HANDY MANUAL

CERAMIC INDUSTRY

UNIDO

Output of a Seminar on
Energy Conservation
in Ceramic Industry

Sponsored by

**United Nations Industrial Development Organization
(UNIDO)**

and

**Ministry of International Trade and Industry
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Hosted by

Ministry of Energy   Ministry of Power
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Bangladesh   Sri Lanka

PREFACE

The conservation of energy is an essential step we can all take towards overcoming the mounting problems of the worldwide energy crisis and environmental degradation. In particular, developing countries are interested to increase their awareness on the inefficient power generation and energy usage in their countries. However, usually only limited information sources on the rational use of energy are available.

The know-how on modern energy saving and conservation technologies should, therefore, be disseminated to government and industrial managers, as well as to engineers and operators at the plant level in developing countries. It is particularly important that they acquire practical knowledge of the currently available energy conservation technologies and techniques.

In December 1983, UNIDO organized a Regional Meeting on Energy Consumption as well as an Expert Group Meeting on Energy Conservation in small- and medium-scale industries for Asian countries. During these meetings, it was brought out that, for some energy intensive industries, savings up to 10% could be achieved through basic housekeeping activities, such as auditing and energy management.

All these experiences brought UNIDO to prepare a regional programme on the promotion and application of energy saving technologies in selected subsectors, since the rational use of energy calls for a broad application of energy conservation technologies in the various industrial sectors where energy is wasted. One of these energy intensive industrial sectors to be considered to improve efficiency through the introduction of modern energy conservation technologies is the ceramic industry.

The ceramic industry consumes much energy. The ceramic industry is also noted for great percentage of the energy cost in the total production cost.

In the ceramic industry, appreciable amounts of energy could be saved or conserved by preventing of leakage in the kilns and controlling of combustion, modifying the equipment to recover heat from the kiln in the process of ceramic-firing.

Currently, UNIDO is implementing this programme with the financial support of the Japanese Government, in selected Asian developing countries. This programme aims at adapting these innovative energy conservation technologies, developed in Japan, to the conditions of developing countries.

In this programme, we are considering that the transfer of these technologies could be achieved through:

(i)   Conducting surveys of energy usage and efficiency at the plant level;

(ii)   Preparing handy manuals on energy management and energy conservation/saving technologies, based on the findings of the above survey;

(iii)   Presenting and discussing the handy manuals at seminars held for government officials, representatives of industries, plant managers and engineers;

(iv)   Disseminating the handy manuals to other developing countries for their proper utilization and application by the industrial sector.

The experience obtained through this programme will be applied to other programmes/projects which involve other industrial sectors as well as other developing countries and regions.

UNIDO has started this programme with the project US/RAS/90/075 - Rational Use of Energy Resources in Steel and Textile Industry in Malaysia and Indonesia and the project US/RAS/92/035 - Rational Use of Energy Saving Technologies in Pulp/Paper and Glass Industry in Philippines and Thailand. These were followed by project US/RAS/93/039 Program for the Use of Energy Saving Technologies in the Ceramic and Cement Industries in Sri Lanka and Bangladesh.

The present Handy Manual on Ceramic Industry was prepared by UNIDO, with the cooperation of experts from the Energy Conservation Center (ECC) of Japan, on energy saving technologies in the framework of the above-mentioned UNIDO project. It is based on the results of the surveys carried out, the plant observations and the recommendations and suggestions emanating from the Seminars on Energy Conservation in the Ceramic Industry, held under the same project in May 1994 in Dhaka, Bangladesh and Colombo, Sri Lanka respectively. The handy manual will not only be interesting for government and representatives from industry, but it is, in particular, designed for plant-level engineers and operators in developing countries as a tool to improve energy efficiency in the production process.

Appreciation is expressed for the valuable contribution made by the following institutions to the successful preparation and publication of the manual mentioned above:

Ministry of Energy and Mineral Resources, Bangladesh

Ministry of Power and Energy, Sri Lanka

Ministry of International Trade and Industry (MITI), Japan

The Energy Conservation Center (ECC), Japan
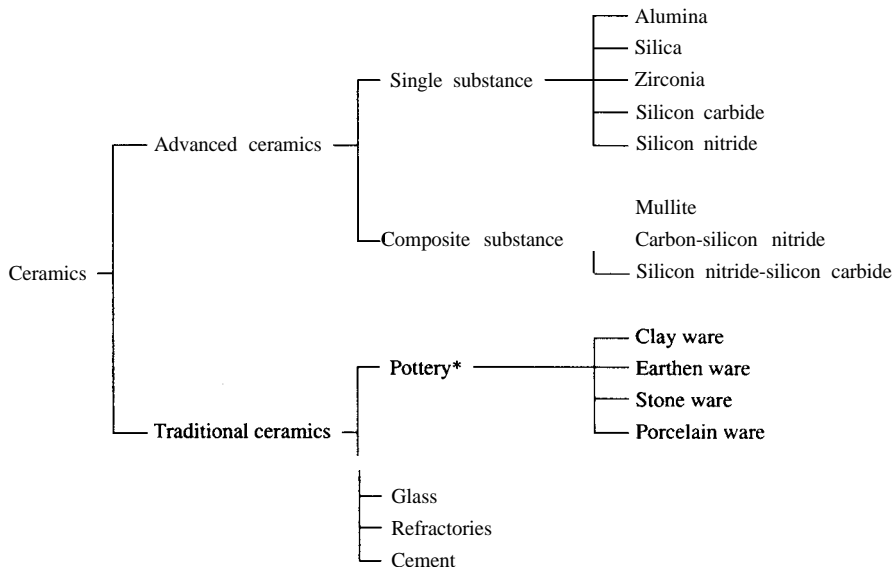
June 1994

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PREFACE

1. Manufacturing process of ceramics

Naturally occurring inorganic substances are heat-treated after adjustment of the grain size and moisture, and some of them are completely molten to be formed into ceramics; while others are formed, heat-treated and made into the ceramic products in the sintered state immediately before being molten. The former product formed in the molten state is known as glass, and the latter product finished in the sintered state includes pottery, refractories, sanitary ware, tiles and cement. These ceramics are called traditional ceramics. By contrast, extremely fine particles of high-purity inorganic substances such as alumina (Al_2O_3), silica (SiO_2), zirconia (ZrO_2) and silicon nitride (Si_3N_4) are sintered at a high temperature and made into ceramics; they are called advanced ceramics. These advanced ceramics are used in electronic parts and mechanical parts. The following describes the traditional ceramics production process:

1.1 Classification of ceramics

Ceramics can be classified in many ways; Table 1 shows one of the classifications and Fig. 1 illustrates the classification of the pottery.
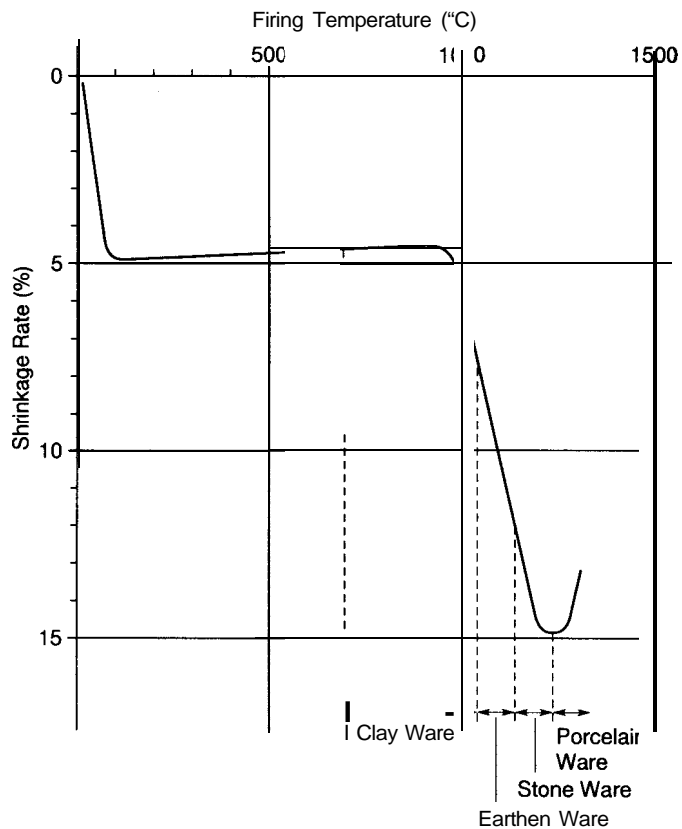
Table 1 Classification of ceramics

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                                                        ┌─── Alumina
                                                        ├─── Silica
                                   ┌─ Single substance ─┼─── Zirconia
                                   │                    ├─── Silicon carbide
              ┌─ Advanced ceramics ┤                    └─── Silicon nitride
              │                    │                        Mullite
              │                    └─ Composite substance   Carbon-silicon nitride
   Ceramics ──┤                                             └─ Silicon nitride-silicon carbide
              │                                         ┌─── Clay ware
              │                     ┌─ Pottery* ────────┼─── Earthen ware
              │                     │                   ├─── Stone ware
              └─ Traditional ceramics ┤                 └─── Porcelain ware
                                    │─── Glass
                                    ├─── Refractories
                                    └─── Cement
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* Clay ware: Clay ware is produced by firing the clay material at a low temperature (1050°C) after
the water of crystallization has been dehydrated. It includes tiles and flowerpots.

Earthen ware : The earthen ware is produced by firing in the shrinking period of the crystallization process of new crystals (mullite, cristobalite by solid reaction, etc.), and the firing temperature is from 1050 to 1150°C.

