type low frequency furnace of 1,200 kW, 5 t, 1,200 V at a furnace current of about 5,000A, but doubling the number of cables will lead to energy conservation of about 1%.

(4) Changed material

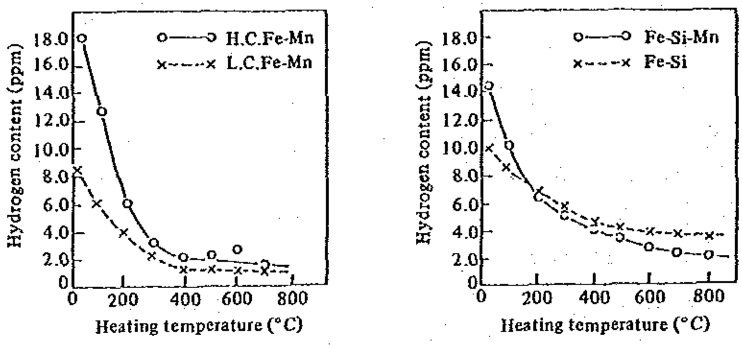
Refining is not made in an induction furnace because of the slag at low temperature with poor fluidity. Therefore, clean raw material with clear chemical composition must be used.

When the raw material containing such impurities as molding sand, oxides, etc., are charged to a furnace as it is, sand and oxides are melted as well causing such disadvantages as increase in power consumption and heat loss due to slag removal job, shortened service life of furnace material, decrease in input due to slag adhesion to furnace walls, shelf fixing of materials, etc. For instance, inclusion of sand or oxide in molten material by 1% causes increase in basic unit of electricity by about 10 kwh/t.

Since the depth of current penetration is inversely proportional to frequency, the material which is charged into a high frequency furnace should be as small as possible with minimized mutual spacings. As to the charging method, easily meltable materials such as machined scraps, punched scraps, etc. should be compactly charged at first on furnace bottom to prevent furnace bottom damage by subsequently charged materials. As melting proceeds, additional material with a size not larger than one-third the furnace diameter should be charged with care not to cause shelf fixing. As alloy steel usually contains a considerable amount of hydrogen in addition to moisture as shown in Table 10-9, preheating of such steel before charging is necessary to prevent hydrogen from mixing in molten steel. Figure 10-11 shows the relation between heating temperature and hydrogen content. For instance, heating at about 600°C for 3 hours can reduce hydrogen content to 4 ppm or less.

Table 10–9 Hydrogen Contained in Alloy Iron

Alloy iron	7.5% Ferrosilicon	Low C ferro-chromium	High C ferro-manganese	Low C ferro-manganese	Silicoman-ganese	Silico-chromium	Electrolytic nickel
Hydrogen (ppm)	9.8 ~ 17.6	4.3 ~ 6.0	7.6 ~ 18.1	8.2	14.4	6.0 ~ 9.4	0.2
Shape (mm)	40 ~ 60	100 ~ 150	60 ~ 100	25 ~ 40	40 ~ 60	40 ~ 60	Thickness 10



(a) (b)

Figure 10–11 Effect of Heating Temperature (Heat Retaining for 3 Hours) on Hydrogen Content in Alloy Iron

(5) Preheating material to be charged

An example shows electric energy conservation of about 10% by preheating the material to be charged at about 500°C. Table 10-10 and Figure 10-12 indicate the comparison between the conditions before and after preheating furnace, and the installation of the preheater for 3 t high frequency furnace, respectively.

Table 10–10 Comparison of Factors before and after Installation of Oscillating Type Preheater

	Before the installation of preheater	After the installation of preheater	Improvement rate after installation
Energizing time per day	17 – 18 hours	15 – 16 hours	
Molten metal output time per day	14 – 15 hours	12 hours and 19 minutes	Decrease of 12 – 18%
Amount of molten metal output per month	340 t	420 t	Increase of 23.5%
Unit electric power consumption rate for melting	684 kWh/t	596 kWh/t	Decrease of 12.9%
Fuel (kerosene)	–	20.1 *l*/t	

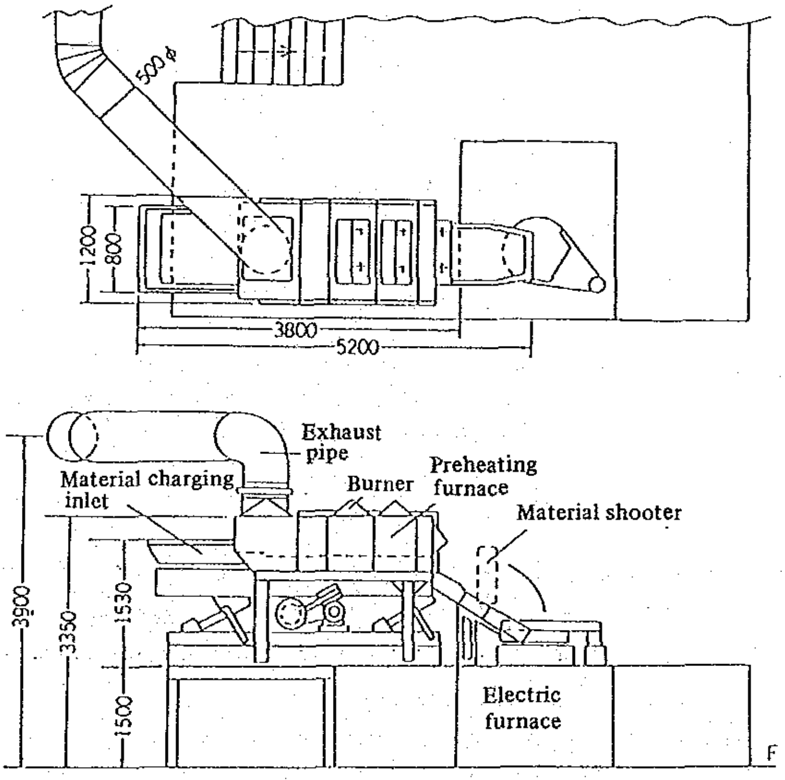


Figure 10–12 Example of 3-Ton High Frequency Furnace and Preheater of 700 kg/rpm

(6) Temperature control

In general, a tapping temperature is liable to be selected in the higher side in fear of misrun. The temperature, however, should be directed to the lowest possible by preheating the ladle. A temperature difference of 50°C will cause difference in electric energy by 15 – 20 kwh/t. It is necessary in a high frequency furnace to prevent excessive heating by means of properly arranging temperature measurement and pouring because of a higher rate of temperature rise, e.g. temperature rise of 60 to 90°C or higher per 2 to 3 minutes. Further, the thermometers should be periodically calibrated to assure accuracy and precision.

(7) Preventing heat release from furnace openings

Heat radiation from a hot body is proportional to the heat radiation area, and to the 4th power of absolute temperature. Therefore, much heat is lost by heat release from the surface of molten steel. The furnace cover should be placed in the right position as much as possible during melting operation. For instance, heat release loss from the molten steel at 1,500°C in a 8 t low frequency furnace amounts to about 150 kW, and the basic unit of electricity is worsened by about 10 kwh/t when the furnace cover is kept open for 10 minutes.

Figure 10-13 shows the difference in insulated electric energy due to opening and closing of a furnace cover.

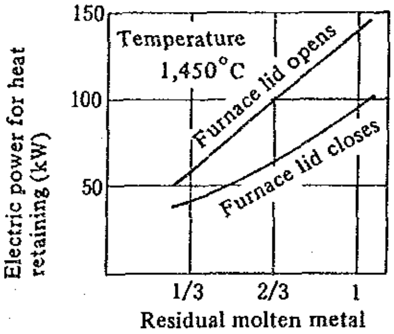


Figure 10–13 Effect of Furnace Lid on Electric Power for Heat Retaining (Used the 2-ton Crucible-Type Low-Frequency Furnace at 600 kW for Measurement)

(8) Coil cooling

A low feed-water temperature cools furnace walls, but the effect of decreasing the loss of copper coil tubes, cables, etc. is greater than the above effect of wall cooling. So far as the trouble by dew condensation does not take place, therefore, it is better to cool the coils and cables with a large amount of cooling water.

An example shows improvement on efficiency by about 0.8 to 0.9% per 10°C cooling in a 2 t furnace of 1,200 kW at 500 Hz.

In addition, the effluent water at about 50°C after cooling can be used for air-conditioning and cleaning.

(9) Making furnace operation continuous

Continuous operation is desirable for the furnace in which a large amount of refractory is used and much heat is accumulated. For instance, the electric energy required to raise wall temperatures as high as 1,500°C is about 650 kwh for a 8 t low frequency furnace using about 2.7 t of refractory, and about 170 kwh for a 2 t high frequency furnace using about 0.7 t of refractory.

10.2.3 Casting

(1) Ladle

A ladle to be used should be well insulated and covered with a lid during transport to prevent temperature drop. Casting procedure should be well arranged to minimize waiting time.

Empty ladle after casting should also be convered with a lid to prevent heat release.

Preheating, when executed, must match with the time of tapping to prevent unnecessarily long hours of heating, with the ladle covered with a lid.

(2) Mold

The amount of melt pour can be decreased by a mold of proper disign which minimizes flush. In addition, fuel can be saved by making a mold by use of organic solvent instead of thermal curing.

11. Metal

11. Metal

11.1 Characteristics of Energy Consumption

11.1.1 Production Processes and Main Equipment

There are a very wide range of products manufactured by machining and a wide variety of production processes, which however can be summarized as follows:

Material forming : Casting, forging, plastic working
Secondary forming : Press, bending, drawing, rolling
Cutting joining : Cutting, shearing, welding
Removing : Cutting, grinding
Finishing : Removing burrs, heat treatment, surface coating, painting
Assembling

The production processes of a machining factory are shown for example in Figure 11-1.

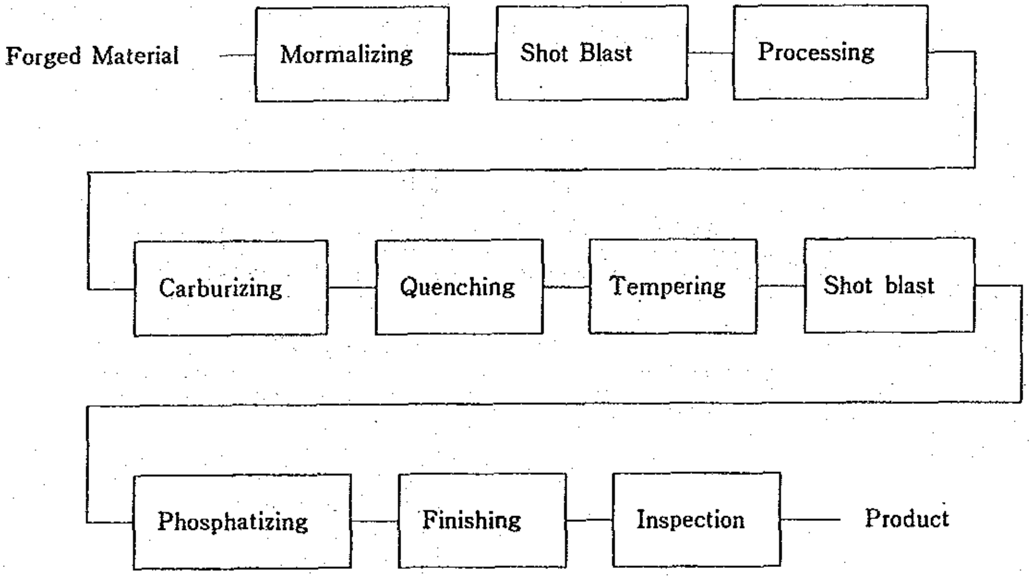


Figure 11–1 Manufacturing Process Chart for Machine Processing

Fig. 11-1

Steel is an alloy of iron, carbon, and other elements, and its steady state and mechanical properties vary depending on the constituents and temperature. Heat treatment means treating the material under conditions involving a specific temperature, holding time, heating and cooling speeds, and environment to give it the required properties. Heat treatment includes the kinds shown in Table 11-1.

Table 11–1 Types of Heat Treatment

Broad division	Medium division		Subdivision
Regular heat treatment	Annealing		Complete annealing Sphrtofixinh annealing Unstressing annealing Low temperature annealing Diffusion annealing Bright annealing Box annealing
	Normalizing		Regular normalizing Double normalizing
	Hardening		Regular hardening Graduated hardening Air-blast quenching Oil hardening Water hardening Press hardening Bright hardening
	Tempering		Low temperature tempering High temperature tempering Temper hardening Press tempering Bright tempering
Isothermal heat treatment	Isothermal annealing		Isothermal annealing
	Isothermal normalizing		Isothermal normalizing
	Isothermal hardening		Marquench Austempering
	Isothermal tempering		Isothermal tempering Martempering
Surface heat treatment	Chemical heat treatment	Carburizing	Solid carburizing Liquid carburizing Gas carburizing Carbonitriding
		Nitriding	Gas nitriding Liquid nitriding Salt soft nitriding Gas soft nitriding
		Sulphurizing	High temperature sulphurizing Low temperature sulphurizing
	Phisical heat treatment	Surface hardening	High frequency hardening Flame hardening

Heat treatment conditions vary widely depending on the purpose of treatment, carbon content, dimensions, etc., but are generally as shown in Figure 11-2.

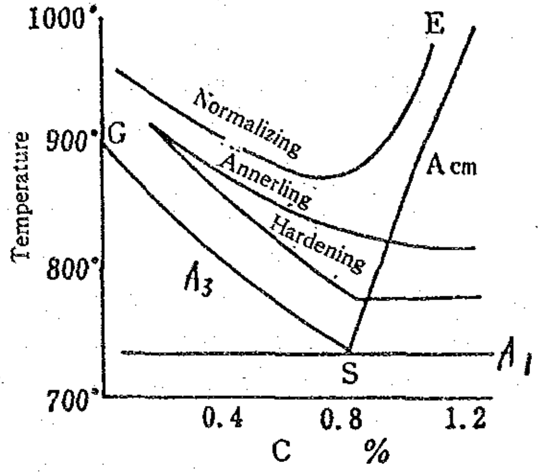


Figure 11–2 Heat Treatment Temperature of Carbon Steel

Annealing : To remove stress, soften, and improve cold process-ability, steel is heated to an appropriate temperature, kept at that level for a specified time, and then slowly closed.

Normaling : To make the structure uniform and remove internal stress, steel is heated up to 40°C to 60°C above transformation points A_3, Acm to remove carbides, followed by air cooling.

Quenching : Steel is heated red-hot, kept in that state for a specified time, and then rapidly cooled to harden. The temperature varies depending on the carbon content.

Tempering : To stabilize the structure of quenched steel and remove stress from it, steel is heated to a temperature below transformation point A_t where it softens.

Carburization : To harden the surface layer of steel, it is heated in a carburizer to increase the carbon content of the surface layer.

Examples of heating furnace and heat treatment furnace used for heating and heat-treating steel are described below.

(1) Annealing furnaces

(A) Box type batch furnace

Simple in construction and versatile, the box type batch furnace is suited to limited production of many kinds. However, it has disadvantages of generally low thermal efficiency and uneven heating time for reasons that operation is performed under an excessive hearth load and that air enters the furnace when the door is opened and closed.

(B) Truck type batch furnace

This furnace has a truck type hearth that can be pulled out, and is suited to heating large products. A sand seal is used between the truck and furnace casing to keep air out.

Figure 11-3 shows a truck type heating furnace.

(C) Pusher type furnace

This type furnace uses a tray to directly carry treating products, or carry them in a basket placed on the tray, which is pushed from the charging end into the furnace with a hydraulic cylinder or the like. There are several types falling into this category, including the roller rail type, skid rail type, and roller tray type. Before shutting down the furnace, an empty tray must be sent into the furnace so that there will be no treating products left inside.

Because the tray is heated and cooled together with the treating products, the quantity of heat carried away by the tray will be directly equal to heat loss.

Manual power, electric power, pneumatic power, hydraulic power, etc. are used as pusher power. Of these, hydraulic power has come to be used most for reasons that it can stands heavy loads, is accurate of operation, and permits even complex automatic operation.

(D) Conveyor type furnace

The conveyor type furnace is used in applications where cycle time is shorter and hearth load [kg/m^2] is smaller than in the case of the pusher type furnace. Belt types include link belt, chain belt, and mesh belt.

The conveyor often runs outside the furnace on its way back, but the type which returns the conveyor through the furnace on the way back is increasing because heat loss can be reduced this way. Figure 11-4 shows the external return type.

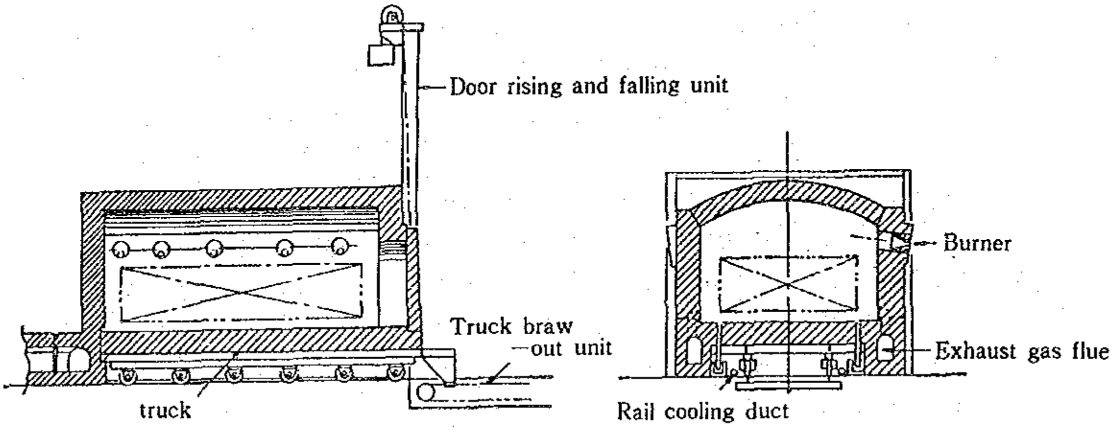


Figure 11–3 Shuttle Type Heating Furnace

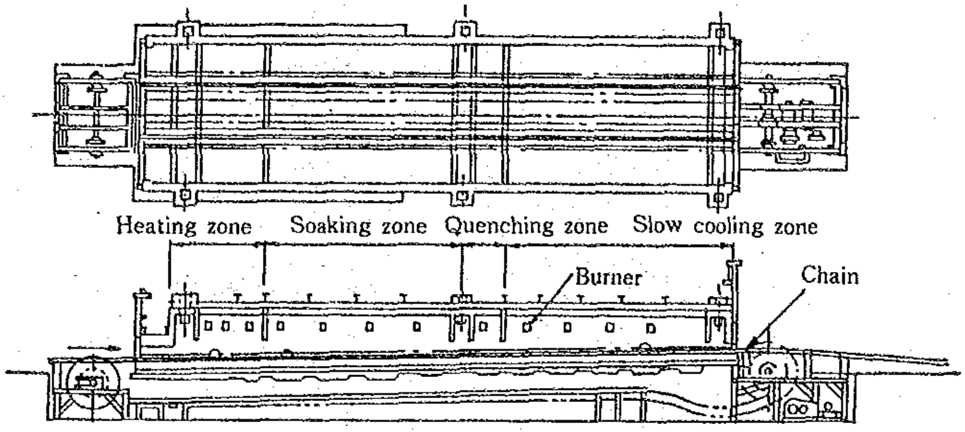


Figure 11–4 Ductile Cast Iron Annealing Furnace

(2) Carburizing furnaces

Carburizing means exposing the surface of low-carbon steel or low-carbon steel alloys to a carbonaceous material and heating them above the transformation range to harden the surface.

Heat-absorbing gas (20% CO, 40% H_2) is used alone, or in combination with hydrocarbon gas.

(A) Pit type furnace

This is the simplest of carburizing furnaces. A stirring fan is provided at the bottom or the top, and a treating material is charged into, and removed from, the furnace at the top together with a heat-resistant alloy jig or basket, using a crane or hoist under manual control.

Because of its structure, this type furnace uses a separate, independent quenching tank. After carburizing, the material is taken out of the furnace into the atmosphere, and then moved to the quenching tank to be quenched.

This type is suited to large parts, particularly long shafts. Because the material can be treated hanging, it offers an advantage in point of preventing distortion.

An example of furnace structure is shown in Figure 11-5.

(B) Horizontal furnace

This type is an improved version of the conventional batch type box furnace used as a carburizer.

The furnace consisting of a charging chamber, a quenching oil tank under it, and a carburizing furnace. The charging chamber has a door of its own, and there is a heating chamber door between the charging chamber and heating chamber. The one-piece construction of the quenching oil tank permits quenching without exposure to air.

This type can be classified into an in-out type and a straight-through type depending on the direction of charging material into the furnace and removing it from the furnace.

Figures 11-6 and 11-7 show the structures of these respective types.

