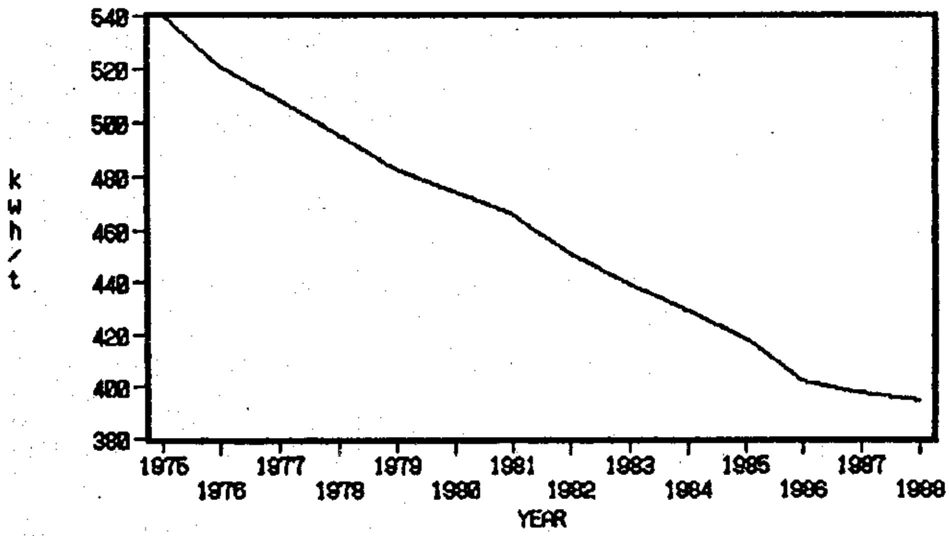


Table 3.5 Average Electric Power Consumption Rate for Mild Steel

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

Table 3.6 shows an example of heat balance for an arc furnace. The thermal efficiency is approx 50%. The factors with large heat loss include 16.5% of exhaust gas and 8.2% of furnace body cooling water.

Table 3.6 Heat Balance of Arc Furnace

Item		Kind of steel				Furnace capacity				Total	
		Mild steel (N = 7)		Special steel (N = 11)		30–50 t furnace (N = 7)		50 t or more furnace (N = 11)			
		10^3 kcal/steel discharge t	%	10^3 kcal/steel discharge t	%	10^3 kcal/steel discharge t	%	10^3 kcal/steel discharge t	%	10^3 kcal/steel discharge t	%
Heat input	Heat quantity of electric power	373.0	59.1	438.3	61.5	437.6	62.2	398.2	59.8	412.9	60.6
	Calorific value of fuel	24.9	3.9	16.7	2.3	6.7	1.0	29.4	4.4	20.7	3.0
	Oxidation heat of electrode	25.7	4.1	34.3	4.8	35.9	5.1	28.9	4.3	32.1	4.7
	Oxidation heat of charged raw materials	192.4	30.5	208.4	29.2	204.5	29.0	199.5	30.0	201.5	29.6
	Heat of slag formation	11.2	1.8	12.6	1.8	15.0	2.1	10.2	1.5	12.1	1.8
	Others	3.6	0.6	2.7	0.4	4.4	0.6	–	–	1.7	0.3
	Total heat input	630.8	100	713.0	100	704.1	100	666.2	100	681.0	100
Heat output	Potential heat of molten steel	339.6	53.8	347.5	48.7	342.9	48.7	344.7	51.8	344.0	50.5
	Potential heat of slag	46.5	7.4	55.0	7.7	63.4	9.0	44.2	6.6	51.7	7.6
	Heat loss on transformer and secondary conductor	28.1	4.4	37.9	5.3	46.4	6.6	26.7	4.0	34.5	5.1
	Sensible heat of exhaust gas	111.0	17.6	115.9	16.3	115.1	16.3	112.2	16.8	112.4	16.5
	Heat carried out by cooling water	30.3	4.9	72.3	10.1	49.7	7.1	59.9	9.0	56.1	8.2
	Others (heat release from furnace body, radiant heat at time of additional charging, etc.)	75.3	11.9	84.4	11.8	86.6	12.3	78.5	11.8	82.3	12.1
	Total heat output	630.8	100	713.9	100	704.1	100	666.2	100	681.0	100

(2) Reheating furnace

In the 1960s, the fuel consumption rate of the continuous reheating furnace was $370 \times 10^3 \sim 450 \times 10^3$ kcal/t for the pusher-type furnace, and $450 \times 10^3 \sim 590 \times 10^3$ kcal/t for the walking beam furnace. Recently, however, the walking type furnace has taken the place of the pusher-type furnace, thus serving as the most popular large-scale furnace. In 1989, the energy consumption rate was $202 \times 10^3 \sim 566 \times 10^3$ kcal/t, and 267×10^3 kcal/t on the average. This drastic decline in the fuel consumption rate owes much to the improvement in thermal efficiency resulting from the effects of such measures as will be described later.

The major factors contributing to this decline in the fuel consumption rate include the dissemination of the hot charge method by the continuous use of a high temperature of the preceding process and the increase of the rate. Table 3.7 represents an example of heat balance of the reheating furnace.

Table 3.7 Heat Balance Table

Heat input			Heat output		
Item	10^3 kcal/t	%	Item	10^3 kcal/t	%
(1) Combustion heat of fuel	442.9	94.7	(8) Quantity of heat contained by extracted steel	200.4	42.8
(2) Sensible heat of fuel	0.8	0.2	(9) Sensible heat of scale	5.0	1.1
(3) Sensible heat of air	5.0	1.1	(10) Sensible heat of exhaust gas	94.1	20.1
(4) Heat brought in by atomizer	0	0	(11) Heat loss by incomplete burning	0	0
(5) Quantity of heat contained by charged steel	0	0	(12) Quantity of heat brought out by cooling water	57.2	12.3
(6) Heat of scale formation	19.0	4.0	(13) Other heat loss	111.0	23.8
(7) Heat recovered by preheater	(0)	(0)	(14) Heat recovered by preheater	(0)	(0)
Total (1) + (2) + (3) + (4) + (5) + (6)	467.7	100.0	Total (8) + (9) + (10) + (11) + (12) + (13)	467.7	100.0

Remark 1. For recording the quantity of heat, use 10^3 kcal/t as a unit and round out figures after the decimal point into a single digit.

2. Round out figures after the decimal point into a single digit in the percentage.

3.2 Rationalizing the Use of Energy

3.2.1 Arc furnace

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

Table 3.8 lists the energy conservation items for an electric arc furnace. A few examples are described below:

Table 3.8 Items on Energy Conservation for Arc Furnace

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

(1) Improving oil combustion

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

Figure 3.10 and Figure 3.11 show the condition of burner installation and the relation between fuel consumption rate and electric power comsumption rate. Considering heat loss in power generation, the conversion of heat source from electric energy to fuel leads to energy conservation.

Figure 3.10 Example of Installation of Combustion Supporting Burner

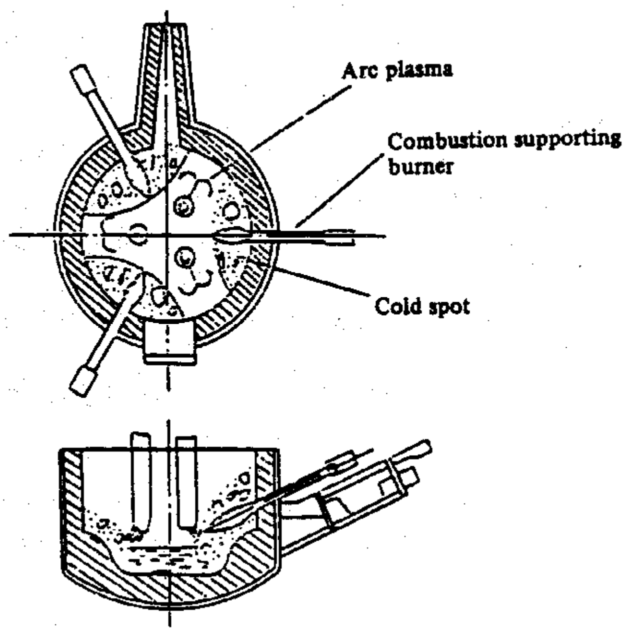
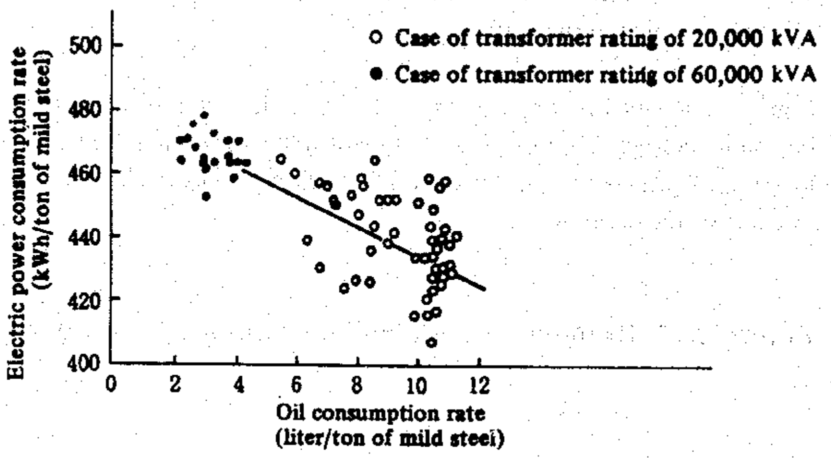


Figure 3.11 Oil Consumption Rate and Electric Power Consumption Rate Showing the Effect of Combustion Supporting (Per Ton of Mild Steel)

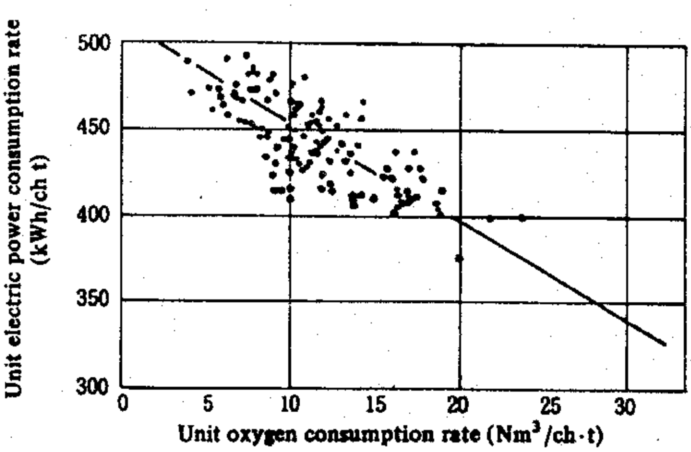


(2) Oxygen blowing

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

Figure 3.12 indicates the relation between comsumption rate of oxygen and electricity.

Figure 3.12 Relationship between Unit Oxygen Consumption Rate and Unit Electric Power Consumption Rate in Oxygen Enriching Operation

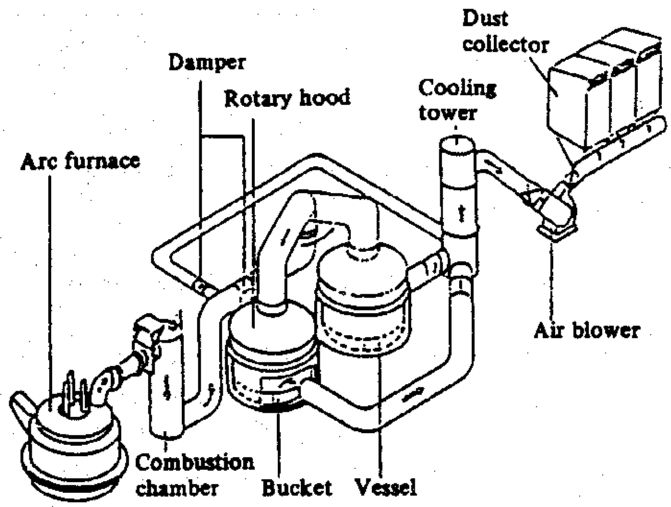


(3) Scrap preheating

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

Figure 3.13 shows an example of scrap preheater that preheats scrap in charging bucket using the arc furnace exhaust gas.

Figure 3.13 Scrap Preheater Using Arc Furnace Exhaust Gas for Heating Scrap in Charging Bucket



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

An example of the energy saving effect in scrap preheating by the arc furnace exhaust gas is shown in Table 3.9.

Table 3.9 Example of Energy Saving Effect in Scrap Preheating by Arc Furnace Exhaust Gas

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

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

(4) Suppressing heat release from openings of furnace body

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

(5) Suppressing heat release during furnace repair

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

(6) Optimizing power charge

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

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

3.2.2 Reheating furnace

The basic concept of energy conservation in steel production with a reheating furnace is to rationalize fuel combustion, heating, cooling and heat transfer, to prevent heat loss due to radiation, conduction, etc., and to recover and reuse waste heat.

A characteristics diagram of energy conservation for reheating furnace is shown in Figure 3.14 and the principal items of these characteristics are presented in Figure 3.15.