Stone ware : Stone ware is produced by firing at the maximum density (1150 to 1250°C) in the advanced glassification process.

Porcelain : Porcelain is produced by firing (at the temperature of 1250°C or more) until the product becomes translucent with an increase in glass phase.

Figure 1 Classification of the pottery and shrinkage rate

1.2 Manufacturing process of ceramics

The following describes the recent production process of traditional ceramics.

The basic production process of traditional ceramics is shown below:

Raw material → crushing and secondary crushing → blending → pulverization and kneading → forming → drying → firing → processing and shipment
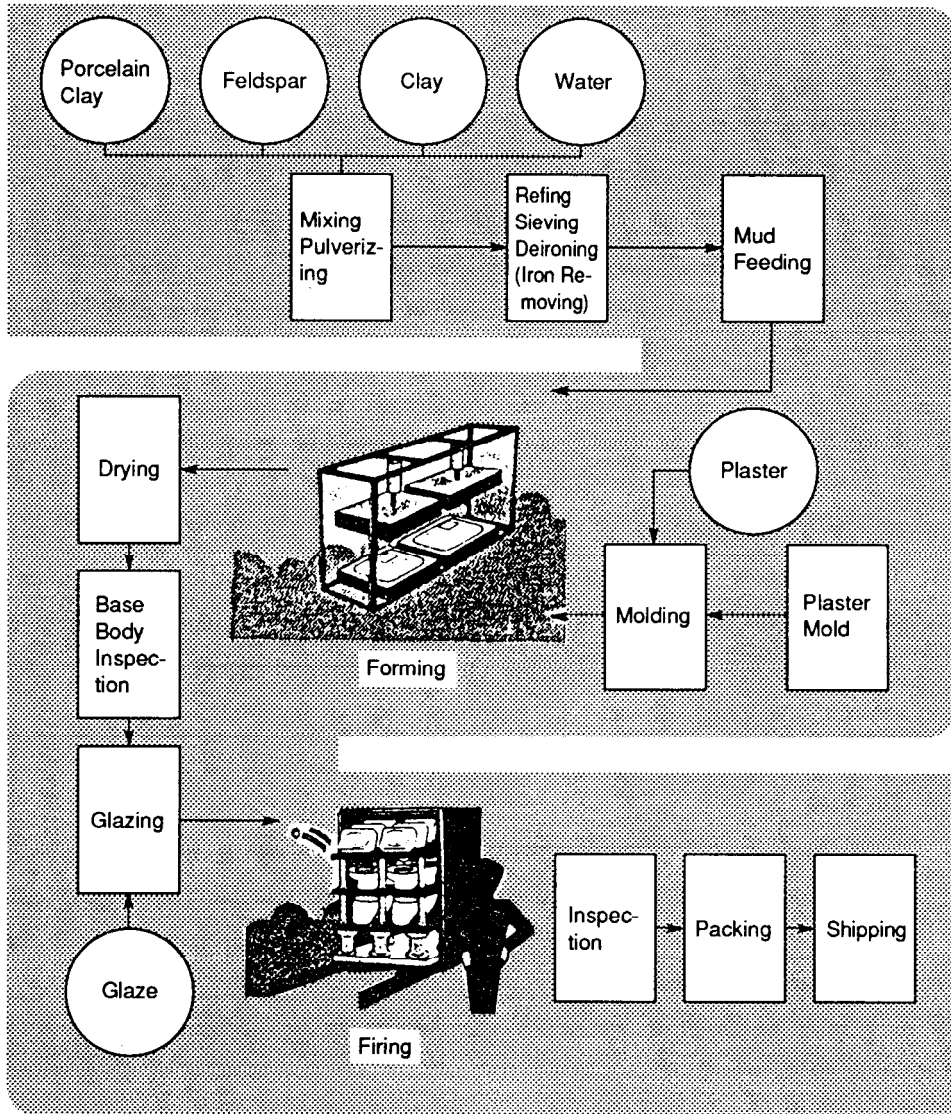

Figure 2 Manufacturing flow of sanitary ware

(1) Raw material

Natural raw materials contain mixtures of various components. The quality of ceramic products will deteriorate if much iron and titanium are contained, so it is necessary to use the materials containing the least of these elements. The components of the natural raw material vary according to the lot to be produced; therefore, it is essential to set up material acceptance standards to inspect chemical components, refractoriness, ignition loss and other related factors.

(2) Crushing

The ore is crushed to get raw materials, and forming and sintering properties vary according to the grain size, as shown below:

	Forming	Sintering
Coarse	Poor	Poor
Fine	Good	Good

It can be seen from the above that the material should be crushed to finer particles.

(3) Blending and kneading

Technical know-how is the most important in this process second to the firing process, and the final product depends on this blending process. The yield, quality and workability are also affected by this process. The major points in the kneading process is how to knead the material uniformly with water and how to mix various materials.

(4) Forming

Metal molds and plaster molds patterns are used in most cases of ceramics forming. Since the ceramics will shrink when fired, it is necessary to take it into account when determining the shape of these molds. Thus, special production know-how is required to produce a mold with a complicated shape.

(5) Drying

The drying process is an important process affecting the product yield, and requires a longer time than many of other processes.

Inappropriate drying may cause the products to be cut or broken; this makes it essential to find out appropriate conditions of temperature, humidity and time.

The waste heat of the kiln is generally used as the heat source for drying. If this is insufficient, the hot air generator is also used to make up for the insufficiency.

(6) Firing

Firing for the pottery and refractories is actually sintering which causes the crystals to be combined with one another. Firing is terminated before the material gets molten. In contrast, temperature is raised until the fired product is molten completely; this is called glass. A kiln is used to manufacture the former product, while a furnace is used to produce the latter.

2. Characteristics of energy consumption in ceramic manufacturing

2.1 Energy consumption

Two types of energy are used in the ceramic industry; electric energy and chemical energy.

The electric energy is used in two different ways; mechanical energy when used in the motor and fan of the machine, and thermal energy when used to heat the kilns and furnaces.

The chemical energy of petroleum fuel is all converted into thermal energy through combustion reaction. Energy used in the ceramic industry is predominantly occupied by petroleum energy. Table 2 illustrates the percentage of the energy cost in the production cost in Japan. As shown, the percentage of the ceramic industry (including cement, glass and pottery) is 8.9 percent, the greatest figure second to iron and steel. The percentage of the energy cost in the total ceramics production cost is between 5 and 20 percent, although it varies according to the product type and fuel price. Reduction of energy cost will contribute to cutting down of the production cost, and increasing of the profit.

Table 2 Energy cost by industry

|	
Basic chemicals	14.2%
Chemical fiber materials	11.3
Pig iron and crude steel	10.3
Ceramic industry	8.9
Pulp and paper	5.3
Rubber product	2.8
Fishery and foodstuff	1.2
Electric machinery	1.0
Precision machinery	0.9
Transportation machinery	0.8
Printing and publication	0.7

Source: Agency of National Resources and Energy

The drying and firing processes in ceramic production use much energy; furthermore, electric machineries (e.g. motor, fan) use electric energy. Of these processes, the firing process is the greatest energy consumer.

Firing is an essential process in the ceramic production process, and heat (combusted exhaust gas, heat when cooling, namely, waste heat) produced in this process is used as a heat source to dry the formed product or as the secondary air for combustion, thus leading to energy conservation.

2.2 Drying process

The drying process in the ceramic industry is the greatest energy consumer second to the firing process. Drying means loss of moisture from the surface of the substance by evaporation, and the drying speed depends on the temperature and humidity. When the substance is dried and moisture is lost, particles are put close to each other, resulting in shrinkage.

Fig. 3 shows the relationship between the drying time and speed. The constant rate drying period is the period when balance is kept between moisture shifting from inside the substance to the surface and moisture evaporation from the surface. The first falling drying rate period is the period when moisture shifts from inside the substance to the surface with reduced moisture evaporating from the surface. The second falling drying rate period is the period when evaporation takes place inside and vapor diffuses to the surface, without moisture shifting from inside the substance. Cracks due to drying is caused during the period when the green body shrinks that is, when the temperature gradient is steep under drying conditions between the constant rate drying period and first falling drying rate period, or when the temperature is excessively low. It is essential to have a correct understanding on these conditions before starting the drying process.
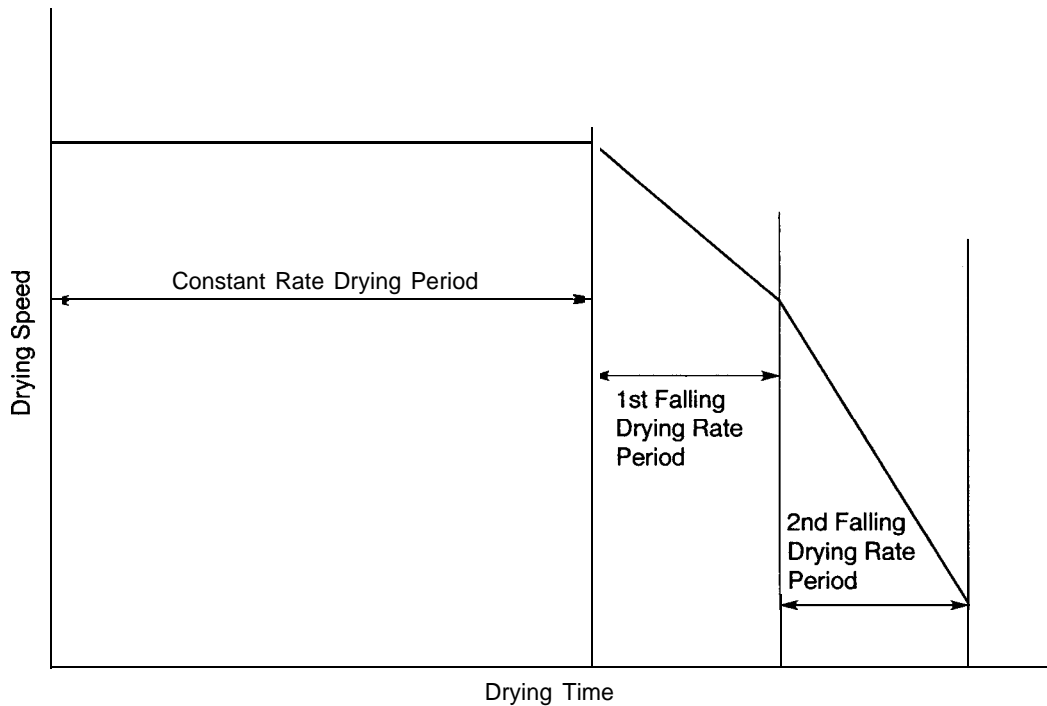
Figure 3 Drying time and speed