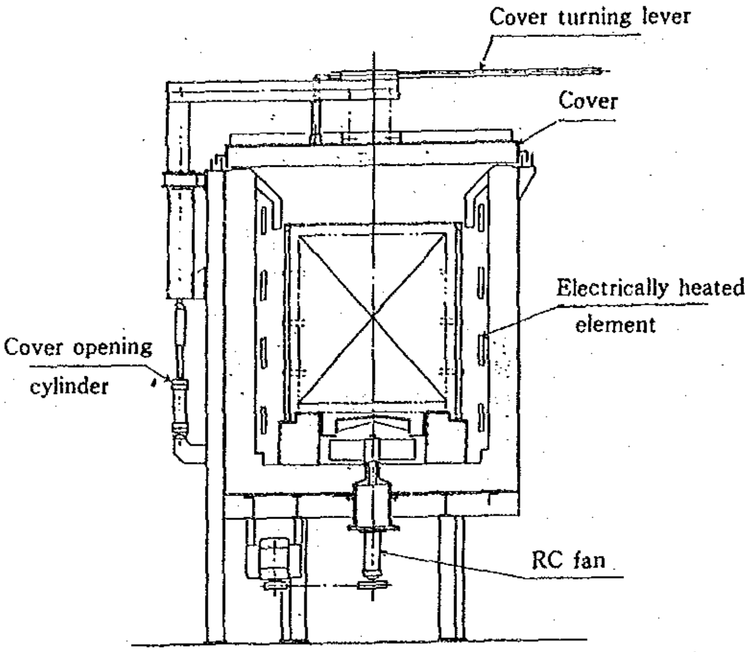


Figure 11–5 Pit-Shaped Furnace

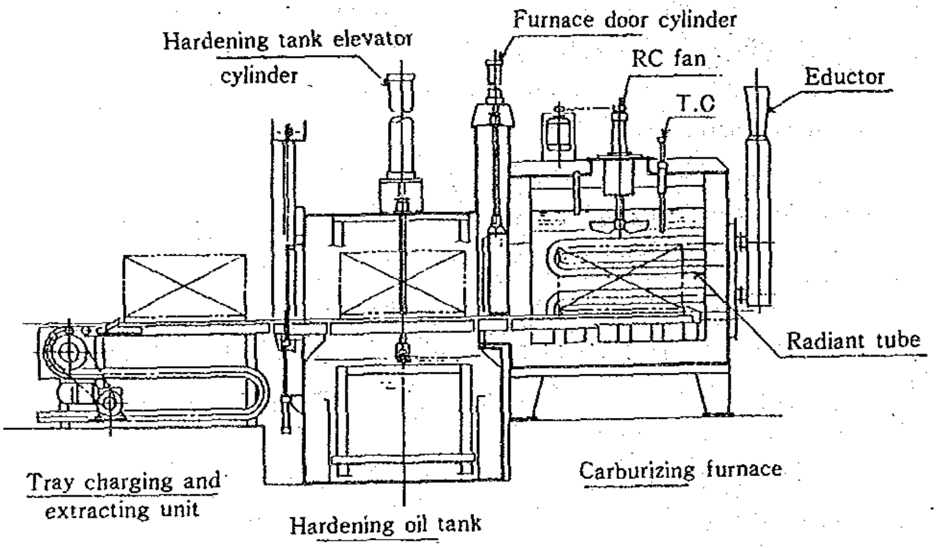


Figure 11–6 In-Out-Type Horizontal Furnace

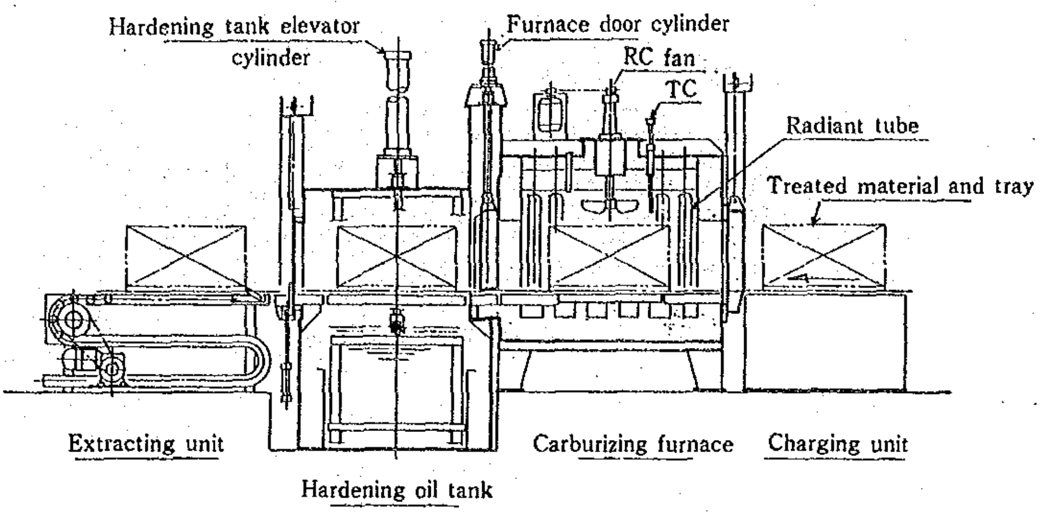


Figure 11–7 Straight Through Type Horizontal Furnace

(C) Tray pusher type furnace

This type is used most as a continuous carburizing furnace. It is indispensable for carburizing automotive gears, in particular, that require mass production and uniform, high quality.

There is a vestibule at the charging and discharging ends to prevent the internal atmosphere from being affected by the outside air.

The furnace is divided into four zones, that is, heating, carburizing, dispersing, and cooling/holding, in the direction of material movement.

Material is placed on the tray, which is pushed into the furnace by the pusher. The material on the tray moves along the skid rails from one zone to another without contact with the outside air until it reaches the quenching tank located at the outlet, where it is quenched, or it may be gradually cooled without quenching, and taken out of the furnace.

Gas is supplied to each zone, and is so controlled that the carbon concentration required for the purpose of each zone will be maintained. Each zone is provided with a fan to ensure powerful circulation of the internal gas as required for uniform, heat-treatment quality. After quenching, the material is automatically discharged from the furnace, and goes through the cleaner and tempering furnace to end heat treatment.

Figure 11-8 shows the construction of this type furnace, and Figure 11-9 shows an example of continuous carburizing equipment.

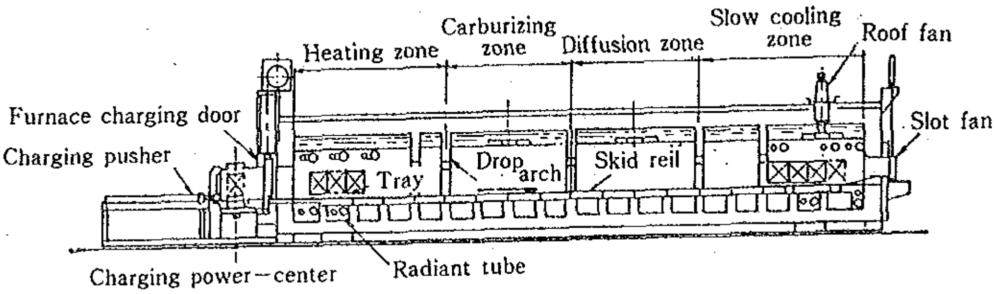


Figure 11–8 Tray Pusher-Type Furnace

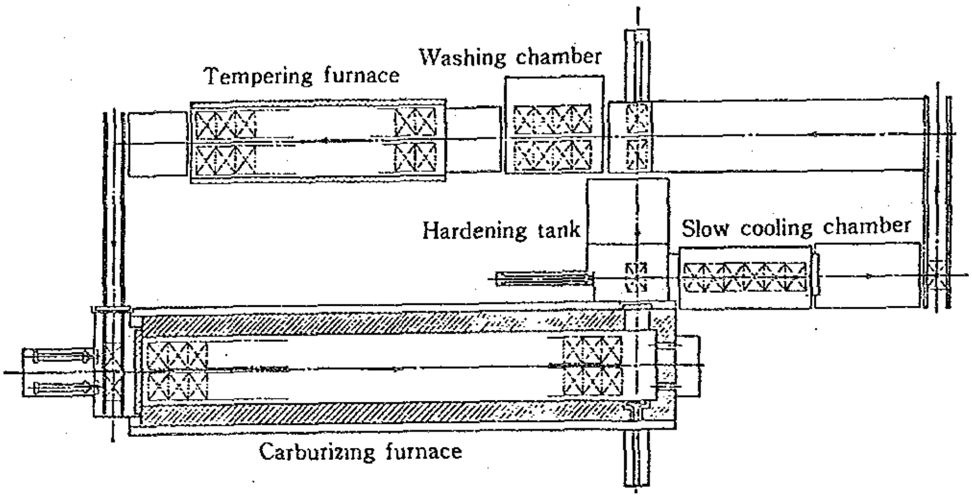


Figure 11–9 Continuous Carburizing Equipment

(3) Billet reheating furnace

This type furnace is used in the iron and steel industry to reheat steel up to the required temperatures of 1,000°C to 1,300°C prior to hot rolling.

The reheating furnace comes in two types: Batch and continuous. The batch type is an auxiliary furnace to reheat mainly materials of special shapes. The continuous type is mainly used for mass production.

The continuous reheating furnace comes in a variety of types, including the walking beam type, walking hearth type, and rotary hearth type.

The oldest and elementary one is the pusher type single-zone reheating furnace shown in Figure 11-10, with heating capacity ranging up to about 50 tons/hour. Billets are heated only from above over the entire length of the furnace so that there is a large temperature difference between top and bottom. Besides, single-zone control of furnace temperature makes operation inflexible. This type is unsuited to furnaces of great length or large capacity.

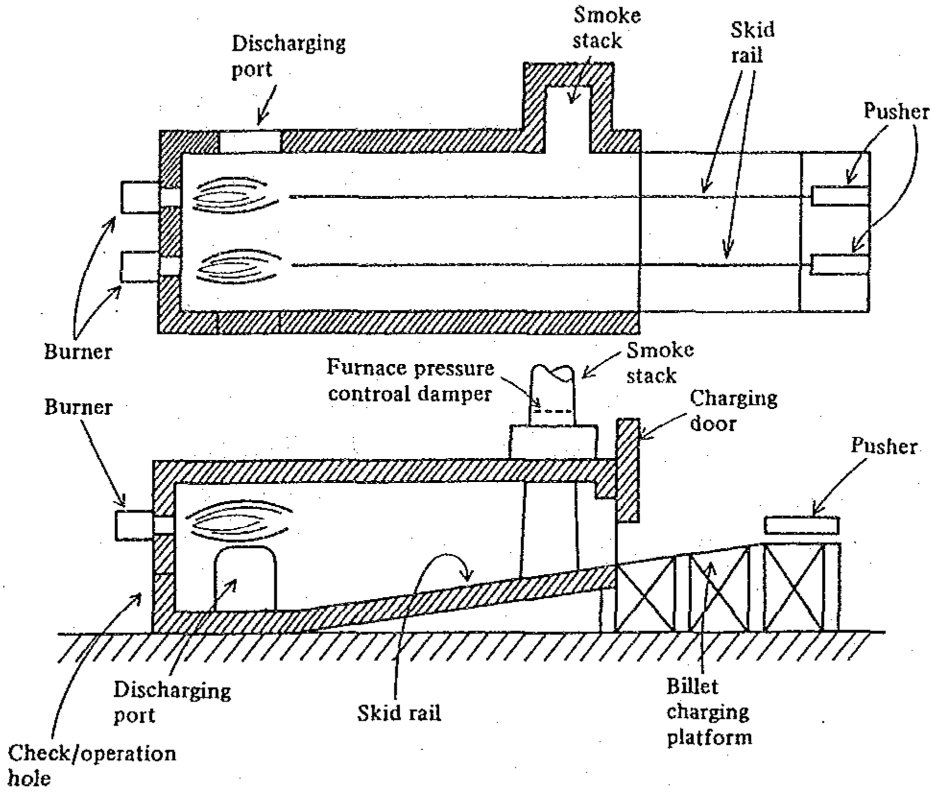


Figure 11–10 Pusher-Type Single Zone Reheating Furnace

Furnaces with a heating capacity of 60 to 120 tons/hour include the pusher type 3-zone reheating furnace shown in Figure 11-11. This furnace is divided into two distinct zones, heating and soaking. Billets are heated to the rolling temperature from above and under in the heating zone, while skid marks are decreased and the billet temperature is made even in the soaking zone. Each of the three zones can be individually controlled, and heating speed can be changed to a certain extent. In other words, this type furnace offers flexibility of operation.

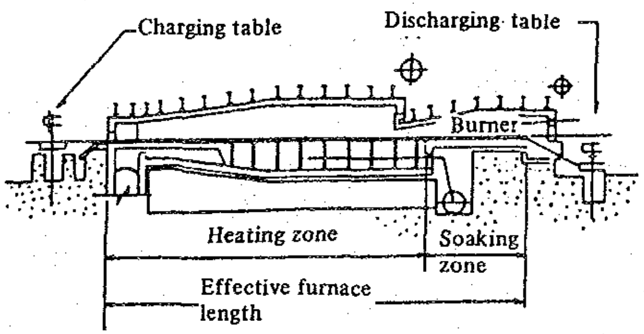


Figure 11–11 Pusher-Type 3-Zone Reheating Furnace

A pusher type 5-zone reheating furnace has a still larger heating capacity of 200 to 250 tons/hour. (See Figure 11-12.) This is an extension of 3-zone reheating furnace, and is distinctly divided into the preheating zone, heating zone, and soaking zone.

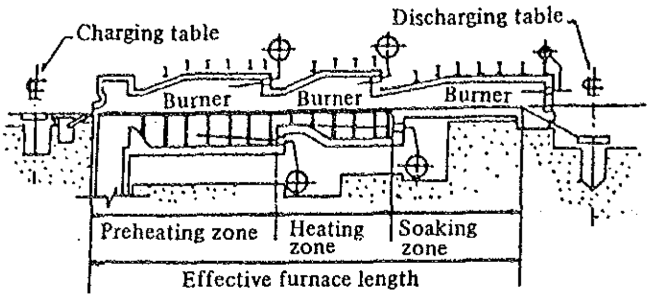


Figure 11–12 Pusher-Type 5-Zone Reheating Furnace

The pusher type has disadvantages of producing skid marks and scars on the back of billets resulting from conveyance. There is also a walking beam type reheating furnace with a larger capacity which overcomes these disadvantages. (See Figure 11-13.) The heating capacity of this type ranges from 200 to 400 tons/hour. Reheating furnaces of large capacity are now mostly of this type.

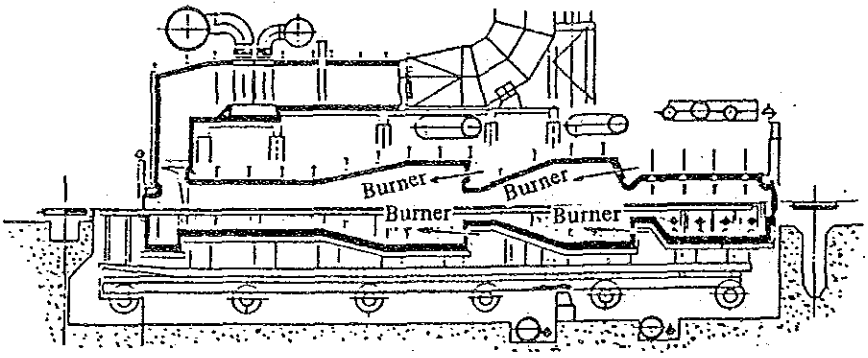


Figure 11–13 Walking Beam-Type Reheating Furnace

11.1.2 Energy Consumption

Apart from the electricity consumed in these processes for machining, part of melting furnaces, welding, and cutting, energy is mostly consumed in the reheating and heat treatment furnaces in the form of thermal energy generated by burning fuel.

Energy consumption by heat treatment furnaces varies largely depending on the type of treatment and the size of the furnace. Generally, heat treatment furnaces have low thermal efficiency. Table 11-2 shows an example of fuel consumption and thermal efficiency of heat treatment furnaces in Japan for your reference. Of these types of furnaces, the roller hearth type, the walking beam type, and bell type have better thermal efficiency than the others because they are mostly of large producers. As described later, efforts are exerted to improve the thermal efficiency of the individual types of furnaces. In the case of spherodizing, for example, the energy consumption rate has been lowered to less than 15 x 10^4 kcal/ton, less than one-fifth of the past figure.

Billet reheating furnaces, operated mostly by large producers, have shown a fall in the fuel consumption rate to 30 x 10^4 kcal/ton or less. "Hot charge" uses the high temperature of the preceding process directly, and there are cases where the heating process is omitted. Thus, simple comparison of fuel consumption rates will not be meaningful.

Table 11–2 Fuel Consumption and Thermal Efficiency by Type of Heat Treatment Furnace

Item Type	No. furnace	Fuel consumption (10^4kcal/t)		Thermal efficiency (%)		Heat treatment temperature (inside of furnace) (℃)		Capacity Continuous(t/h) Butch(t/charge)	
		£	R	£	R	£	R	£	R
Continous Type									
Tray pusher type	42	129	39~319	11.2	4.6~37.4	875	560~ 970	1.19	0.125~9.5
Roller hearth type	25	42.5	20~ 79	33.4	19.7~50.7	863	700~1,000	5.59	0.4 ~18.0
Conveyor type	29	93.8	10~262	11.1	4.2~48.0	724	400~1,000	0.78	0.17~ 2.9
Bogie type	22	124.4	31~226	12.7	7.4~25.0	937	580~1,000	0.84	0.3 ~ 2.0
Walking beam type	11	49.1	18~100	30.1	3.5~55.8	890	570~1,280	14.1	0.6 ~58.4
Batch type									
Bogie type	109	177.4	21~920	8.5	1.8~32.9	900	500~1,200	42.8	0.3 ~350
Box type	52	119.2	34~609	12.3	2.5~34.4	886	600~1,100	1.73	0.05~ 40
Pit pot type	14	173.8	48~710	8.4	2.1~29.2	849	500~1,100	10.5	0.03~ 80
Bell type	7	37.7	23~ 63	29.9	18.1~40.9	723	580~ 900	87.9	2.4 ~360

Note: £: Average
R: Range

11.2 Rationalization of Energy Consumption

In the metal industries, thermal energy is consumed mostly by combustion furnaces. A diagram of characteristic factors for energy conservation for reheating and heat treatment furnaces is shown in Figure 11-14. The main items thereof are illustrated in Figure 11-15.

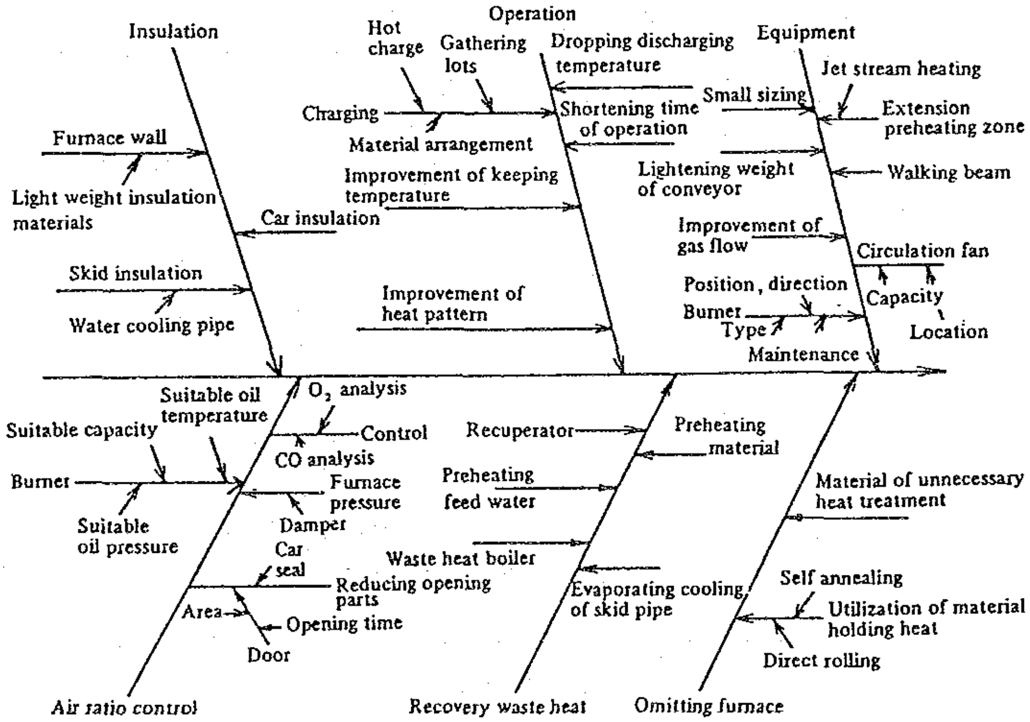


Figure 11–14 Characteristic Diagram of Energy Conservation for Reheating Furnace and Heat Treatment Furnace

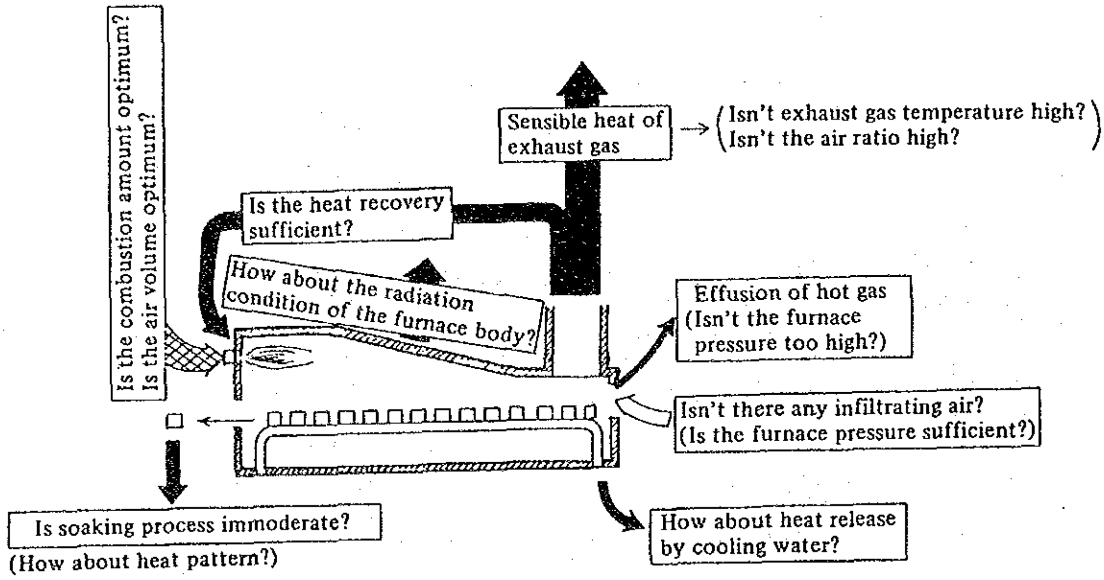


Figure 11–15 Reduction Point for Fuel Consumption Rate

11.2.1 Rationalization of Fuel Combustion

11.2.1.1 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 11-16, 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.