Figure 3.14 Characteristics Diagram of Energy Conservation for Reheating Furnace

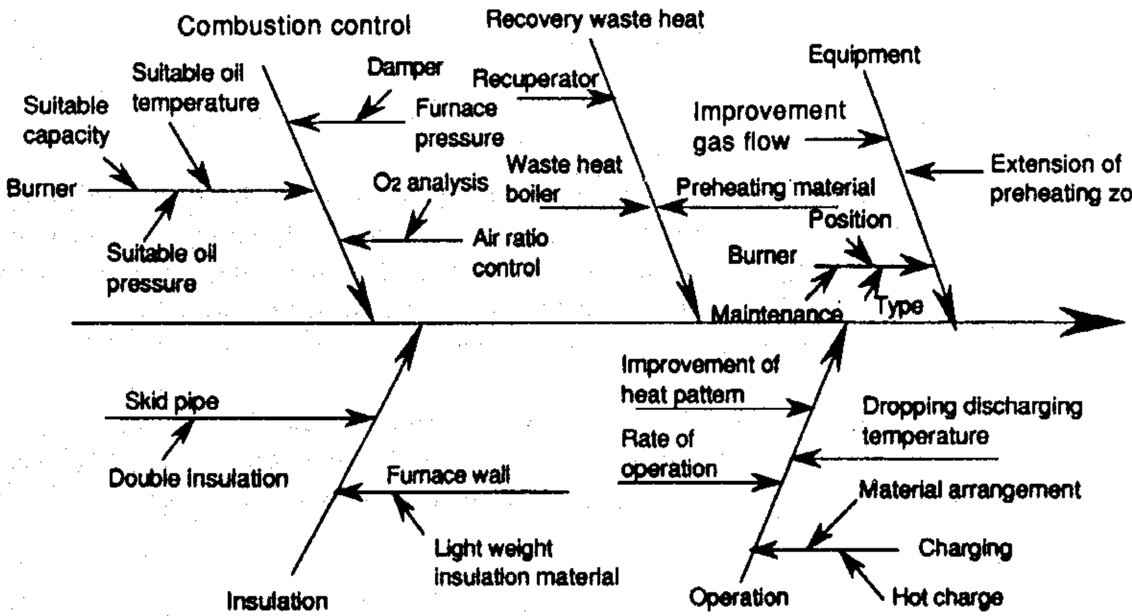
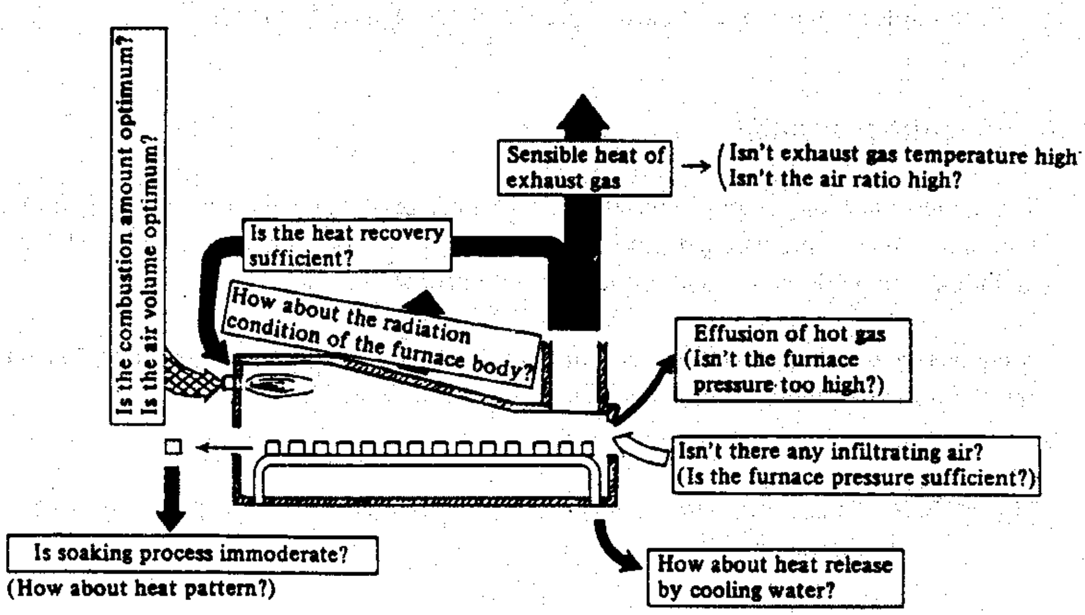


Figure 3.15 Reduction Point for Fuel Consumption Rate



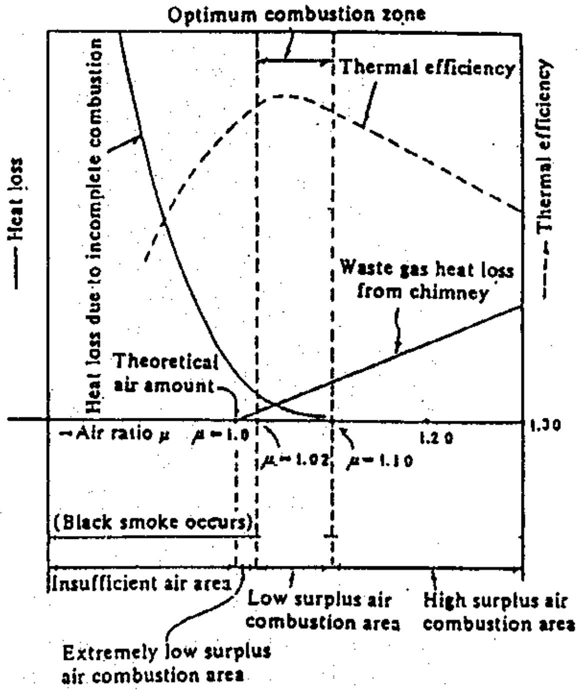
(1) Rationalization of fuel combustion

a. Air ratio

In burning a fuel to convert its chemical energy into thermal energy, it is necessary to burn all the fuel without leaving any part of it unburnt, and to bring the amount of air required for its combustion as close to a theoretical amount of air calculated as required as possible, so that thermal efficiency will be raised as high as possible. For this purpose, it is important to reduce the air ratio.

If fuel is burning incompletely as shown in Figure 3.16, there will be heat loss due to an unburnt portion of it. If combustion air is supplied more than necessary for complete combustion, heat loss will also arise from giving heat to the excess air.

Figure 3.16 Relation between Air Ratio and Thermal Efficiency

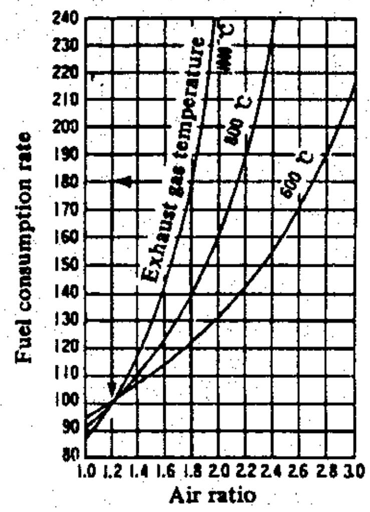


Thus, rational combustion is to completely burn fuel while maintaining air supply slightly more than the theoretical amount of air.

The extent of excess air can be expressed by the ratio of the theoretical amount of air deemed necessary from combustion calculations to the actual amount of combustion air, that is, the air ratio.

Figure 3.17 shows how fuel consumption rate varies with the air ratio. If the air ratio is lowered from 1.8 to 1.2 when exhaust gas temperature is 1,000°C, the fuel consumption rate will decrease from 180 to 100 for an energy saving of about 45% over the original fuel consumption rate.

Figure 3.17 Energy Saving Effect under Air Ratio Control



Because the air ratio is an important index for rationalizing the use of thermal energy, it is necessary to set up a standard air ratio for each type of combustion equipment and fuel, and manage it.

For your reference, standard air ratios for industrial furnace in Japan are shown in Table 3.10, and the target air ratios in Table 3.11. The standard air ratio here means the reference value for setting up a control standard of air ratio of combustion equipment. The target air ratio is the target value for which efforts should be made to decrease the air ratio of combustion equipment.

Table 3.10 Standard Air Ratios for Industrial Furnaces

Division	Standard air ratio		
	Furnace type, etc.		
	Continuous type	Intermittent type	Remarks
Melting furnaces for metal casting	1.3	1.4	
Continuous steel billet, bloom and slab heating furnace	1.25	–	
Metal heating furnaces other than continuous steel billet, bloom and slab heating furnaces	1.25	1.35	
Metal heat treatment furnaces	1.25	1.3	
Petroleum heating furnaces	1.25	–	
Thermal cracking and reforming furnaces	1.25	–	
Cement kilns	1.30	–	
Lime kilns	1.30	1.35	
Drying furnace	1.3	1.5	Burner combustion parts only

Remarks 1. The values of the standard air ratios shown in the above table are those of the air ratios measured at the exhaust gas outlet of industrial furnaces when such furnaces conduct combustion, after inspection and repairing, at a load near the rated load.

2. The values of the standard air ratios shown in the above table shall not apply to the air ratio of the following industrial furnaces:

(1) Furnaces using solid fuels (excluding those exclusively using pulverized coal);

(2) Furnaces having a rated capacity (combustion capacity of burner fuels) less than 50 liters/h (in terms of heavy oil equivalent);

(3) Furnaces requiring a specific atmosphere for oxidation or reduction;

(4) Furnaces requiring frequent opening and shutting of the lid or frequent igniting and extinguishing of the burner;

(5) Furnaces requiring dilute air for keeping the heat pattern or uniforming temperatures in the furnace;

(6) Furnaces for burning a by-product gas having a heating value of 900 kcal/Nm^3 (3,765.6/kJ/Nm^3) or less;

(7) Furnaces at the time of the periodical inspection or not operated regularly or used for research, development or prototype manufacturing purposes;

(8) Furnaces made of the materials affected by high temperatures and requiring air for cooled dilution;

(9) Furnaces burning flammable wastes

Table 3.11 Target Air Ratios for Industrial Furnaces

Division	Target air ratio		
	Furnace type, etc.		
	Continuous type	Intermittent type	Remarks
Melting furnaces for metal casting	1.25	1.3	
Continuous steel billet, bloom and slab heating furnace	1.2	–	
Metal heating furnaces other than continuous steel billet, bloom and slab heating furnaces	1.2	1.3	
Metal heat treatment furnaces	1.2	1.3	
Petroleum heating furnaces	1.25	–	
Thermal cracking and reforming furnaces	1.25	–	
Cement kilns	1.25	–	
Lime kilns	1.25	1.35	
Drying furnace	1.3	1.5	Burner combustion parts only

Remarks 1. The values of the target air ratios shown in the above table are those of the air ratios measured at the exhaust gas outlet of industrial furnaces when such furnaces conduct combustion, after inspection and repairing, at a load near the rated load.

2. The values of the standard air ratios shown in the above table shall not apply to the air ratio of the following industrial furnaces, provided, however, that if possible, examinations shall be made to ensure that the air ratio of the following furnaces is managed based on the same table:

(1) Furnaces having a rated capacity (combustion capacity of burner fuels) less than 50 liters/h (in terms of heavy oil equivalent);

(2) Furnaces requiring a specific atmosphere for oxidation or reduction;

(3) Furnaces requiring frequent opening and shutting of the lid or frequent igniting and extinguishing of the burner;

(4) Furnaces requiring dilute air for keeping the heat pattern or uniforming temperatures in the furnace;

(5) Furnaces for burning a by-product gas having a heating value of 900 kcal/Nm^3 (3,765.6/kJ/Nm^3) or less;

(6) Furnaces at the time of the periodical inspection or not operated regularly or used for research, development or prototype manufacturing purposes;

(7) Furnaces made of the materials affected by high temperatures and requiring air for cooled dilution.

b. Burners

Combustion heat energy is the largest heat input to a combustion furnace, and the overall efficiency of the furnace depends largely on the efficiency in the process of generating and using heat. In selecting a burner, all the factors, including the type of furnace, kind of fuel, conditions of use, and the purpose of furnace, must be examined to select the one that best meets them. Burner types can be classified by kind of fuel as shown in Figure 3.18.

Figure 3.18 Classification of Burners

- Gas burner
  - Internal mixing type
  - External mixing type
  - Semi-mixing type
- Oil burner
  - High-pressure atomizing type
    - Internal mixing type
    - External mixing type
  - Low-pressure air atomizing type
    - Non-proportioning type
    - Proportioning type
  - Oil pressure type
    - Non-circulation type
    - Circulation type
  - Rotary type
- Gas and oil mixture burner

1) Internal mixing type gas burner

The internal mixing-type gas burner is so designed as to blow out and burn the gas mixture and all the required volume of air for gas combustion. It also can burn rapidly in a non-luminous flame without the secondary combustion air. If the mixing ratio of gas and air is set, it is possible to create a desired intrafurnace atmosphere.

Since rapid combustion takes place, the combustion chamber can be made compact. In addition, it can generate high temperatures and also adjust the mixing ratio accurately.

In the internal mixing-type gas burner, the operator must be careful about backfire.

The mixture of gas and air can only burn or explode within a certain range of the mixing ratio. This is called the "combustible range." This range varies according to the kind of gas. The combustible range slightly changes due to gas pressure and temperature. But the propagation velocity of flame changes according to the mixing ratio of gas and air.

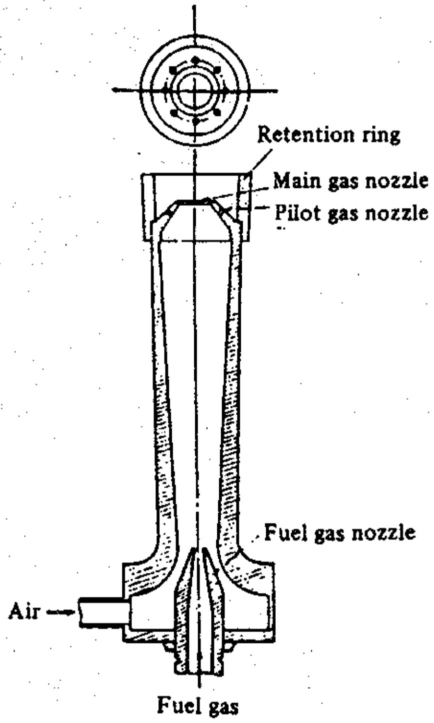
The backfire of the burner occurs when the blow-out speed of the gas mixture is lower than the propagation velocity of flame at the tip. This backfire runs back in the pipe through the burner and retreats as far as the mixing section.

For the above reason, it is necessary that the blow-out speed of the gas mixture be sufficiently higher than the propagation velocity of flame even when the combustion quantity is minimized. Accordingly, the gas mixture at high pressure allows a selection of a wide combustion adjustment range.

When the blow-out speed of the gas mixture is extremely high, there is a fear that it might be accompanied by a "blow off flame" phenomenon. So some measures are taken. For instance, the mixture gas is blown out of numerous small holes so that the blow-out speed may be reduced by a vortex generated in the neighborhood of an individual blow-out nozzle, or the combustion is stabilized by making the gas mixture run into the surface of refractories so that the blow-out speed may be reduced.

Figure 3.19 shows the structure of an internal mixing type gas burner.

Figure 3.19 Structure of Internal Mixing Type Gas Burner



2) External mixing type gas burner

The external mixing type gas burner diffuses and mixes gas with combustion air outside the burner, and burns the mixture. It is also called the nozzle mixing type. Because a combustible mixed gas is not generated inside this type burner, the combustion rate can be adjusted over a wide range without the danger of backfire. Air preheated to high temperature can be used for combustion, and gas can be preheated. For these characteristics, the external mixing type gas burner is extensively used in capacities ranging from small to large for industrial furnaces.