2.3 Firing process

The firing process uses a kiln featuring great energy consumption, and natural raw materials are used to produce ceramics. It is essential to have a correct understanding on the following thermal changes (drying, dehydration, decomposition, combination, inversion, vitrification) before working out the firing curve. Fig. 4 shows the heat curve of the porcelain.

(1) Room temperature to 900°C

The green body is dried in the first phase. Normally drying is completed before firing, but it may contain 1 to 2 percent moisture before entering the kiln. This moisture is evaporated before the temperature reaches 200°C. Then, when the temperature is between 300 and 500°C, organic substances contained in the material are carbonized or combusted. The strength of the material is reduced in this period. The water of crystallization of the clay mineral contained in the material is subjected to hydration and decomposition at 500 to 700°C. Since this reaction is an endothermic reaction, heat is absorbed into the gray body, and temperature does not rise. This requires supply of necessary heat in sufficient amount.

The organic substance carbonized at 300 to 500°C is subjected to oxidation from about 800°C and so-called soot removal is carried out. To remove soot completely during this period, it is necessary to take time to supply sufficient amount of air.

Firing-starts partly at the end of the oxidation period, the strength is increased slightly over that of the gray body. If left cooled, the biscuit ware (unglazed earthen ware) will be produced. This is provided with glazing and glost firing. In the case of pottery, there is no dehydration of carbonized clay mineral of the organic substance or oxidation of carbon up to 900°C; therefore, it is not necessary to pay particular attention to the heat curve.

(2) **From 900°C to the maximum temperature**

Active sintering takes place during this period, and the gray body goes on shrinking considerably. Therefore, temperature must be raised uniformly while sufficient attention is paid to avoid uneven shrinkage and deformation. At this stage of temperature, reduction and sintering may be performed depending on the type of the firing goods. The temperature of the sintered pottery and refractories is raised to the specified value, then heating is terminated. When the gray body is large, temperature differences occur. To prevent this, the product must be kept for some time at the maximum temperature zone.

(3) Cooling

When cooling has started after the maximum temperature is exceeded, the gray body is vitrified to the maximum density, and the glaze is molten to be vitreous. The key point in the cooling process is to cool glass inversion point of the cristobalite at about 573°C and about 250°C gradually when quartz (SiO_2) is included in the gray body. At other temperature ranges it is not affected by the cooling speed, so the speed should be increased maximally to reduce the firing period.
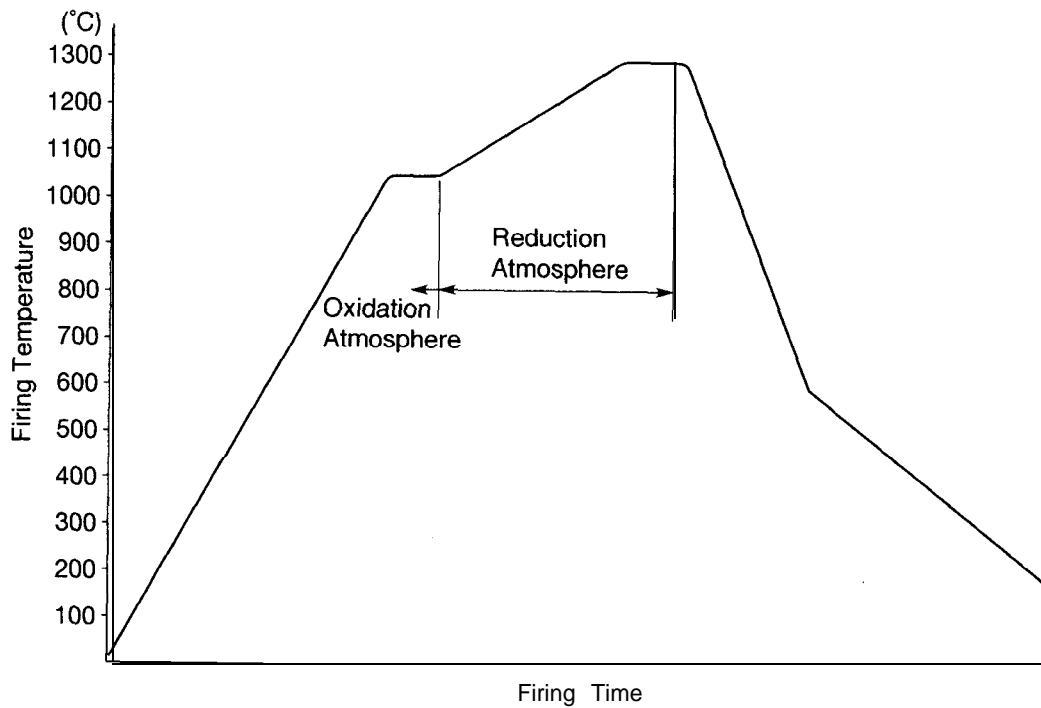
Figure 4 Porcelain heat curve

3. Promotion of energy conservation technique

Energy conservation in industrial sectors starts from the software including operation control and process control, then extends into the field of hardware including equipment improvement and process improvement. Generally, energy conservation efforts can be classified into the following three steps:

Step 1 - Good housekeeping

Energy conservation efforts are made without much equipment investment, including elimination of the minor waste, review of the operation standards in the production line, more effective management, improvement of employees' cost consciousness, group activities, and improvement of operation technique.

For example, such efforts include management to prevent unnecessary lighting of the electric lamps and idle operation of the motors, repair of steam leakage, as well as reinforcement of heat insulations.

Step 2 - Equipment improvement

This is the phase of improving the energy efficiency of the equipment by minor modification of the existing production line to provide a waste heat recovery equipment and a gas pressure recovery equipment or by introduction of efficient energy conservation equipment, including replacement by advanced equipment. For example, energy conservation efforts in this step include an effective use of the waste heat recovery in combustion furnaces and introduction of the furnace top gas pressure recovery generator in the iron and steel works and waste heat recovery generator in cement plant.

Step 3 - Process improvement

This is intended to reduce energy consumption by substantial modification of the production process itself by technological development. Needless to say, this is accompanied by a large equipment investment. However, this is linked to modernization of the process aimed at energy conservation, high quality, higher added value, improved product yield and man power saving.

The following shows the classification of energy conservation techniques in the ceramic industry:

	Drying process	Firing process
1 st step	1) Combustion control (combustion temperature)	1) Exhaust gas temperature control 2) kiln seal 3) Cooling air 4) Air ratio 5) Firing management (heat curve, temperature distribution in the kiln, kiln pressure, atmosphere) 6) Loading pattern on the kiln car 7) Clearance between the kiln wall and kiln car 8) Sand seal 9) Kiln car pushing speed
2nd step	2) Heat insulation	1) Refractories on the kiln car (to be light in weight) 2) Refractories in the periodic kiln (to be light in weight) 3) Form of the tunnel kiln 4) Recovery of the exhaust gas 5) Kiln car pushing speed
3rd step		1) Conversion from the tunnel kiln to the roller hearth kiln

3.1 Energy conservation technique in drying process

Electric and gas energy are used for material adjustment and forming in the ceramic production process. The greatest amounts of energy are consumed to dry the formed product and by the kiln (tunnel kiln and shuttle kiln) in the firing process.

Heat during the cooling in the above kiln is generally used as heat source for the formed products in the ceramic production process. However, this heat alone is not sufficient, and the heat regenerator (boiler, hot air generator) is used to make up for this insufficiency.

Therefore, the structure of the drier is so designed that the outer wall is provided with the heat insulation board and wool in order to prevent heat dissipation.

To improve the drying efficiency, the jet type drier is also used in recent years, where hot air directly hits the formed product. What should be borne in mind in this case, however, is that the product may be broken or the plaster mould may be cracked if air with excessive temperature or

humidity is used; this is because hot air hits the product at a very high speed. Efforts must be made to find out the appropriate temperature and humidity.

3.2   Energy conservation technique in firing process

3.2.1 Heat balance

The kiln including the tunnel kiln and shuttle kiln consumes the greatest amount of energy in the production process. The following describes the energy conservation for the tunnel kiln and shuttle kiln:

The first step in promoting energy conservation activities is a correct understanding of the current situation. Namely, correct information on how, where and how much energy is used and wasted will make it possible to determine the target for reducing the energy loss and to initiate the improvements. This is known as "heat balance". The heat balance defines the quantitative relationship between the heat supplied to the thermal equipment (heat input) and the consumed heat (heat output). In all cases, the total heat input is perfectly equal to the total heat output. The degree of economic use of heat in a thermal equipment depends on distribution of various types of heat constituting the heat output with respect to heat input.