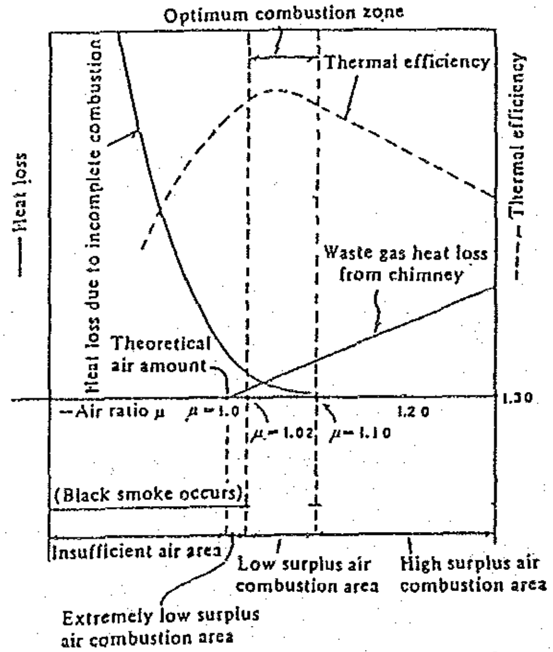


Figure 11–16 Relation between Air Ratio and Thermal Efficiency

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 11-17 shows how fuel consumption 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.

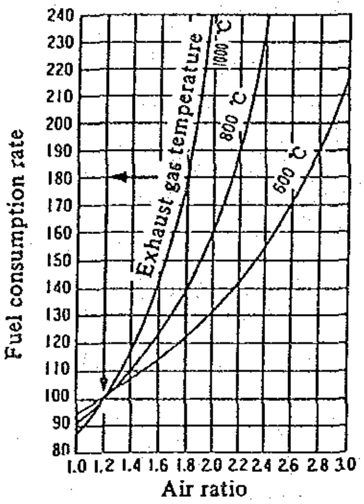


Figure 11–17 Energy Saving Effect under Air Ratio Control

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 furnaces in Japan are shown in Table 11-3.

Table 11–3 Standard Air Ratio of Industrial Furnaces

Classification	Standard air ratio
Melting furnace for metal casting	1.3
Continuous reheating furnace for bloom	1.25
Metal reheating furnace other than continuous reheating furnace for bloom	1.3
Continuous heat treatment furnace	1.3
Gas producer and gas heating furnace	1.4
Petroleum heating furnace	1.4
Thermal cracking furnace and reformer	1.3
Cement kiln	1.3
Alumina kiln and lime kiln	1.4
Continuous glass melting furnace	1.3

(Remark)

1. The values of the standard air ratio listed in this Table are determined regarding the air ratio measured at the outlet of the furnace, when the burning is carried out at a load in the neighborhood of a rating after inspection and repair.
2. The values of the standard air ratio listed in this Table will not apply to the air ratio of the undermentioned industrial furnaces as a standard:
   (1) Those using a solid fuel.
   (2) Those having a rated capacity of not more than 200,000 kcal/hour.
   (3) Those requiring a special atmosphere for oxidation or reduction.
   (4) Those requiring a frequent operation of furnace cover or frequent ignition and fire extinguishment.
   (5) Those requiring a diluted air for maintaining a heat pattern or equalization of intrafurnace temperature.
   (6) Those requiring an opening because of the structure of burning equipment and through which a large amount of external air flows in.
   (7) Those operated annually with the maximum operating time limited to 1,000 hours.

11.2.1.2 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 11-18.

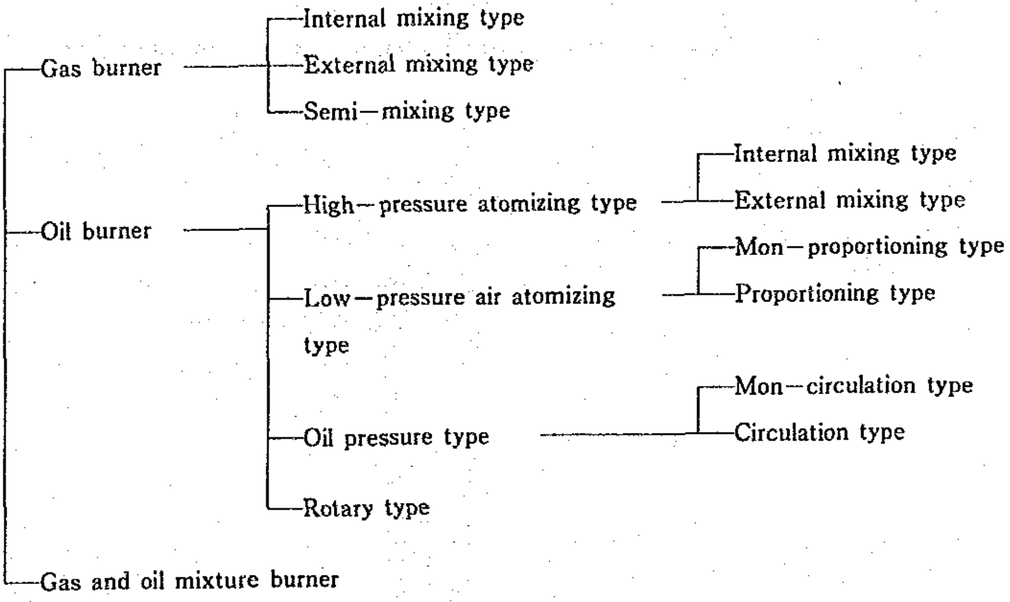


Figure 11–18 Classification of Burners

(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 is stabilized the combustion by making the gas mixture run into the surface of refractories so that the blow-out speed may be reduced.

Figure 11-19 shows the structure of an internal mixing type gas burner.

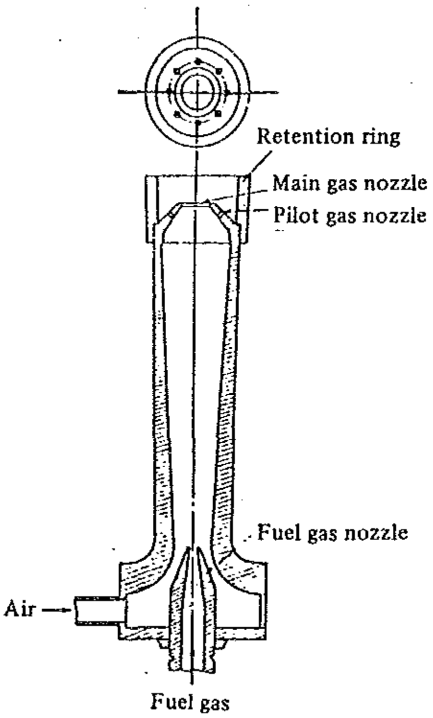


Figure 11—19 Structure of Internal Mixing Type Gas Burner

(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 burner is that flames of diverse degrees of intensity, different lengths, and characteristics can be obtained by selecting a nozzle structure and air ejection speed. Typical external mixing type burners are shown in Figures 11-20 and 11-21.

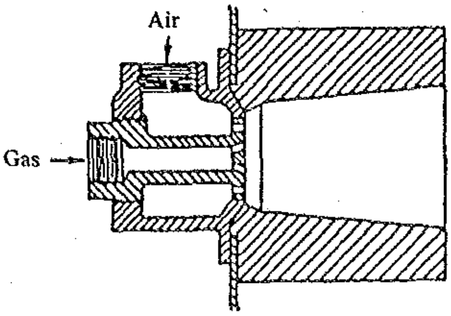


Figure 11–20 Compact External Mixing Type Gas Burner

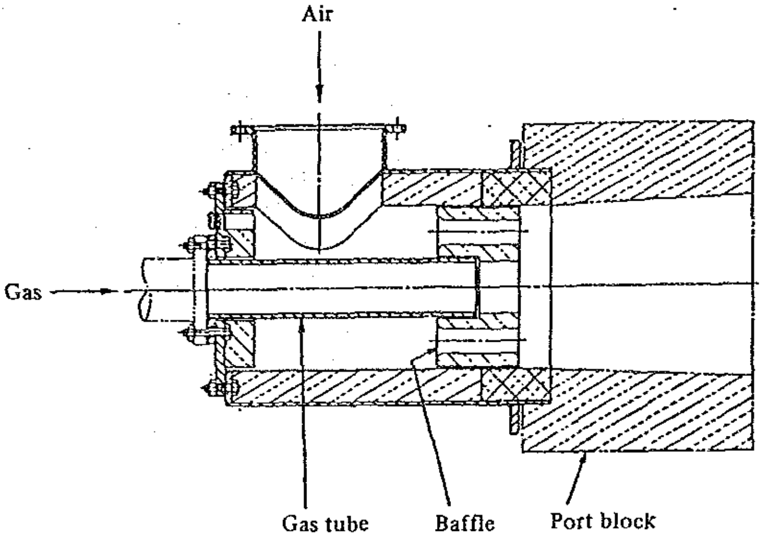


Figure 11–21 Structure of External Mixing Type Gas Burner

The burner shown in Figure 11-20 has a relatively small capacity. Gas is supplied from the nozzle located in the center, while air enters from around it toproduce 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 11-21 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 11-22 shows the structure of a semi-mixing type gas burner.

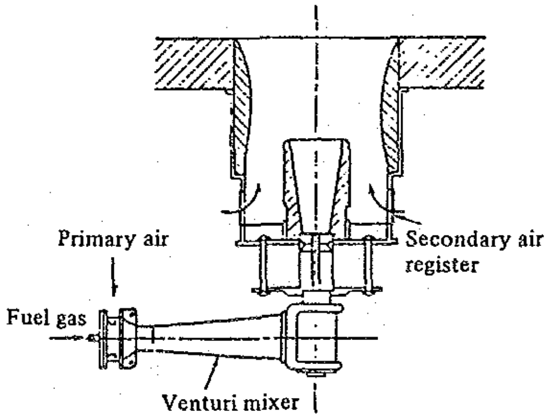


Figure 11–22 Structure of Semi-Mixing Type Gas Burner

(4) High-pressure atomizing type oil burner

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

As shown in Figure 11-23, 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 classified into two types, internal mixing and external mixing, which vary with where oil and atomizing medium are mixed.

Figure 11-24 shows an example of internal mixing type, which mixes oil and atomizing medium before the nozzle outlet.

Figure 11-25 shows an example of external mixing type, which mixes oil and atomizing medium outside the nozzle outlet.

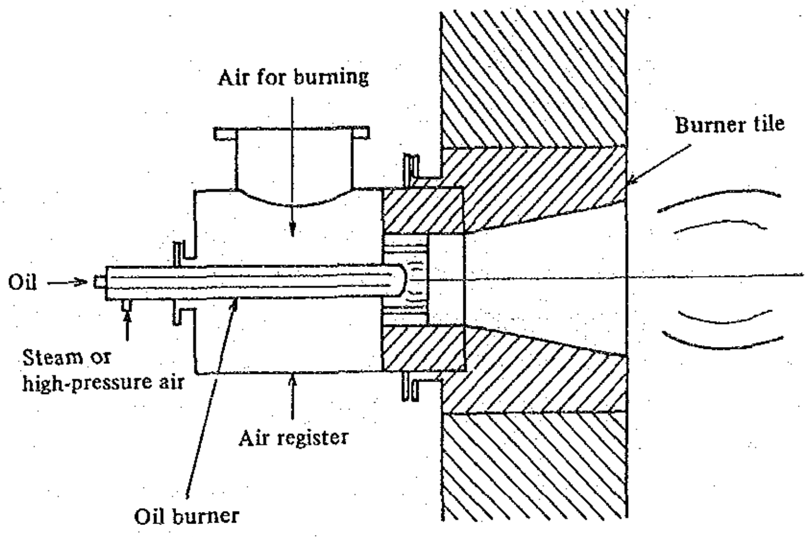


Figure 11–23 Installation Chart for High-Pressure Atomizing Type Oil Burner

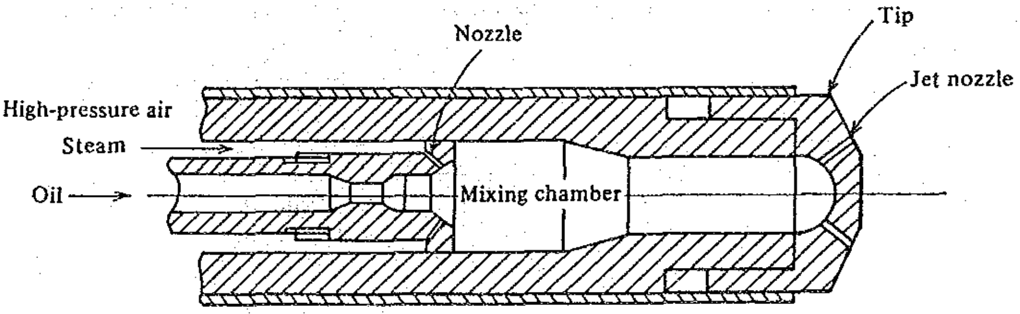


Figure 11–24 Structure of High-Pressure Atomizing Type Oil Burner (Internal Mixing Type)

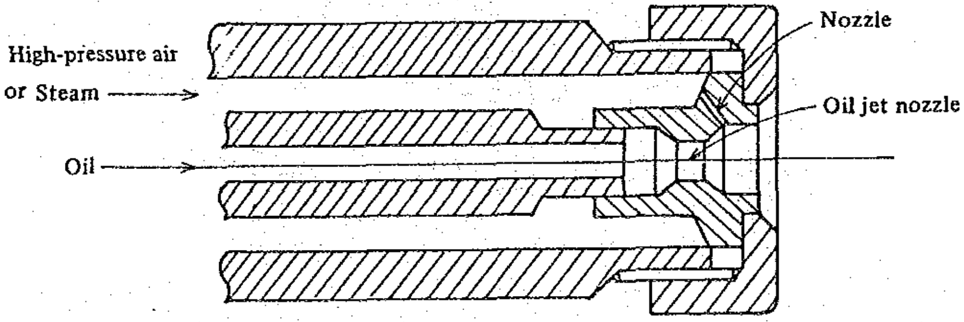


Figure 11–25 Structure of High-Pressure Atomizing Type Oil Burner (External Mixing Type)

(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 counterpart. 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 ventilation or forced draft.

The proportioning type 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 11-26 shows an example of non-proportioning, low-pressure air type oil burner, and Figure 11-27 an example of proportioning type, low-pressure air type oil burner.

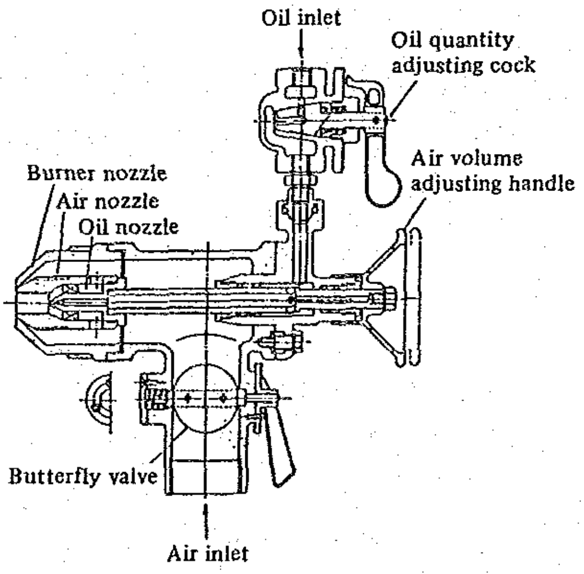


Figure 11–26 Structure of Low-Pressure Air Type Oil Burner (Non-Proportioning Type)

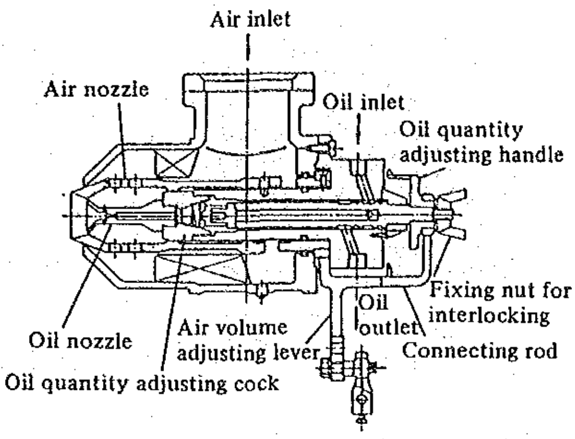


Figure 11–27 Structure of Low-Pressure Air Type Oil Burner (Proportioning Type)

(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/cm². Some large burners of recent make, however, use a maximum oil pressure of 100 kg/cm² 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 to the burner body. 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 11-28 shows the structure of a non-return oil type oil-pressure burner, and Figure 11-29 the structure of a return oil type oil-pressure burner.

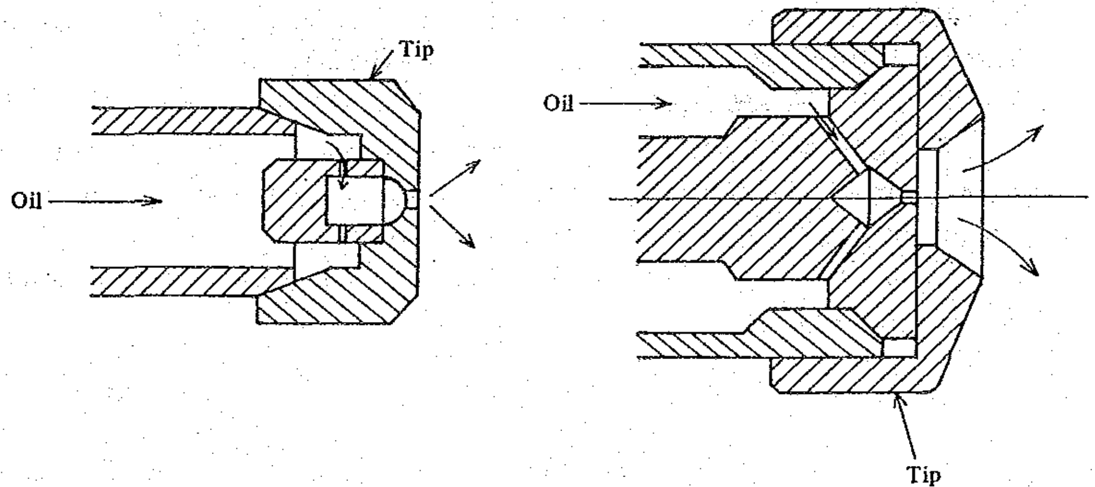


Figure 11–28 Structure of Non-Return Oil Type Oil-Pressure Burner

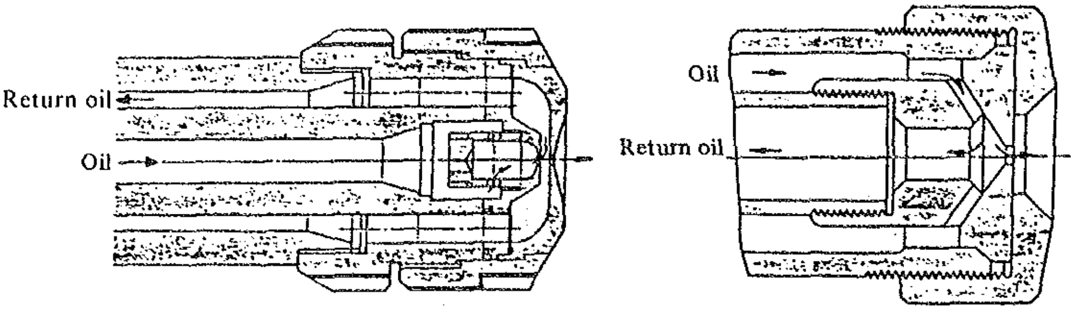


Figure 11–29 Structure of Return Oil Type Oil-Pressure Burner

(7) Rotary type oil burner

The rotary type oil burner atomizes oil using a rotary disk. Figure 11-30 shows the structure of it.

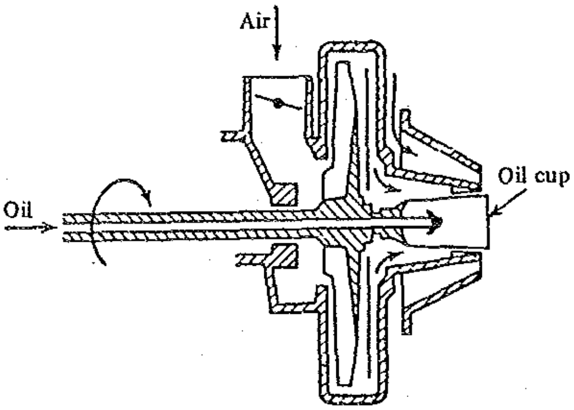


Figure 11–30 Structure of Rotary Type Oil Burner

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 11-31 shows a type of oil and gas mixture burner used for many soaking and reheating furnaces.