Another outstanding feature of this type of burner is that flames of diverse degrees of intensity, different lengths, and temperature characteristics can be obtained by selecting a nozzle structure and air ejection speed. Typical extermal mixing type burners are shown in Figure 3.20 and 3.21.

Figure 3.20 Compact External Mixing Type Gas Burner

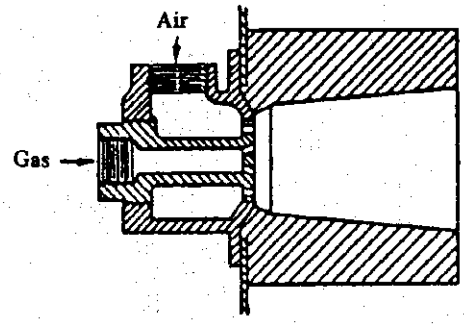
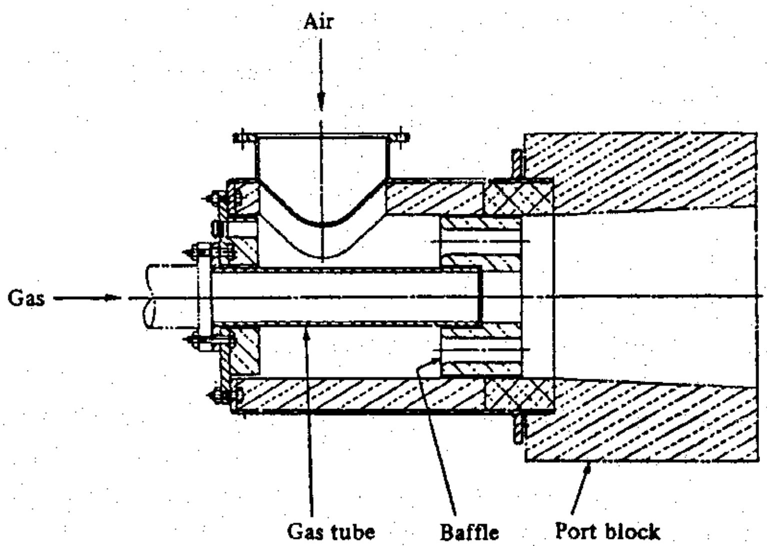


Figure 3.21 Structure of External Mixing Type Gas Burner



The burner shown in Figure 3.20 has a relatively small capacity. Gas is supplied from the nozzle located in the center, while air enters from around it to produce a uniform jet stream inside the burner tile for effective diffusion and mixing. When air and gas shoot at low speed, a soft, long flame of relatively low temperature is produced. Thus, it is suited to the radiant tube burner which requires local overheating.

The burner shown in Figure 3.21 is used for soaking and reheating furnaces. It may have a baffle made of refractories at the outlet, or a refractory venturi with an outlet throttled as appropriate. Because preheated air of high temperature is normally used, the casing must be lined with a heat insulation material of appropriate thickness.

3) Semi-mixing type gas burner

The semi-mixing type gas burner receives a premixture of part of combustion air and gas, and adds the required amount of secondary air at the nozzle tip to burn the gas mixture. It is also called the atmospheric pressure burner. A venturi tube is normally used for premixing air. Air is drawn from the atmosphere by the dynamic pressure energy of the gas and mixed with it.

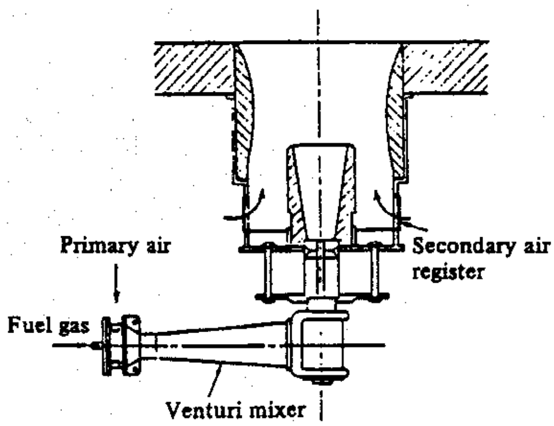
Premixing air ranges from about 30% to 70% of the total amount of combustion air, and flame length and intensity can be changed by adjusting the amount of primary air.

Small-sized burners for simple equipment are used at low gas pressures ranging about 50 to 250 mmH_2O. Industrial burners with large combustion capacity require higher gas pressure to produce a gas mixture of proper pressure, which depends on the kind of gas, the percentage of premixing air, and the required range of adjusting the combustion rate.

Premixing air, though only part of total combustion air, produces a combustible mixture in most cases. This means that due care must be exercised against backfire.

Figure 3.22 shows the structure of a semi-mixing type gas burner.

Figure 3.22 Structure of Semi-mixing Type Gas Burner



4) High-pressure atomizing type oil burner

This type oil burner normally uses compressed air or steam of about 2 kg/cm^2G to 10 kg/cm^2G as an atomizing medium to atomize oil.

As shown in Figure 3.23, the high-pressure atomizing type oil burner needs an air register to supply and control combustion air, apart from the burner itself. The burner can be roughly classifed into two types, internal mixing and external mixing, which vary with where oil and atomizing medium are mixed.

Figure 3.24 shows an example of internal mixing type, which mixes oil and atomizing medium before the nozzle outlet.

Figure 3.25 shows an example of external mixing type, which mixes oil and atomizing medium outside the nozzle outlet.

Figure 3.23 Installation Chart for High-Pressure Atomizing Type Oil Burner

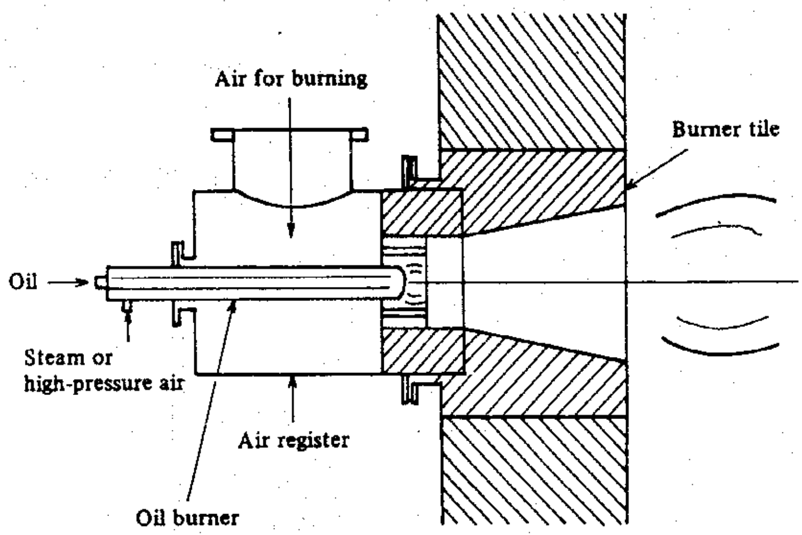


Figure 3.24 Structure of High-Pressure Atomizing Type Oil Burner (Internal Mixing Type)

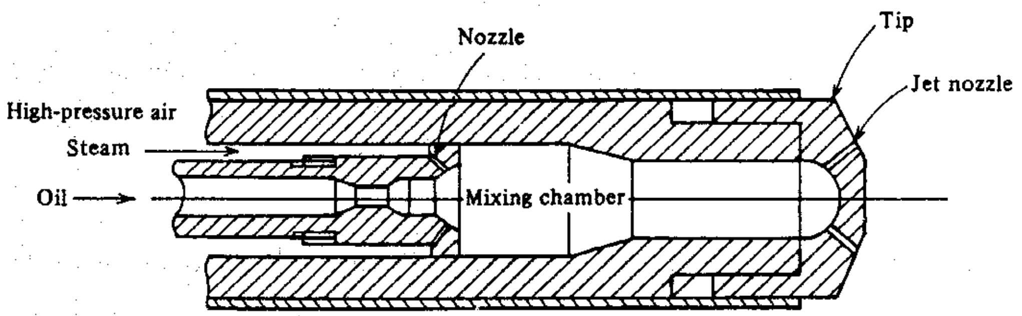
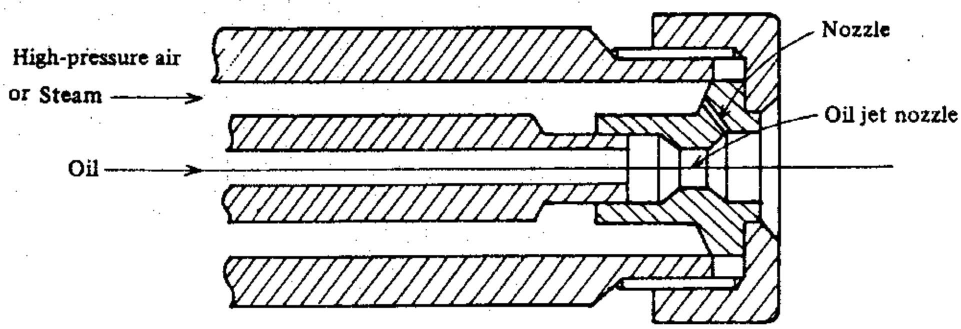


Figure 3.25 Structure of High-Pressure Atomizing Type Oil Burner (External Mixing Type)



5) Low-pressure air type oil burner

This type oil burner uses low-pressure air of 600 to 1,000 mmH_2O as an oil atomizing medium. The atomizing theory is the same as that of the high-pressure atomizing type. That is, oil is atomized by the shooting energy of air. The burner can be roughly classified into two types, the non-proportioning type which supplies only the required amount of air for atomizing oil to the burner body, and the proportioning type which supplies all the amount of air required for combustion to the burner body.

Most of the non-proportioning type burners supply about 20% to 30% of the theoretical amount of air required for combustion to atomize oil. To ensure complete combustion, therefore, remaining 70% to 80% air must be additionally supplied by natural draft or forced draft.

The proportioning type burner supplies all combustion air, including atomizing air, to the burner, and interlocks oil adjustment with air adjustment.

Because all the amount of air required for combustion is supplied from the burner, it will be hardly affected by furnace pressure, and the air ratio can be maintained with relatively high accuracy.

Figure 3.26 shows an example of non-proportioning, low-pressure air type oil burner, and Figure 3.27 an example of proportioning type, low-pressure air type oil burner.

Figure 3.26 Structure of Low-Pressure Air Type Oil Burner (Non-Proportioning Type)

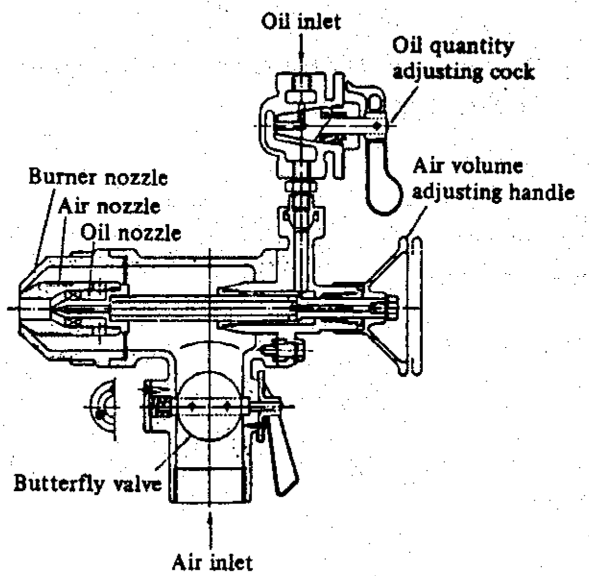
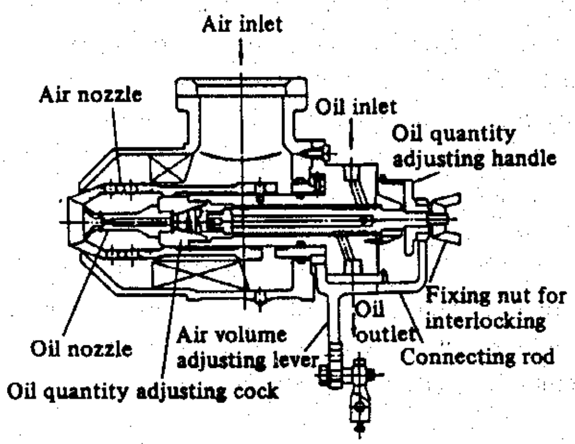


Figure 3.27 Structure of Low-Pressure Air Type Oil Burner (Proportioning Type)



6) Oil-pressure oil burner

The oil-pressure oil burner atomizes oil using only the energy of oil pressure. Oil is supplied at relatively high pressure, and neither air nor steam is necessary to atomize it.

Oil pressure to atomize oil normally ranges from 5 to 20 kg/cm^2. Some large burners of recent make, however, use a maximum oil pressure of 100 kg/cm^2 or even more.

The oil-pressure oil burner comes in two types, one which cannot return the oil that has been fed to the burner body, and the other that returns the oil. The former is simple in structure and easy to operate, and is suited to burning at a constant oil flow rate because of a limited adjusting range. It employs on-off control to regulate the oil flow rate.

The latter has a wide adjusting range to compensate for the disadvantage of the former.

Figure 3.28 shows the structure of a non-return oil type oil-pressure burner, and Figure 3.29 the structure of a return oil type oil-pressure burner.