(1) Heat input
- Heat retained by fuel
  Combustion heat = calorific value of fuel x fuel consumption
- Heat carried in by the heated object
  Volume of heated object x its specific heat x temperature difference

(2) **Heat output**
- Heat carried away by the heated object
  Volume of heated object x its specific heat x temperature   difference
- Heat carried away by waste heat
  Volume of waste heat x its specific heat x temperature difference
- Heat carried away by combusted exhaust gas
  Volume of exhaust gas x its specific heat x temperature difference
- Heat loss by radiation and conduction
 Difference between total heat input and total heat output

(3) Thermal efficiency

The thermal efficiency is expressed by "effective heat" divided by "heat input". The effective heat is defined as the heat required to fire the heated object; namely, it is the volume of heated object by its specific heat by maximum temperature.

Based on the calculation method discussed above, the heat balance of the tunnel kiln (biscuit kiln, glost kiln) and shuttle kiln for the tableware is shown in Table 3 and Fig. 5.

Table 3 Heat balance

		Biscuit kiln		Glost kiln		Shuttle kiln (Glost firing)
		Calorific value (kcal)	%	Calorific Value (kcal)	%	
Input	Heat from combustion of fuel	1685.4×10^3	98.5	6492.6×10^3	99.7	
	Heat from prefiring goods, sagger and kiln furniture	11.2	0.7	6.2	0.2	
	Heat from kiln car	13.9	0.8	3.2	0.1	
	Total	1710.5	100.0	6502	100.0	
Output	Heat loss from firing goods, sagger and kiln furniture	118.0×10^3	6.9	161.3×10^3	2.5	
	Heat loss from kiln car	171.3	10.0	206.1	3.2	
	Heat loss from waste heat	119.0	7.0	2576.4	39.6	
	Heat loss from combustion gas	358.4	21.0	1497.1	23.0	
	Heat loss from radiation, conduction	943.8	55.1	2061.1	31.7	
	Total	1710.5	100.0	6502	100.0	
Thermal efficiency of firing goods		22.3%		7.3%		4.6%
Thermal efficiency of tiring goods, sagger and kiln furniture		66.1%		32.9%		18.7%
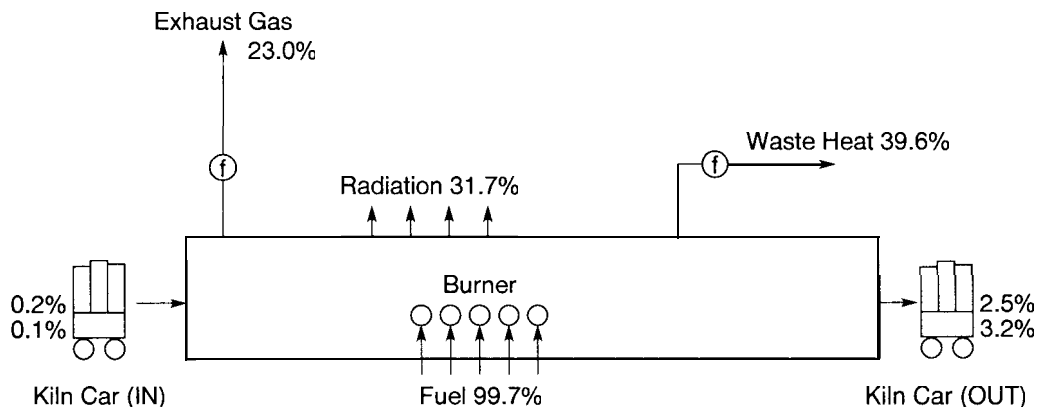
Figure 5 Heat flow of glost kiln

The heat balance clearly shows how heat is used. The thermal efficiency of the fired products alone is very close to 7.3 percent in glost firing. This means that, even when 100 liters of oil are combusted, only 7.3 liters contribute to firing, and the remaining 92.7 liters of oil are wasted, evidencing that this is an extremely ineffective thermal equipment. Then where is it wasted?

As will be clear from the description of the heat output, heat losses by combusted exhaust gas, radiation, conduction, waste heat and kiln car are great.

(1) Heat loss by combusted exhaust gas

Heat loss by exhaust gas can be calculated in the following equation:

$$Q = V \times Cp \times \Delta t$$

where V : Exhaust gas (Nm^3/h)

Cp: Specific heat of exhaust gas (kcal/Nm^3 °C)

Δt : Difference between exhaust gas temperature and outer air temperature (°C)

Of these factors, At, exhaust gas temperature, should be kept as low as possible, but it should be noted that problems may lie with the dew point. When the fuel has much sulfur content, the dew point is from 120 to 160°C, and the exhaust gas temperature cannot be set below this point. The specific heat of the exhaust gas depends on the temperature, but not very much. Therefore, heat loss by exhaust gas can be considered to be proportional to the volume of exhaust gas.

Normally, many of the tunnel kilns have a smaller internal pressure than the atmospheric pressure in the prefiring zone; this results in entry of the outer air into the kiln. The incoming air not only increases the volume of the exhaust gas , but also reduces the temperature near the position where it has entered. This will cause temperature difference to occur between the upper and lower parts. Therefore, small clearances must be sealed with fibers or similar materials.

(2) Heat loss by radiation and conduction

This heat loss is the loss of heat radiated from the kiln wall, and is related to the surface area of the kiln. This suggests that kiln shape is very crucial.

(3) Heat loss by waste heat

Normally heat is taken from the cooling zone and is used to dry the products. This is considered to be an effective use of heat. However, the heat cannot be obtained without any fuel; some amount of fuel is required. From the viewpoint of the kiln alone, use of much of this waste heat for drying will reduce thermal efficiency of the kiln.

(4) Heat loss by kiln car

This heat corresponds to the heat carried away by the kiln car when it comes out of the kiln. It can be calculated in the following equation:

$$Q = W \times Cp \times \Delta t$$

where W : Weight of the car (kg/car)

   Cp: Specific heat of the car refractory (kcal/kg°C)

   Δt : Difference between the car temperature at the kiln outlet and outer air temperature (°C)

Cp is a constant to be determined by the material of the refractory to be used. Use of the heat insulation bricks or ceramic fibers will reduce the weight, so the result will be "killing two birds with one stone".

The thermal efficiency of the periodic kiln is 4.6 poorer than that of the tunnel kiln; this is because the temperature is raised or lowered every time, in other words, the kiln is heated and cooled. This is because the heat to raise kiln temperature is greater than the heat released from the kiln wall surface.

The heat reserve Q (kcal) of the kiln is determined by the kiln weight W (kg), the average temperature rise At (°C) of the kiln wall within the heating time, and the specific heat of the kiln material Cw (kcal/kg °C).

$$Q = W \times Cw \times \Delta t$$

Thus, in order to make Cw smaller, the periodic kilns in recent years use insulating bricks and ceramic fibers rather than refractory bricks, as is the case with the above mentioned car structure. In this way, reduction in the weight of the kiln material will also mean a reduced Cw-value. This will reduce Q, resulting in a reduced amount of fuel consumption.

Table 4 shows an example of the heat balance recording format for the tunnel kiln for firing the pottery and refractories.

Table 4 Heat balance recording format

(1) Outline of kilns

Factory name		Location	
Person in charge			
Kiln number			
Type and form			
Dimensions (length, width, height) m			
Effective area m^2			
Surface area m^2			
Number of cars in kiln			
Total floor area of car m^2			
Type, capacity and number of burners			
Ventilation	System		
	Fan	Type	
		Volume and pressure $Pa\{m^3_N \cdot mmAq\}$	
	Chimney	Dimensions (diameter, height) m	
		Name and number of the equipment for joint use	
Type, form and capacity of the equipment using waste heat			
History			
Remarks			

Source: JIS R0301 Heat balancing of pottery and refractory firing tunnel kiln

(2) Measurement items

Measurement period (time and date)						
Name of measuring person(s)						
Climate		Atmospheric pressure Pa{mmHg}	Outside air temperature °C	Humidity %		Inside air temperature °C
Combustion equipment and ventilator with their conditions						
Firing product						
Kiln load rate %						
Firing time and cooling time h						
Atmosphere within firing zone %			CO₂	O₂		CO

Fuel	Type					
	Properties	Moisture				
		Specific gravity				
		Viscosity				
	Com-position	Liquid fuel c, h, s, n, o %				
		Fuel gas O₂, H₂, N₂, CO, % CO₂, CH₄, C₂H₆, C₃H₈, C₄H₁₀				
	Calorific value	High heat value	kJ/kg {kcal/kg} or kJ/m³ₙ {kcal/m³ₙ}			
		Low heat value	kJ/kg {kcal/kg} or kJ/m³ₙ {kcal/m³ₙ}			
Air for combustion	Operating temperature °C					
	Used quantity	Total kg or m³ₙ	Total	Firing zone		Preheating zone
		Per product kg or m³ₙ				
	Volume	Primary air m³ₙ				
		Secondary air m³ₙ				
		Per kg or m³ of fuel m³ₙ				
	Tempera-ture	Primary air °C				
		Secondary air °C				
	Pressure	Blower outlet Pa {mmAq}				
		Preheater inlet Pa {mmAq}				
		Preheater outlet Pa {mmAq}				
	Air ratio	Combustion chamber outlet				
		Kiln outlet				
Air for cooling	Volume m³ₙ					
	Tempera-ture	Inlet to kiln °C				
		Outlet from kiln °C				
	Pressure	Inlet to kiln Pa {mmAq}				
		Outlet from kiln Pa {mmAq}				