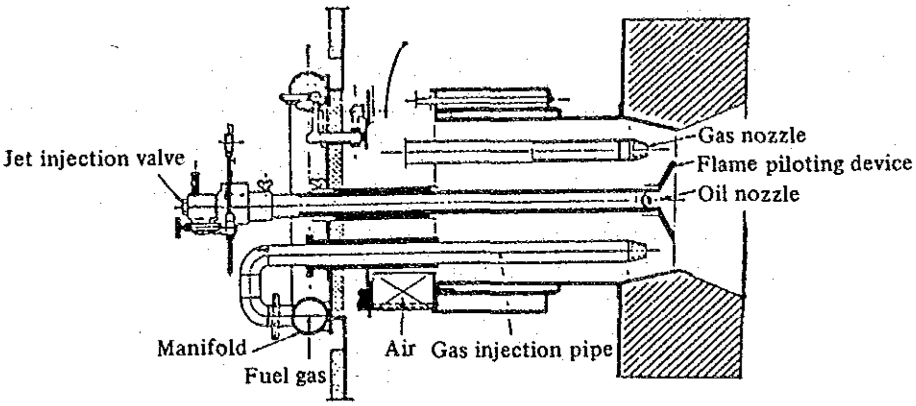


Figure 11–31 Structure of Oil and Gas Mixture Burner

For your reference, check points and remedial measures for combustion equipment are shown in Table 11-4.

Table 11–4 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 matter 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 for 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).

11.2.1.3 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.

11.2.1.4 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 11-5.

Table 11–5 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.

11.2.1.5 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.

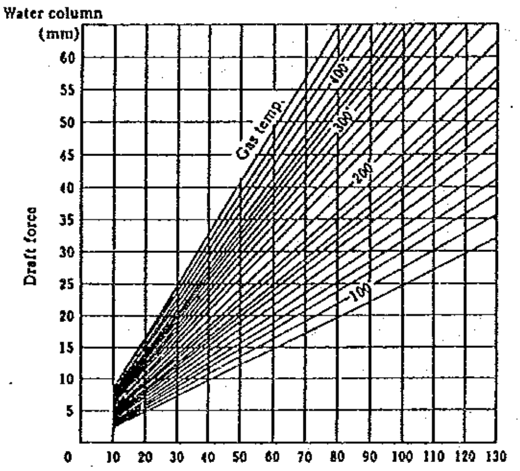
(C) Balanced draft

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) inside 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 11-32 shows the relationship between average gas temperature and draft force inside smoke stack.



Note: When the atmospheric temperature is 15°C

Figure 11–32 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 11-6.

Table 11–6 Example of Draft Resistance (Water Column mm) in Flue

Heat transfer area	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 enough.

(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.

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

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 internal 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 11-33.

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

where

P: Internal furnace pressure set (mmH_2O);

L: Height of measuring point above hearth (m).

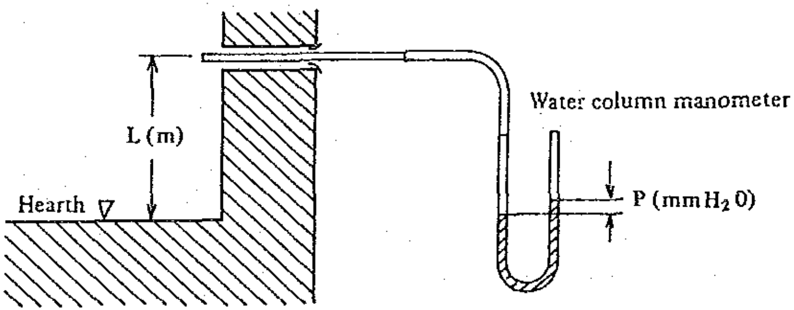


Figure 11–33 Furnace Pressure Measurement Port and Pressure Setting

11.2.1.6 Rationalization of Heating, Cooling, and Heat Transfer

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

(1) 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.

(2) Heat transfer by convection

If a gaseous fluid flows parallel to the surface of a solid as shown in Figure 11-34, 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 purpose of increasing the amount of heat transfer, gas velocity is raised to increase the coefficient of heat transfer to 30 $kcal/m^2 h ^\circ C$ or more.

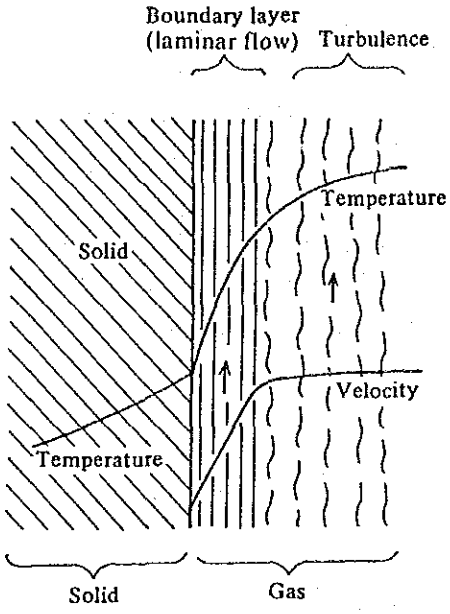


Figure 11–34 Heat Transfer to Surface by Convection

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.

(3) Heat transfer by emission between solids

A solid emits heat, and this is more so at high temperature. The amount of heat transfered 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 11-35 shows emissivity versus the surface temperatures of various kinds of metal.

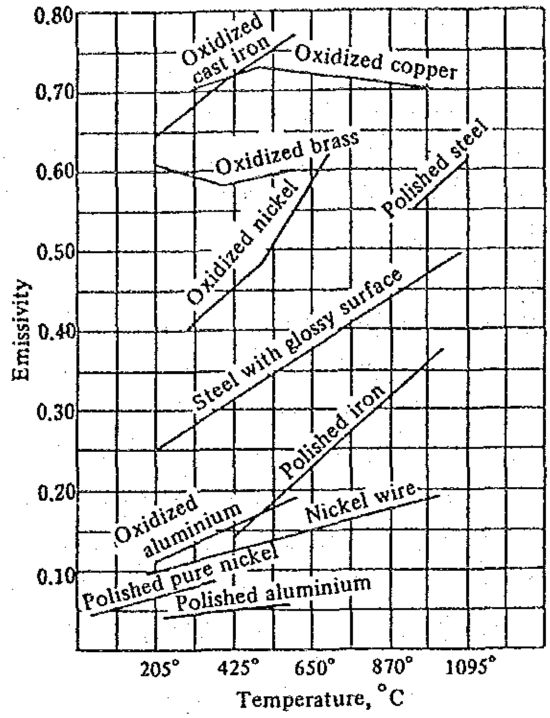


Figure 11–35 Emissivity of Metal

(4) 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 H_2, 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.

(5) 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 coal dust 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.

(6) 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.

(7) 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 convention inside the furnace acts on only the upper part of the material, leaving the lower part of it less heated by heat conduction because of 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.

11.2.1.7 Prevention of Heat Loss by Radiation, Heat Transfer, etc.

(1) 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.

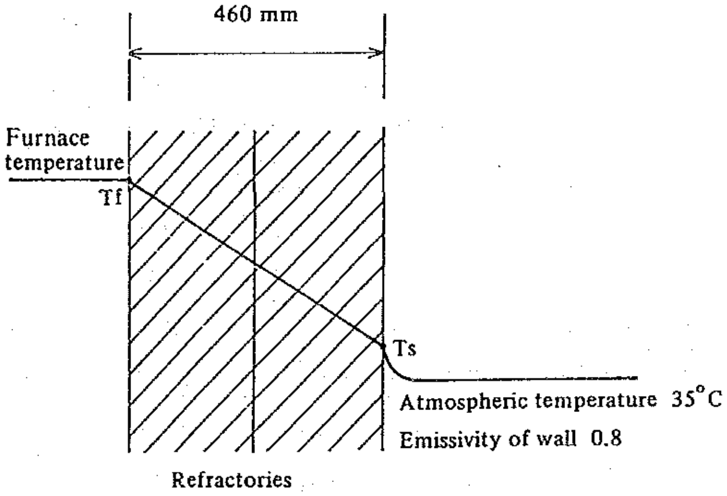
Recently built furnaces have walls made of lightweight ceramic fibers with small specific heat, featuring excellent heat insulation, small heat accumulation, and decreased heat loss from the furnace walls.

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 11-36 shows the standard furnace wall temperature of a reheating furnace lined with only refractory bricks 460 mm thick.

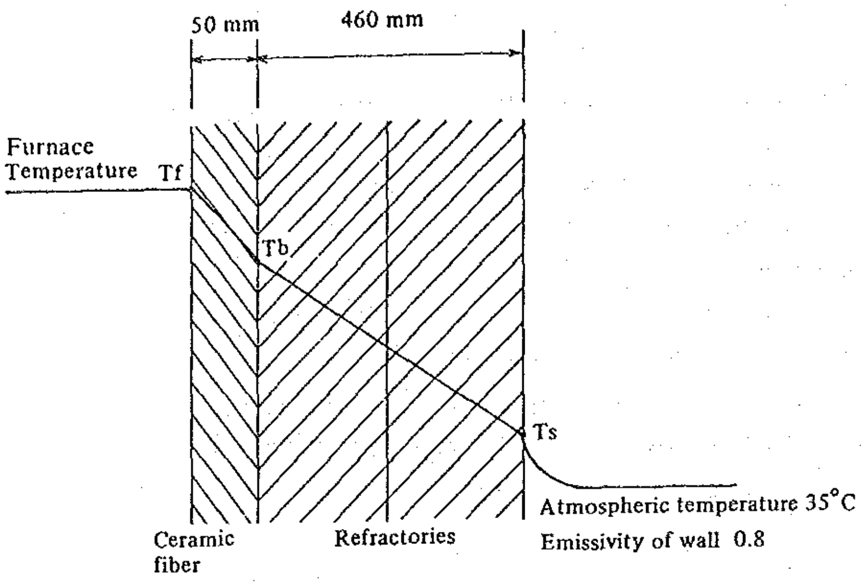
Figure 11-37 shows the same furnace as shown in Figure 11-36 except that it was better heat-insulated by lining the walls with ceramic fibers 50 mm thick.



$\lambda = 1.2$ kcal/mh°C
$C_p = 600$ kcal/m^3°C

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/m^{2}h
Quantity of accumulated heat	H	206,837	191,765	161,463	130,914	kcal/m^2

Figure 11–36 Typical Wall Temperature 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

Figure 11–37 Improvement Plan for Wall Composition of Reheating Furnace

These improvements produced energy saving effects as observed below. As shown in Table 11-7, 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 11–7 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/m²h	1,700 kcal/m²h	41% decrease in quantity of radiant heat
Quantity accumulated heat	206,837 kcal/m²	133,562 kcal/m²	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.

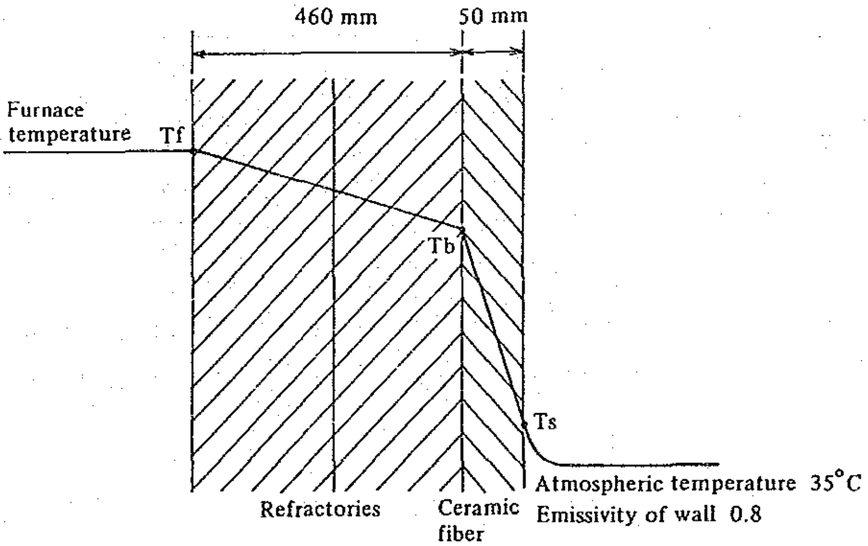
Figure 11-38 shows the temperature, etc. of furnace walls of refractories covered with ceramic fibers 50 mm thick. The refractories show an abnormally high average temperature with a rise in the quantity of accumulated heat.

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.

For your reference, the standard outer surface temperature of industrial furnaces in Japan is shown in Table 11-8.

The main characteristics of major refractory insulation materials are shown in Table 11-9, and the working temperature ranges of typical heat insulating materials in Figure 11-39.



λ = 1.2 kcal/mh°C λ = 0.17 kcal/mh°C

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

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

Figure 11–38 Inferior Reconstruction Plan for Wall Composition of Reheating Furnace

Table 11–8 Standard Wall Temperature of Reheating Furnace in Japan

Intrafurnace temperature (Unit °C)	Standard external wall surface temperature of furnace	
	Ceiling	Side wall
1,300	140°C	120°C
1,100	125°C	110°C
900	110°C	95°C
700	90°C	80°C

(Remark)

1. The values of external wall surface temperatures of the furnace listed in this Table were determined concerning the average temperature of the furnace's external wall surface (excluding the peculiar parts) at an atmospheric temperature of 20°C during a regular operation.
2. The values of external wall surface temperatures of the furnace listed in the Table will not apply to the external wall surface temperatures of the under-mentioned industrial furnaces as a standard:
   (1) Those having a rated capacity of not more than 200,000 kcal/hr.
   (2) Those whose walls are forcibly cooled.
   (3) Rotary kilns.

Table 11–9 Main Characteristics of Insulating Fire Materials

	Bulk specific gravity t/m³	Specific heat kcal/m³ °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 B 5	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)	0.06~0.3	20~ 80	0.05~0.3	1,100

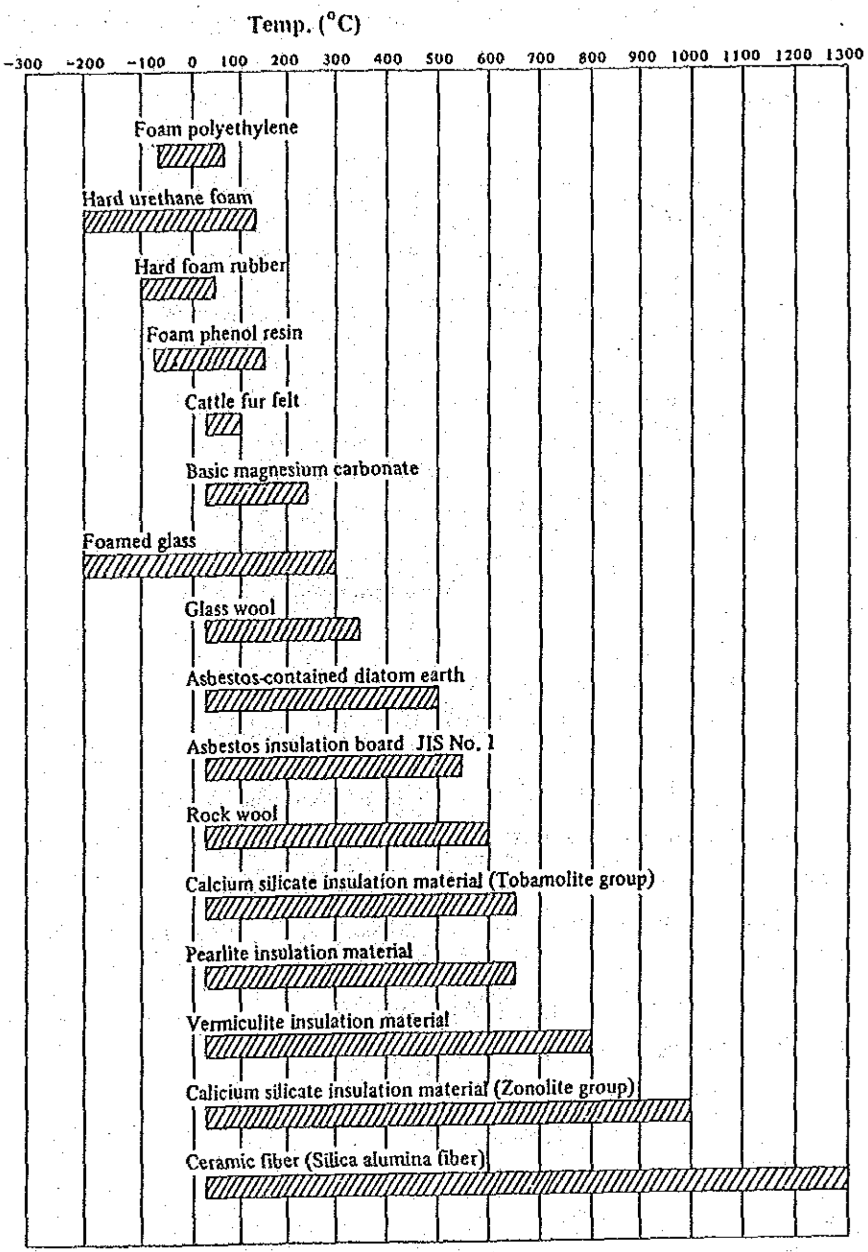


Figure 11–39 Working Temperature Range of Typical Insulating Materials Temperature

(2) Prevention of heat loss from 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.

(A) Heat loss by radiation from openings

If a furnace has an opening, the heat inside the furnace is radiated away from the furnace.

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

The ratio of the amount of heat radiation of a plane plate fully exposed outside to the amount of heat radiation from an opening in a furnace is as shown in Figure 11-40 according to J.D. Keller.

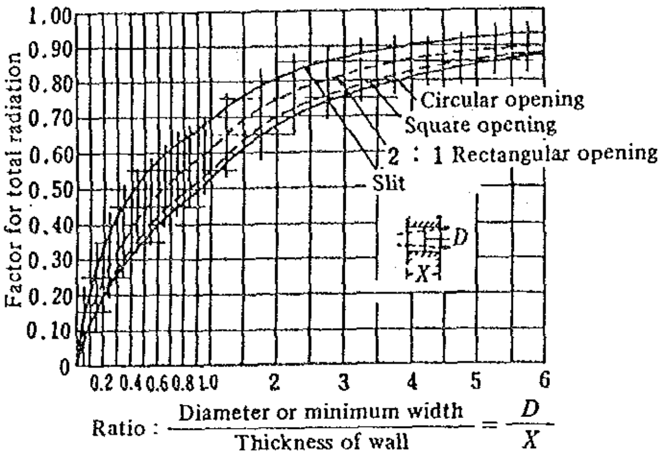


Figure 11−40 Factor for Determining the Equivalent of Heat Release from Openings to the Quantity of Radiant Heat from Perfect Black Body

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

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

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

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

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

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 11-40.

(B) 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.

(3) 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 12-10 shows a survey report on equipment; Table 11-11, a survey report on long-term operations; Table 11-12, a list of measuring items and results, and Table 11-13, a heat balance table for your reference.

Table 11−10 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 x furnace width	mm x 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 11−11 Survey Report on Actual Long-Term Operations

1	Date of operation					
2	Breakdown of operating time		Heating	Heat boosting	Heat retaining	Shutdown
		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, kg/month or Nm^3/month				
7	Low calorific value of fuel	kcal/kg or kcal/Nm^3				
8	Energy consumption rate per ton of heated steel	10^3kcal/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 upto an "extractable" temperature.

Table 11−13 Heat Balance Table

Heat input			Heat output		
Item	10^3kcal/t	%	Item	10^3kcal/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.

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

(Remark) As to the measurement method for Item 41, describe in the furnace sketch.

11.2.1.8 Recovery of Waste Heat

Methods of heat recovery from exhaust gas include (1) preheating combustion air or fuel gas using a heat exchanger, (2) steam generation using a waste heat boiler, (3) preheating material using exhaust gas, and (4) use of cascade as other heat source.

For your reference, standard waste recovery rates for industrial furnaces in Japan are shown in Table 11-14.

Table 11–14 Standard Waste Heat Recovery Rate of Industrial Furnace in Japan

Exhaust gas temperature (°C)	Classification of capacity	Standard waste heat recovery rate (%)	Reference	
			Exhaust gas temperature (°C)	Preheated air temperature (°C)
500	A · B	20	200	130
600	A · B	20	290	155
700	A B C	30 25 20	300 330 370	260 220 180
800	A B C	30 25 20	370 410 450	300 250 205
900	A B C	35 25 20	400 490 530	385 285 230
1,000	A B C	40 30 25	420 520 570	490 375 315
over 1,000	A B C	40 30 25	–	–

(Note)

1. "Exhaust Gas Temperature" means the temperature of exhaust gas discharged from the furnace chamber at the outlet of furnace.
2. The classification of the capacity of industrial furnace is as follows:
   - A. Industrial furnace whose rated capacity is more than 20MM kcal/hr.
   - B. Industrial furnace whose rated capacity is from 5MM kcal to not more than 20MM kcal/hr.
   - C. Industrial furnace whose rated capacity is from 1MM kcal to not more than 5MM kcal/hr.

(Remark)

1. The values of standard waste heat recovery rate listed in this Table are determined concerning the ratio of a recovered quantity of heat to a quantity of sensible heat in an exhaust gas discharged from the furnace chamber when a combustion is carried out under a load in the neighborhood of a rating.
2. The values of standard waste heat recovery rate listed in this Table shall be a standard for the continuous operating furnaces built on and after January 1, 1980.
3. The values of standard waste heat recovery rate listed in this Table shall not be a standard for the waste heat recovery rate of the under-mentioned industrial furnaces:
   - (1) Those whose rated capacity is not more than 1MM kcal/hr.
   - (2) Those whose annual operating time does not exceed 1,000 hours.
4. The values of exhaust gas temperature and preheated air temperature listed as references are values obtained by calculating the temperature of exhaust gas when the waste heat of standard waste heat recovery rate has been recovered and the temperature of preheated air when the air has been preheated by the afore-mentioned recovered waste heat, on the following conditions:
   - (1) Temperature drop due to released heat loss, etc. from the furnace outlet to the heat exchanger for preheating air: 200°C
   - (2) Fuel: liquid fuel
   - (3) Atmospheric temperature: 20°C
   - (4) Air ratio: 1.2

(1) 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 11-41. Fuel can be saved by using hot air as combustion air.