Figure 3.28 Structure of Non-Return Oil Type Oil-Pressure Burner

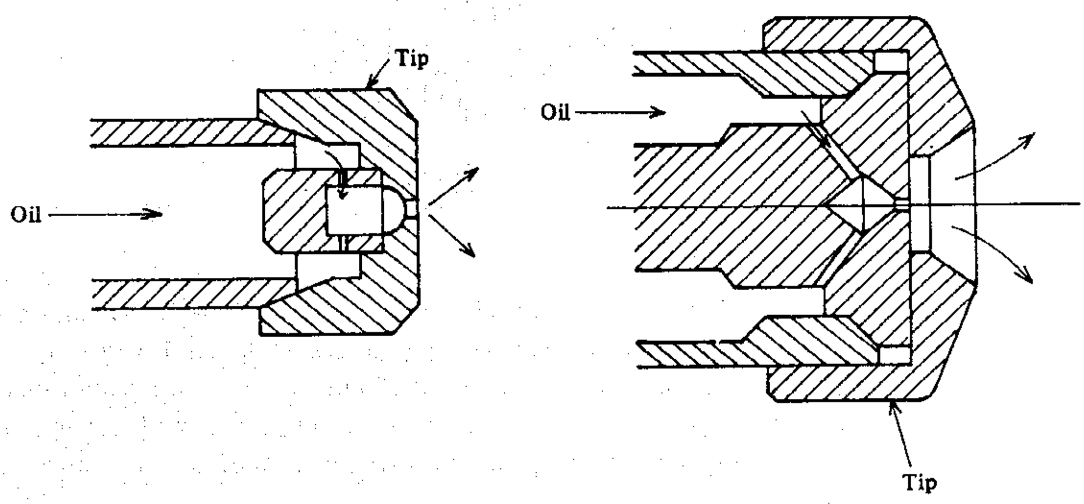
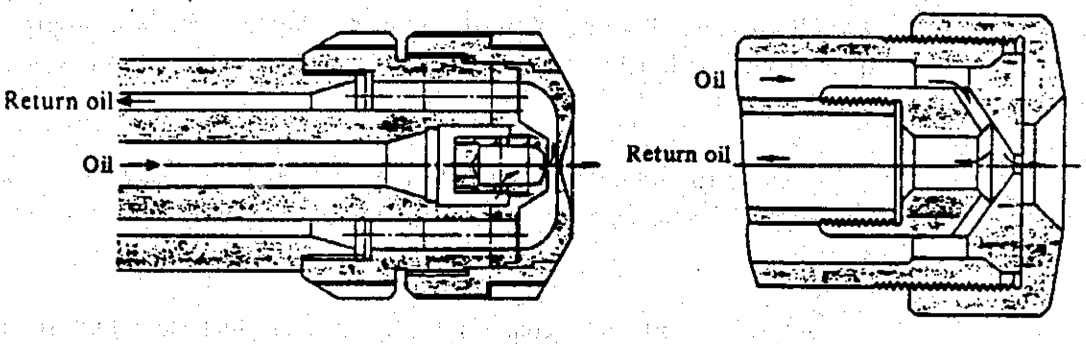


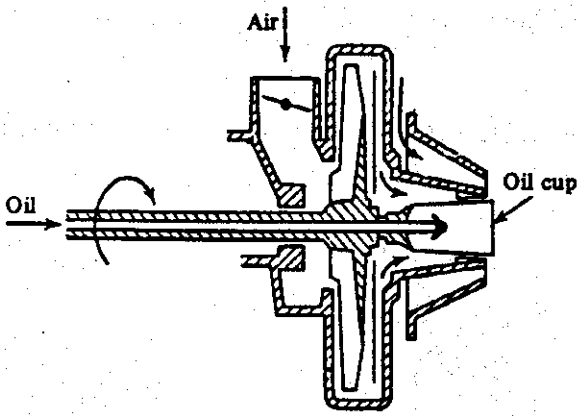
Figure 3.29 Structure of Return Oil Type Oil-Pressure Burner



7) Rotary type oil burner

The rotary type oil burner atomizes oil using a rotary disk. Figure 3.30 shows the structure of it.

Figure 3.30 Structure of Rotary Type Oil Burner



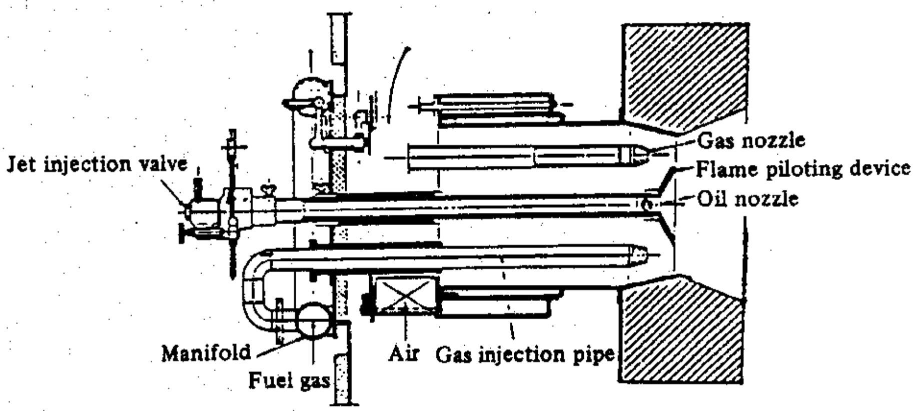
The atomizing mechanism of this burner works as follows: Oil flows along the inner tapered surface of the rotary cup (atomizing tube), is driven away from its tip by centrifugal force, forming a thin film in the tangential direction from the tip of the atomizing tube. That thin film is atomized by primary air blowing from outside the atomizing tube. This type is an evolved version of low-pressure air atomizing burner.

8) Oil and gas mixture burner

This type burner burns oil or gas singly, or oil and gas together. Normally, the oil burner guns are located in the center of the burner, and are used in combination with different types of other external mixing type gas burner.

Figure 3.31 shows a type of oil and gas mixture burner used for many soaking and reheating furnaces.

Figure 3.31 Structure of Oil and Gas Mixture Burner



For your reference, check points and remedial measures for combustion equipment are shown in Table 3.13.

Table 3.13 Points of Check and Maintenance Services for Burning Equipment

Check spot	Points of check	Procedures (Maintenance)
Fuel piping (oil and gas)	• Check leaking spots and tightened parts. • Check if there are any foreign matters or accumulated materials in piping.	• Retighten defective spots. • Blow the air into piping.
Attached equipment with piping	• Disassemble and check the oil pump.	• Check worn-out parts, specially bearing, and if defective, replace them. • If the whole pump is defective, replace it with a spare pump. • Check V-belt and coupling, and replace them, if necessary.
	• Disassemble and check oil strainer.	• Check the interior of strainer. • Clean the clogged strainer. • If broken, replace the strainer or repair by partial welding and padding.
	• Disassemble and check oil heater.	• Check and clean the heater. • If defective, replace it.
	• Check valves such as pressure adjusting, stop and relief.	• If any function is found, disassemble and check, and replace the whole set of valves. • For the relief valve and safety valve, check and adjust their working pressure.
Interior of furnace	• Check burner tiles.	• Check if there is any carbon attaching to the burner tile. Scrape it off while it is hot as far as circumstances allow. • Check if there are any cracks.
	• Check refractories.	• Check if there are cracks or a large break. • Check the joints of refractories. • Check the alignment of refractories.
	• Check the castable or furnace body.	• In addition to the castable, check the furnace body. • Check the peep hole and the explosion door.
Instruments	• Check the flow meter. • Check the thermometer. • Check the manometer. • Check the fuel safety device.	• Check the accuracy of indication. (check the zero point) • Check a leakage and breakage of the connections. • Test the flame suppression action. It is necessary to disassemble and clean the flame detector (e.g. ultra-violet detector).

c. Prevention of explosion

In handling combustion equipment, it is necessary first of all to exercise caution to prevent explosion. Explosion may result in human casualties, equipment destruction, or long interruption of operations, thus making all the efforts for energy conservation and improvement of operations useless. Take the following steps, bearing in mind that explosion of combustion gas tends to occur at start or end of work.

- Purge the inside of the furnace to fully discharge remaining gas before ignition, using a blower.
- If ignition fails, stop operation without hesitation, and purge the inside of the furnace again.
- Keep attention to the flame detector to see that it is operating normally.
- Fully purge the inside of the furnace to discharge gas after turning the burner off.
- If gas is used as fuel, water-seal the gas supply pipe to shut the gas off after work.

d. Management for oil combustion

Complete atomization of oil is essential to complete combustion of it. Unsatisfactory atomization may result in an unsteady flame, black smoke from incomplete combustion, or staining the furnace walls with carbon.

Unsatisfactory atomization may be caused by interruption of spray or variation of oil pressure due to sludge or other foreign matter in the fuel; incorrect amount or pressure of air or steam for atomization, and lack of oil preheating.

To properly atomize oil, oil viscosity at the burner inlet must be within the range shown in Table 3.14

Table 3.14 Required Viscosity of Oil at Burner Inlet

Type of burner	Required viscosity of oil at burner inlet	
	RW. No. 1	Kinematic viscosity
High-pressure atomizing type	230 sec. max.	59 cst max.
Low-pressure air type	230 sec. max.	59 cst max.
Oil pressure type	150 sec. max.	32 cst max.
Rotary type	150 sec. max.	32 cst max.

e. Internal furnace pressure and smoke stack draft force

Draft means supplying combustion air and discharging burnt gas, and its intensity is expressed by pressure difference in water column (mm). Draft force is a very important factor in judging the draft capacity of a combustion furnace and the propriety of furnace operation.

Draft takes place by means of a smoke stack or a blower, and can be classified into two kinds as follows:

1) Natural draft (smoke stack)

2) Forced draft (blower)

(A) Forced draft

Combustion air is sent into the furnace with a blower, and burnt gas is discharged through the smoke stack by its draft force. There may be cases where inside furnace pressure rises higher than the atmospheric pressure, in which the gas may shoot out if the furnace body has clearances.

(B) Induced draft

Burnt gas is discharged by the blower or ejector in the smoke stack. There may be cases where inside furnace pressure falls below the atmospheric pressure, in which outside air leaks into the furnace if the furnace body has clearances.

(C) Balanced draft

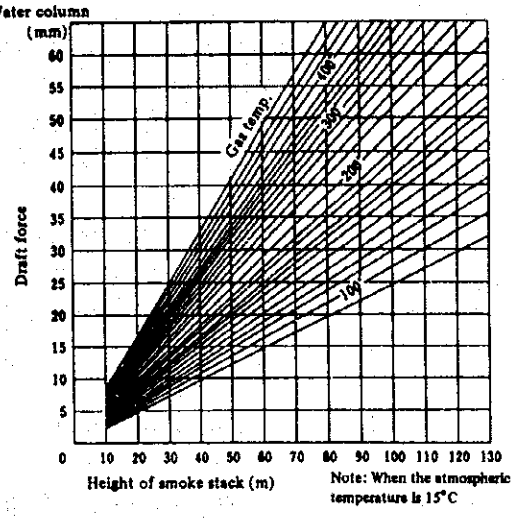
This is a combustion of forced draft and induced draft, and inside furnace pressure can be freely adjusted.

If draft force is too great, (1) there will be much excess air and heat loss will increase due to exhaust gas, and (2) inner furnace temperature will fall and temperature distribution will be uneven.

If draft force is insufficient, (1) soot will be produced due to incomplete combustion, and (2) there is the danger of after burn if gas is used as fuel.

Figure 3.32 shows the relationship between average gas temperature and draft force inside smoke stack.

Figure 3.32 Average Gas Temperature and Draft Force Inside Smoke Stack



The required draft force for combustion depends on the type of burner and combustion rate. Draft force must be larger than the total of the resistance of air passing the burner and the flue resistance of burnt gas passing the flue.

When a flue has a constant cross section and is straight, flue draft resistance can be expressed in terms of pressure drop per meter of flue length. It is 0.2 to 0.3 mm water column. If a flue has a bend or varies in cross section, or has a superheater, economizer, or air preheater on the way to the smoke stack, draft resistance occurs due to each of those factors, and the required draft force will increase.

An example of draft resistance in flue is shown in Table 3.15.

Table 3.15 Example of Draft Resistance (Water Column mm) In Flue

Heat transfer areas	Flue tube boiler	4 ~ 7
	Smoke tube boiler	7 ~ 10
	Horizontal multitubular boiler	3 ~ 6
	Water tube boiler	2 ~ 5
Superheater		2 ~ 3
Economizer		3 ~ 5
Air preheater		3 ~ 5
Dust collector		2 ~ 3
Damper		1 ~ 3
Horizontal flue per 1 m		0.2 ~ 0.3
Flue 90° bend		3

If an air preheater, for example, is newly installed in a flue, draft resistance will increase and exhaust gas temperature will fall so that draft force will lower.

If fuel gas contains sulfur, sulfur oxides are generated by combustion. Because sulfur oxides corrode the air preheater, economizer, and steel smoke stack, exhaust gas temperature must not be below the dew point. Normally, an exhaust gas temperature of 200°C or more is recommended.

Main causes of insufficient draft force are as follows:

(a) Smoke stack not high enough; smoke stack not large enough is cross sectional area.

(b) Smoke stack is clogged up with soot or dust.

(c) Secondary air inlet of burner is clogged up.

(d) Air enters through the furnace body and brick walls of smoke stack.

(e) Damper is not open wide enougth.

(f) Blower capacity or pressure is insufficient.

The draft force of a smoke stack is generated by the difference between gas density inside the smoke stack and the atmospheric density, and its intensity depends on the gas temperature inside the smoke stack and its height.

A simple equation for calculating the draft force of a smoke stack is shown below.

$$h = 355 \times H\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

where

h: Theoretical draft force that the smoke stack generates (mm water column);
H: Height of smoke stack (m);
T_1: Atmospheric temperature (°C) + 273;
T_2: Average gas temperature inside smoke stack (°C) + 273.

Generally, gas flow velocity through a smoke stack is 4 to 5 m/s. As smoke stack diameter decreases, gas flow velocity increases and resistance also increases. Therefore, a smoke stack with enough diameter and internal area is necessary.

Internal furnace pressure should be set to anywhere between 0.2 and 0.4 mmH_2O in terms of pressure on the hearth.

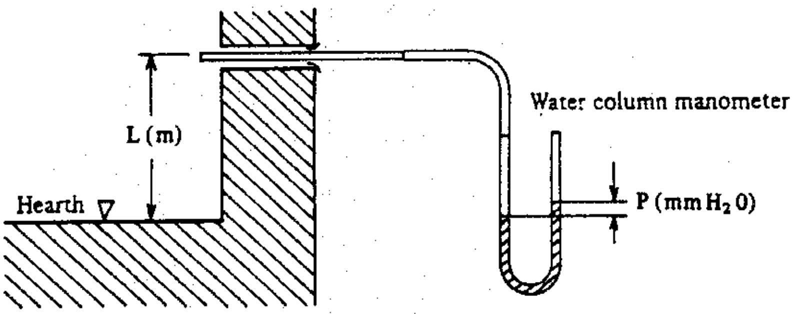
When using a damper or a similar inner furnace pressure regulator, consider the effect on the buoyance of gas inside the furnace and the position of the internal furnace pressure measuring point in furnace pressure setting as shown in Figure 3.33.

$P = (0.2 \sim 0.4) + L\ (mmH_2O)$

where

P: Inner furnace pressure set (mmH_2O)
L: Height of measuring point above hearth (m).