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Cooling water	Volume	m³N or kg		
	Temperature	Inlet °C		
		Outlet °C		
Un-fired product	Type (composition and specific heat)			
	Mass t			
	Moisture	Water adhered %		
		Water of crystallization %		
	Combustible component	%	Calorific value	kJ/kg {kcal/kg}
		%		kJ/kg {kcal/kg}
	Temperature at kiln inlet °C			
Fired product	Mass t			
	Maximum firing temperature °C			
	Temperature at kiln outlet °C			
	Firing ignition loss %			
Sagger and kiln furniture	Type (including specific heat for each type)			
	Mass	Sagger t		
		Kiln furniture t		
	Temperature	at kiln inlet °C		
		at kiln outlet °C		
Kiln car	Number			
	Mass per unit	Refractory t		
		Iron part t		
	Temperature at kiln inlet/ outlet	Refractory °C		
		Iron part °C		
	Specific heat for each type kJ/kg °C {kcal/kg °C}			
Combusted exhaust gas	Volume	Overall volume m³N		
		Per 1kg or 1m² N of fuel, m³N		
	Temperature	Firing zone °C		
		Preheating zone °C		
		Main flue °C		
	Pressure	Firing zone Pa {mmAq}		
		Preheating zone Pa {mmAq}		
		Main flue Pa {mmAq}		
	Composition in main flue (CO_2, O_2, CO) %			
Circulating combustion gas	Volume m³			
	Temperature at outlet and blowing inlet °C			
Surface temperatures on kiln	Inlet (top, side, door) °C			
	Preheating zone (top, side) °C			
	Firing zone (top, side) °C			
	Cooling zone (top, side) °C			
	Outlet (top, side, door) °C			
	Duct leading from kiln and fans °C			
Remarks				

(3) Heat balance

item			Thermal input		Thermal output	
			10^3 kJ{10^3 kcal}	%	10^3 kJ{10^3 kcal}	%
Thermal input Q_1	(1) Heat of combustion of fuel	Q_a				
	(2) Sensible heat of fuel	Q_b				
	(3) Heat carried in by prefiring goods, sagger and kiln furniture	Q_c				
	(a) Heat carried in by prefiring goods	Q_{c1}				
	(b) Heat carried in by sagger and kiln furniture	Q_{c2}				
	(4) Heat carried in by car	Q_d				
	(a) Heat carried in by car (refractory)	Q_{d1}				
	(b) Heat carried in by car (iron)	Q_{d2}				
	(5) Heat carried in by combustible component included in the prefiring goods	Q_e				
Thermal output Q_2	(1) Heat carried away by prefiring goods, sagger and kiln furniture	Q_f				
	(a) Heat carried away by prefiring goods	Q_{f1}				
	(b) Heat carried away by sagger and kiln furniture	Q_{f2}				
	(2) Heat carried away by car	Q_g				
	(a) Heat carried away by car (refractory)	Q_{g1}				
	(b) Heat carried away by car (iron)	Q_{g2}				
	(3) Heat carried away by combusted exhaust gas	Q_h				
	(4) Heat carried away by cooling air	Q_i				
	(a) Heat carried away by dried exhaust gas	Q_{i1}				
	(b) Sensible heat of vapor in the combusted exhaust gas	Q_{i2}				
	(5) Heat loss by incomplete combustion	Q_j				
	(6) Heat carried away by steam evaporated from the prefiring goods moisture	Q_k				
	(7) Heat carried away by cooling water	Q_l				
	(8) Heat loss by radiation and conduction	Q_m				
Total						
Circulating heat Q_3	(1) Heat recovered by air for combustion	Q_n				
	(2) Heat retained by circulation combustion gas	Q_o				
Effective heat Q_4	(1) Effective heat per ton of fired products in the presence of fired products alone	Q_1				
	(a) Heat required to evaporate moisture of the prefiring goods	Q_p				
	(b) Heat required to evaporate water of crystallization from the prefiring goods	Q_q				
	(c) Heat required to decompose the clay	Q_r				
	(d) Heat required to fire the prefiring goods	Q_s				
	(2) Effective heat per ton of the fired products when the sagger and kiln furniture are included	Q_{11}				
	(a) Heat required to heat the sagger and kiln furniture	Q_t				
Thermal efficiency η	(1) Thermal efficiency of the fired product	η_1				%
	(2) Thermal efficiency when the sagger and kiln furniture are included	η_2				%

3.2.2 Structure of kiln

The basic requirement to save fuel is high speed firing-to fire the material in the minimum time. The requirement for rapid firing in the tunnel kiln is that the temperature be uniform at all positions - upper, lower, right or left position - in the sectional area at a right angle to the pass of the kiln car.

Fig. 6 shows the differences in sizes according to the type of the tunnel kiln.

	A	B	C
Capacity (m³)	100	100	100
Surface Area (m²)	200	150	100
Kiln Car (Car)	100	100	50
Floor Area (m²)	100	100	50
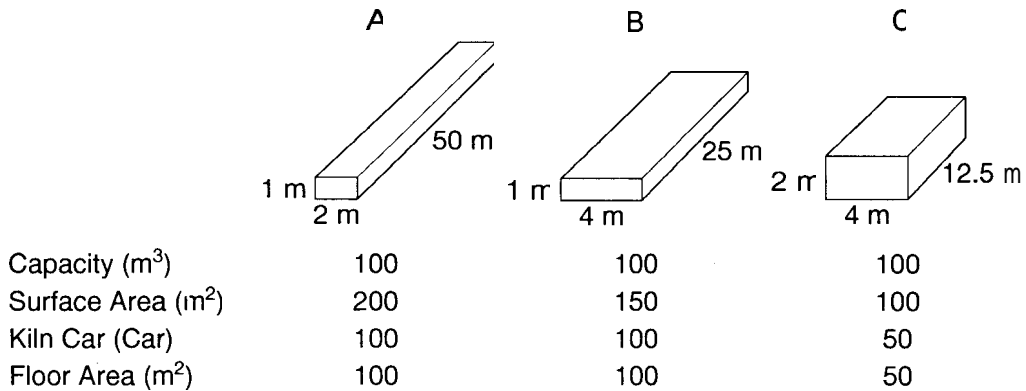
Figure 6 Size of tunnel kiln

As is clear from the above, assuming that the material is to be heated at the same firing curve whether in the tunnel kiln or shuttle kiln: Then if the internal capacity of the kiln is constant, the surface area of kiln C which is close to a cube, is half as much as that of kiln A, allowing the required amount of the kiln refractories, the number of the firing cars, floor space and heat carried away by the cars also to be reduced to a half.

Reduction of the surface area to a half will reduce the heat radiated from the kiln surface again to a half, resulting in substantial fuel saving.

The pushing speed of kiln car of kiln C is one fourth that of kiln A. As can be seen, the physical travel distance of the kiln car is small even if time required for heating and cooling is the same.

Rapid firing ensures energy conservation. To cut the firing time as well as to reduce the weight of the kiln refractories, the modern shuttle kiln uses a high speed burner or excess air burner which agitates within the kiln to ensure uniform temperature distribution. Fig. 7 shows the layout of the shuttle kiln burner.

As discussed previously, in the kiln car fiber board is used to minimize the weight, thereby improving insulation effect and reducing the fuel consumption. Fig. 8 shows the insulation materials of the kiln car.
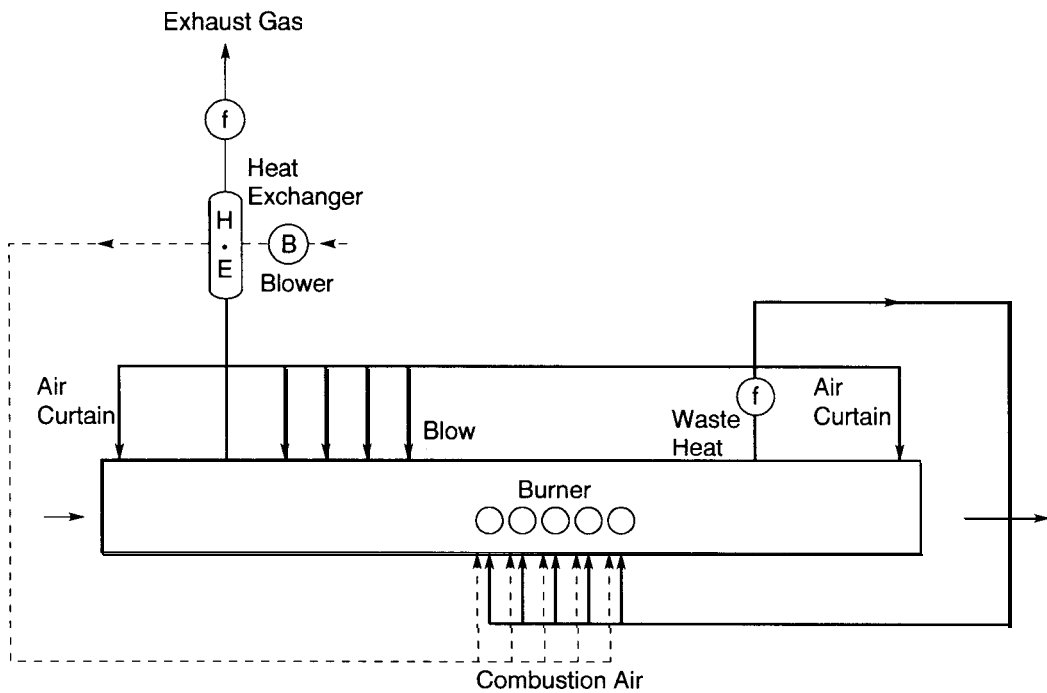
The following describes the use of waste heat in the tunnel kiln. As shown in Fig. 9, heat of exhaust gas is used for preheating of combustion air with a heat exchanger. Waste heat from cooling zone is used for drying the products and the heated cooling air from cooling zone is used as the secondary combustion air.
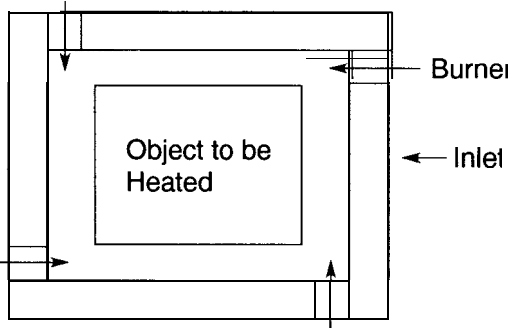
Figure 7 Shuttle kiln
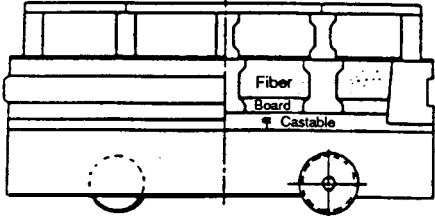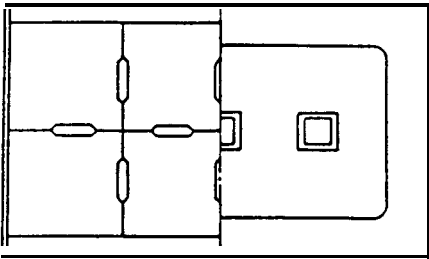
Figure 8 Kiln car