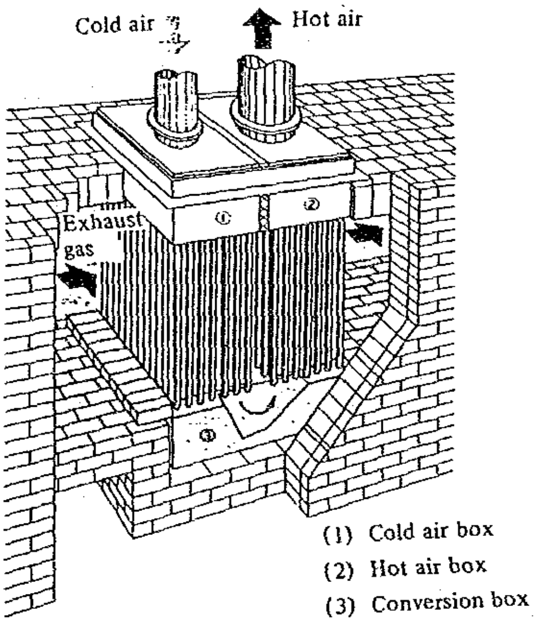


Figure 11-41 Example of Preheater of Air for Burning (Recuperator)

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

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

where

S: Fuel saving percentage (%);

F: Quantity of heat generated by 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 percentages of saving fuel oil and natural gas were calculated by exhaust gas temperature and preheated air temperature as shown in Figures 11-42 and 11-43.

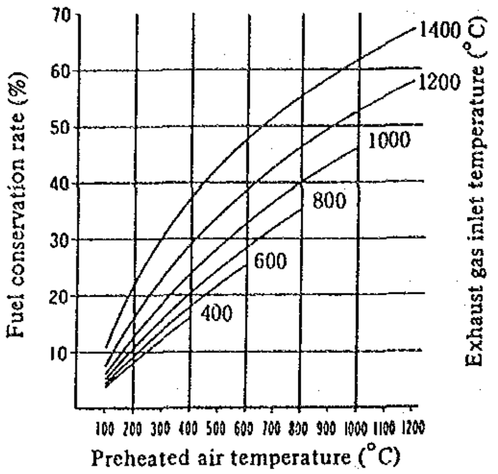


Figure 11—42 Fuel conservation rate when fuel oil is used

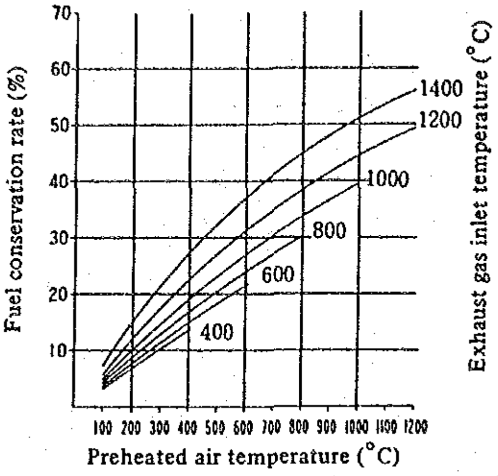


Figure 11—43 Fuel conservation rate when natural gas is used

The higher the exhaust gas temperature, the greater will be the percentage of fuel saving 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^2 h°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 11-44.

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

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

In the case of counter flow, Δt max and Δt min will be as follows from Figure 11-45.

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

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

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

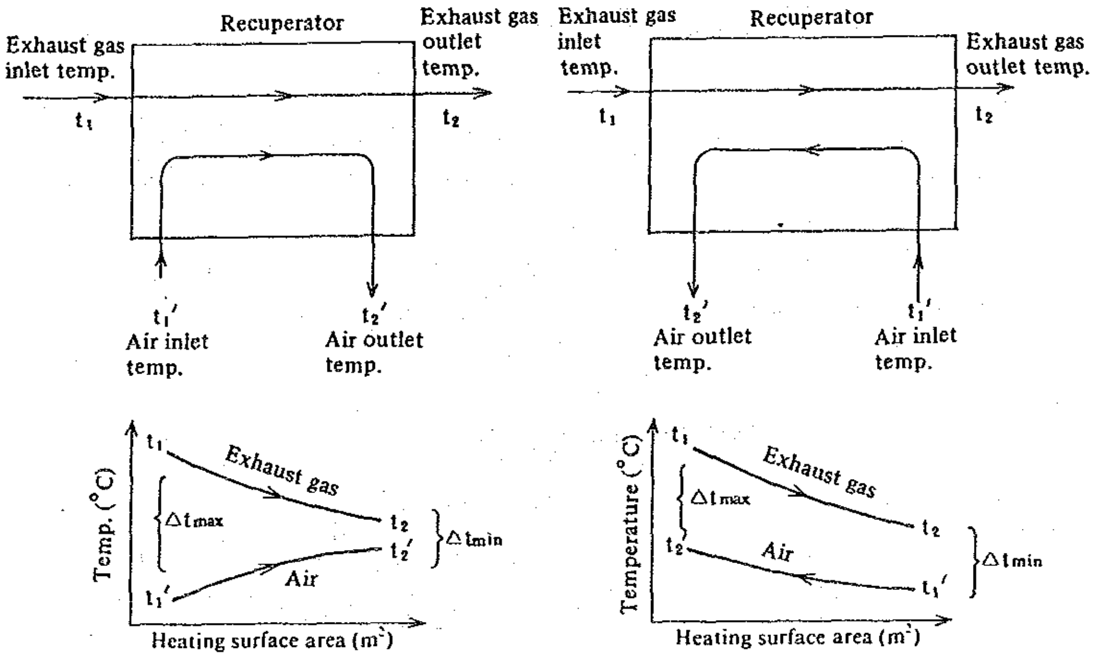


Figure 11–44 Temperature Difference in Case of Parallel Flow

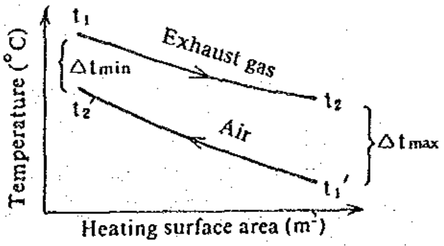


Figure 11–45 Temperature Difference in Case of Counter Flow

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

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

$t_1 = 800°C \qquad t_2 = 500°C$

$t_1' = 20°C \qquad t_2' = 350°C$

- Case of parallel flow

  $\Delta t \max = 800 - 20 = 780°C$

  $\Delta t \min = 500 - 350 = 150°C$

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

- Case of counter flow

  $\Delta t \max = 500 - 20 = 480°C$

  $\Delta t \min = 800 - 350 = 450°C$

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

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 11-15.

Table 11–15 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 constituents, pressure conditions, etc.

(A) 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.

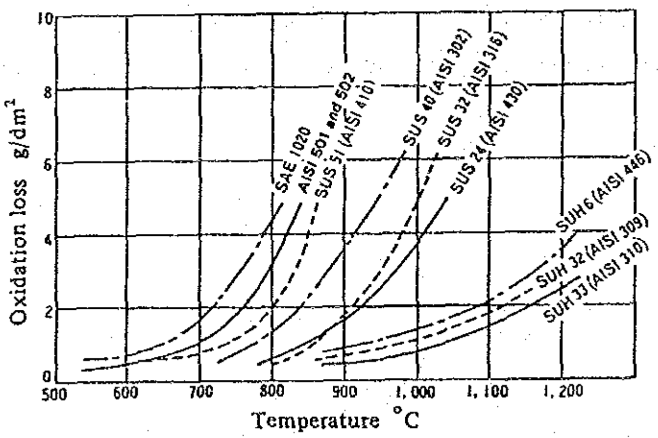
Environment will be even more severe if a heating-cooling cycle or a cycle of oxidizing-reducing atmosphere is repeated at high temperature.

Table 11-16 shows working temperatures by material and Figure 11-46 the relationship between temperature and weight reduction by oxidation.

Table 11–16 Working Temperature of Heating Pipe by Material

Material (Customary indication)	Max. working temp. (°C)	Ordinary working temp. (°C)
Carbon steel	565	400
½ Mo steel	565	450
1 Cr-½ Mo steel	565	450
1¼ Cr-½ Mo steel	590	550~575
2¼ Cr-1 Mo steel	635	600
5 Cr-½ 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.



Test conditions : 12 intermittent cycles of heating and cooling
By courtesy of : Welding Research Council Bulletin Series No.31 "Stainless Steel for Pressure Vessels"

Figure 11–46 Relationship between Temperature and Oxidation Loss

(2) Radiant tube with recuperator

All carburizing furnaces are a radiant tube type except for the special muffle type. There is a method of preheating combustion air by mounting a recuperator on the exhaust end of the radiant tube.

Figure 11-47 shows the structure of the radiant tube type recuperator, and Table 11-17 an example of recuperator performance and fuel saving percentage.

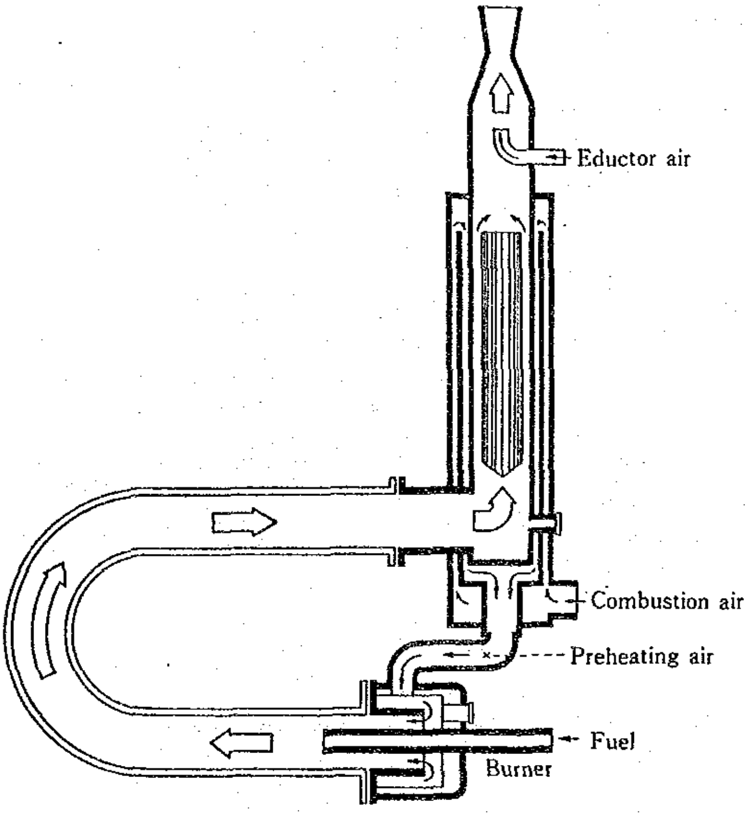


Figure 11–47 Structure of Recuperator for Radiant Tube

Table 11−17 Performance of the Recuperator for Radiant Tube

Fuel used		Kerosene
Fuel consumption		4~ 6 l/h
Flow rate	Exhaust gas side	50~80 Nm^3/h
	Air side	40~70 Nm^3/h
Pressure loss	Exhaust gas side	5mmH_2O
	Air side	28mmH_2O
Temperature	Exhaust gas side	Inlet 900℃ Outlet 550℃
	Air side	Inlet 30℃ Outlet 330℃
Heat transfer area		0.5m^2

Fuel saving rate by recuperator (actually measured value)
In case of carburizing at 930℃, fuel: kerosene

Item	Fuel saving effect
Preheating of combustion air	15%
Adjustment of air ratio m= 1.36 ⟶ 1.16	9%
closing of burner	3%
Reduction of draft loss	8%
Fuel saving rate	35%

Before improvement: 58 l/h, after improvement: 38 l/h

(3) Preheating material by exhaust gas

In the past, the heat possessed by heat-treated materials was left dissipating without use. A heat recovery type furnace has a heat exchange chamber, where this heat is recovered to preheat untreated materials up to 500°C.

Figure 11-48 shows an example of such a furnace, which has a vacuum purge chamber between the heat exchange chamber and heat treatment chamber to prevent loss of ambient gas.

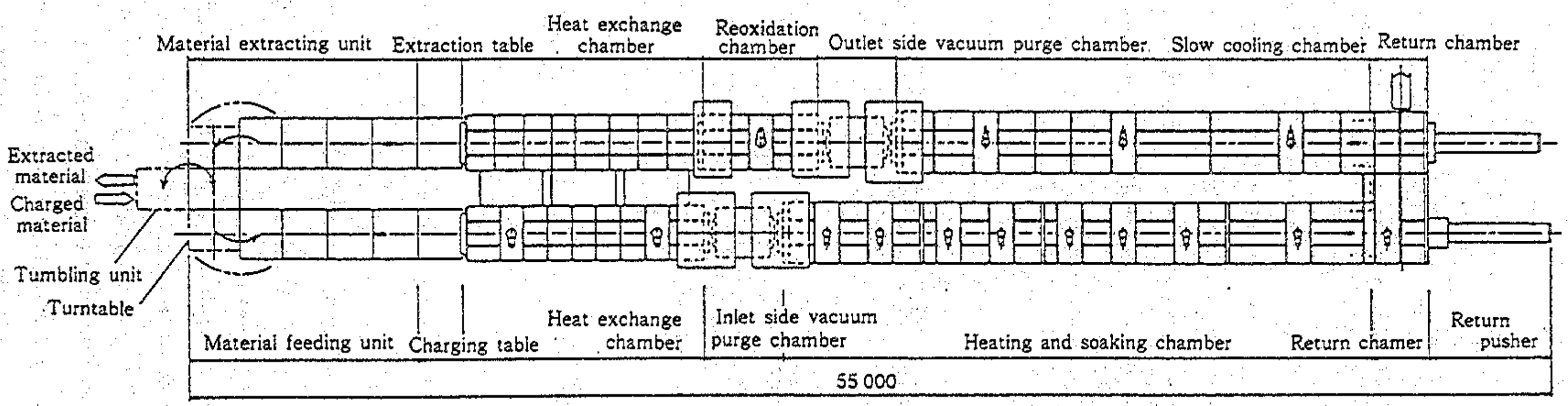


Figure 11—48 Continuous Roller Hearth Annealing Furnace with Heat Exchange Chamber

(4) Use of other heat sources

If the sensible heat of exhaust gas meets the conditions of other devices in the same process as to heat quantity, temperature range, and operating time, a great saving can be made in fuel consumption.

Figure 11-49 shows an example of using exhaust gas from a carburizing furnace for a tempering furnace. Burned exhaust gas from the gas carburizing furnace is supplied to the tempering furnace, making unnecessary the fuel used for heating. Because the exhaust gas flow rate is not stabilized due to the combustion control of the burner, the heat accumulator is installed to prevent the fluctuation of the temperature of gas supplied to the tempering furnace. The three-way cock located in the duct piping is intended to make a circulating loop for tempering furnace → heat accumulator → tempering furnace in case the exhaust gas flow becomes insufficient due to the low combustion (or off) of the burner of the carburizing furnace.

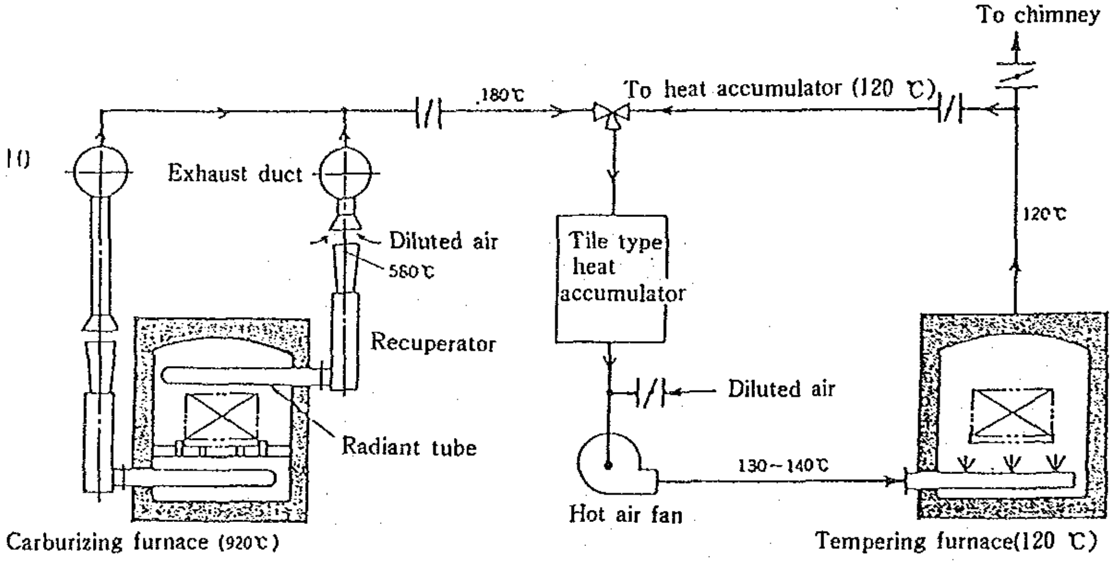


Figure 11−49 Use of the Exhaust Gas of Carburizing Furnace for Tempering Furnace

11.2.1.9 Generation of ambient gas

RX gas (CO 25%, H_2 33%), which is modified from propane or other hydrocarbon gas, is used as an ambient gas for heat treatment of automotive parts and machine parts, such as carburizing and oxidation-free quenching.

Ambient gas is generally generated in a separately installed gas generator. However, it was necessary to reheat the gas in the heat-treatment furnace because it had to be rapidly cooled immediately after modifying to prevent change in its composition due to temperature drop through the conveyance pipeline, and to prevent generation of soot. .

To deal with this problem, a reaction tube filled with a catalyst such as shown in Figure 11-50 is directly mounted on the heatment furnace. Because it is no longer necessary to cool the generated ambient gas, the energy used for reheating it can be saved, and there will no loss of heat radiation from the generator. An energy consumption comparison is shown in Table 11-18.

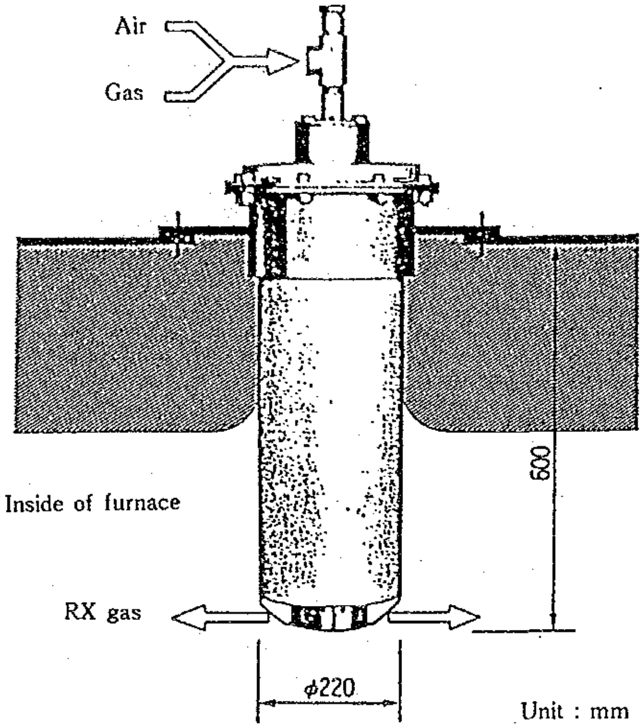


Figure 11—50 Rough Drawing of Reaction Tube

Table 11—18 Comparison of Energy Consumption

Unit: kcal/m³RX

	Conventi-onal type	CRX	characteristic of CRX
Power for heater	390	110	Small-sized heater installed in furnace
Power for blower	25	25	
Heat for reheating RX gas	305	0	Heat for reheating not required
Vent pilot burner	65	0	Not required at regular operation
Control power	15	15	
Total	800	150	

There is also an instance in which NX gas (N_2) for oxidation-free quenching is generated not by means of a separate gas generator but removing carbon dioxide gas from the exhaust gas discharged by the heat-treatment furnace.

Temperature is not constant under the combustion control of the burner so that a regenerator is installed to prevent variation of supply gas to the tempering furnace. The duct has a three-way cock to form the circulation loop of "tempering furnace — regenerator — tempering furnace" in case exhaust gas flow becomes short due to low combustion (or stoppage) of the burner for the carburizing furnace.