Figure 3.33 Furnace Pressure Measurement Port and Pressure Setting



(2) Rationalization of heating, cooling, and heat transfer

In a reheating furnace, heat is transferred to the material as follows:

a. Heat transfer by conduction

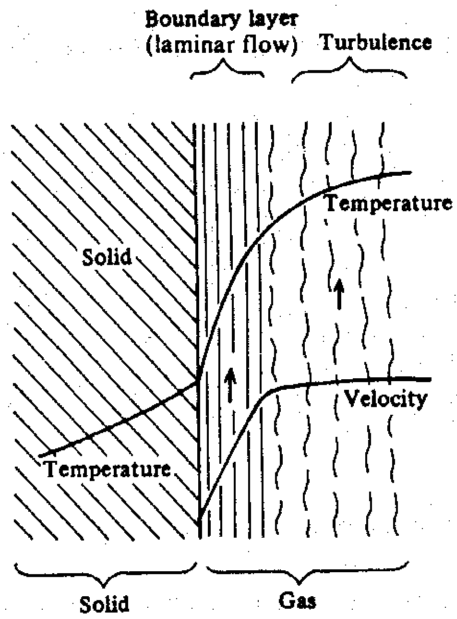
When a low-temperature material is placed on a hot hearth, heat is transferred by conduction.

When two solids come into contact, the contact surface instantly reaches a temperature halfway between the temperatures of the two solids. Actually, the amount of heat transferred by conduction is relatively small.

b. Heat transfer by convection

If a gaseous fluid flows parallel to the surface of a solid as shown in Figure 3.34, the fluid is layered over the surface of the solid by inter-molecular attracting force, and heat is transferred by conduction along this stationary (boundary) layer. In cases where furnace temperature is below 600°C, heat transfer by convection is most important. According to experiments, the amount of heat transfer per unit area and unit time from gas flow along a plane is a function of the mass of the gas and the temperature difference. There is an instance in which, for the purose of increasing the amount of heat transfer, gas velocity is raised to increase the coefficient of heat transfer to 30 kcal/.m²h°C or more.

Figure 3.34 Heat Transfer to Surface by Convection



For low-temperature reheating furnaces, raising gas velocity inside the furnace is the only way of increasing the coefficient of heat transfer.

Actually, gas temperature and velocity vary inside a furnace from one point to another. In cases, gas flows along the top without contacting the heating material. In many reheating furnaces, small pieces are placed together on a tray for heating. Such pieces may not always have flat surfaces. Gas flowing to their surfaces will have a different way of heat transfer from what has been described above.

c. Heat transfer by emission between solids

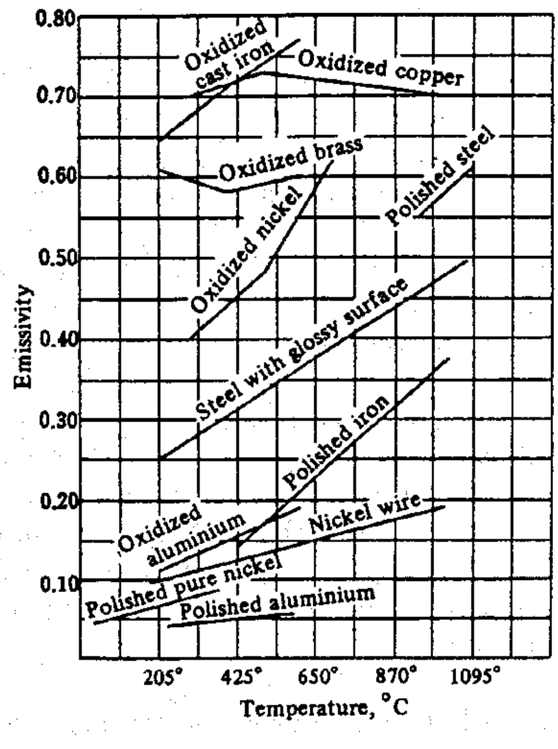
A solid emits heat, and this is more so at high temperature. The amount of heat transferred from a high-temperature solid to a low-temperature solid by emission corresponds to the difference between the amount of heat emitted from the high-temperature solid to the low-temperature solid and the amount of heat emitted from the low-temperature solid to the high-temperature solid.

The amount of heat emission from a solid is in direct proportion to fourth power of the absolute surface temperature of the solid, and is also directly proportionate to the emissivity of the solid.

The emissivity is equal to absorptivity, and complete emissivity is called blackbody emissivity.

Figure 3.35 shows emissivity versus the surface temperatures of various kinds of metal.

Figure 3.35 Emissivity of Metal



d. Heat transfer from clear gases to solids by emission

When discussing emission from burnt gas to solids, emission from clear gas must be treated apart from emission from luminous flame.

Of clear gases, only CO_2, H_2O, and SO_2 emit a considerable amount of heat. The other clear gases, including O_2, N_2, and H2, radiate only a negligible amount of heat.

Of these gases, CO_2 and H_2O are generally important in point of heat radiation, and its intensity depends on the product of partial gas pressure multiplied by gas layer thickness, and the gas temperature.

e. Heat transfer by emission from luminous flame

Luminous flames are orange-like flames that can be observed when a liquid fuel is burnt, or when a gaseous fuel is burnt without enough air supply, or when pulverized coal is burnt.

Luminous flame radiation is considered as a combination of radiation of gas, like CO_2 or H_2O, with solid radiation by a group of high-temperature, fine carbon particles contained in the flame.

Radiation by a luminous flame is generally far higher than gas radiation of a non-luminous flame.

f. Use of preheat of the preceding process by hot charge

In cases where a continuous casting mill is located close to a charging machine for a reheating furnace in a rolling mill, offering a big advantage for hot charge, fuel consumption can be reduced by using hot charge.

It is desirable that cut billets of high temperature for continuous casting be directly charged into the reheating furnace, but it would be extremely difficult to hot charge all the billets because of the difference in production capacity between the continuous casting machine and the rolling line. It is for this reason that a hot box is generally used as a buffer to temporarily store high-temperature billets for continuous casting. The hot box is a steel-plate box lined with heat-insulating material, and has a movable cover to take billets in and out.

The capacity and number of hot boxes are determined depending on the capacity of the continuous casting machine, billet storage quantity planned, etc.

Energy saving by hot charge will be 20×10^3 kcal/ton (or 2.2 liters/ton in terms of fuel oil C) per 100°C in charging temperature.

g. Raising efficiency of heat transfer in furnace by improving material charging method

Heat transfer in a furnace can be raised by improving the material charging method.

If a piled material is charged as it is, heat transfer by radiation and convection inside the furnace acts on only the upper part of the material, leaving the lower part of it less heated by heat conduction because the individual pieces of the material are not in close contact with each other.

As described above, heat transfer in a combustion furnace depends basically on the heat radiation of combustion gas. To increase the heat radiation capacity of combustion gas, it is necessary to make the internal furnace capacity considerably larger than the size of the heating object in order that the so-called "effective gas thickness" will increase. Increasing the internal furnace capacity will increase heat loss due to furnace wall heat accumulation and radiation, and equipment construction costs. This indicates a need to increase the heat radiation capacity itself and improve the efficiency of heat transfer from combustion gas to the heating object.

There is an instance of energy saving, which uses gas-permeable solids mounted in a reheating furnace, taking advantage of the fact that solid heat radiation capacity is far higher than gas heat radiation capacity, to convert gas heat radiation into solid heat radiation, and consequently increase the heat radiation capacity of the furnace.

(3) Prevention of heat loss by radiation, heat transfer, etc.

a. Prevention of heat loss from furnace body surfaces

To reduce radiation heat loss from the furnace body surfaces and accumulated heat loss from the furnace body, it is necessary to lower the heat conductivity of the furnace walls and ceiling, and also their heat capacity.

The furnace walls must meet specific requirements for strength and fire resistance, and the kinds of furnace wall material, combinations, thickness, and other specifications vary according to the requirements.

The furnace ceiling is generally thinner than the furnace walls for reasons of furnace strength. The sidewalls have peepholes, doors, burner mount, etc. and may be thick or thin depending on the structure.

Recently built furnaces have walls made of lightweight ceramic fibers with small specific heat, featuring excellent heat insulation, small heat accumulation, and decreased heat loss from the furnace walls.

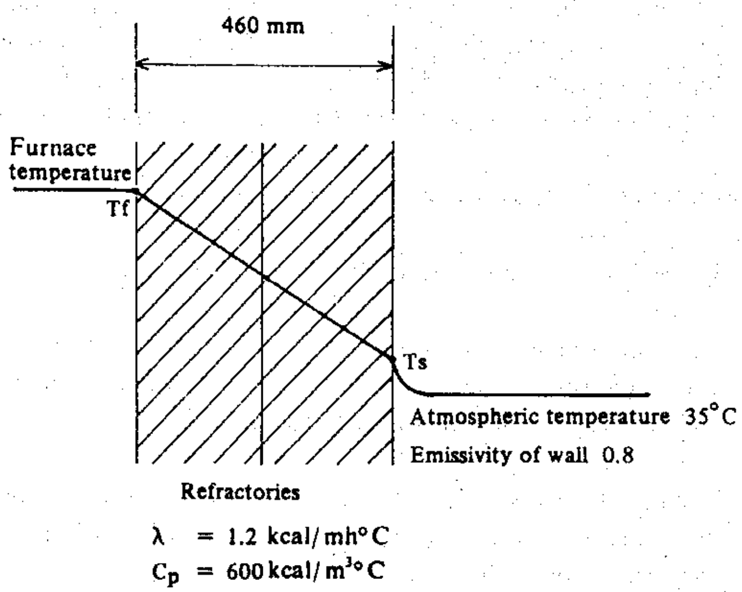
The existing furnaces with brick walls may have to be lined with ceramic fibers to deal with the problem, provided that reduction of furnace capacity by it will pose no problem. Heat radiation loss from the furnace body surfaces can be reduced by improving heat insulation.

There are two ways of heat-insulating furnaces. One is to line the furnace walls with ceramic fibers, and the other is to cover the furnace walls with ceramic fibers, rockwool, or glasswool.

Figure 3.36 shows the standard furnace wall temperature of a reheating furnace lined with only refractory bricks 460 mm thick.

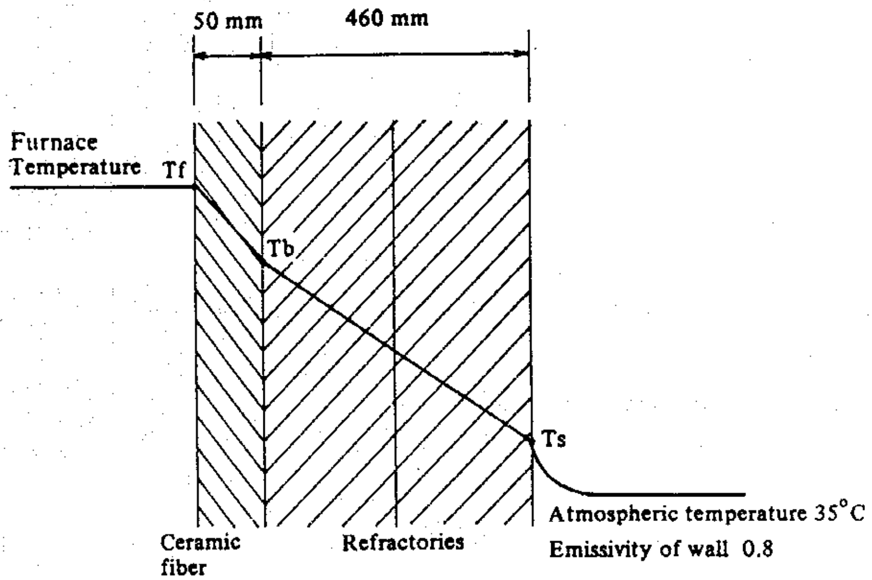
Figure 3.37 shows the same furnace as shown in Figure 3.36 except that it was better heat-insulated by lining the walls with ceramic fibers 50 mm thick.

Figure 3.36 Typical Wall Temperature of Reheating Furnace



Furnace temperature	Tf	1300	1200	1000	800	°C
Surface temperature	Ts	199	190	170	149	°C
Quantity of radiant heat	Q	2,873	2,636	2,165	1,699	kcal/m²h
Quantity of accumulated heat	H	206,837	191,765	161,463	130,914	kcal/m²

Figure 3.37 Improvement Plan for Wall Composition of Reheating Furnace



λ = 0.17 Kcal/mh°C λ = 1.2 Kcal/mh°C

C_p = 50 kcal/m³°C C_p = 600 kcal/m³ °C

Furnace temperature	Tf	1300	1200	1000	800	°C
Boundary temperature	Tb	800	741	621	307	°C
Surface temperature	Ts	149	142	128	112	°C
Quantity of radiant heat	Q	1,700	1,562	1,288	1,015	kcal/m²h
Quantity of accumulated heat	H	133,562	124,215	105,384	86,341	kcal/m²

These improvements produced energy saving effects as observed below. As shown in Table 3.16, both the quantity of radiant heat and the quantity of accumulated heat decrease by 30% to 40% as the surface temperature of the outer walls falls. Ceramic fibers having great resistance to fire and heat lower the temperature of the refractory bricks, and thus extend brick life, producing desirable effects in all aspects. Although lining the furnace walls with ceramic fibers poses two problems — decreasing the internal capacity of the furnace and the difficulty of lining the whole area of the hearth — these problems are not serious.

Table 3.16 Improvement Effects of Wall Composition of Reheating Furnace

	When furnace temp. is at 1,300°C		Improvement effects
	Before improvement	After improvement	
Surface temperature	199°C	149°C	25% drop of surfacial temperature
Quantity of radiant heat	2,873 kcal/m^{2}h	1,700 kcal/m^{2}h	41% decrease in quantity of radiant heat
Quantity of accumulated heat	206,837 kcal/m^2	133,562 kcal/m^2	35% decrease in quantity of radiant heat

A plan of improving the furnace walls by covering them with rock wool will now be discussed.