Figure 9 Tunnel kiln

3.2.3 Roller hearth kiln

As discussed previously, rapid firing requires uniform temperature. This, in turn, requires the reduced height inside the kiln; the ratio of the width to height within the kiln is normally 1 to 0.8. If the ratio is reduced to 1 to 0.2, it will further reduce the temperature differences between the top and bottom.

The roller hearth kiln represents the kiln with reduced height. Figs. 10 and 11 show the roller hearth kiln. This kiln is designed as a continuous kiln where the roller conveyer is installed from the kiln inlet to the outlet. Each roller (made of ceramic) rotates to carry the product to be fired from the inlet to the outlet.

Unlike the tunnel kiln, this structure eliminates the use of the kiln car, and the material is placed to be fired on the matting (refractory) known as "setter" whenever required.
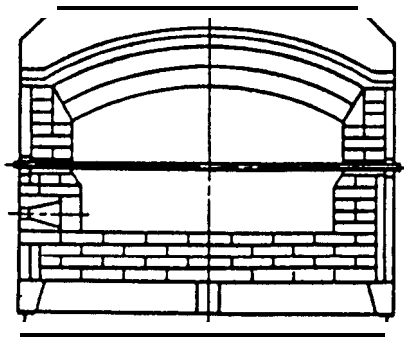
As described, the temperature difference of the roller hearth kiln is within plus-minus 3°C at the place where temperature is the maximum, and this feature ensures stable quality of the fired products and improved yield.

Exhaust   Blow   W.H

Inlet →
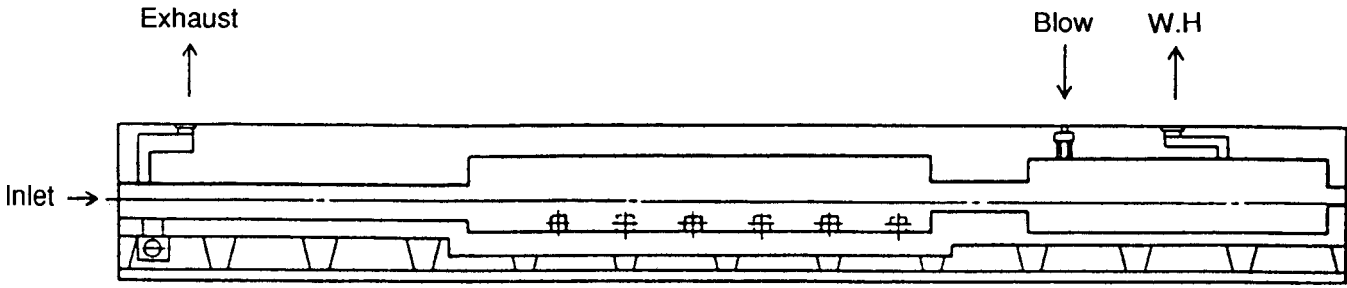
Figure 10 Roller hearth kiln
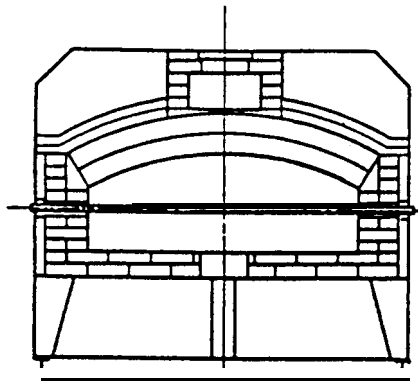
Pre-firing Zone

Firing Zone

Figure 11 Roller hearth kiln

Small differences of temperatures allow faster firing of the product than by the conventional tunnel kiln, requiring less fuel and contributing to energy conservation.

Tables 4 and 5 show the comparison of the firing cycle and fuel unit consumption between the tunnel kiln and roller hearth kiln.

In addition to the above features, the roller hearth kiln permits quick temperature rise, shut-down, cooling and easy change of the temperature and atmosphere; temperature control is automatic, and firing and shut-down can be performed by the one-touch operation.

Table 4 Firing temperature and firing time

| | | Temperature | Firing cycle | |
			Conventional tunnel kiln	Roller hearth kiln
Table ware	Decoration	750 - 850°C	2 - 5 hours	120 minutes
	Biscuit firing	800 - 1000	20 - 30	120
	Glost firing	1250 - 1350	30 - 40	240
	In-glaze	1200 - 1300	30 - 40	120
Tile	Floor	1250 - 1300	20 - 30	80
	Wall	1060 - 1150	20 - 30	30
Sanitary ware		1220 - 1250	20 - 30	420

Table 5 Thermal efficiency

		Conventional tunnel kiln	Roller hearth kiln
Table ware	Decoration	2500 - 4000 kcal/kg	1500 - 2500 kca/kg
	Biscuit firing	2500 - 4000	1500 - 2500
	Glost firing	5000 - 7000	3000 - 4000
	In-glaze	4000 - 5000	2000 - 3000
Tile	Floor	2300 - 3500	1200 - 1400
	Wall	1500 - 2500	500 - 600
Sanitary ware		5000 - 7000	3000 - 4000

3.2.4 Air ratio in kiln

When the fuel is combusted at the outlet of the firing kiln, it would not be an effective combustion if smoke is produced from the kiln and the smoke of offensive smell is led through the factory, or combustion is intermittent. The air ratio in the combustion chamber (excess air ratio) may be used to check if the burner combustion is effective or not.

Generally, complete combustion of the fuel requires excess air.

The relationship between the volume of actual combustion air A and volume of theoretical combustion air A,, can be expressed in the following equation:

$$A = mA_0$$

The ratio "m" of the volume of actual air to the volume of theoretical air is called air ratio or excess air ratio.

When this ratio "m" is over 1, complete combustion takes place to create oxidizing atmosphere; in contrast when this ratio "m" is below 1, incomplete combustion takes place to create reducing atmosphere.

Generally, for pottery firing in oxidizing atmosphere, "m" should preferably be within the range from 1.2 to 1.5; below 1.2, the amount of combustion gas becomes insufficient resulting in larger difference in temperature in the kiln, while over 1.5, the amount of combustion gas becomes excessive resulting in smaller difference in temperature in the kiln, but requires fuel more than necessary.

On the other hand, in reducing atmosphere there is no need to increase the value more than necessary (m = below 0.8). To check the air ratio in the combustion chamber in practice, it is possible to calculate it by gas analysis for the combustion chamber.

Liquid fuel

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

Gas fuel

$$m = \frac{(O_2) - 0.5(CO)}{5 \cdot C_3H_8 + 6.5\,C_4H_{10} \times \dfrac{(CO_2) + (CO)}{3\,C_3H_8 + 4\,C_4H_{10}}}$$

where symbols in parentheses indicate the composition of the combustion gas (%), and C_3H_8 and C_4H_{10} show the percentage of propane and butane contained in the fuel gas.