12. Glass

12. Glass

12.1 Characteristics of Use of Energy

12.1.1 Manufacturing Process and Main Equipment

The manufacturing process of bottles and glassware is relatively simple as shown in Figure

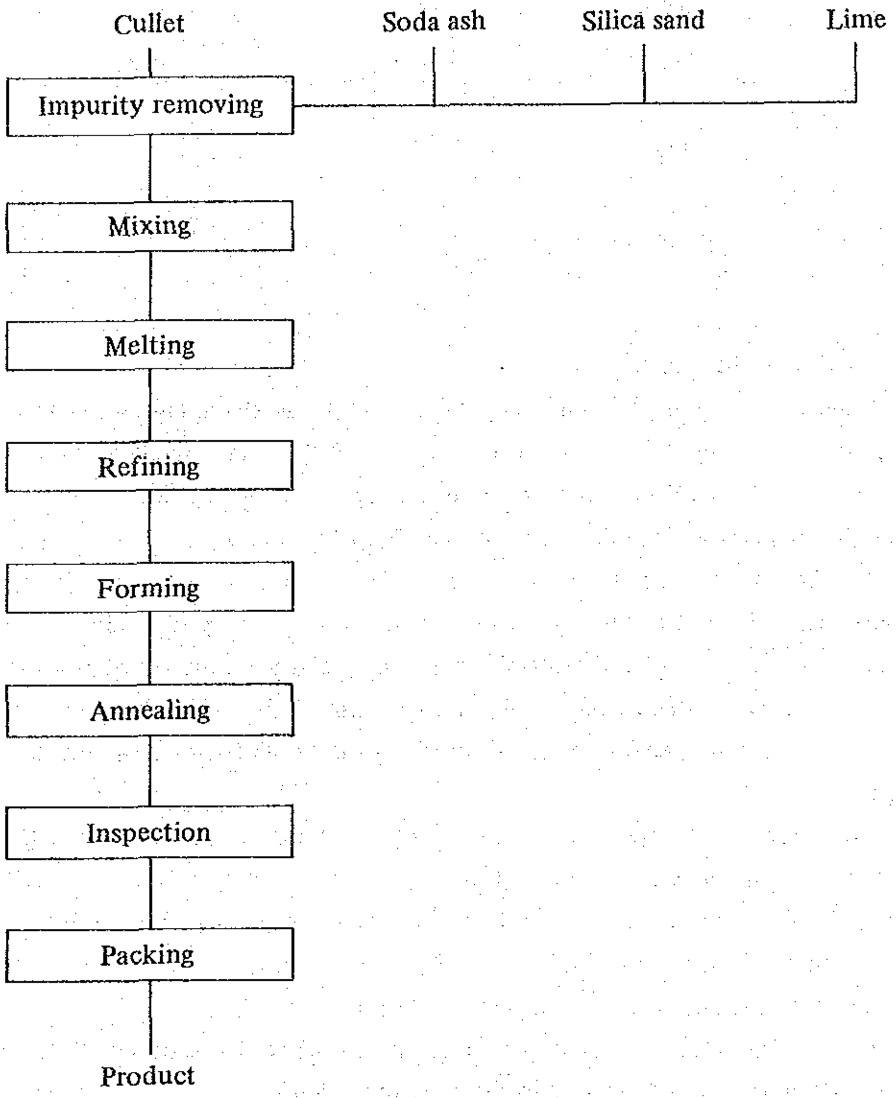


Figure 12–1 Manufacturing Process

The composition of glass varies from one application to another. Bottles and tableware are made of soda ash glass of the composition shown in Table 12–1.

Table 12–1 Composition of Glass for Vessel

Components	Contents
SiO_2	70 ~ 74 %
$A\ell_2O_3$ Fe_2O_3	1.5 ~ 2.0
CaO MgO	8 ~ 12
Na_2O K_2O	13 ~ 16

(1) Manufacturing process

According to the glass composition required for the manufacturing process, silica sand, soda ash, limestone, dolomite, etc. are mixed, and small amounts of auxiliary materials, such as clarifier, colorant, and decolorant, as well as an appropriate amount of cullet, are blended with the mixture into a composite material.

The composite material is charged into the furnace (see Figure 12–2) that is kept at about 1,500°C, where the material is heated and melted by the radiating heat of flames in the upper space. Then the molten material is clarified and its bubbles are separated. The center part of the furnace is kept higher in temperature than the rest so that unmolten or low-temperature material in the furnace will not flow out to the working hearth.

The molten, clarified glass runs through the throat to the working hearth, from which it is supplied through the forehearth to the forming machines. When the molten glass is in the working hearth and forehearth, its temperature is adjusted to suit the molding of products according to their weights and shapes. There, the material is heated by a number of small burners or directly by applying electricity.

Except for some cases in which glass is formed by manual blowing, individual section machines are generally used for mass production.

Formed products are annealed in an annealing furnace so that there will be no thermal strain left in the products. Annealing temperature and time very depending the glass composition, product wall thickness, etc. Generally, however, formed products are gradually cooled from 500°C – 550°C to about 400°C at a speed of 1°C to 5°C per minute. Although batch furnaces are also used for annealing, a continuous, tunnel furnace with a mesh belt, called lehr, is mostly used.

After annealing, the products are checked and packed.

(2) Main equipment

There are two types of furnace for melting glass material: the tank furnace that is suited to continuous, mass production, and the pot furnace for producing a variety of kinds in small quantities. Figure 12–2 shows a typical, medium-sized tank furnace.

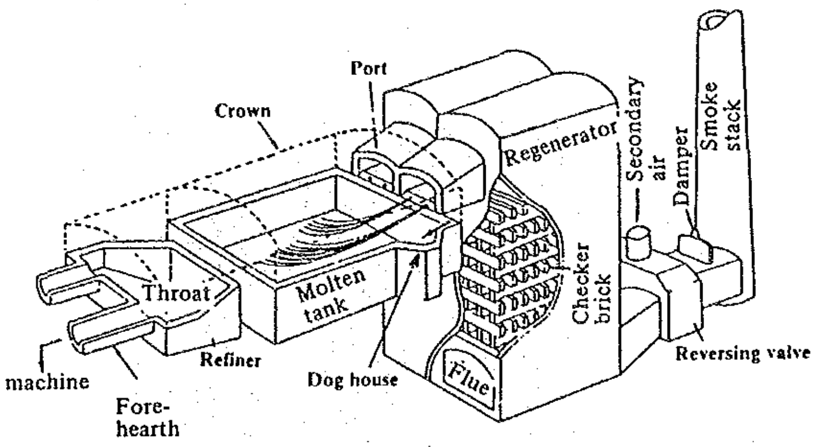


Figure 12–2 **Outline Sketch for Middle-Size Tank Furnace (End Port Type)**

A high temperature of about 1,500°C is necessary to melt glass so that combustion air must be preheated by heat exchange with combustion exhaust gas. A regenerator or recuperator such as shown in the figure is used for this preheating. Instead of heating with fuel, or as a complementary means, an electrode may be directly inserted into molten glass to directly heat it with electricity.

The melting furnace is lined with erosion-resistant electrocast bricks of $ZrO_2-Al_2O_3-SiO_2$ in the lower part which is exposed to molten glass, and with silica bricks in the upper part.

The burners are arranged in the axial direction of the furnace (end port type) except for large-sized furnaces. A furnace that has a regenerator uses an even number of burners, alternately operating a half of the burners every specific time, usually every 15 to 20 minutes.

The regenerator is divided into two rooms. The one on the side of the operating burners is used to preheat combustion air, and the other heats the checker bricks through combustion exhaust gas to store the heat in the bricks. Generally, the regenerator type has a higher rate of heat recovery than the recuperator.

12.1.2 State of Use of Energy

In glass factories, energy is consumed as shown in the table below.

Purpose	Equipment	Energy
Melting glass	Melting tank	Fuel oil, gas, electricity
Clarifying	Working hearth	Fuel oil, gas
Cooling	Forehearth	Gas, electricity
Annealing	Lehr	Fuel oil, gas
Air compression	Air compressor	Electricity
Lights, etc.		Electricity

Figures 12–3 and 12–4 show an average ratio of energy consumption by purpose of use at some glass bottle factories. As is clear from these figures, energy conservation is important for the melting and other furnaces.

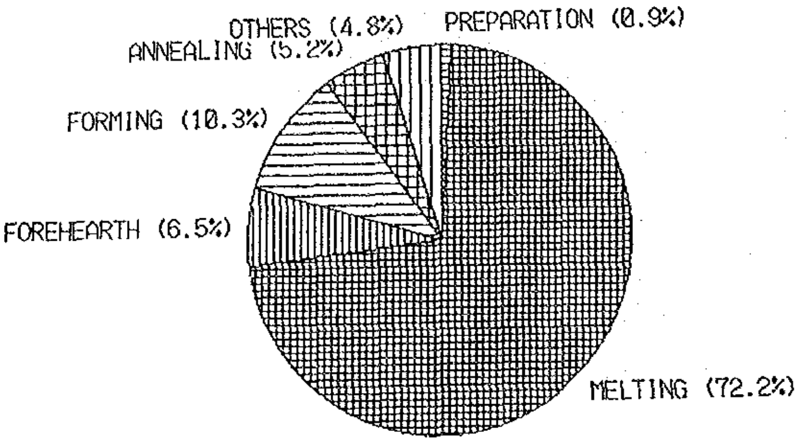


Figure 12–3 Share of Total Energy Consumption

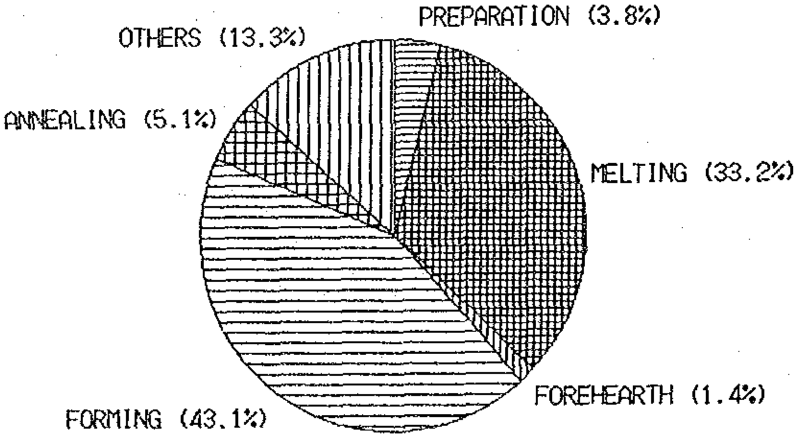


Figure 12–4 Share of Electricity Consumption

For your reference, a heat balance chart for a medium-sized melting tank in Japan is shown in Figure 12–5. This furnace has a thermal efficiency of about 40 percent, and heat loss is mainly from the furnace walls except that about 20 percent of the heat is lost in the combustion exhaust gas.

Energy consumption rate, including power consumption, for the production of glass bottles cannot be simply compared because it varies depending on the kind of glass, whether a printing process is involved, and other factors. The example in Japan shown in Figure 12–6 for your reference reveals that overall energy consumption rate was improved by about 26 percent in 1986 over the reference year of 1975.

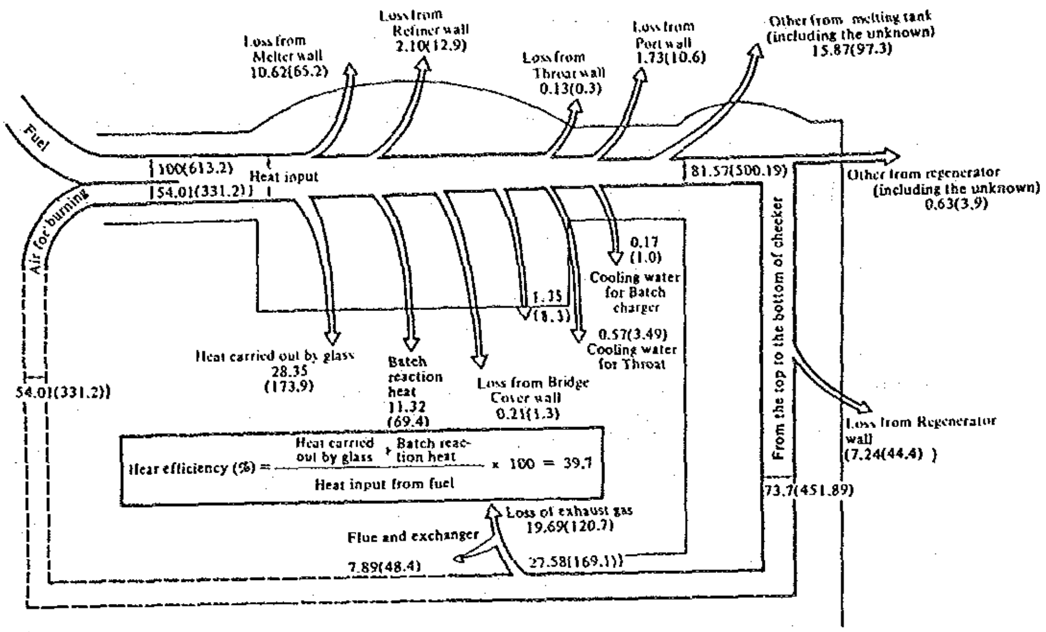


Figure 12–5 Heat Balance Chart for Glass Melting Tank

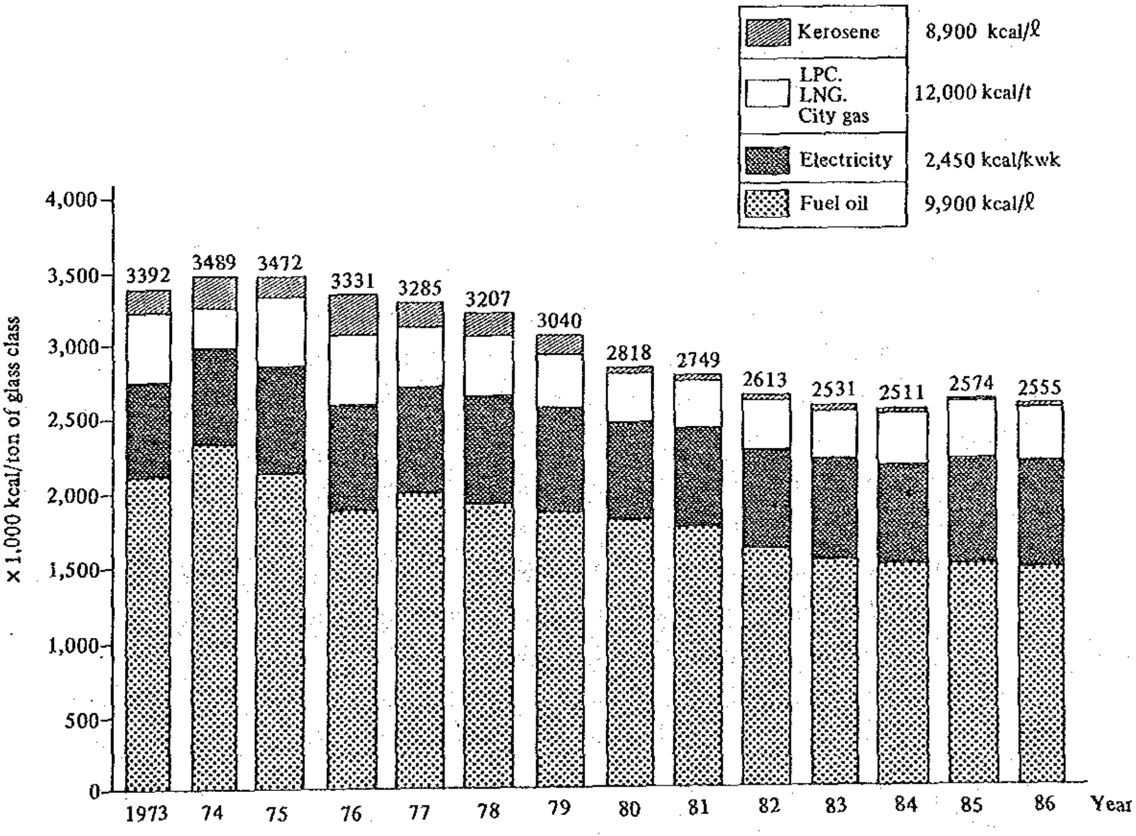


Figure 12–6 Manufacturing Energy Consumption Rate for Glass Bottle

Statistic data by factory scale have not been disclosed, but the average for the glass bottle industry was 2,560,000 kcal/ton in 1986. A glass bottle factory with new furnace of the highest efficiency (200 tons/day) showed an energy consumption rate of 1,820,000 kcal/ton, of which energy consumption for melting was 950,000 kcal/ton. By kind of energy, fuel consumption was 1,310,000 kcal/ton and electricity consumption 510,000 kcal/ton.

A breakdown of electricity consumption at a glass bottle factory in Japan is shown below.

Equipment	Purpose	Percentage
Large fan	Furnace wall cooling; supplying combustion air	28%
Compressor	Driving bottle forming machines; cooling	27%
Electric booster	Melting	21%
Other motors		21%
Lights		3%

12.2 Rationalization of Use of Heat Energy

12.2.1 Melting Furnace

(1) Optimization of air ratio

Glass is melted at a high temperature of about 1,500°C, and heat is conducted predominantly by radiation at such a high temperature. The quantity of heat, Q, radiated from an object T_1 K in absolute temperature to another object T_2 K in absolute temperature can be expressed by the following equation.

$$Q = 4.88\,\epsilon\ \left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4 \quad \text{kcal/m}^2\text{h}$$

where ϵ is the emissivity.

It is known from the above equation that the amount of heat transferred increases as flame temperature rises. Because flame temperature lowers as excess air increases, however, the air ratio must be lowered within a range in which incomplate combustion will not occur.

It is also important to decrease the amount of exhaust gas because it still has a temperature of about 500°C after waste heat recovery.

If the actual amount of exhaust gas is G, the theoretical amount of exhaust gas G_0, the theoretical amount of combustion air A_0, and the ratio m,

$$G = G_0 + (m - 1)\,A_0 \quad \text{Nm}^3/\text{kg}(\text{Nm}^3)\ \text{fuel}$$

As expressed above, lowering the air ratio will help reduce the amount of exhaust gas. Although G_0 and A_0 should be calculated from the composition of the fuel, they can be approximately calculated from the lower heating value of the fuel by the equation (Rosin's equation) of Table 12–2.

Table 12-2 Relationship Between Low Calorific Value $H\ell$ and Go, Ao (By Rosin)

Fuel	Go	Ao
Solid fuel ($H\ell$: kcal/kg fuel)	$\frac{0.89\,H\ell}{1{,}000} + 1.65\ \mathrm{Nm^3/kg\ fuel}$	$\frac{1.01\,H\ell}{1{,}000} + 0.5\ \mathrm{Nm^3/kg\ fuel}$
Liquid fuel ($H\ell$: kcal/kg fuel)	$\frac{1.11\,H\ell}{1{,}000}\ \mathrm{Nm^3/kg\ fuel}$	$\frac{0.85\,H\ell}{1{,}000} + 2.0\ \mathrm{Nm^3/kg\ fuel}$
Low calorific value gaseous fuel ($H\ell$ = 500 to 3,000 kcal/Nm^3 fuel)	$\frac{0.725\,H\ell}{1{,}000} + 1.0\ \mathrm{Nm^3/Nm^3\ fuel}$	$\frac{0.875\,H\ell}{1{,}000}\ \mathrm{Nm^3/Nm^3\ fuel}$
High calorific value gaseous fuel ($H\ell$ = 4,000 to 7,000 kcal/Nm^3 fuel)	$\frac{1.14\,H\ell}{1{,}000} + 0.25\ \mathrm{Nm^3/Nm^3\ fuel}$	$\frac{1.09\,H\ell}{1{,}000} - 0.25\ \mathrm{Nm^3/Nm^3\ fuel}$

If the amount of exhaust gas decreases from G_1 to G_2 by improving the air ratio, the decreased exhaust gas loss will reduce the amount of fuel to further decrease the amount of exhaust gas. In this case, the percentage of fuel saving can be expressed by the following equation.

$$\text{Fuel saving (\%)} = \frac{100R\left(1 - \frac{G_2}{G_1}\right)}{100 - RG_2/G_1}$$

(there R is the percentage of exhaust gas loss before the improvement.)

The results of actually measuring a tank furnace in Japan showed that fuel consumption was least in the range of m = 1.07 to 1.16. The criteria formulated by the Japanese government specify a target air ratio of 1.3 for continuous glass melting furnaces.

An amount of combustion air cannot be directly measured because, apart from preheated air for combustion, there is air entering through the openings. Thus, it is determined by measuring the concentration of oxygen or CO_2 in the exhaust gas and calculating the material balance. If fuel has only small nitrogen content, burns completely, and if the nitrogen content of combustion air is 79 percent, air ratio can be calculated by the following equation.

$$m = \frac{2}{21 - (O_2) + 0.5\,(CO)}$$

where (O_2) is the concentration of oxygen in exhaust gas (%);

(CO) is the concentration of CO in exhaust gas (%).

$$\text{Or, } m = \frac{1 - (CO_2) - 1.5\,(CO)}{\frac{1 - (CO_2)\,\mathrm{max}}{0.79} \times \frac{(CO_2) + (CO)}{(CO_2)\,\mathrm{max}}} + 0.21$$

where (CO_2) is the concentration of carbon dioxide gas in exhaust gas (%);

(CO_2) max, the maximum concentration of carbon dioxide gas in theoretical dry exhaust gas (%).

$$(CO_2)\,\max = \frac{1{,}867.C}{G_0'} \times 100\% \qquad \text{(solid/liquid fuel)}$$

$$G_0' = G_0 - (11.2\,h + 1.244\,W)\ Nm^3/kg.$$

where h is hydrogen content (kg) in 1 kg fuel;

W, water content (kg) in 1 kg fuel;

C, carbon content (kg) in 1 kg fuel.

In the case of gas fuel, the same can be calculated from analyzed values of the components.

The following values may also be used for (CO_2).

Coal (18.5%); fuel oil (15.7%); natural gas (12%); LPG (14.5%).

To keep the air ratio appropriate, the following must be borne in mind.

(a) In the case of liquid fuel, observe the following.

(a–1) Preheat it to an appropriate level of viscosity.

(a–2) Remove solids from the fuel using a filter.

(a–3) Keep the burner tips clean.

(a–4) Adjust atomizing steam or air to appropriate pressure.

There was an instance in which fuel consumption was reduced by 2 or 3 percent by atomizing natural gas instead of air.

(b) Preventing air infiltration

Air sucking through the dog house, around the burners, sightholes, etc. will not only increase the amount of exhaust gas but also lower the temperature inside the furnace because that air is cool.

It is necessary to take the following steps in order to reduce air sucking to a minimum.

Make the openings as small as possible by, for example, completely sealing the joints, using water-cooled burners to narrow the clearances around the burners, or sealing the dog house with batch.

Adjust the damper to maintain the correct furnace pressure.

(c) Control

Control the amount of secondary air in proportion to the amount of fuel. In cases, a computer is employed for more accurate control, involving compensation for changes in crown temperature, O_2 concentration in exhaust gas, and secondary air temperature, and shortening of switching time.

(2) Improving flame emissivity

In gas combustion, heat is transferred mainly by radiation from the clear flames of high-temperature carbon dioxide gas, water vapor, and other triatomic gas.