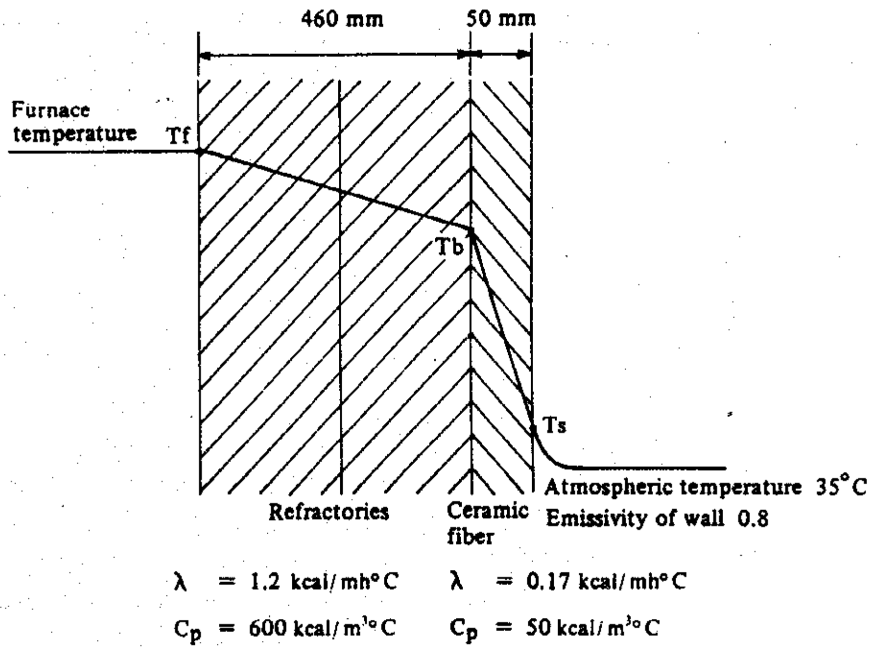
If a furnace is covered with steel plates around its outer walls, additional covering with rock wool will raise the temperature of the steel plates, causing distortion due to thermal expansion and possible breakdown of the furnace shells.

Figure 3.38 shows the temperature, etc. of furnace walls of refractories covered with ceramic fibers 50 mm thick. The refractories show an abnormally high average temperature with a rise in the quantity of accumulated heat.

The furnace walls in this case were covered with ceramic fibers, not with rock wool, because the boundary temperature was higher than the safe working temperature of rock wool.

As temperature rises, refractory bricks lower in strength and may break down, or otherwise shorten in service life.

Figure 3.38 Inferior Reconstruction Plan for Wall Composition of Reheating Furnace



Furnace temperature	Tf	1300	1200	1000	800	°C
Boundary temperature	Tb	649	601	506	411	°C
Surface temperature	Ts	149	142	128	112	°C
Quantity of radiant heat	Q	1,700	1,562	1,288	1,015	kcal/m²h
Quantity of accumulated heat	H	269,893	249,506	208,676	167,761	kcal/m²

For your reference, the standard temperatures of industrial furnace outer walls in Japan are shown in Table 3.17, and target temperatures of furnace outer walls in Table 3.18. The values of the standard and target temperatures of furnace outer walls in the tables are the same as those described in the previous section of air ratio.

In addition, the main characteristions of typical insulating fire materials are shown in Table 3.19 and the working temperature range of typical insulating materials is shown in Figure 3.39.

Table 3.17 Standard Temperatures of Furnace Outer Walls

Temperature in furnace (°C)	Standard temperature of furnace outer wall (°C)		
	Ceiling	Side wall	Hearth contacting with outer air
1,300°C or more	140	120	180
1,100°C or more but less than 1,300°C	125	110	145
900°C or more but less than 1,100°C	110	95	120
Less than 900°C	90	80	100

Remarks 1. The values of the standard temperatures of furnace outer walls shown in the above table are those of the average temperatures of furnace outer walls (excluding unusual parts) during normal operation at an outer air temperature of 20°C or less.

2. The values of the standard temperatures of furnace outer walls shown in the above table shall not apply to the outer walls of the following industrial furnaces:

(1) Furnaces having a rated capacity (combustion capacity of burner fuels) less than 50 liters/h (in terms of heavy oil equivalent);

(2) Furnaces for forced cooling furnace walls;

(3) Rotary kilns;

(4) Furnaces used for research, development or prototype manufacturing purposes.

Table 3.18 Target Temperatures of Furnace Outer Walls

Temperature in furnace (°C)	Target temperature of furnace outer wall (°C)		
	Ceiling	Side wall	Hearth contacting with outer air
1,300°C or more	120	110	160
1,100°C or more but less than 1,300°C	110	100	135
900°C or more but less than 1,100°C	100	90	110
Less than 900°C	80	70	90

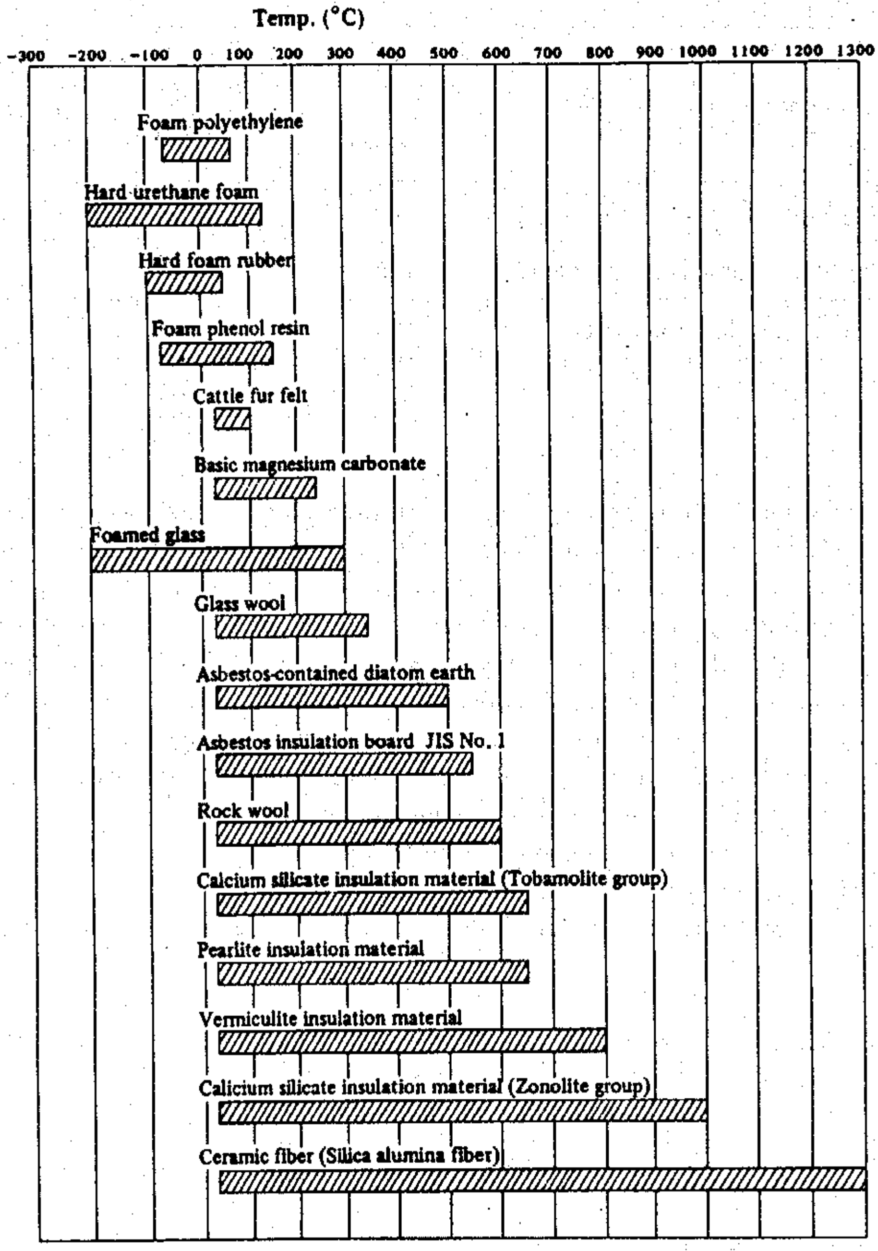
Remarks 1. The values of the target temperatures of furnace outer walls shown in the above table are those of the average temperatures of furnace outer walls (excluding unusual parts) during normal operation at an outer air temperature of 20°C or less.

2. The values of the target temperatures of furnace outer walls shown in the above table shall not apply to the outer walls of the following industrial furnaces, provided, however, that if possible, examinations shall be made to ensure that the insulation of the walls of the follwing furnaces is increased based on the same table:
   (1) Furnaces having a rated capacity (combustion capacity of burner fuels) less than 50 liters/h (in terms of heavy oil equivalent);
   (2) Furnaces for forced cooling furnace walls;
   (3) Rotary kilns;
   (4) Furnaces used for research, development or prototype manufacturing purposes.

Table 3.19 Main Characteristics of Insulating Fire Materials

	Bulk specific gravity t/m^3	Specific heat $kcal/m^3$ °C	Thermal conductivity kcal/mh °C	Safe working temp. °C
Refractory brick S K32	2.0~2.5	520~650	0.9~1.4	1,300
Plastic refractory S K32	1.9~2.3	380~500	0.6~1.4	1,300
Insulating fire brick B5	0.7~0.8	160~200	0.2~0.4	1,100
Insulating fire brick B1	0.6~0.7	140~160	0.1~0.2	700
Insulating fire castable (1,300°C)	1.0~1.3	240~300	0.2~0.4	1,100
Ceramic fiber (lower than 1,300°C)	0.6~0.3	20~80	0.05~0.3	1,100

Figure 3.39 Working Temperature Range of Typical Insulating Materials



b. Prevention of heat loss through openings

There are two kinds of heat loss from openings. One is due to direct radiation from openings, and the other is due to combustion gas leaking from openings.

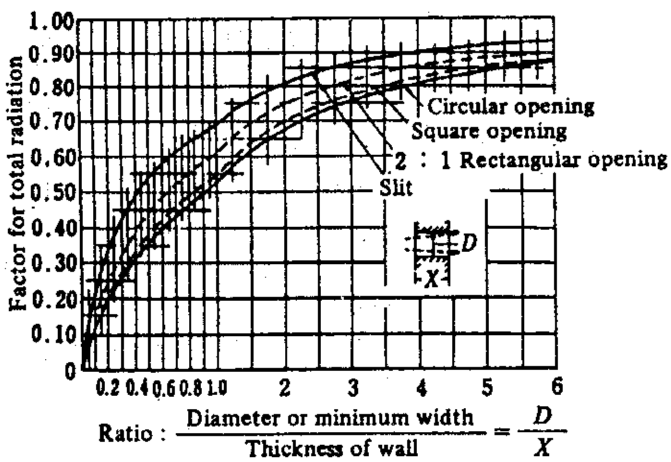
1) Heat loss by radiation from openings

When a furnace has an opening on a part of the body, the heat inside the furnace is radiated from the furnace.

The amount of heat loss due to radiation from an opening differs depending on the thickness of the furnace wall and the shape of the opening. The amount of heat loss from the opening is the total of heat loss from secondary radiation to outside of part of the heat of the opening in the furnace wall heated by radiation from inside the furnace and the heat loss by direct heat radiation from inside the furnace.

The ratio of the amount of heat radiation from a plane plate fully exposed outside to the amount of heat radiation from an opening in a furnace is as shown in Figure 3.40 according to J.D Keller.

Figure 3.40 Factor for Determining the Equivalent of Heat Release from Openings to the Quantity of Radiant Heat from Perfect Black Body



This can be explained, referring to an example as follows:

Suppose that a furnace has a rectangular steel discharge port 1 m high (D) and 1 m wide, without a door, and has walls 0.46 m thick (X).

The opening is square, and D/X = 1/0.46 = 2.17. Thus, the coefficient for total radiation will be 0.71.

If the furnace temperature is 1,340°C, the amount of heat loss by radiation from this opening will be obtained as follows:

$$4.88\times\left(\frac{1,340+273}{100}\right)^4\times 0.71\times 1\times 1=234,500\ \mathrm{kcal/h}$$

The above example applies to cases of a steady state where the opening remains open.

These conditions do not apply to cases in which an opening has a door. While the door is closed, the wall around the opening has the same temperature as the internal furnace temperature uniformly from the part close to the inner surface of the furnace to the part adjacent to the door. Thus, the amount of heat radiation the moment the door is opened will be equal to the amount of heat radiation from a plane plate fully exposed outside. After the door is opened, the wall around the opening rapidly cools to be close to temperature distribution in a steady state, and the amount of heat radiation decreases to the percentage shown in Figure 3.40.

2) Heat loss due to burnt gas leakage from opening

The internal pressure of a reheating furnace is slightly higher than the atmospheric pressure during its operation, so some heat loss is inevitable due to burnt gas blowing out of the furnace from the opening. Because entry of fresh air into the furnace to cool it and oxide the material is more harmful, reheating furnaces are generally opened at an internal pressure higher than the atmospheric pressure. There is little burnt gas blowing through the clearances between the door and opening, and heat loss due to it accounts for about 1% of the total quantity of heat generated inside the furnace.

c. Prevention of heat loss from cooling water

Cooling heat loss through water cooled skid pipes in a continuous reheating furnace amounts to as much as 10% to 15% of the total fuel consumption in the furnace. To cope with this problem, double insulation method for skid pipes has been developed, and is now in wide use for existing furnaces as well as newly installed ones.

As shown in Figure 3.41, the double insulation method employs ceramic fiber with excellent heat insulation performarce for the internal layer and covers the outer surface with castable.