Thus, it is important always to analyze the combustion gas to ensure appropriate combustion. In other words, the easiest way of energy conservation for using fuel without investment is to reduce the air ratio. Figures 12 and 13 show the relationship between the air ratio, fuel saving and heat loss. It was pointed out in the discussion of heat balance in 3.2.1 that loss of exhaust gas is great. The volume of exhaust gas depends on the m-value of that gas. Thus, it is important to minimize the percentage of O_2 in the exhaust gas.
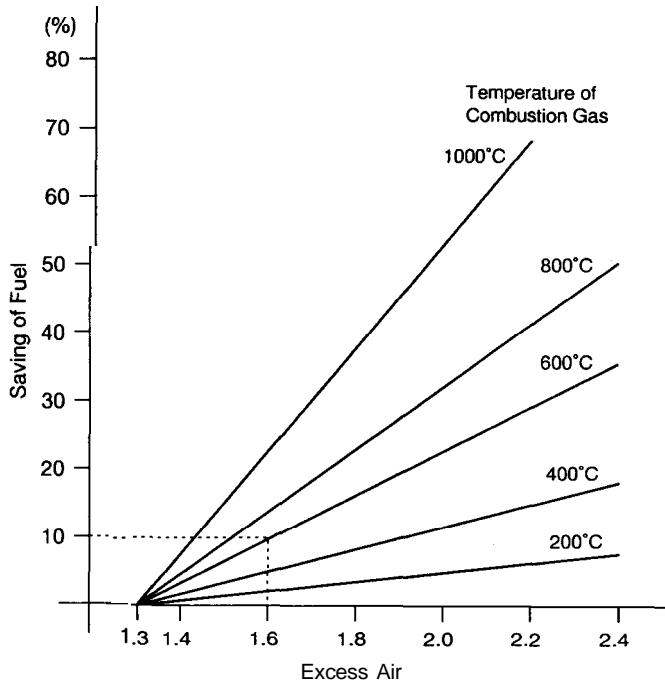
Figure 12 Excess air - saving of fuel
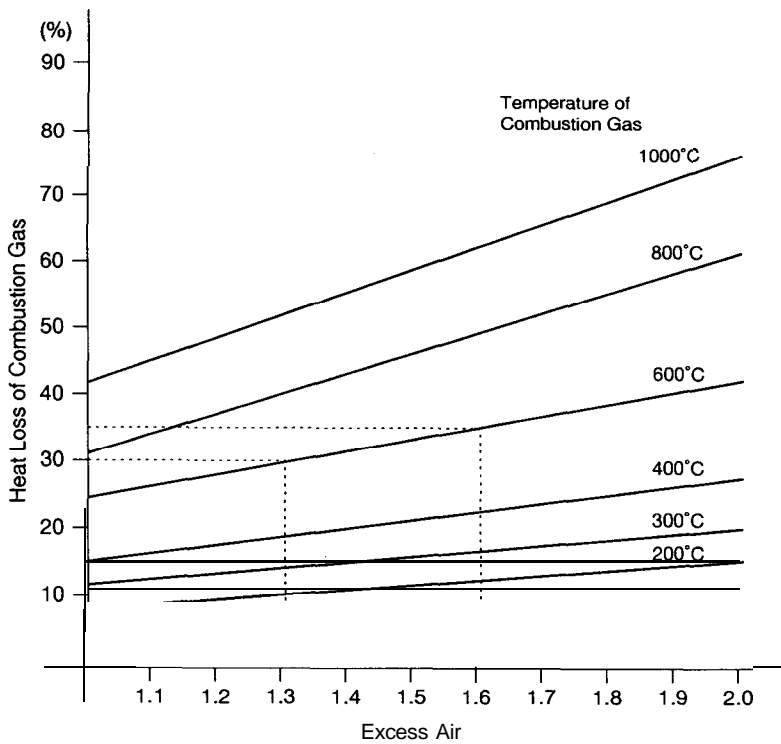
Figure 13 Excess air - heat loss of combustion gas

3.2.5 Pushing speed of kiln car

As discussed in 3.2 and 3.3, uniform temperature is essential to ensure rapid firing. Uniform temperature ensures stable product quality and improved yield.

Although not widely known, the faster the kiln car pushing speed (shorter the firing cycle), the less fuel will be consumed in the tunnel kiln; this will contribute to energy conservation.

The following examples will explain this:

Conditions   Current car speed   30 cars/day
                     Fuel consumption   100 ℓ/hour
                     Thermal efficiency 30%

The fuel required to fire the products of daily 30 cars under these conditions is given by:

100 ℓ/hour × 0.3 = 30 ℓ/hour

Fuel required to maintain the kiln temperature is:

100 ℓ/hour × 0.7 = 70 ℓ/hour

Let us assume that the thermal efficiency and the fuel required to maintain the kiln temperature remain unchanged, despite possible change of the car speed. If the car speed is increased to 40 cars per day, then the fuel requirement can be expressed in the following equation:

Fuel required to maintain the kiln temperature: 70 ℓ/hour
Fuel required to fire the products:

30 ℓ/hour × 40 cars/day / 30 cars/day = 40 ℓ/hour

Total 70 ℓ + 40 ℓ = 110 ℓ = 110 ℓ/hour

On the other hand,
the fuel consumption per car is given by the following:

30 cars/day: 100 ℓ/hour × 24 hours/day / 30 cars/day = 80 ℓ/car
40 cars/day: 110 ℓ/hour × 24 hours/day / 40 cars/day = 66 ℓ/car

Thus, an increase of the car speed from 30 to 40 cars per day will increase fuel consumption per hour by 10 percent from 100 ℓ/hour to 110 ℓ/hour. In terms of per-car value, the value changes from 80 ℓ/car to 66 ℓ/car, showing that as much as 20 percent energy conservation can be achieved. Thus, less fuel consumption will result in less cost.

3.3   Firing control of kiln

The pottery firing kiln can be classified broadly into two types, the continuous kiln such as tunnel kiln, and the periodic kiln (batch kiln) such as shuttle kiln. The tunnel kiln is suited to mass production, while the periodic kiln is fitted to small quantity production of multiple product types. The kiln should be selected according to the type and volume of the products. The tunnel kiln suited to mass production is less fitted to handle variations of the production volume, whereas the periodic kiln is more fitted to handle such a situation. In this way, each type has its own merits and demerits. Even if the appropriate type of the kiln has been selected, product quality and yield will be poor without adequate daily firing control; it will have an adverse impact on the production and will cause waste of much energy. Thus, firing control is a key point in the firing process.

The following describes the firing control for the tunnel kiln:

The basic concept in the tunnel kiln is that the specified products will be obtained if input and output are kept constant. This should be borne in mind in the firing control; then stable product quality and improved yield will be ensured.

Major points for firing controls are:
(1)   Heat curve conforming to the fired product type and production volume
(2)   Uniform kiln internal temperature distribution
(3)   Maintenance of adequate kiln pressure
(4)   Maintenance of adequate atmosphere

These requirements must be met. For this purpose, firing conditions should be controlled using such measuring instruments as the thermometer, pressure gauge and gas analyzer.

Fig. 14 shows the temperature, atmosphere and pressure of the tunnel kiln for porcelain glost firing; it exhibits the specific characteristics of high-temperature reducing atmosphere. It is important to ensure complete oxidizing atmosphere in the prefiring zone, with top priority in keeping the reducing atmosphere of the firing zone constant. While the volume of the combustion gas in the

firing zone is kept constant, and the flow of the combustion gas going from the firing zone to the prefiring zone is also kept constant at all times, adequate kiln pressure should be ensured so that counterflow against the cooling zone will not occur.
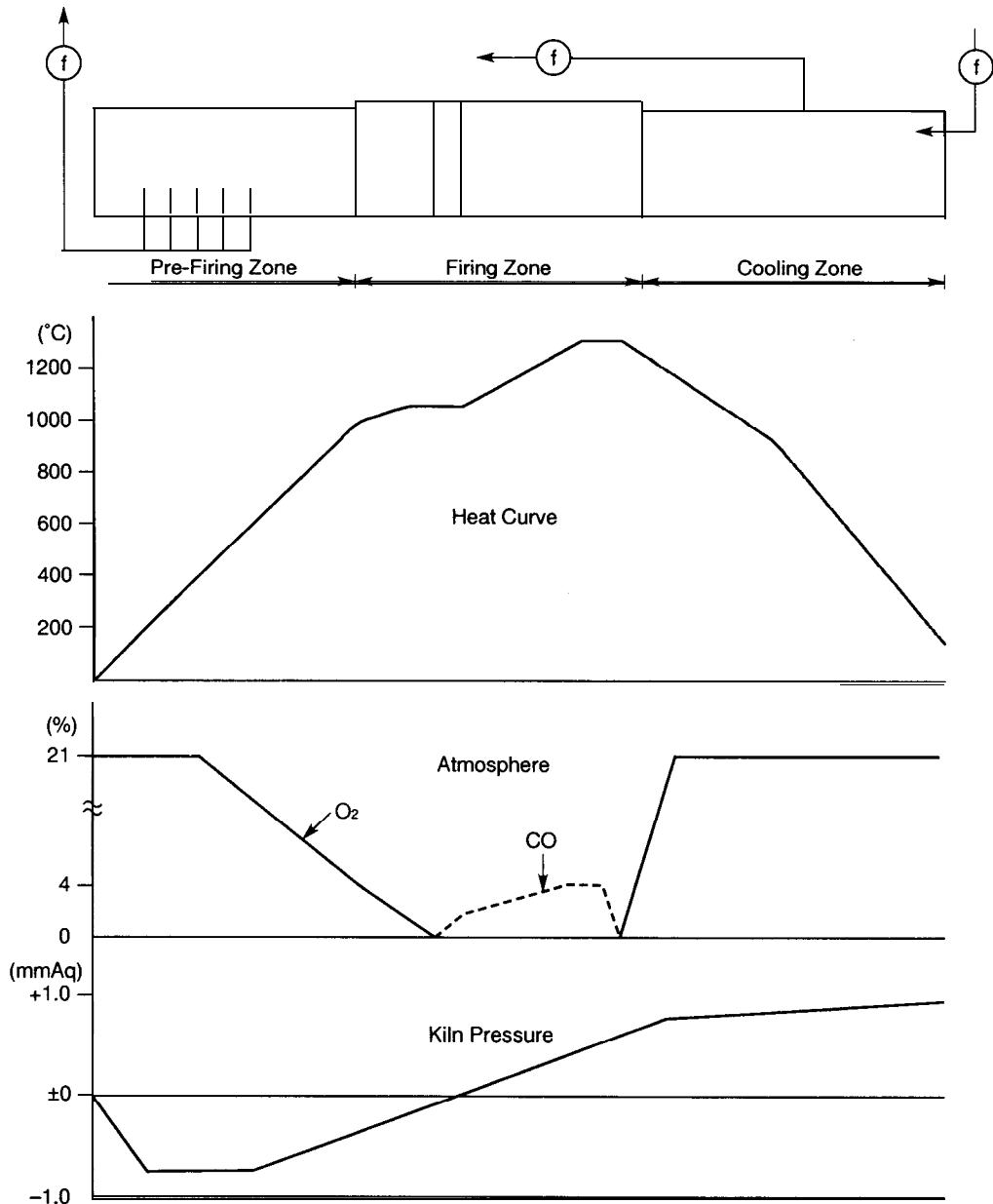

Figure 14 Tunnel kiln operating conditions

To keep the flow of the combustion gas in the firing zone constant, it is necessary to keep kiln pressure before and after the firing zone constant at all times. To keep the volume of this combustion gas and kiln pressure constant, the following steps must be taken:

(1) The pattern of loading the fired products on the kiln car must be uniform.