In fuel oil combustion, heat is transferred by luminous flame radiation, and solid radiation from the suspended carbon particles that are generated in the flames during combustion plays an important role.

Emissivity ϵ of radiation heat transfer differs between fuel oil (0.5 – 0.6) and gas (0.1 – 0.2) in the initial phase of combustion. In actual furnaces, the effect will be less because there is re-radiation from the furnace walls in addition to radiation from the flames, but gas has less amount of radiation heat transfer than fuel oil.

Figure 12–7 shows an instance, in which a baffle is provided in the port. Fuel gas is injected in back of it to be burnt in a state of rather insufficient air so that fine carbon particles will be generated and they will be burnt into luminous flames in secondary combustion.

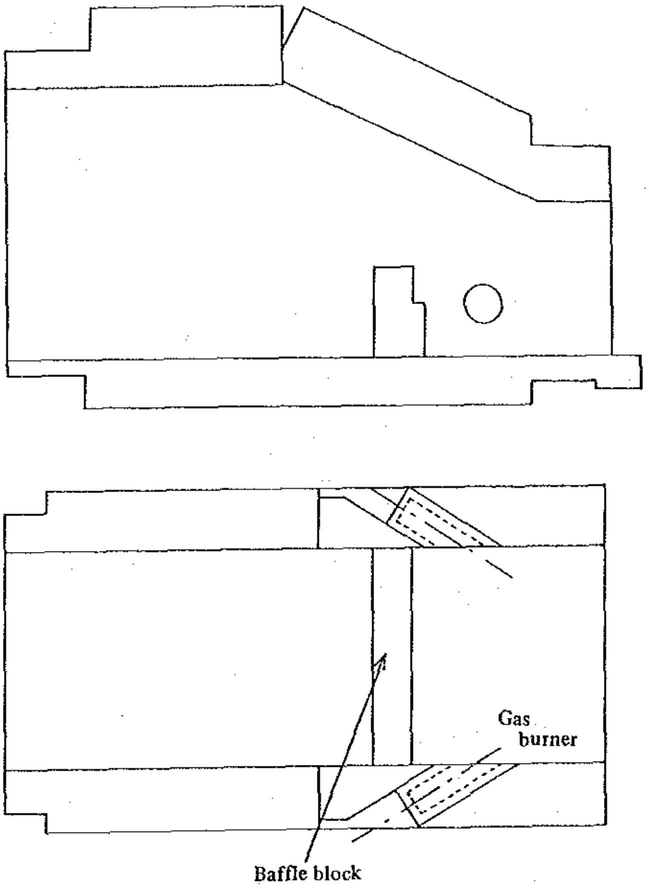
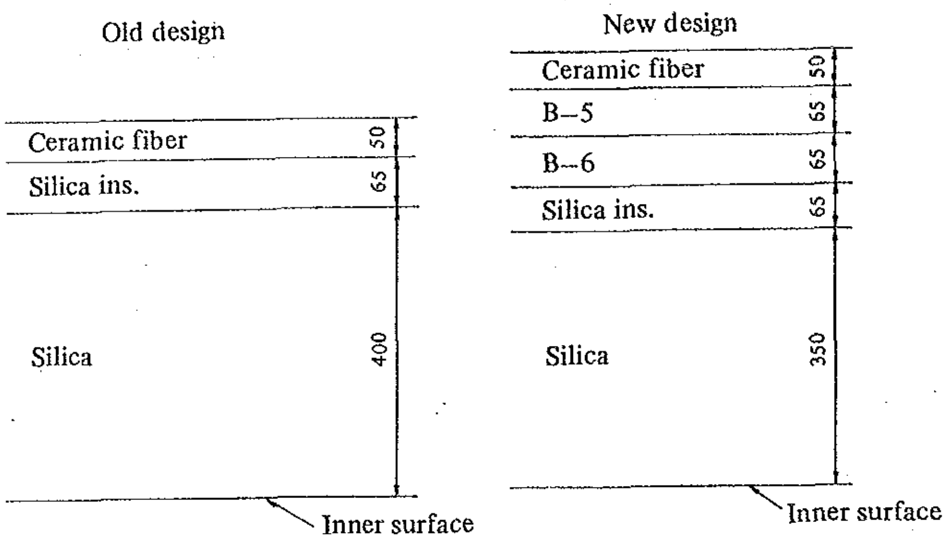


Figure 12–7 Baffle Block in the Port

(3) Reinforcing heat insulation

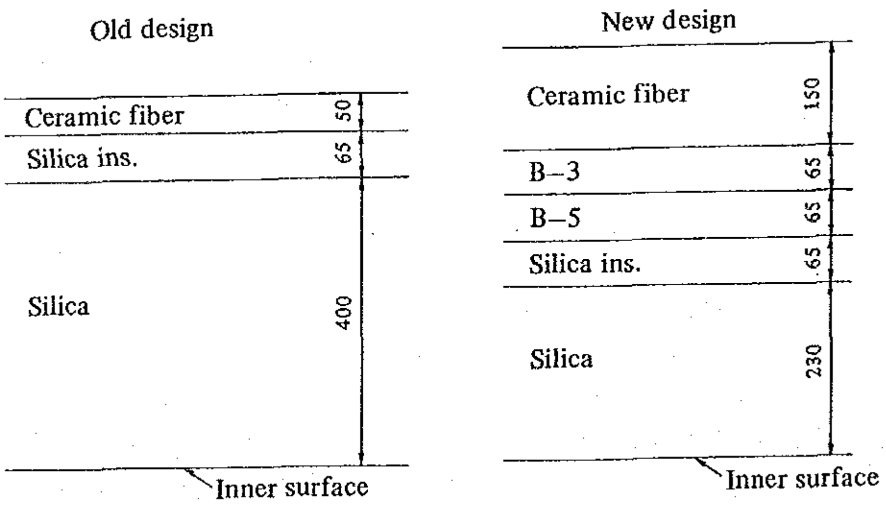
The refractories of the melting furnace are exposed to very severe conditions in terms of temperature and corrosion by the glass. Consequently, they had not been sufficiently heat-insulated, and the outer surface of wall of molten glass level was cooled by air. As is clear from the heat balance chart, heat radiation from the furnace walls accounts for a large percentage of heat loss, so the furnace was being improved in heat insulation using high-grade refractories. Specifically, the furnace crown was lined with super-duty silica bricks having small alkali or alumina content; the tank block and bottom were lined with electrocast bricks of alumina, zirconium, silica inside and with refractory bricks, insulating bricks, or ceramic fiber outside.

Figures 12–8 to 12–16 show the bricks lining various parts of the old and new furnaces, and the difference in their heat radiation.



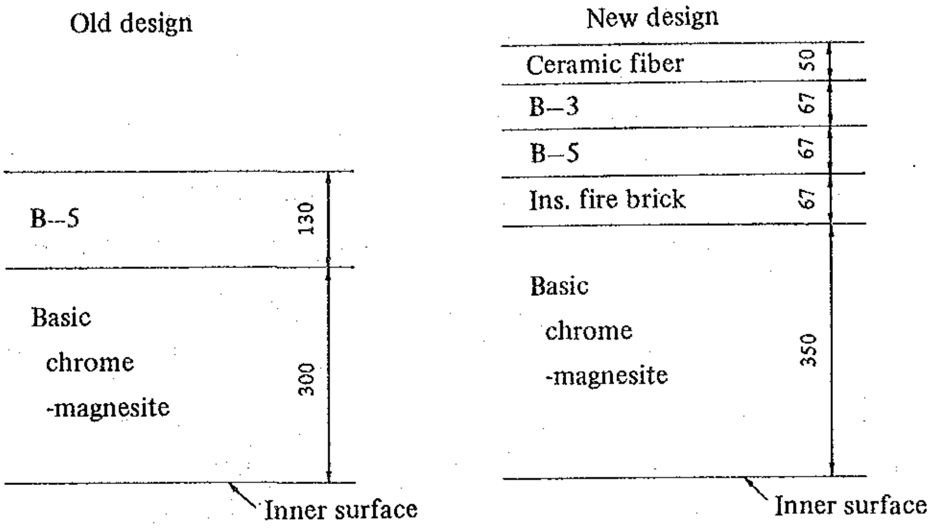
Inner surface temperature	1550 °C	1550 °C
Outer surface temperature	109.6 °C	83.4 °C
Amount of heat radiation	1505 kcal/m² ·h	1046 kcal/m² ·h

Figure 12–8 Heat Insulation of Melting Furnace Crown



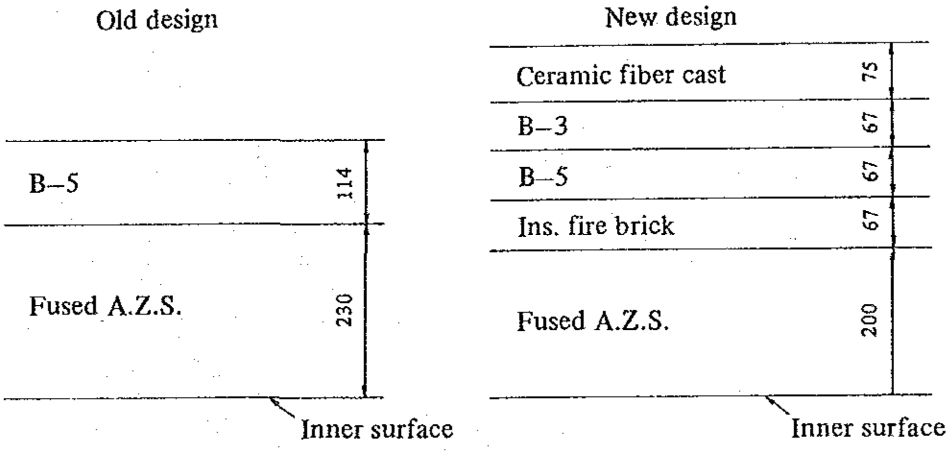
Inner surface temperature	1250 °C	1250 °C
Outer surface temperature	85.4 °C	43 °C
Amount of heat radiation	1078 kcal/m² ·h	463 kcal/m² ·h

Figure 12–9 Heat Insulation of Working Hearth Crown



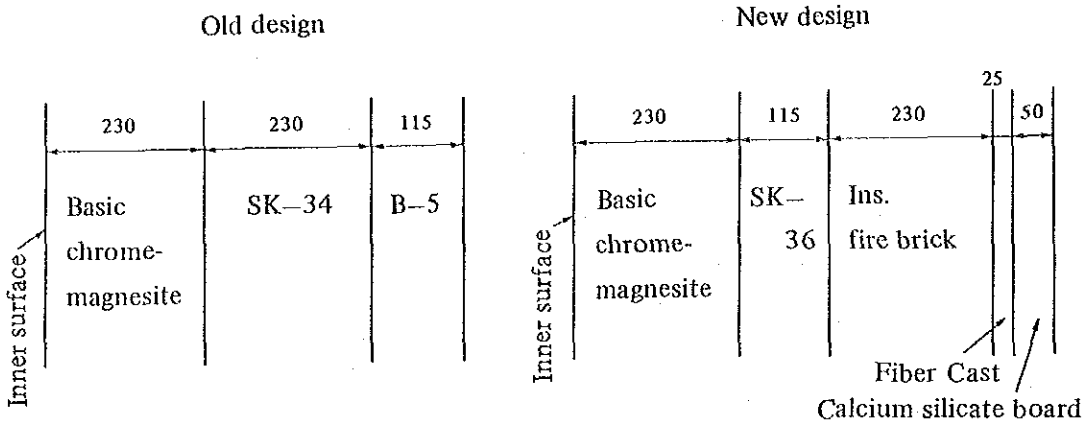
Inner surface temperature	1450 °C	1450 °C
Other surface temperature	128.4 °C	75.2 °C
Amount of heat radiation	1900 kcal/m² ·h	919 kcal/m² ·h

Figure 12–10 Heat Insulation of Regenerator Crown



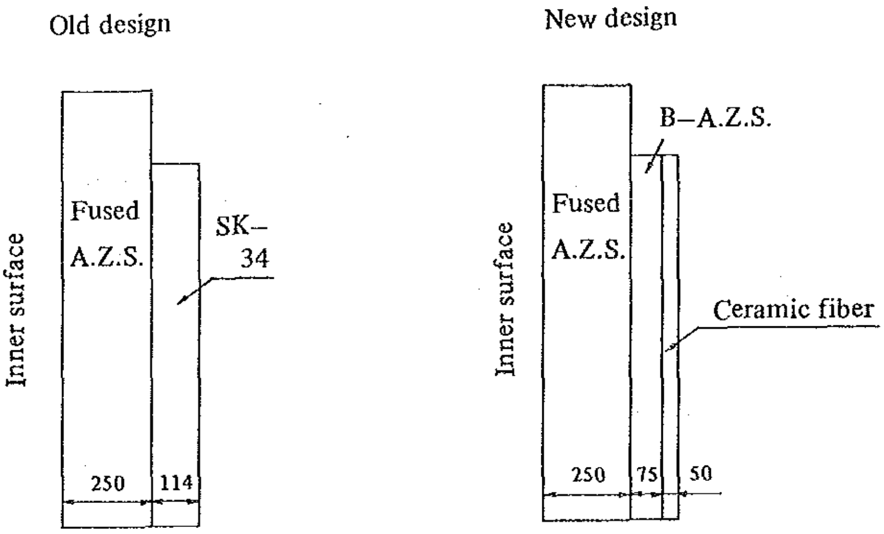
Inner surface temperature	1500 °C	1500 °C
Outer surface temperature	164 °C	86.6 °C
Amount of heat radiation	2778 kcal/m² ·h	1097 kcal/m² ·h

Figure 12–11 Heat Insulation of Port Crown



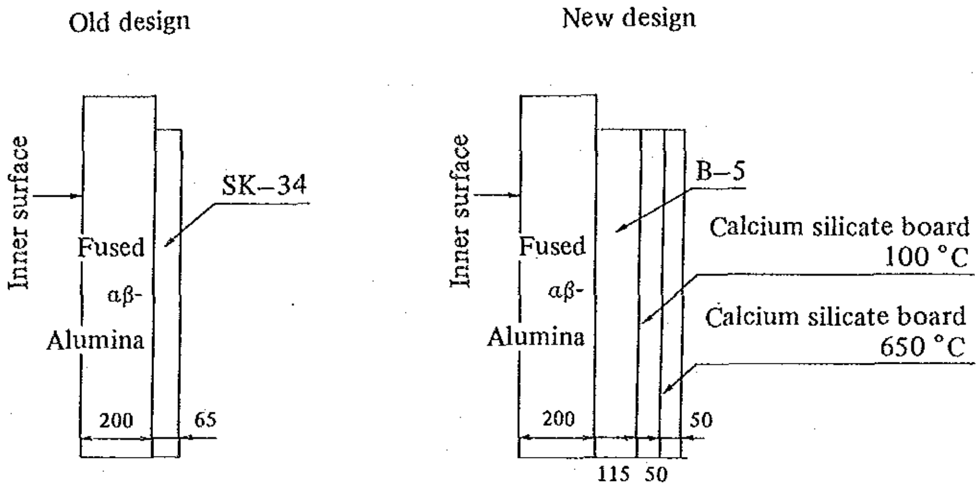
Inner surface temperature	1450 °C	1450 °C
Outer surface temperature	122.2 °C	81.2 °C
Amount of heat radiation	1554 kcal/m² ·h	814 kcal/m² ·h

Figure 12–12 **Heat Insulation of Regenerator Sidewalls (Upper Part)**



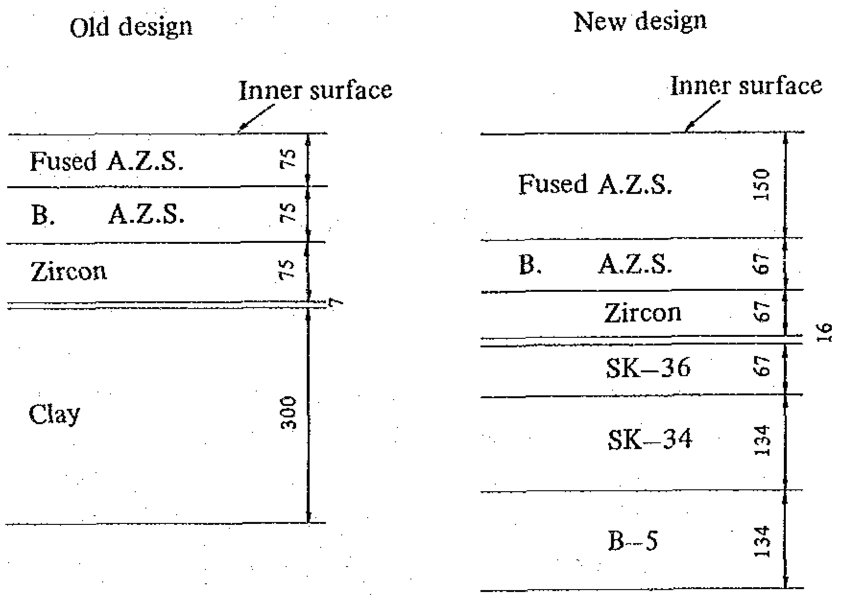
Inner surface temperature	1350 °C	1350 °C
Outer surface temperature	231.6 °C	141 °C
Amount of heat radiation	6102 kcal/m² ·h	2017 kcal/m² ·h

Figure 12–13 **Heat Insulation of Melting Tank Block**



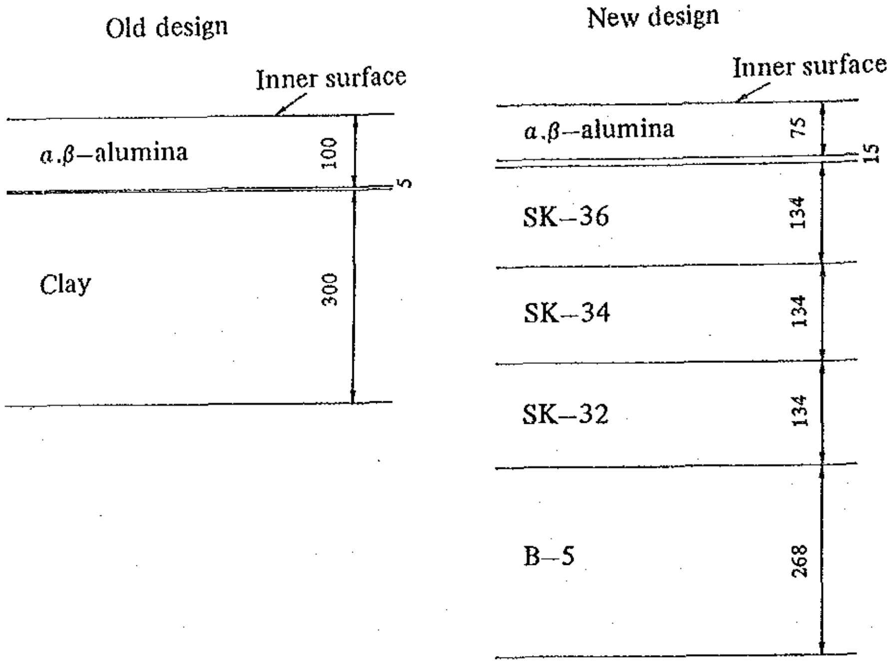
Inner surface temperature	1200 °C	1200 °C
Outer surface temperature	251.6 °C	74.2 °C
Amount of heat radiation	7624 kcal/m²·h	717 kcal/m²·h

Figure 12–14 **Heat Insulation of Working Hearth Tank Block**



Inner surface temperature	1350 °C	1350 °C
Outer surface temperature	187 °C	114 °C
Amount of heat radiation	3240 kcal/m²·h	1381 kcal/m²·h

Figure 12–15 **Heat Insulation of Melting Tank Bottom**



Inner surface temperature	1100 °C	1150 °C
Outer surface temperature	181.8 °C	63.4 °C
Amount of heat radiation	3070 kcal/m² ·h	631 kcal/m² ·h

Figure 12–16 Heat Insulation of Working Hearth Bottom

(4) Waste heat recovery

Because a melting furnace requires high temperature, the waste heat of burnt exhaust gas is recovered to preheat secondary air. Either a regenerator or recuperator is used as a waste heat recovery unit. Generally, a regenerator is used except for small-sized furnaces.

The heat recovery ratio of the regenerator can be improved by decreasing the thickness of checker bricks, increasing the velocity of exhaust gas running through the checker bricks, and raising the height of the regenerator and thus increasing the amount of checker bricks. (See Figures 12–17 and 12–18.) Normally, secondary air is preheated to about 1,250°C – 1,300°C. The checker bricks care breaking down by reaction with the dust in exhaust gas over years of use, clogging up the gaps and reducing the heat exchange area. Therefore, high-grade bricks of high corrosion resistance have come to be used to last as long as the melting furnace itself.