Figure 3.41 Double Insulation Method for Skid

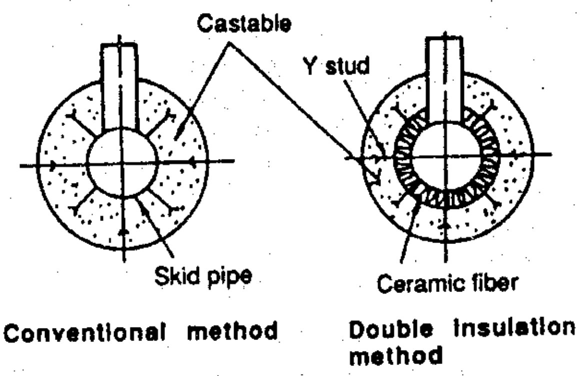
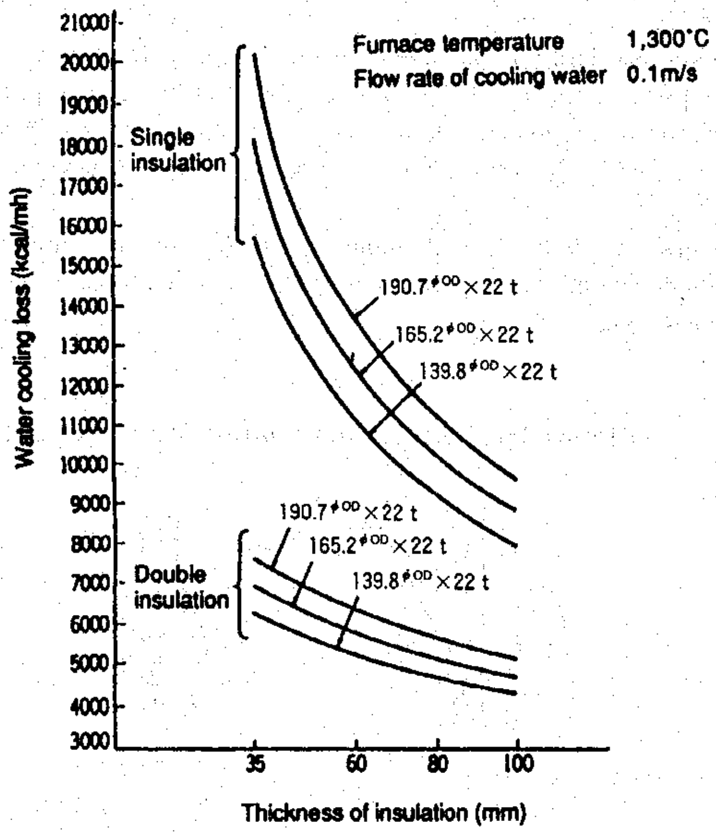


Figure 3.42 shows a comparison (calculated values) in water cooling loss between the single insulation method and the double insulation method.

Figure 3.42 Comparison of Water Cooling Loss (Calculated Values)



As known from the above figure, in case of the pipe with an outside diameter of 165.2 mm, the water cooling loss in double insulation by 15 mm ceramic fiber and 45 mm thick castable shows a 47% decline, as compared with that in 60 mm thick single insulation. This shows that a furnace using double insulation allows a considerable reduction of fuel consumption compared with a furnace using single insulated skid pipes.

Furthermore, the amount of water used for cooling can be significantly reduced by adopting double insulation. Also it has the advantage that skid marks are smaller because the temperature of the outer surface of the insulation layer is higher than that in single insulation.

d. Heat balance

JIS G0702 "Heat Balance Method for Continuous Steel Reheating Furnaces" is intended for accurately determining the heat loss and efficiency of reheating furnaces. Table 3.20 shows a survey report on equipment; Table 3.21, a survey report on longterm operations; Table 3.22, a list of measuring items and results, and Table 3.23, a heat balance table for your reference.

Table 3.20 Survey Report on the Outline of Equipment

1	Name of Co. Factory			
2	Address			
3	Name of furnace manufacturer			
4	No. of furnace			
5	Rolling mill	Type		
6		Nominal capacity	t/yr	
7		Name of main finished product		
8	Reheating furnace	Type		
9		Nominal capacity	t/h	
10		Effective furnace length × furnace width	mm × mm	
11		Size and quality of furnace refractories and insulation material		
12		Kind of fuel used		
13		Type, capacity and No. of burning units		
14		Type and capacity of draft equipment		
15		Type and heating surface area of preheater	m^2	
16		Quality, size and unit weight of main heated steel	mm, kg	

Remark As to Items 10, 11 and 15, attach simple charts representing the vertical and horizontal cross-sections of the furnace (including the size of main parts of the furnace and preheating unit, kind of refractories and main measurement spots).

Table 3.21 Survey Report on Actual Long-Term Operations

1	Date of operation					
			Heating	Heat boosting	Heat retaining	Shutdown
2	Breakdown of operating time	h/month				
		%				
3	Heated tonnage	t/month				
4	Tonnage per heating time	t/hour				
5	Average weight of typical heated steel (Max. and Min. range)	kg				
6	Fuel consumption	t/month, kℓ/month or Nm^3/month				
7	Low calorific value of fuel	kcal/kg or kcal/Nm^3				
8	Energy consumptpion rate per ton of heated steel	10^3 kcal/t				
9	Status of operational shift					

Remark The definition of the breakdown of operating time is as follows:

Heating times: Time during which steel is extracted, i.e. the rolling mill runs.

Heat boosting time: Time required for increasing the furnace temperature up to an "extractable" temperature.

Table 3.22 Table for Measurement Items and Results of Measurement

1	Date and time of measurement (Hours)				
2	Person in charge of measurement				
3	Weather	Atmospheric pressure	Atmospheric temp.	Room temp.	Relative humidity
		mmHg	°C	°C	%
4	Fuel	Soaking zone	consumption	kg/t or m³/Nt	
5	Fuel	Upper heating zone	consumption	kg/t or m³/Nt	
6	Fuel	Lower heating zone	consumption	kg/t or m³/Nt	
7	Fuel	Pressure		kgf/cm³ or mmAq	
8	Fuel	Temperature		°C	
9	Fuel	Components		%	
10	Fuel	Low calorific value		kcal/kg or kcal/m³N	
11	Atomizer	Kind			
12	Atomizer	Soaking zone	consumption	kg/t or m³/Nt	
13	Atomizer	Upper heating zone	consumption	kg/t or m³/Nt	
14	Atomizer	Lower heating zone	consumption	kg/t or m³/Nt	
15	Atomizer	Pressure		kgf/cm² or mmAq	
16	Atomizer	Temperature		°C	
17	Secondary air	Soaking zone	consumption	kg/t or m³/Nt	
18	Secondary air	Upper heating zone	consumption	kg/t or m³/Nt	
19	Secondary air	Lower heating zone	consumption	kg/t or m³/Nt	
20	Secondary air	Pressure		mmAq	
21	Secondary air	Pre-preheating temp.		°C	
22	Secondary air	Post-preheating temp.		°C	
23	Cooling water	Consumption		t/t	
24	Cooling water	Inlet temp.		°C	
25	Cooling water	Outlet temp.		°C	
26	Cooling water	Pressure		kgf/cm²	
27	Combustion gas	Furnace tail temp.		°C	
28	Combustion gas	Inlet temp. of preheater		°C	
29	Combustion gas	Outlet temp. of preheater		°C	
30	Combustion gas	Components		%	CO_2, O_2, CO, (CH_4, H_2)
31	Cinder	Combustible amount		%	
32	Cinder	Cinder amount		kg/kg	
33	Heated steel	Size (Thickness x Width x Length)		mm x mm x mm	
34	Heated steel	Unit weight		kg	
35	Heated steel	Total charged tonnage		t	
36	Heated steel	Charging temp.		°C	
37	Heated steel	Discharging temp.		°C	
38	Heated steel	Burning loss		kg/t	
39	Heated steel	Average in-furnace holding time		h	
40	Furnace pressure			mmAq	
41	Surface temp. of each part of furnace body			°C	

Remarks As to the measurement method for Item 41, describe in the furnace sketch.

Table 3.23 Heat Balance Table

Heat input			Heat output		
Item	10^3 kcal/t	%	Item	10^3 kcal/t	%
(1) Combustion heat of fuel			(8) Quantity of heat contained by extracted steel		
(2) Sensible heat of fuel			(9) Sensible heat of scale		
(3) Sensible heat of air			(10) Sensible heat of exhaust gas		
(4) Heat brought in by atomizer			(11) Heat loss by incomplete burning		
(5) Quantity of heat contained by charged steel			(12) Quantity of heat brought out by cinder		
(6) Heat of scale formation			(13) Quantity of heat brought out by cooling water		
(7) Heat recovered by preheater	( )	( )			
			(14) Other heat loss		
			(15) Heat recovered by preheater	( )	( )
Total (1) + (2) + (3) + (4) + (5) + (6)			Total (8) + (9) + (10) + (11) + (12) + (13) + (14)		

Remark 1. For recording the quantity of heat, use 10^3 kcal/t as a unit and round out figures after the decimal point into a single digit.
2. Round out figures after the decimal point into a single digit in the percentage.

(4) Recovery of Waste heat

Methods for recovering heat from exhaust gas include; (1) preheating combustion air or fuel gas by a heat exchanger, (2) generating steam by a waste heat boiler, (3) preheating material by exhaust gas and (4) using cascade as other heat source.

For reference, Table 4.24 shows standard waste heat recovery ratios for industrial furnaces in Japan, and Table 3.25 shows the target waste heat recovery ratios.

The standard and target values of the waste heat recovery ratios shown in the above tables are as previously described in the item of air ratio.

Table 3.24 Standard Waste Heat Recovery Ratios for Industrial Furnaces

Exhaust gas temperature (°C)	Capacity	Standard waste heat recovery ratio (%)
Less than 500	A · B	25
500 or more but less than 600	A · B	25
600 or more but less than 700	A	35
	B	30
	C	25
700 or more but less than 800	A	35
	B	30
	C	25
800 or more but less than 900	A	40
	B	30
	C	25
900 or more but less than 1,000	A	45
	B	35
	C	30
1,000 or more	A	45
	B	35
	C	30

Notes: 1. "Exhaust gas temperature" means the temperature of the exhaust gas discharged from the furnace chamber at the furnace outlet and at the inlet of the recuperator.

2. Industrial furnaces shall be divided into the following three types according to their rated capacity:

A: Furnaces having a rated capacity of 20,000,000 kcal/h (83,680,000 kJ) or more;

B: Furnaces having a rated capacity of 5,000,000 kcal/h (20,920,000 kJ) or more but less than 20,000,000 kcal/h (83,680,000 kJ)

C: Furnaces having a rated capacity of 1,000,000 kcal/h (4,184,000 kJ) or more but less than 5,000,000 kcal/h (20,920,000 kJ).

Remarks 1. The values of the standard waste heat recovery ratios shown in the above table are the ratios of the calorific value of recovered heat to that of sensible heat from the exhaust gas discharged from the furnace chamber when combustion is conducted at a load close to the rated load.

2. The values of the standard waste heat recovery ratios shown in the above table shall apply to the industrial furnaces installed on January 1, 1980 and after.

3. The values of the standard waste heat recovery ratios shown in the above table shall not apply to the waste heat recovery ratios of the folleing industrial furnaces, provided, however, that if possible, examinations shall be made to ensure that the waste heat recovery ratios of such furnaces are increased based on the same table:

(1) Furnaces having a rated capacity less than 1,000,000 kcal/h (4,184,000 kJ);

(2) Furnaces requiring a specific atmosphere for oxidation or reduction;

(3) Furnaces for burning a by-product gas having a heating value of 900 kcal/Nm^3 (3,765.6 kJ/Nm^3) or less;

(4) Furnaces at the time of the periodical inspection or not operated regularly or used for research, development or prototype manufacturing purposes.

Table 3.25 Target Waste Heat Recovery Ratios for Industrial Furnaces

Exhaust gas tempeature (°C)	Capacity	Target waste heat recovery ratio (%)	(For reference)	
			Exhaust gas temperature (°C)	Preheated air temperature (°C)
Less than 500	A · B	30	300	165
500 or more but less than 600	A · B	30	365	200
600 or more but less than 700	A	35	400	270
	B	30	435	230
	C	25	470	195
700 or more but less than 800	A	35	460	310
	B	30	505	265
	C	25	545	220
800 or more but less than 900	A	40	480	395
	B	35	525	345
	C	30	575	295
900 or more but less than 1,000	A	50	430	550
	B	40	535	440
	C	35	590	385
1,000 or more	A	50		
	B	40	–	–
	C	35		

Notes: 1. "Exhaust gas temperature" means the temperature of the exhaust gas discharged from the furnace chamber at the furnace outlet and at the inlet of the recuperator.

2. Industrial furnaces shall be divided into the following three types according to their rated capacity:

A: Furnaces having a rated capacity of 20,000,000 kcal/h (83,680,000 kJ) or more;

B: Furnaces having a rated capacity of 5,000,000 kcal/h (20,920,000 kJ) or more but less than 20,000,000 kcal/h (83,680,000 kJ);

C: Furnaces having a rated capacity of 1,000,000 kcal/h (4,184,000 kJ) or more but less than 5,000,000 kcal/h (20,920,000 kJ)

Remarks 1. The values of target waste heat recovery ratios shown in the above table are the ratios of the calorific value of recovered heat to that of sensible heat from the exhaust gas discharged from the furnace chamber when combustion is conducted at a load close to the rated load.

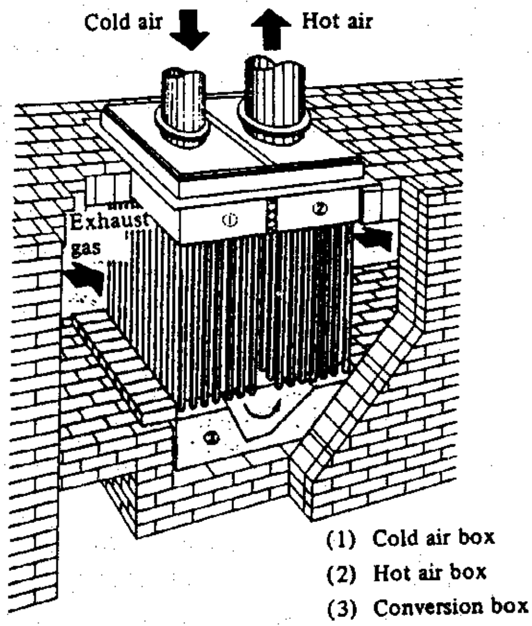
2. The values of the target waste heat recovery ratios shown in the above table shall not apply to the waste heat recovery ratios of the following industrial furnaces, provided, however, that if possible, examinations shall be made to ensure that the waste heat recovery ratios of such furnaces are increased based on the same table:
   (1) Furnaces having a rated capacity less than 1,000,000 kcal/h (4,184,000 kJ);
   (2) Furnaces requiring a specific atmosphere for oxidation or reduction;
   (3) Furnaces for burning a by-product gas having a value of 900 kcal/Nm^3 (3,765.6 kJ/Nm^3) or less;
   (4) Furnaces at the time of the periodical inspection or not operated regularly or used for research, development or prototype manufacturing purposes.

3. The values of exhaust gas temperatures and preheated air temperatures given for reference are those values of the exhaust gas temperatures in a case where waste heat is recovered at the target waste gas recovery ratio and those values of the preheated air temperatures in a case where air preheating is conducted using such recovered waste heat which are calculated under the following conditions:
   (1) Temperature fall owing to heat loss by radiation, etc. that occurs in the process from the furnace outlet to the heat exhanger for air preheating: 60°C;
   (2) Heat radiation from such heat exchanger: 5%;
   (3) Fuel: liquid fuel (in terms of heavy oil equivalent);
   (4) Outer air temperature: 20°C;
   (5) Air ratio: 1.2.

a. Preheating combustion air by burnt exhaust gas using recuperator

There are two types of recuperator: One is a metal recuperator whose heating surfaces are made of metal, and the other is a ceramic recuperator whose heating surfaces are made of refractories. Metal recuperators are mostly used today. An example is shown in Figure 3.43. Use of preheated combustion air allows saving of fuel.

Figure 3.43 Example of Preheater of Air for Burning (Recuperator)



The fuel saving rate in this case can be expressed by the following equation.

$$S = \frac{P}{F+P-Q} = 100\,(\%)$$

where

S: Fuel saving rate (%);
F: Low calorific value of fuel (kcal/kg fuel);
P: Quantity of heat brought in by preheated air (kcal/kg fuel);
Q: Quantity of heat taken away by exhaust gas (kcal/kg fuel).

Using the above equation, the full saving rate for fuel oil and natural gas were calculated by exhaust gas temperature and preheated air temperature as shown in Figures 3.44 and 3.45.

Figure 3.44 Fuel Conservation Rate When Fuel Oil Is Used

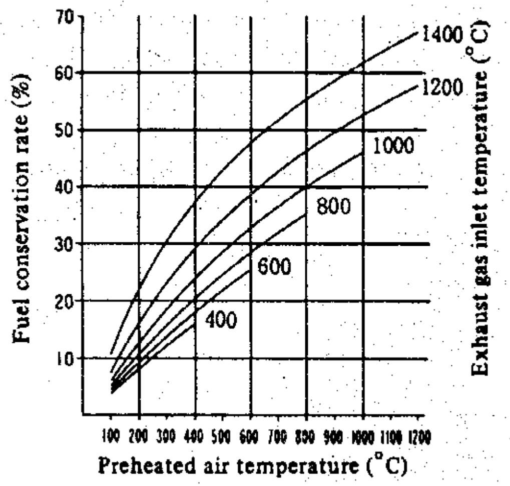
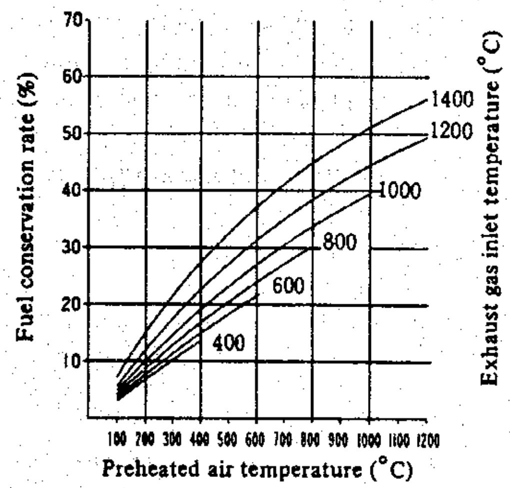


Figure 3.45 Fuel Conservation Rate When Natural Gas Is Used



The higher the exhaust gas temperature, the greater will be the fuel saving rate at the same preheated air temperature.

The recuperator comes in two types: Convection type and radiation type.

The convection type recuperator is a heat exchange system based mainly on convection heat transfer, and is suited to applications at temperatures below 1,000°C because of the problem of thermal expansion at high exhaust gas temperature. The radiation type recuperator is a heat exchange system based mainly on radiation heat transfer. Heat transfer depends on absolute temperature, and is little affected by exhaust gas velocity. The ordinary radiation recuperator has heating surfaces in the form of a simple cylinder, and is suited to applications at temperatures over 800°C.

The recuperator is classified by the flow of exhaust gas and air, parallel or counter. A difference arises in logarithmic average temperature due to parallel or counter flow, and becomes a difference in the heat transfer area of the recuperator.

The heat transfer area of a recuperator can be expressed by the following equation.

$$F = \frac{Q}{\Delta tm \times k}$$

where

F: Heat transfer area (m^2);
Q: Quantity of heat exchange (kcal/h);
Δtm: Logarithmic average temperature difference (°C);
k: Overall heat transfer coefficient (kcal/m^2h°C).

The logarithmic average temperature difference can be expressed by the following equation.

$$\Delta tm = \frac{\Delta t\ max - \Delta t\ min}{\ell n \dfrac{\Delta t\ max}{\Delta t\ min}}$$

In the case of parallel flow, Δt max and Δt min will be as follows from Figure 3.40.

$$\Delta t\ max = t_1 - t_1'$$
$$\Delta t\ min = t_2 - t_2'$$

In the case of counter flow, Δt max and Δt min will be as follows from Figure 3.41.

(a) If $(t_1 - t_2') > (t_2 - t_1')$

$$\Delta t\ max = t_1 - t_2'$$
$$\Delta t\ min = t_2 - t_1'$$

(b) If $(t_1 - t_2') < (t_2 - t_1')$

$$\Delta t\ max = t_2 - t_1'$$
$$\Delta t\ min = t_1 - t_2'$$

Figure 3.46 Temperature Difference in Case of Parallel Flow

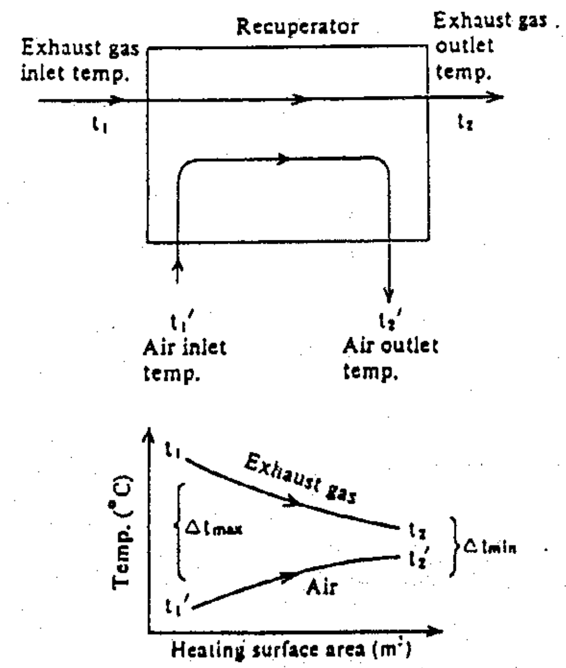
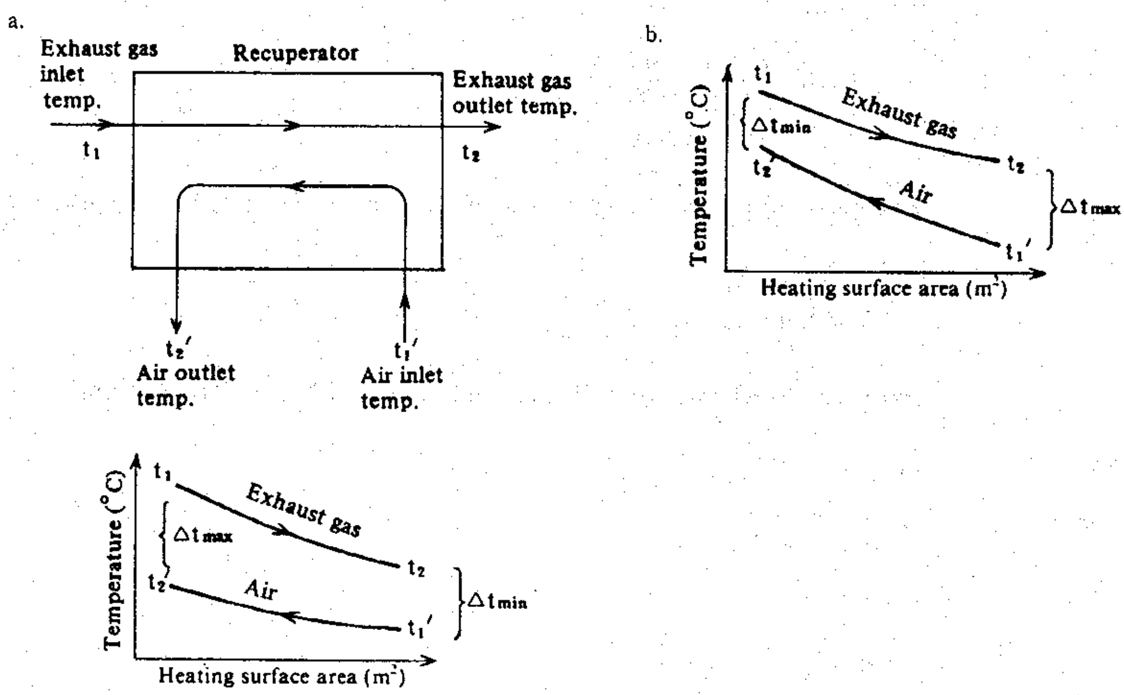


Figure 3.47 Temperature Difference In Case of Counter Flow



Using an example, the logarithmic average temperature difference between parallel flow and counter fow may be expressed as follows:

First, inlet and outlet temperatures are assumed to be as specified below.

t_1 = 800°C $\quad$ t_2 = 500°C
t_1' = 20°C $\quad$ t_2' = 350°C

- Case of parallel flow

Δt max = 800 – 20 = 780°C
Δt min = 500 – 350 = 150°C

$$\Delta tm\,(\text{parallel}) = \frac{780-150}{\ell n\dfrac{780}{150}} = 382\,^{\circ}C$$

- Case of counter flow (b)

Δt max = 500 – 20 = 480°C
Δt min = 800 –350 = 450°C

$$\Delta tm\,(\text{counter flow}) = \frac{480-450}{\ell n\dfrac{480}{450}} = 465\,^{\circ}C$$

Thus, Δtm is 22% larger for counter flow than for parallel flow. If k is the same between parallel flow and counter flow, heat transfer area will be about 18% smaller for counter flow than for parallel flow.

The temperature of heat transfer area may be safely assumed as about halfway between the exhaust gas temperature and air temperature so that the case mentioned above can be calculated as shown in Table 3.26

Table 3.26 Temperature of Heat Transfer Area

	Parallel flow		Counter flow	
Exhaust gas temperature	800°C	500°C	800°C	500°C
Air temperature	20°C	350°C	350°C	20°C
Temperature of heat transfer area	410°C	425°C	575°C	260°C

In this example, the temperature of heat transfer area is about even at 410°C to 425°C for parallel flow, but varies greatly from 260°C to 575°C for counter flow.

The factors having a great influence on recuperator life include resistance to oxidation, corrosion resistance, mechanical strength, and absorption of thermal expansion. When it comes to selecting a material for the above example from the standpoint of resistance to oxidation, the following may be mentioned.

- Parallel flow

  High temperature parts: Carbon steel
  Low temperature parts: Carbon steel

- Counter flow

  High temperature parts: Stainless steel
  Low temperature parts: Carbon steel

From the standpoint of thermal expansion, parallel flow is more steady than counter flow because material temperature is more or less even. Whichever you may select, parallel flow or counter flow, it is necessary to examine installation conditions, price, etc.

Selection of a material for heating surfaces depends on temperature conditions, exhaust gas components, pressure conditions, etc.

1) Reduction of thickness by oxidation

Metal becomes thin as it reacts to O_2 at high temperature and produces oxides on the surface.

Generally, oxidation tends to progress if oxidized film on the metal surface easily comes off, or if the surface is porous to permit easy entry of O_2.

Oxides of Mo and W, which are volatile or have a low melting point, also show high oxidation speed.

Cr forms a sticky oxide so that resistance to oxidation increases as Cr content increases. Al and Si also improve oxidation resistance, but adversely affect the mechanical properties.

Ni makes oxides dense to form a protective film, which prevents further internal oxidation. CO_2 gas also causes oxidation because O_2 is generated by the reaction $2CO_2 \rightarrow 2CO + O_2$.

If water is present in an oxidizing atmosphere, oxidation is accelerated because the oxide protective film that is formed becomes porous because of water.

Environment will be even more severe if a heating-cooling cycle or a cycle of oxidizing-reducing atmosphere is repeated at high temperature.

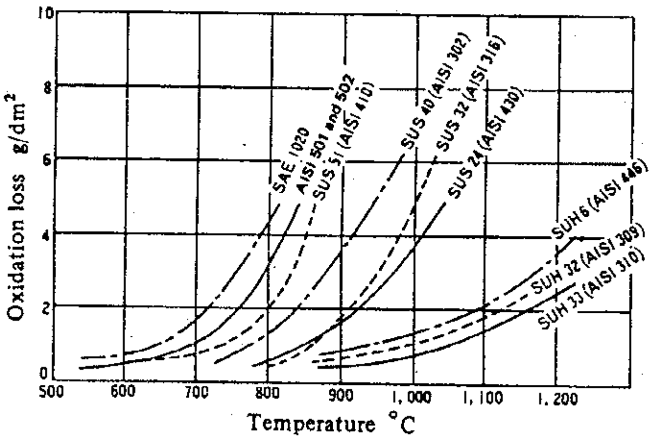
Table 3.27 shows working temperatures by material and Figure 3.48 the relationship between temperature and weight reduction by oxidation.

Table 3.27 Working Temperature of Heating Pipe by Material

Material (Customary indication)	Maxi. working temp (°C)	Ordinary working temp. (°C)
Carbon steel	565	400
1/2 Mo steel	565	450
1 Cr-1/2 Mo steel	565	450
1 1/4 Cr-1/2 Mo steel	590	550~575
2 1/4 Cr-1 Mo steel	635	600
5 Cr-1/2 Mo steel	620~650	600
9 Cr-1 Mo steel	650~700	600 ~ 650
13 Cr steel	650	600
25 Cr steel	1,000~1,100	1,000
18 Cr-8 Ni steel	870	800
18 Cr-12 Ni-Mo steel	870	800
18 Cr-12 Ni-Ti steel	870	800
18 Cr-12 Ni-Nb steel	870	800
25 Cr-12 Ni steel	1,000~1,100	1,000
25 Cr-20 Ni steel	1,100	1,000

Note: The max. working temperature varies slightly according to literature.
The ordinary working temperature was determined considering oxidation limits, tolerable stress, graphitization, etc. and referring to US Steel's technical data.

Figure 3.48 Relationship between Temperature and Oxidation Loss



Test conditions : 12 intermittent cycles of heating and cooling

By courtesy of : Welding Research Council Bulletin Series No.31 "Stainless Steel for Pressure Vessels"