In practice this is difficult for some types of production. However, it is very important to ensure stable flow of combustion gas. Basically, clearances between saggers should be uniform. The major consideration need not be placed on the weight of the products and saggers, except when there are some considerable changes. It is necessary that the sagger stack height and the area the saggers occupy in the kiln car be the same for all cars.

Fig. 15 shows an example of the loading pattern.

A : 10" Plate
B : 9" Plate
C : 7$^{1/2}$" Plate
D : 6" Plate
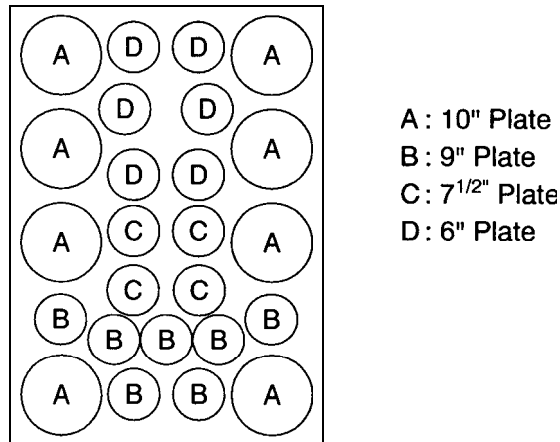
Figure 15 Loading pattern

(2) The fuel (oil, gas) to be supplied must be made constant.

(3) The volume of the primary and secondary air for fuels to be supplied must be made constant.

(4) The kiln pressure after the firing zone must be constant.

To keep the flow of the air going from the cooling zone to the firing zone always constant, a balance should be maintained at some point between the waste heat directly taken out of the cooling zone and the product cooling air to be blown in from the kiln outlet. Then the flow is automatically kept constant.

If the above discussed procedures are taken, the temperature curve and atmosphere will be kept constant, the product quality will be improved and maintained at a stable level.

In addition to the firing control discussed above the following steps should be taken in the daily operation:

(5) Thermometer (thermocouple) maintenance

Normally, the thermocouple inserted in the kiln will deteriorate as it is used, so the current deterioration must be compensated. To measure the deterioration, read the temperature of the currently inserted thermocouple and extract it from the kiln; then insert a new thermocouple. When the temperature has been stable, read the temperature of the thermocouple. This will inform the difference of temperatures between the new thermocouple and the old one, and this difference corresponds to the degree of deterioration. Thus, the target temperature must be reduced by the amount of this deterioration.

E.g.:

Current target temperature	1250°C
Current temperature	1245°C
Temperature of the new thermocouple	1255°C
Deterioration (difference)	10°C
New target temperature	1250°C → 1240°C

In addition to the compensation for the thermometer, it is necessary to calibrate the temperature recorder and indicator, using a special-purpose calibration instrument. The thermocouple undergoes deterioration quickly when it is exposed to the reducing gas such as carbon monoxide. So care should be taken to prevent it from being exposed directly to the gas. Especially when the protective tube is loaded into the kiln or is removed from the kiln, it is likely to break. So sufficient care must be taken to avoid such an accident.

The thermocouple and temperature recorder should be calibrated once in six months at least. Fig. 16 shows the thermocouple.
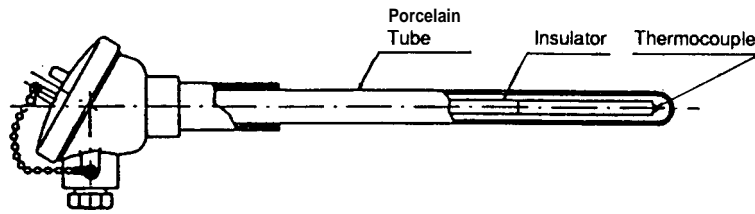
Figure 16 Thermocouple

(6) The space between the kiln wall and kiln car should be made as close as possible.

The combustion gas flowing in the kiln will flow where resistance is the smallest. If there is a big clearance between the kiln wall, kiln car and ceiling, the gas will go there without flowing to the center; this will create temperature differences. To prevent this, the space between the kiln wall and kiln car should be made as close as possible so that gas will flow to the center.

Fig. 17 shows the relationship between the tunnel kiln and kiln car.
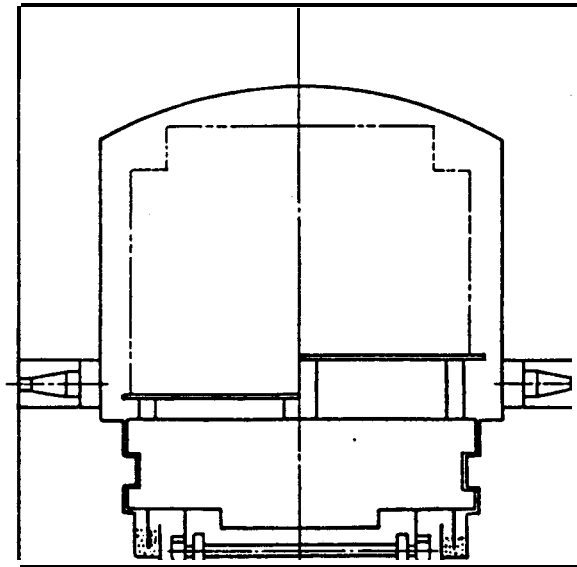
**Figure 17 Section of tunnel kiln and kiln car**

(7) Fill the kiln with sand for sand sealing.

The sand which seals the kiln interior and the kiln car is provided to prevent air from entering the kiln through the car bottom.

If air enters the kiln due to shortage of this sand, the incoming air reduces the temperature at the bottom of the prefiring zone in the tunnel kiln, resulting in greater temperature differences between the top and bottom.

If the incoming air enters the firing zone fired by reducing atmosphere through the car bottom, the atmosphere will change locally into oxidizing atmosphere, causing the temperature to be raised and the atmosphere to be disturbed. Then defects will occur to the fired product, resulting in poor yield. Thus, the sand seal is a very important part in the kiln structure. It is essential to check the amount of the sand in the daily inspection routine. If the sand is found to be insufficient, replenish it.

Fig. 18 shows the sand seal section.
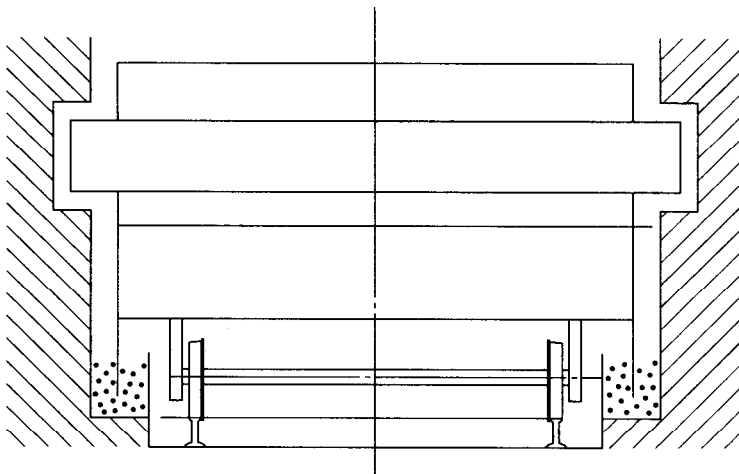
Figure 18 Sand seal of kiln car

(8) Do not allow the kiln car pushing speed to be changed suddenly.

The kiln car pushing speed may have to be changed due to increase or decrease in the amount of production. In this case, do not change the speed very much at one time; it must be slowly changed little by little.

Even if the temperature is raised or lowered, the effect on the product will be delayed. Even though the thermometer indicates a temperature change, there is no change to the product temperature; time will be required before the normal state is resumed.

Normally when the pushing speed is changed, the range of adjustment should be within 5 minutes and a change should be made once a week, even though it varies according to the kiln size. If the speed is changed more frequently, firing of the product may be insufficient or excessive.

To change the kiln car pushing speed, the fuel must be increased or decreased.

For this adjustment, it will be advisable to use the method of calculation as discussed in items 3.2.5 and to use it as a guideline.

(9) Implementation of heat balance

Calculation of fuel consumption to the change of the production volume as described in Item (8) and the heat balance of a kiln should be implemented once a year at least.

Implementation of these firing control items will lead to stable temperature distribution and atmosphere, resulting in higher product quality and improved yield.