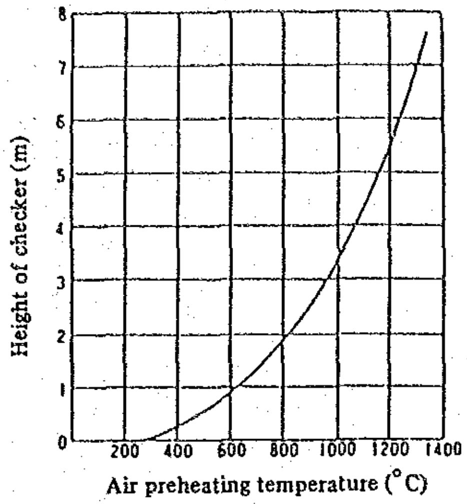


Figure 12–17 Relationship Between Height of Checker and Air Preheating Temperature

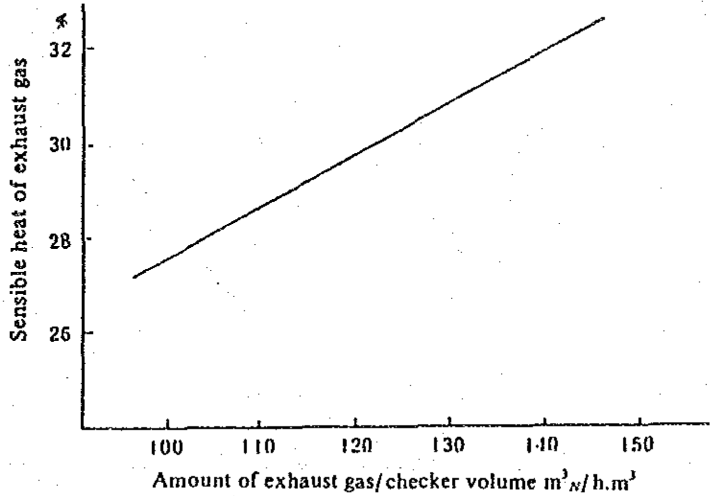


Figure 12–18 Relationship Between Amount of Exhaust Gas/Checker Volume and Sensible Heat of Exhaust Gas

As for recuperator, the radiating type recuperator which is free of clogging with dust is mostly used, but a multiple ceramic tube recuperator is also used. There is also used. There is also a type which withstands exhaust gas temperatures of up to about 1,500°C, but its heat recovery ratio is low because preheated air temperature is up to about 800°C. However, it is used for small-sized furnaces for reasons that it costs low to install and does not require much floor space.

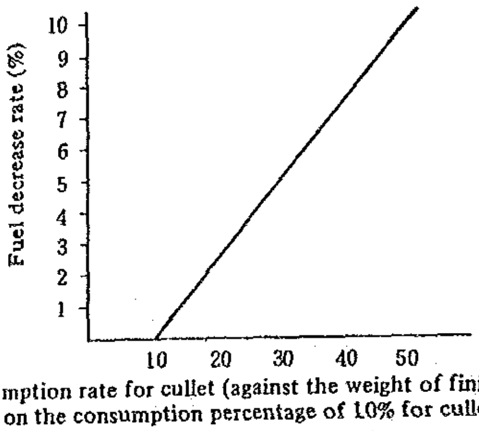
To make maximum use of preheated air, it is necessary to reduce the entry of air of normal ambient temperature through the openings.

(5) Material mixing

The energy used for melting can be reduced of cullet and limestone are mixed in a larger percentage, provided that product quality will not be adversely affected by their increased percentage. The relationship between the percentage of cullet and required heat is shown in Table 12–3 and Figure 12–19.

Table 12–3 Heat Required for Production of Various Kinds of Glass at 1,400°C and Pull Temperatures (Theoretical Value)

Kind of glass	Temperature °C	Heat required for melting glass q (kcal/kg glass)					
		Cullet addition rate %					
		0	20	40	60	80	100
Tableware glass	1,400	576	543	510	477	444	411
	1,250	530	497	464	431	398	365
Sheet glass	1,400	666	615	563	512	460	409
	1,150	571	520	468	417	365	314
Laboratory appliances	1,400	508	482	455	429	402	376
	1,300	477	451	424	398	371	345
Lead glass	1,400	496	472	448	424	400	376
	1,100	391	367	343	319	295	271



Based on the consumption percentage of 10% for cullet.

Figure 12–19 Consumption Rate for Cullet and Fuel Saving Rate

For your reference, the percentage of cullet used in producing glass bottles in Japan was 54 percent in 1987. Because impurities cannot be removed in the melting furnace, they must be removed from cullet beforehand. The cullet quality standard and processing method are shown in an item of the survey report of the Rayen Cura factory.

Use of a clarifing agent will shorten the clarifying time, and result in saving energy. A type and quantity of clarifing agent must be selected to suit the furnace conditions.

(6) Electric melting

This method uses an electrode inserted into the melting furnace to directly apply electricity to glass which becomes electro-conductive at about 800°C. If it is used in a fuel-heating furnace as an auxiliary means to increase the amount of pull and adjust the temperature inside the furnace, it is called booster. About 100 kW of electricity is required to increase quantity by 3 tons or more per day. If the efficiency of conversion from fuel oil to electricity is 35 percent and if the fuel consumption rate is 175 liters or more per ton, energy can be saved by using a booster.

Table 12–4 shows the heat output ratio of an electric melting furnace. Electric melting may be more economical for small-sized furnaces, taking the prices of energy and auxiliary equipment into account. Electric melting also offers the advantages of less air pollution, easy temperature control, and high product quality.

Table 12–4 Heat Output ratio of Electric Melting Furnace

	Heat output (kcal/h)	Ratio (%)
Heat release from ceiling	28	(0.07)
Heat release from furnace bottom	5,883	
Heat release from throat side wall	5,200	
Other walls	7,850	
Total	18,961	44.1
Loss by water cooling for electrode	10,455	24.3
For glass heating	13,584	31.6

(Capacity 750 kg, pull quantity 400 kg/day)

	Heat Output (kcal/h)	Ratio (%)	
Ceiling	1,800	2	30
Side wall	10,700	15	
Bottom	9,300	13	
Cooling water for electrode	1,400	2	2
Calorific value required for vitrification	2,200	3	68
Soaring temp. of glass	46,600	65	
Total	72,000	100	100

(Pull quantity 60 t/day)

12.2.2 Forehearth

The forehearth is used to adjust the glass temperature to suit bottle production. In the case of using fuel in the forehearth control of the air ratio and improved heat insulation will be as important items of energy conservation measures as for the melting furnace.

Electric heating is also considered effective for energy conservation.

12.2.3 Lehr

(1) Increase in the heat carried in

Formed products still have a temperature of over 600°C, so if they are taken into the lehr without losing this heat, heating shoudl be theoretically unnecessary, provided that the following conditions are met.

- To shorten the distance between the forming machine and lehr
- To charge formed products from the forming machine into the lehr as quickly as possible.

(2) Preventing heat radiation

While the glass is still at high temperature, it must be gradually cooled. For this purpose the following conditions must be met.

- Heat insulation of the high-temperature parts and prevention of hot air leakage
- Controlling cold air leakage into the lehr through the charging port
- A lehr sectional shape suited to product dimensions and production
- Shortening spaces of charged products

(3) Use of direct heating method

In case of using fuel oil, the indirect heating method using muffles or radiant tubes was usually employed to prevent the burning gas from directly touching the products and possibly making their surfaces cloudy.

However, the lehr has a heating temperature range of less than 600°C, and radiation heat transfer by indirect heating is inefficient. For this reason, direct heating comes, common when using gas as fuel.

(4) Lowering of mesh belt heat capacity

The example shown below indicates that the quantity of heat required to heat the mesh belt is larger than normally expected.

Product processing rate : 630 kg/h
Average specific heat of products : 0.252
Product temperature before entering lehr : 400°C
Annealing temperature : 550°C

In this case, the quantity of heat Q_1 required to heat the products can be calculated as follows:

$$Q_1 = 0.252 \times (550 - 400) \times 630 = 23814 \text{ (kcal/h)}$$

Suppose that the products are conveyed on a 1,500 mm width belt into the lehr.

Belt weight : 20 kg/m²
Belt speed : 380 mm/min
Temperature before entering lehr : Normal temperature 15°C
Maximum heating temperature of belt in lehr : 550°C
Average specific heat : 0.132

In this case, the quantity of heat Q_2 required to heat the belt will be:

$$Q_2 = 0.132 \times (550 - 15) \times 20 \times 0.38 \times 1.5 \times 60 = 48304 \text{ (kcal/h)}$$

As shown, more than twice as much heat is consumed to heat the belt as to heat the products Possible measures to reduce this heat include decreasing belt wire diameter, increasing wire pitch, and thus reducing belt weight per unit area.

Furhrer, the mesh belt may be preheated by exhaust gas on the return way.

The heat consumption rate of the lehr varies largely depending on the charging temperature of the products, their shape, wall thickness, the number of times these parameters change, operating time, processing quantity, and the type of lehr. For your reference, some of the lehrs used in Japan show a heat consumption rate ranging from 380 to 830 kcal/kg in most cases, and some large ones show an extremely low heat consumption rate of 50 kcal/kg.

12.2.4 Product Weight Reduction

Reducing the quantity of glass required to produce a specific quantity of bottles helps decrease the energy used for production. To maintain the required bottle strength using a limited quantity of glass material, it is necessary to improve form design and wall thickness distribution, and enforce strict control on surface treatment and manufacturing conditions.

12.2.5 Productivity Improvement

Glass bottle production requires high temperature and consumes much heat even during temporary suspensions of production. Therefore, it is necessary to prevent mechanical trouble from interrupting work, shorten the time of changing molds in the forming machines, and decreasing the frequency of changing the molds.

The glass melting furnace has a high percentage of fixed heat loss, and its fuel consumption rate lowers as the amount of pull increases. It is also necessary, therefore, to try increasing the amount of pull while preventing quality deterioration by better stirring the material in the furnace.

12.2.6 Preventing Rejects

If products are defective and must be returned as rejects into the material, it means loss of all energy consumed for them. Efforts must be made to enforce better control on material quality, working conditions in each of the manufacturing processes, and equipment maintenance so that there will be no rejects on the production line.

13. Boiler and Steam

13. Boilers

13.1.1 Classification

Now, boilers used universally can be classified by structure as shown in Table 13-1.

Table 13–1 Classification of Boiler

Type	Model
Cylindrical boiler	Vertical boiler Flue boiler Smoke tube boiler tube boiler
Water tube boiler	Natural circulation water tube boiler Forced circulation water tube boiler Once-through boiler
Others	Sectional boiler etc.

13.1.1.1 Cylindrical boiler

Cylindrical boiler is mainly composed of a large diameter cylinder and unsuitable for a high pressure and a larger capacity due to its structure. It has been used as a boiler of less than 10 kg/cm^2 and 8 t/h in evaporation.

Since the cylindrical boiler has a larger water retaining volume per capacity compared with water-tube boiler, it demands much time to start-up but a pressure fluctuation due to loading change is small.

a. Vertical boiler

As shown in Figure 13-1, vertical boiler has a vertical cylinder and a combustion chamber in the bottom section. There are two systems of horizontal tube type and multi-tube type. Becuase it can not be provided with large heating surface area, the capacity is limited to 1 t/h or less.

It can do with a small floor area and can be set simply up, but it is hard to check and clean because of its small size. Because of the small surface area, entrainment contained in the generated steam tends to be too much.

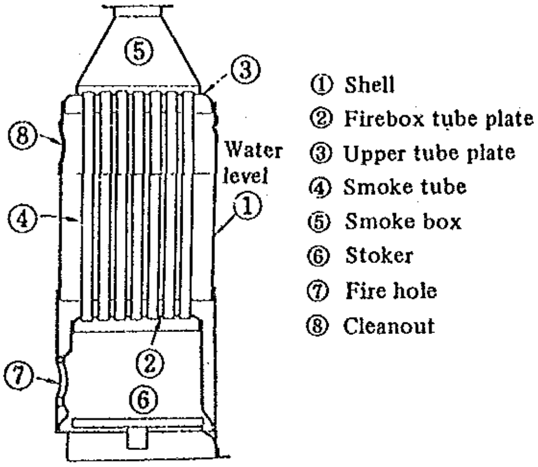


Figure 13 - 1 Vertical boiler (multitublar type)

b. Flue boiler

The flue boiler is provided with one or two flues through shell and the burners are equipped in the flue. One flue type is called a Cornish boiler and two flues type is referred to as a Lancashire boiler. Since the boiler has a small heating surface area and has lower efficiency, recently it has been scarcely manufactured.

c. Smoke tube boiler

As shown in Figure 13-2, a smoke tube boiler is equipped with a combustion chamber formed with brick laying beneath the cylinder and arranged with a number of smoke tubes in the shell. The combustion gas heats the lower section of shell and then heats again the side surface of shell after passing the smoke tubes. As the heat loss through the brick wall is large in case of outside combustion chamber, some boiler is equipped with the combustion chamber in a part of the flue.

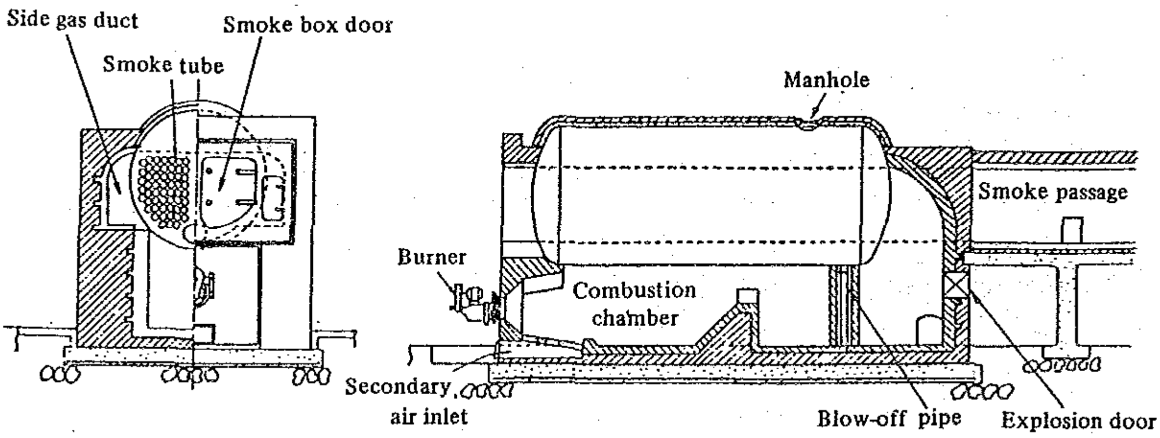


Figure 13—2 Externally Fired Horizontal Smoke Tube Boiler

d. Flue smoke tube boiler

As shown in Figure 13-3, a flue smoke tube boiler is an internally fired boiler equipped with both of flue and smoke tubes in the shell. The boiler is generally used as a package boiler with characteristics of a relatively larger heating surface area of high efficiency even in a small capacity and has easy installation and handling. The boiler is limited to 15 kg/cm^2 in pressure and 25 t/h in capacity. An efficiency of 85 to 92% is obtainable. On the other hand, the structure is complex, check and cleaning in the inside are difficult and feed water is required to be high quality.

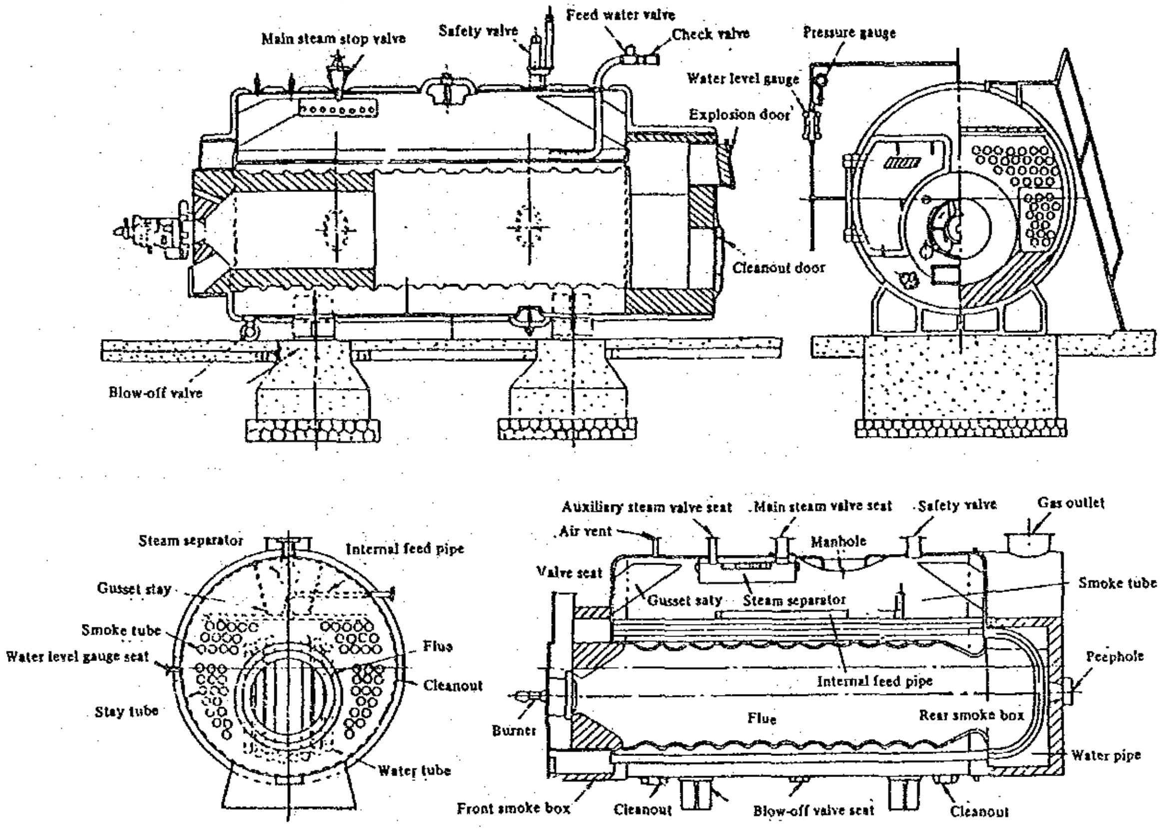


Figure 13–3 Flue Smoke Tube Boiler

13. 1.1.2 Water-Tube Boiler

As shown in Figure 13-4, a water-tube boiler is composed of a drum for steam and water separation and a number of water tubes formed with a heating surface, and is designed to make evaporate feed water in the water tubes. Accordingly, since the heating surface can be made larger through increasing the number of water tubes, the boiler is suitable even for a large capacity and is able to obtain easily a high pressure. The features of water-tube boilers are as follows:

a. Because the combustion chamber is able to be made in any size, the combustion is in good condition and various fuels can be adapted easily.

b. The thermal efficiency is higher because of a larger heating surface area.

c. The start-up time is shorter because of the small amount of retaining water per heating surface area. While a fine regulation is required since the pressure and water levels are prone to fluctuate with a loading variation.

d. Consideration should be given to feed water and boiler water treatment.

The water-tube boiler has two systems: a natural circulation system, which utilizes the differences of the specific gravities between steam and water, and forced circulation, which uses a pump (see Figure 13-5). A high pressure boiler is required to adopt a forced circulation system because of the density difference between steam and water is small.

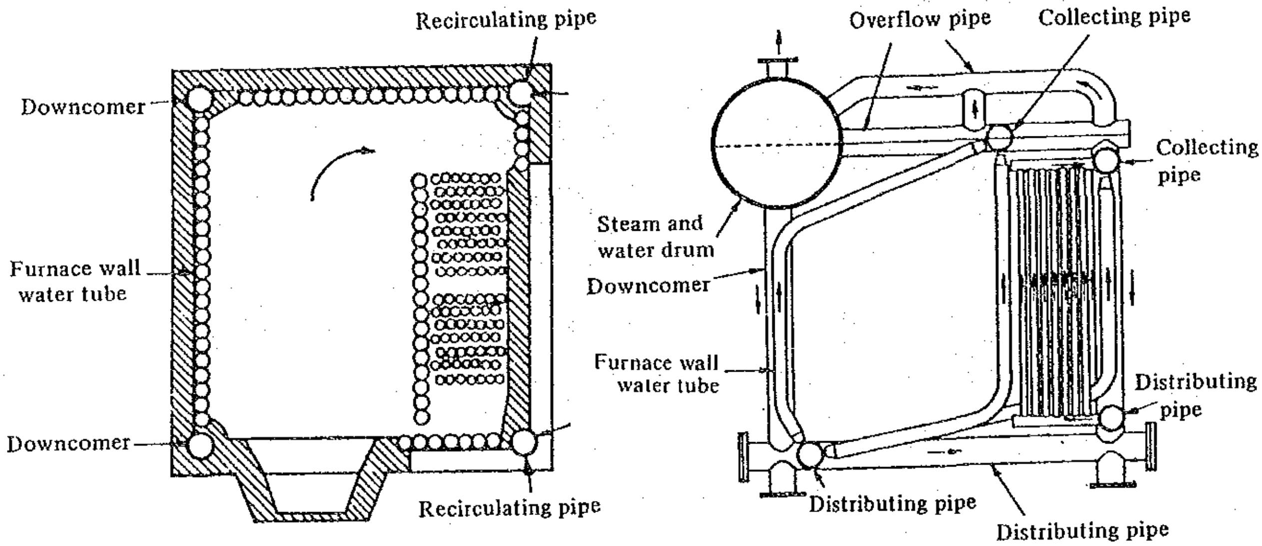


Figure 13—4 Bending Water Tube Boiler

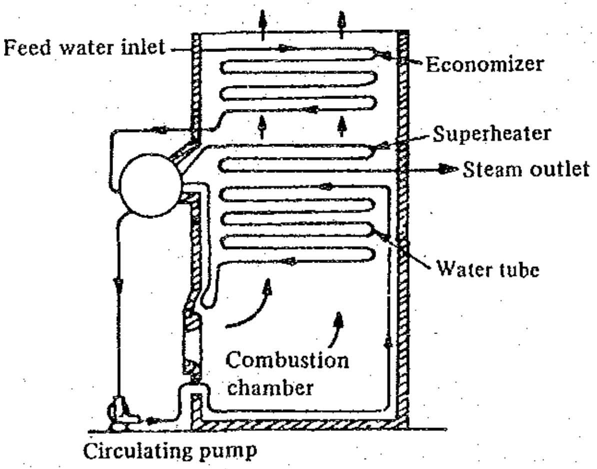


Figure 13—5 Forced Circulation Boiler

An one-through boiler only composed of a series of long water tubes is designed so that feed water is pushed into the tube by a pump from the end of the tube, by turn temperature is raised, evaporated, superheated and taken out as superheated steam from another end of the tube. Accordingly boiler water is not circulated (see Figure 13-6). The features of this one-through boiler are as follows: