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INTRODUCTION

With respect to energy saving of industrial furnaces, controlling and reducing heat loss to be emitted from the surface of each part of the furnace body by means of insulating construction is a very important factor together with the waste heat recovery problem since emission heat loss accounts for a high proportion of the total heat loss. Its improvement directly results in the promotion of furnace efficiency. The basic requirement for constructing a lining suitable for the reduction of the amount of the emission heat is, of course, to select refractories and insulating material of low heat conductivity (small structure mass) and that is sufficiently durable for use under any furnace operating condition. However, since the operating conditions for industrial furnaces, furnace form, etc. vary widely, for selecting an insulation method, the actual condition of each must be thoroughly determined, and the total economy including insulation effect (insulation effectiveness), etc. from the viewpoint of the furnace objective, function, durability, and the proportion of emission heat loss must also be considered.

1. Positioning of the Furnace Wall Emission Heat Loss

Typical heat losses other than the furnace wall emission heat loss are described on the basis of their mutual relationship.

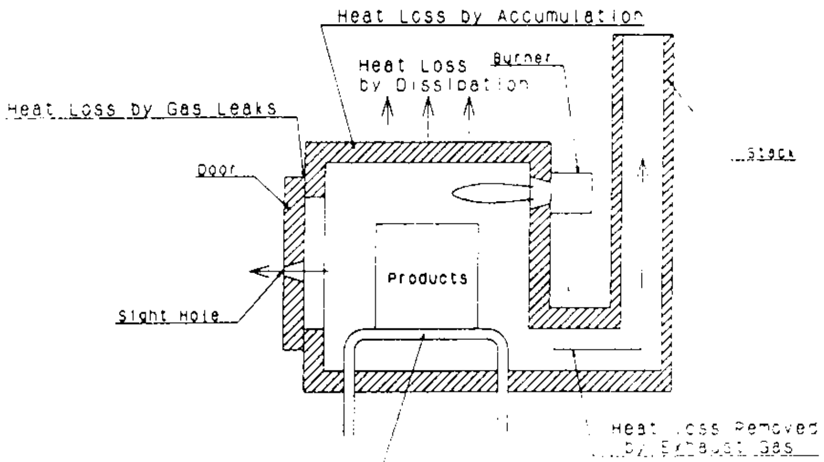


Figure 1 Typical heat losses of the furnace

1.1 The heat loss removed by exhaust gas

Heat loss by exhaust gas has the highest proportion of all the heat losses of industrial furnaces. Accordingly, its effective recovery and utilization have a great effect on the problem of improving furnace efficiency. A typical measures for exhaust gas sensible heat recovery and effective utilization are as follows:

1) By the provision of an air preheater, waste heat boiler, heat accumulator (brick construction), etc., conversion to other energy and utilization for the combustion of preheated air which has had heat exchange performed.

2) Heating by exhaust gas circulation, and utilization to drying, preheat, calcination, etc. For the effective recovery of latent heat of exhaust gas, not only is the performance of the recovery system important, but also, the heat insulation should be intensified in the exhaust gas circulation route, such as connection duct and flue to prevent emission heat as far as possible.

1.2 Heat radiation, leaks, and the entry of cold air from the opening

In the case of batch type furnaces, etc., at the time of charging or removing material to be heated or burned, the cover, door, etc. are opened/closed, thereby allowing outside air to enter, furnace hot gas to be released, and heat loss by radiation to occur. Designing the openings to an appropriate shape and size, changing the door structure (double door, etc.), and improvement of the furnace pressure adjustment, combustion control, etc. are required.

On the other hand, when airtightness of the continuous operation furnace is not maintained completely, cold air enters at the gap of the opening leakage occurs from the brick joints of the melting furnace roof, etc., and leakage from the furnace walls, roof joints and the filler material portion of expansion joint occurs. Heat loss due to imperfection of industrial furnace design, construction, maintenance, etc. will therefore occur. However, such heat losses have recently been reduced through the improvement of heat pattern, adoption of suitable furnace form and furnace construction at the time of the furnace design, progress in the filler material according to the purpose, such as the fiber insulating material, and capability to maintain furnace airtightness by the proper use of these materials.

1.3 Accumulation loss of furnace insulation

When firebricks (or monolythic refractories) are used for so-called atmospheric furnaces, such as batch type forging heating furnaces and heat treatment furnaces, the material to be heated is extracted in the heating/cooling cycle, the furnace is left empty for a predetermined time, the material to be heated is charged afresh after the furnace temperature drops to a certain extent, and the furnace is reheated. In such cases, the initial heating energy is spent for heating the furnace refractories. That is, the above energy is absorbed by the furnace wall as heat accumulation loss until the furnace wall refractories reach a predetermined temperature. In addition, rapid heating used to be restricted out of consideration for the thermal spalling of lining refractories, and a certain temperature rise time had to be observed to, create a bottleneck for energy saving.

The calorific value required for furnace body heat accumulation can be empirically given by the following expression.

$$Q \propto \sqrt{P \cdot Cp \cdot \lambda \cdot H} \times (T - T_0) \cdot F$$

where Q = Calorific value required-for heat accumulation (kcal)

p = Density of refractory (kg/m^3)

Cp = Specific heat of refractory (kcal/kg°C)

λ = Thermal conductivity of refractory (kcal/mh°C)

T = Set temperature (°C)

T_0 = Initial temperature (°C)

F = Effective furnace area (m^2)

H = Temperature rise time (hours)

As apparent from the above expression, the amount of heat accumulation Q can be reduced by lowering P, Cp, and λ.

In the heat valance of batch furnace, the proportion of furnace body heat accumulation loss is as high as 30%–35% in brick furnaces. Reducing the mass of furnace forming material directly reduces the heat loss.

Recently, various high temperature insulating materials have been developed. An example is the fibrous insulating material on the surface of refractory of existing furnaces. Another example, is when fibrous insulating material alone is used for new furnaces. In the above cases, furnace wall accumulation heat loss has been reduced to a large degree and rapid heating/cooling has become possible. These and others contributed to the improvement of operation furnace, and energy saving has been further promoted. Likewise in continuous heating furnaces, similar practices have reduced heat accumulation in the refractory, contributing to outer wall temperature drops.

1.4 Heat loss due to the provision of a cooling part

When the operating temperature of the furnace is extremely high, a water cooling jacket is provided on the side of the furnace shell iron skin for forced cooling of the back of the refractory for preventing the lining refractory from melting and eroding, as well as for maintaining durability. Also when there is reinforcement with the metallic structure material due to insufficient strength with the refractory alone, a furnace body structure which is an essential requirement, is sometimes adopted to sacrificing heat loss typically by making the steel material of the cooling system as its core.

Typical of the former is the water cooling mechanism of the blast furnace, melting furnace, etc., while the latter involves skid pipes, extraction openings, etc. In various other burning furnaces, etc. a natural air cooling mechanism is adopted in many cases. Cooling heat loss and refractory damage prevention have a mutually opposing relationship. It is determined on the basis of the economic balance between the refractory melting/erosion control effect and heat loss. Though these measures to avoid heat loss are in many cases absolutely necessary, future problems involve improving the operating method and R D of refractories that can endure conditions without cooling.

For the main factors mentioned above, considerable improvement has already been made in the existing furnace, considering the rises in energy prices, for the exhaust gas loss and furnace wall emission heat loss which are major elements of the total, and thorough improvement, such as the addition of waste heat recovery systems, and intensification of heat insulation, etc. made to enhance the total heat efficiency.

2. Various Heat Insulating Materials and Characteristics

2.1 Refractory bricks and insulating materials

2.2.1 Firebricks

(1) Typical qualities of various firebricks (Table 1)

Table 1 Typical quality of refractory bricks

Material / Item		Fire clay ①	Fire clay ②	Fire clay ③	High alumina ①	High alumina ②	High alumina ③	Silica	Basic ①	Basic ②	Basic ③	Basic ④	Silicon carbide
Refractoriness (SK)		32	34	34	35	38	40 <	33	40 <	40 <	40 <	40 <	
Apparent porosity (%)		23.0	21.5	18.0	23.0	22.5	18.0	19.0	11.0	20.0	17.0	18.0	15.0
Bulk density		2.00	2.15	2.25	2.20	2.75	2.95	2.31	3.15	2.90	3.00	2.85	2.70
Cold crushing strength (kg/cm^2)		350	450	500	400	700	900	450	500	400	450	700	1270
Refractoriness under load T_2 (°C)		1345	1440	1470	1470	1530	1700<	1620	1610	1615	1650	1620	1700<
Thermal expansion at 1000°C		0.5	0.6	0.6	0.6	0.5	0.6	1.4	0.6	1.0	1.2	1.3	0.4
Permanent linear change (%)		0	0	0	0	0	0	+ 0.1	+ 0.4	+ 0.2	+ 0.1	- 0.1	0
Chemical composition (%)	SiO_2							96.6					
	Al_2O_3	32.5	38.8	40.9	48.0	84.8	90.5	0.5					
	Fe_2O_3	2.5	2.0	1.6	2.0	1.8	0.4	1.0					0.3
	MgO								34.7	71.3	78.6	94.8	
	Cr_2O_3								25.8	9.9	8.6		
	SiC												86.8

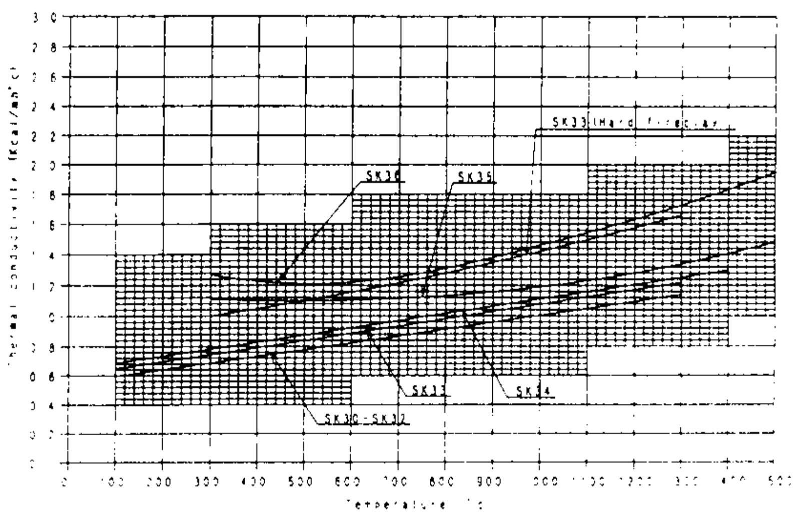


Figure 2 Thermal Conductivity of ordinary refractory bricks

(2) Thermal conductivity of various firebricks

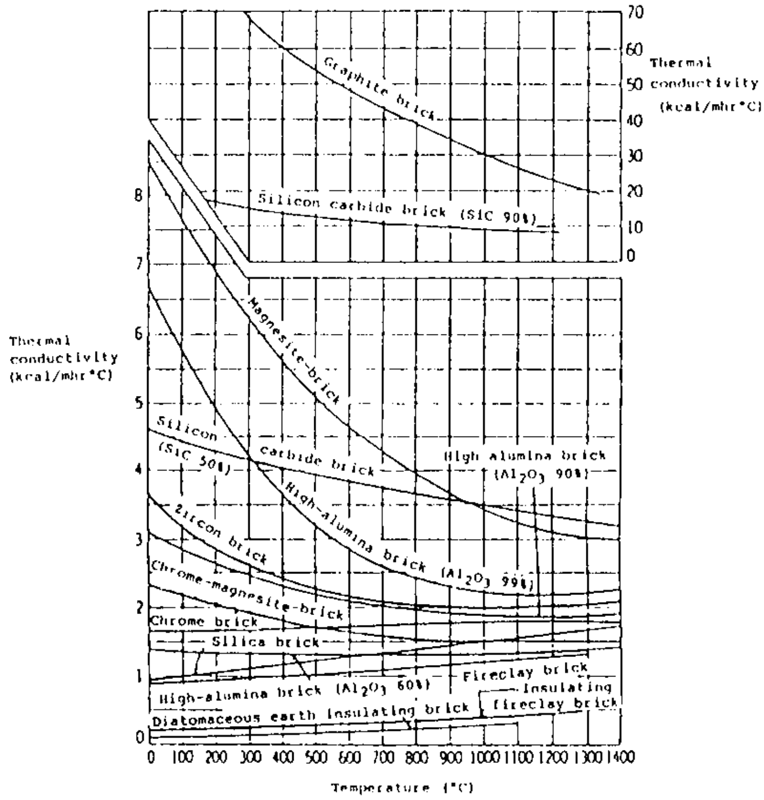


Figure 3 Thermal conductivity of refractory bricks (example)[1]

(3) Mean specific heat of various firebricks

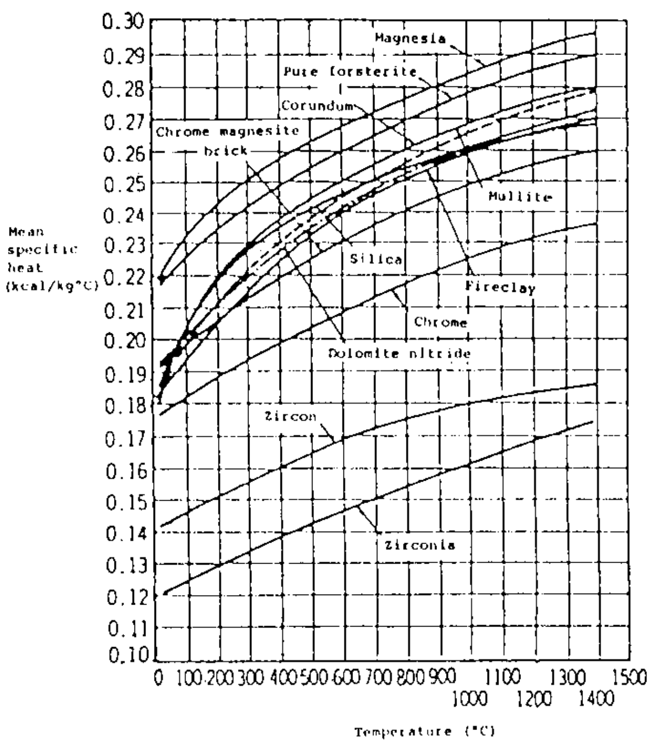


Figure 4 Mean specific heat of refractory bricks[1]

2.1.2 Insulating firebricks

Insulating firebricks in Japan are standardized by JIS R2611 as shown in Table 2. Class A is characterized by low heat conductivity, and class C is characterized by bricks with the emphasis placed on the crushing strength. Class B is intermediate, small in heat conductivity, large in crushing strength to some extent, and used most generally.

Table 2 JIS on insulating firebricks (JIS R2611)

Type		Temperature not exceeding reheat shrinkage 2% (°C)	Bulk density	Cold crushing strength (kgf/cm^2) MPa	Thermal conductivity (mean temperature 350 ±10°C) (kcal/mhr°C) W/(m·K)
Group A	Class 1	900	0.50 or less	5 or more [0.49]	0.13 or less [0.15]
	Class 2	1000	0.50 or less	5 or more [0.49]	0.14 or less [0.16]
	Class 3	1100	0.50 or less	5 or more [0.49]	0.15 or less [0.17]
	Class 4	1200	0.55 or less	8 or more [0.78]	0.16 or less [0.19]
	Class 5	1300	0.60 or less	8 or more [0.78]	0.17 or less [0.20]
	Class 6	1400	0.70 or less	10 or more [0.98]	0.20 or less [0.23]
	Class 7	1500	0.75 or less	10 or more [0.98]	0.22 or less [0.26]
Group B	Class 1	900	0.70 or less	25 or more [2.45]	0.17 or less [0.20]
	Class 2	1000	0.70 or less	25 or more [2.45]	0.18 or less [0.21]
	Class 3	1100	0.75 or less	25 or more [2.45]	0.20 or less [0.23]
	Class 4	1200	0.80 or less	25 or more [2.45]	0.22 or less [0.26]
	Class 5	1300	0.80 or less	25 or more [2.45]	0.23 or less [0.27]
	Class 6	1400	0.90 or less	30 or more [2.94]	0.27 or less [0.31]
	Class 7	1500	1.00 or less	30 or more [2.94]	0.31 or less [0.36]
Group C	Class 1	1300	1.10 or less	50 or more [4.90]	0.30 or less [0.35]
	Class 2	1400	1.20 or less	70 or more [6.86]	0.38 or less [0.44]
	Class 3	1500	1.25 or less	100 or more [9.81]	0.45 or less [0.52]

Fire insulating bricks can be generally classified according to the raw material to (1) those mainly of diatomaceous earth, (2) those mainly of fireclay, and (3) those of mainly fire resisting material.

(1) Diatomaceous earth insulating firebricks

These bricks are the main of low temperature insulating fire bricks. Bricks of this category are further divided into diatomaceous earth single bricks manufactured by first granulating diatomaceous earth and then mixing sawdust, and fire insulating bricks manufactured by adding plastic fireclay to diatomaceous earth.

Table 3 Physical properties of diatomaceous earth single-fired bricks (example) 2)

Type	A_1	A_2	B_1	B_2	H_1	H_2
Temperature not exceeding reheat shrinkage 2.0% (°C)	900	1000	900	1000	900	1000
Reheat shrinkage (%)	0.50	0.66	0.57	0.56	0.40	0.58
Bulk density	0.47	0.46	0.65	0.65	0.80	0.75
Cold crushing strength (MPa)	0.9	1.1	3.3	3.2	9.0	9.3
Modulus of rupture (MPa)	0.4	0.5	1.5	1.8	3.8	4.2
Thermal conductivity (W/m.K) at 350°C	0.14	0.15	0.19	0.20	0.22	0.27
Porosity (%)	80	80	71	72	65	65
Coefficient of linear expansion/shrinkage at temperature (%) at 1000°C	at 900°C 0.10	0.30	at 900°C 0.10	0.26	at 900°C 0.17	0.23

(2) Fireclay insulating firebricks

Fireclay insulating firebricks are used for reducing emission calorific value from the furnace wall at regions of relatively high temperature and heat accumulation loss at the furnace wall, achieving energy saving, improving the work environment, and promoting equipment efficiency. Generally, the main material is kaolinite and halloysite group clay chamotte, roseki or the like, and production is by adding plastic fireclay, sawdust, etc. thereto.

Table 4 Physical properties of insulating firebricks using fireclay (example) 2)

Type	A_6	A_7	B_5	B_6	C_1
Temperature not exceeding reheat shrinkage 2.0% (°C)	1400	1500	1300	1400	1300
Reheat shrinkage (%)	0.55	0.71	0.53	0.54	0.57
Bulk density	0.68	0.73	0.78	0.86	1.06
Cold crushing strength (MPa)	1.4	1.4	2.8	3.4	6.2
Modulus of rupture (MPa)	0.7	0.7	1.7	2.0	2.5
Thermal conductivity (W/m℃) at 350°C	0.22	0.24	0.26	0.28	0.33
Coefficient of linear expansion/shrinkage at temperature (%) at 1000°C	0.37	0.38	0.50	0.43	0.51

Table 5 Physical properties of fireclay bricks using lightweight grain (example) 2)

Type		A	B	C	D
Temperature not exceeding reheat shrinkage 2.0% (°C)		1450	1300	1400	1300
Max. temperature for safe use (°C)		—	—	—	—
Reheat shrinkage (%)		0.35	at 1300 × 8 hr 1.16	—	—
Bulk density		1.42	1.53	1.5 ≥	1,60
Cold crushing strength (MPa)		12.8	11.8	11.8≦	14.7
Modulus of rupture (MPa)		6.0	—	—	—
Thermal conductivity (W/m.K) at 350°C		0.55	0.59	0.64	0.70
Porosity (%)		44	42	47	33
Coefficient of linear expansion/ shrinkage at temperature (%) at 1000°C		0.42	0.53	0.52	0.60
Refractoriness under load (1 kg/cm^2 · T_2°C)		1340	1310	1340	—
Chemical composition (%)	SiO_2	59	66	57	64
	Al_2O_3	37	27	42	24
	Fe_2O_3	2.9	1.5	2	—

Table 6 Physical properties of insulating firebricks using form styrol or pearlite (example) 3)

Type	A	B	C	D	E
Temperature not exceeding reheat shrinkage 2.0% (°C)	1300	1300	1400	1400	1300
Max. temperature for safe use (°C)					1500
Reheat shrinkage (%)	0.02	0.05	0.08	0.10	0.5 >
Bulk density	0.52	0.53	0.65	0.67	1.10–1.20
Cold crushing strength (MPa)	1.6	1.5	2.9	2.8	7.9—19.6
Modulus of rupture (MPa)	1.0	0.9	1.7	1.5	
Thermal conductivity (W/m℃) at 350°C	0.16	0.17	0.20	0.22	0.35—0.41
Porosity (%)	81	80	76	77	56.2–62.6
Coefficient of linear expansion/ shrinkage at temperature (%) at 1000°C	0.41	0.38	0.42	0.44	—
Refractoriness (SK)	—	—	—	—	35
Refractoriness under load (1 kg/cm^2 · T_1C)	—	—	—	—	1250 <

(3) High alumina/alumina insulating firebricks

Firebricks of this category can be largely classified as those using bubble alumina and those using high alumina material. The former is burned at a high temperature after pressure forming, and binder is added to bubble alumina. The latter is manufactured in a manner similar to fireclay bricks, using electrofused/sintered alumina, mullite, etc. as the main raw material.

Table 7 Physical properties of high-alumina, alumina insulating firebricks (example) [2, 4]

Type		A	B	C	D	E
Temperature not exceeding reheat shrinkage 2.0% (°C)		1800	1800	—	1600	1650
Max. temperature for safe use (°C)		—	—	—	—	—
Reheat shrinkage (%)		0.30	0.10	—	0.38	0.24
Bulk density		1.28	1.53	0.48	0.87	0.86
Cold crushing strength (MPa)		6.4	18.0	1.0	2.2	4.4
Modulus of rupture (MPa)		3.2	7.1	0.9	1.7	2.8
Thermal conductivity (W/m.K) at 350°C		0.71	0.90	—	0.34	0.35
Porosity (%)		63	55	—	—	—
Coefficient of linear expansion/ shrinkage at temperature (%) at 1000°C		0.66	0.79	—	0.48	0.54
Refractoriness (SK)		40 <	40 <	—	—	—
Refractoriness under load (1 kg/cm^2 · T_2°C)		1600 <	1500 <	—	—	—
Chemical composition (%)	SiO_2	13.6	0.4	0.1	—	—
	Al_2O_3	85.7	99.2	99.3	—	—
	Fe_2O_3	0.1	0.1	0.13	0.55	0.51

(4) Silicic acid insulating firebricks

Table 8 Physical properties of silicic acid insulating firebrick (example) [5)]

Type		A	B	C
Temperature not exceeding reheat shrinkage 2.0% (°C)		1550	—	—
Max. temperature for safe use (°C)		—	—	1500
Reheat shrinkage (%)		0.02	—	–0.53
Bulk density		0.96	1.18 or less	1.18
Cold crushing strength (MPa)		4.1	3.9 or more	4.9
Modulus of rupture (MPa)		2.5	—	1.9
Thermal conductivity (W/m.K) at 350°C		0.37	0.5 or less	0.43
Porosity (%)		—	Apparent porosity 48 or more	51
Coefficient of linear expansion/shrinkage at temperature (%) at 1000°C		1.18	1.2 or less	1.09
Refractoriness (SK)		—	31	28
Refractoriness under load (1 $kg/cm^2 \cdot T_2$°C)		—	—	1350
Chemical composition (%)	SiO_2	9.24	88 or more	88.8
	Al_2O_3	—	1.7 or less	0.4
	Fe_2O_3	—	2.5 or less	0.2
	CaO	—	—	5.7

(5) Thermal conductivity of insulating firebricks (JIS Classes A, B, and C)

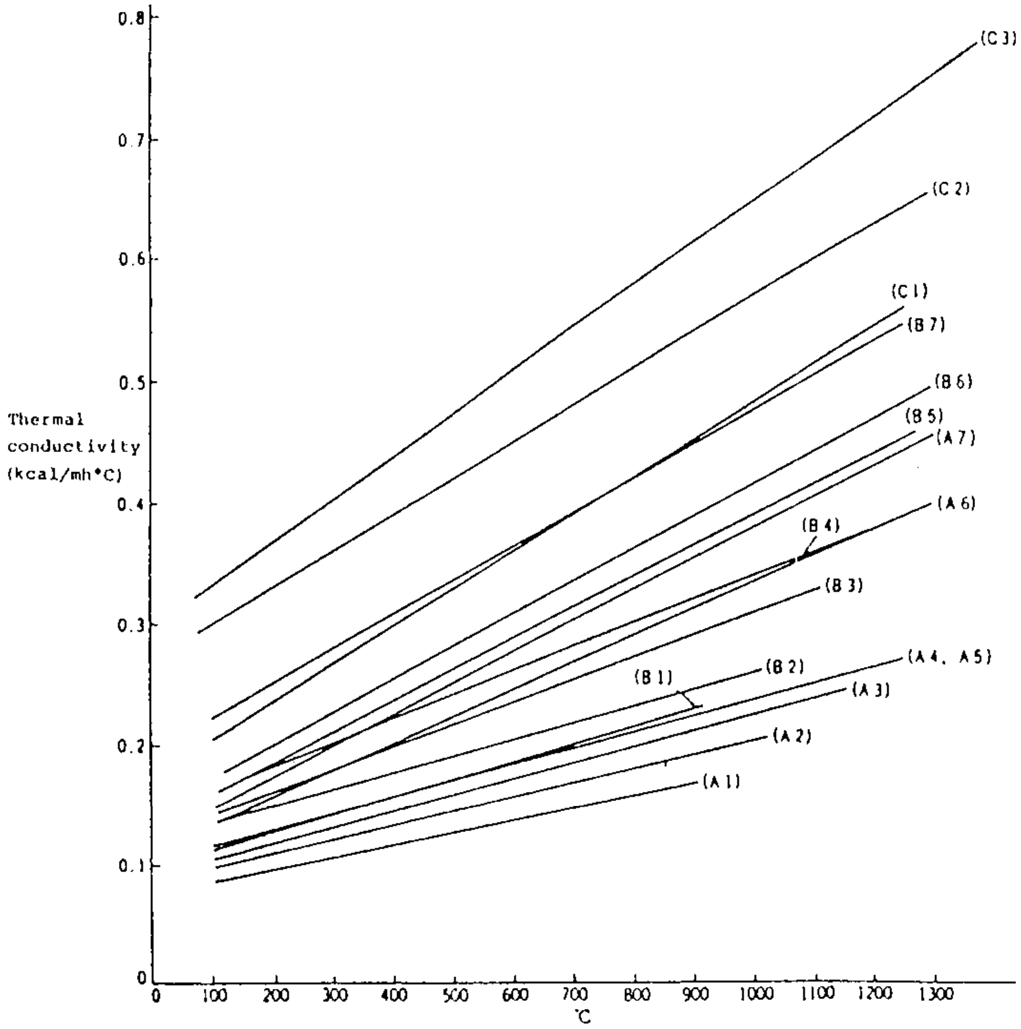


Figure 5 Thermal conductivity of insulating firebricks (JIS Classes A, B, and C) (example)

2.2 Monolithic refractory and insulating material

2.2.1 Fire resistant castables and fire resistant plastics

(1) Typical quality of various fire resistant castables

Table 9 Physical properties of castable refractories (example) [9]

Item	Material	High-alumina		Fireclay	
		①	②	①	②
Max. temperature for use (°C)		1800	1650	1550	1450
Execution required quantity (kg/m^3)		2850	2200	2050	1900
Linear change after heating (%)	110°C - 24 h	0	0	0	0
	1000°C - 3 h	-0.06	-0.20	-0.25	-0.15
	1350°C - 3 h	-0.09	-0.50	+0.50	-0.20
	1500°C - 3 h	-0.20	-0.40	-0.60	—
Crushing strength after heating (MPa)	110°C - 24 h	44	20	26	25
	1000°C - 3 h	33	18	18	15
	1350°C - 3 h	44	20	29	29
	1500°C - 3 h	49	59	64	—
Modulus of rupture after heating(MPa)	110°C - 24 h	7.9	3.9	5.9	4.9
	1000°C - 3 h	5.4	2.5	3.4	2.9
	1350°C - 3 h	3.9	3.9	4.9	6.4
	1500°C - 3 h	7.9	15.2	10.8	—
Thermal conductivity (W/m.K)	at 260°C	1.08	0.76	0.74	0.60
	at 540°C	1.15	0.86	0.85	0.69
	at 800°C	1.21	1.06	0.93	0.73
Chemical composition (%)	Al_2O_3	95	61	47	37
	SiO_2	—	33	43	51

(2) Typical quality of various fire resistant plastics

Table 10 Physical properties of plastic refractories (example) [9]

Item	Material	High-alumina ①	High-alumina ②	Fireclay ①	Fireclay ②
Max. temperature for use (°C)		1800	1750	1650	1400
Execution required quantity (kg/m^3)		2900	2600	2300	2250
Linear change after heating (%)	110°C - 24 h	-0.20	-0.55	-0.70	-0.70
	1000°C - 3 h	-0.25	-0.70	-0.55	-0.90
	1350°C - 3 h	+0.15	-0.75	0	-1.20
	1500°C - 3 h	+0.50	-0.65	-0.10	—
Crushing strength after heating (MPa)	110°C - 24 h	16.7	8.8	2.9	4.4
	1000°C - 3 h	27.5	20.0	16.7	19.6
	1350°C - 3 h	58.8	43.1	31.4	31.4
	1500°C - 3 h	78.5	44.1	37.3	37.3
Modulus of rupture after heating (MPa)	110°C - 24 h	3.4	2.9	1.0	0.5
	1000°C - 3 h	4.4	3.9	1.9	1.9
	1350°C - 3 h	11.8	9.8	3.9	3.9
	1500°C - 3 h	14.7	12.8	9.3	9.3
Thermal conductivity (W/m.K)	at 260°C				
	at 540°C				
	at 800°C				
Chemical composition (%)	Al_2O_3	92	73	44	38
	SiO_2	6	24	49	54

2.2.2 Fire resistant insulating castables and fire resistant insulating plastics

Fire resistant insulating castables (calcined diatomaceous earth, expansion silica, expansion pearlite, clay lightweight chamotte, alumina, bubble, etc.) are used as high insulative lightweight aggregates. Alumina cement is extensively used as the binder.

Fire-resistant insulating plastics are made into a kneaded earth form by kneading after the addition of lightweight aggregate, clay, binder, etc. and a small amount of water.

Table 11 Physical properties of insulating castable refractory and plastic refractory (example)6)

Test item		Insulating castable						Insulating plastic		
Max. temperature for use (°C)		800	900	1000	1200	1500	1800	1200	1400	1600
Bulk density	After drying	0.44	0.91	0.90	1.22	1.48	1.14	--	--	--
	After 500°C firing	0.40	0.85	0.84	1.15	1.44	1.10	--	--	--
	After max. temperature burning	0.89	0.88	0.84	1.10	1.56	1700°C 1.11	--	--	--
Cold crushing strength (MPa)	After drying	0.39	3.33	2.75	5.59	4.90	5.79	3.82	5.69	10.20
	After 500°C firing	0.29	3.04	2.75	4.22	2.55	3.92	--	--	--
	After max. temperature burning	0.29	2.75	2.94	5.39	17.55	1700°C 10.89	4.71	10.20	1400°C 13.24
Linear change (%)	After drying	-0.08	-0.20	-0.25	-0.18	-0.06	-0.06	-0.36	-0.14	-0.18
	After 500°C firing	-0.65	-0.60	-0.65	-0.30	-0.20	-0.10	--	--	--
	After max. temperature burning	-0.93	-0.97	-0.95	-0.48	-0.90	1700°C -0.83	-0.73	-1.03	1400°C -0.07
Thermal conductivity (W/m.K) at 350°C	500°C burned product	0.12	0.22	0.22	0.27	0.34	0.86	400°C 0.29	400°C 0.44	400°C 0.49
Chemical composition (%)	Al_2O_3	29.5	25.9	25.4	39.4	65.2	93.9	31	42	72
	SiO_2	30.1	55.9	56.3	32.8	30.2	1.0	67	45	25
	Fe_2O_3	13.6	5.2	4.9	3.1	2.2	0.2	--	--	--
Aggregate material		Vermiculite	Diatomaceous earth	Vermiculite	Fire-clay	High-alumina	High-alumina	Lightweight insulating	Fire-clay	Bubble alumina

2.2.3 Fiber monolithic composite material

Ceramic fiber has been improved in its fire resistant properties, workability and wind-velocity resistant property, etc. This is a composite product of fiber and existing fire resistant insulating material. Castable composite material is made of alumina cement (binder), ceramic fiber, and fire resistant aggregate. Plastic composite material is manufactured in a form of kneaded earth by adding water, adhesion increasing material, setting agent, and fire resistant aggregate to the ceramic fiber.

Table 12 Physical properties of fibrous composite material (example) 7)

		Castable composite material		Plastic composite material		
Max. temperature for use (°C)		1200	1300	1000	1000	1400
Bulk density	After 105°C drying	0.81	0.76	0.35	0.35	0.89
	After max. temperature burning	0.70	0.63	0.34	0.34	0.87
Modulus of rupture (MPa)	After 105°C drying	1.5	1.2	0.4	0.6	0.8
	After max. temperature burning	0.6	0.4	0.05	0.12	1.0
Cold crushing strength (MPa)	After 105°C drying	1.7	1.6	—	—	—
	After max. temperature burning	0.7	0.5	—	—	—
Heating shrinkage (%)	1000°C					—
	1200°C		—	—	—	
	1300°C	—		—	—	—
	1400°C	—	—	—	—	
	1500°C	—	—	—	—	
Thermal conductivity (W/m.K) at normal temperature		0.17	0.16	0.08	0.08	0.19
Chemical composition (%)	Al_2O_3	53.5	65.2	47	41	65
	SiO_2	29.6	25.4	52	58	34
	CaO	14.8	9.1	—	—	—

2.3 Fibrous insulating materials

2.3.1 Ceramic fiber

(1) Alumina silica fiber

Alumina silica fiber is manufactured by adding boric acid glass, zirconia, chromium oxide, etc. to alumina silica raw materials, such as kaoline calcinated material, bauxite, alumina or silica sand, silica flour, etc. mixing SiO_2 and Al_2O_3 as to become almost 1 : 1, fushing in an electric furnace at a high temperature of 2000°C or more, and causing it to flow out in a thin stream so as to be fiberized. There are two fiberization methods: the blowing process for blasting compressed air or steam jet and spinning process utilizing the centrifugal force of a rotor running at a high speed.

Table 13 Physical properties of commercially available ceramic fiber[8]

Maker	A		B	C	D	E	F	G
	(Short fiber)	(Long fiber)						
Fiber diameter (m)		2.3 2.5	2.8	2-3.5	3.6	3	2.9	-
Fiber length (mm)	< 38	13-254	Mean 100	< 38	Max.length 250	5-30	75	- -
True specific gravity (g/cm^3)	2.73		2.56	2.6	2.73	2.65	3.1	-
Melting point (°C)		>1,760	1,760	1,760	> 1,760	1,800	1,825	
Temperature for use (°C)		1,260	1,260	1,260	1,300	1,260	1,400	1,480
Chemical composition (%)								
Al_2O_3	50.9	51.3	50.1	45.5	51.8	52 53	60.2	40.4
SiO_2	46.8	45.3	49.3	54.0	47.9	45 46	38.7	55.1
Fe_2O_3	---	---	0.1	0.2	0.1	0.1-0.15	0.2	-
TiO_2	-	---	0.1	0.5	tr.	1-1.5	0.2	-
CaO	- -	-	0.1	- -	tr.	---	0.1	- -
MgO	---	---	tr.	---	tr.	---	0.1	---
Na_2O	0.8		0.3	0.2	0.2	0.1 0.2	0.4	-
B_2O_3	1.2	--	---	--	-	0.1-0.2	-	
ZrO_2		3.4	- -	---	-	---	- -	-
Cr_2O_3	- - -	---	---	---	-	---	- -	3.5

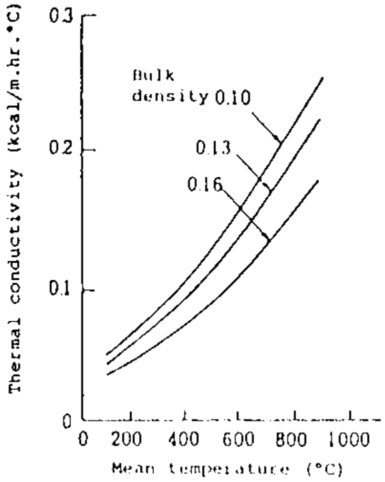


Figure 6 Thermal conductivity of alumina silica fiber

Alumina silica fiber is used for manufacturing secondary products such as blankets, felt, molded paper, rope, braid, blow items , etc. using "bulk fiber" which is the basic material. Its field of application is very extensive now and will be more so in the future.

(2) Alumina fiber

Ceramic fiber is used for atmospheric furnaces of relatively low temperature, such as heat treatment furnace, and has gained attention as an energy saving insulating material. However, its heat resistance and durability for heating furnaces of around 1300°C, such as rolling continuous heating furnace and forging heating furnaces, is insufficient. As super-high temperature insulating materials, alumina fiber has also been developed.

Table 14 Physical properties of alumina fiber [8]

Fiber density	3.4 g/cm^3
Melting point	>2,000°C
Max. temperature for use	>1,600°C
Specific heat	0.25 cal/g°C
Tensile strength	1×102 MN/m^2
Specific tensile strength	40×104 m^3S^2
Young's modulus	1×104 MN/m^2
Specific modulus of elasticity	4×10 m^2S^2
Fiber diameter	3 μ (mean)
Surface area	3 m^2/g
Mohs's hardness	6
Composition	Al_2O_3 95%, SiO_2 5%

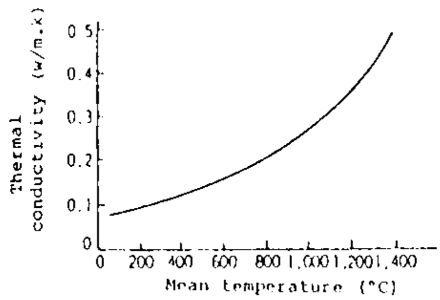


Figure 7 Thermal conductivity of alumina fiber[3]

(3) Zirconia fiber

Zirconia fiber currently has the possibility of being used up to the highest temperature of all ceramic fibers.

Table 15 Characteristics of zirconia fiber [9)]

Appearance	White short fiber-like		
Fiber diameter	Mean 5 μ		
Fiber length	Mean 20–30 mm		
Melting point	2600°C		
True specific gravity	5.8		
Bulk density	80–100 kg/m^3		
Thermal conductivity (kcal/mh° C)		(Bulk density 100)	(Bulk density 400)
	500°C	0.10	0.12
	1000°C	0.26	0.17
	1500°C	0.75	0.23

2.4 Heat and cold insulating materials

Japanese Industrial Standards specify seven heat and cold insulating materials; rock wool, glass wool, cattle hair felt, calcium silicate, polystyrene foam, water repellent perlite and hard urethane foam.

Among them, cattle hair felt, polystyrene foam and hard urethane foam are mostly used for cold insulation since they are 70° to 100°C in maximum working temperature. Rock wool, calcium silicate and water repellent perlite are often used also for lining the refractories of high temperature furnaces since they are relatively high in maximum working temperature. Ceramic fibers are low in thermal conductivity and high in maximum working temperature, but are used as an insulating material for temperatures higher than 1000°C and not used in the areas of the above mentioned heat and cold insulating materials, since they are very expensive compared to those heat and cold insulating materials.

Table 16 Insulating materials specified in JIS

Material Name	Max. Working Temp (°C)	λ at 70°C (W/m.K)
Rock Wool	400~600	0.043~0.052
Glass Wool	350~400	0.040~0.052
Calcium Silicate	650~1000	0.048~0.062
Water Repellent Perlite	650~900	0.056~0.072
Polystyrene Foam	70	0.028~0.040
Hard Urethane Foam	100	0.023~0.025
Cattle Hair Felt	100	0.053

2.4.1 Rock wool insulators

Rock wool insulators are prepared by adding slag and limestone to rocks such as andesite, melting the mixture at a high temperature of 1300° to 1600°C, and blowing it by high pressure water vapor or compressed air or scattering it by centrifugal force, for forming fibers. Various heat insulators are produced from rock wool, to suit respective objects and applications.

Rock wool insulators suddenly rise in thermal conductivity according to the decrease of density in a low density range, like glass wool insulators. This phenomenon is caused mainly because the heat insulating layer transmits radiation, and there is a density at which the thermal conductivity becomes minimum. In a high density range, the thermal conductivity of rock wool rises almost linearly in relation with the temperature, but in a low density range, the relation shows a curve expressed by a quadratic equation.

Table 17 Kinds and main physical properties of rock wool insulators

Material standard No. and name	Kind		Bulk density (kg/m^3)	Maximum working temperature (°C)	Thermal conductivity W/m·K (kcal/m·h·°C)
JIS A 9504 (Rock Wool Insulators)	Rock wool	—	150 or less	650	(Average temperature 70±5°C) 0.044 {0.038} or less
	Heat insulating board	No.1	100 or less	600	0.044 {0.038} or less
		No.2	160 or less	600	0.043 {0.037} or less
		No.3	300 or less	600	0.044 {0.038} or less
		No. 4a	350 or less	650	0.055 {0.047} or less
		No. 4b	350 or less	400	0.055 {0.047} or less
	Felt	—	70 or less	400	0.049 {0.042} or less
	Pipe cover	—	200 or less	600	0.044 {0.038} or less
	Heat insulating belt	No.1	100 or less	600	0.052 {0.045} or less
		No.2	160 or less	600	0.049 {0.042} or less
	Blanket	No. 1	100 or less	600	0.044 {0.038} or less
		No.2	160 or less	600	0.043 {0.037} or less

2.4.2 Glass wool insulators

The production method is almost the same as that for rock wool insulators, but phenol resin is generally often used as a binder. So, glass wool insulators are higher in organic material content than rock wool insulators, and are not very suitable for use at high temperatures.

Table 18 Kinds and main physical properties of glass wool insulators

Material standard No. and name	Kind		Blulk density (kg/m³)	Maximum working temperature (°C)	Thermal conductivity W/m·K (kcal/m·h·°C)
JIS A 9505 (Glass Wool Insulators)	Glass wool	No.2	—	400	(Average temperature 70±5°C) 0.042 {0.036} or less
		No.3	—	400	0.049 {0.042} or less
	Heat insulating board	No.2 24 k	24±2	300	0.049 {0.042} or less
		No.2 32 k	32±4	300	0.047 {0.040} or less
		No.2 40 k	40+4, −3	350	0.044 {0.038} or less
		No.2 48 k	48+4, −3	350	0.043 {0.037} or less
		No.2 64 k	64±6	400	0.042 {0.036} or less
		No.2 80 k	80±7	400	0.042 {0.036} or less
		No.2 96 k	96+9, −8	400	0.042 {0.036} or less
		No.2 120 k	120±12	400	0.042 {0.036} or less
		No.3 80 k	80±7	400	0.047 {0.040} or less
		No.3 96 k	96+9, −8	400	0.047 {0.0340} or less
		No.3 120 k	120±12	400	0.047 {0.040} or less
	Blanket	b	24 or more	350	0.048 {0.041} or less
		c	40 or more	400	0.043 {0.037} or less
	Heat insulating belt	24 k, 32 k	24, 32 or more	300	0.052 {0.045} or less
		40 k, 48 k	40, 48 or more	350	0.052 {0.045} or less
		64 k or more	64 or more	400	0.052 {0.045} or less
	Pipe cover	—	45 or more	350	0.043 {0.037} or less

2.4.3 Cattle hair felt

This is not so popularly used even though specified in JIS.

Table 19 Kinds and main physical properties of cattle hair felt

Material standard No. and name	Kind		Bulk density (kg/m^3)	Maximum working temperature (°C)	Thermal conductivity W/m·K (kcal/m·h·°C)	
		Thickness (mm)			(Average temperature) (70±5°C)	(0°C)
JIS A 9508 (Cattle hair Felt)	No.1	Less than 15	130 or more	100	0.053 {0.046} or less	0.042 {0.036} or less
		15 or more	130 or more	100		
	No.2	Less than 15	130 or more	100		
		15 or more	130 or more	100		
	No.3	Less than 15	100 or more	100		
		15 or more	100 or more	100		

2.4.4 Calcium silicate insulators

The insulators are prepared by adding lime and reinforcing fibers to a siliceous powder such as diatomaceous earth, and causing chemical reaction to produce calcium silicate crystals. Depending on the crystal system produced, products different in performance are obtained; xonotlite of 1000°C in maximum working temperature and tobermorite of 650°C.

For different purposes of use, heat insulating boards and pipe covers are available.

Table 20 Kinds and main physical properties of calcium silicate insulators

Material standard No. and name	Kind	Bulk density (kg/m^3)	Maximum working temperature (°C)	Thermal conductivity W/m·K (kcal/m·h·°C)
				(Average temperature 70±5°C)
JIS A 9510 (Calcium Silicate Insulators)	Heat insulating board No. 1-13	130 or less	1000	0.049 {0.042} or less
	Pipe cover No. 1-13	130 or less	1000	0.049 {0.042} or less
	Heat insulating board No. 2-17	170 or less	650	0.055 {0.047} or less
	Pipe cover No. 2-17	170 or less	650	0.055 {0.047} or less
	Heat insulating board No. 1-22	220 or less	1000	0.062 {0.053} or less
	Pipe cover No. 1-22	220 or less	1000	0.062 {0.053} or less
	Heat insulating board No. 2-22	220 or less	650	0.062 {0.053} or less
	Pipe cover No. 2-22	220 or less	650	0.062 {0.053} or less

2.4.5 Polystyrene foam insulators

The insulators are prepared by adding a foaming agent and a flame retarder to polystyrene resin, and heating the mixture for foaming.

Table 21 Kinds and main physical properties of polystyrene foam insulators

Material standard No. and name	Kind	Bulk density (kg/m³)	Maximum working temperature (°C)	Thermal conductivity W/m·K (kcal/m·h·°C)
				(Average temperature 20±5°C)
JIS A 9511 (Polystyrene Foam Insulators)	Class A heat insulating board special	27 or more	70	0.034 {0.029} or less
	Class A heat insulating board No. 1	30 or more	70	0.036 {0.031} or less
	Class A heat insulating board No. 2	25 or more	70	0.037 {0.032} or less
	Class A heat insulating board No. 3	20 or more	70	0.040 {0.034} or less
	Class A pipe cover No. 1	35 or more	70	0.036 {0.031} or less
	Class A pipe cover No. 2	30 or more	70	0.036 {0.031} or less
	Class A pipe cover No. 3	25 or more	70	0.037 {0.032} or less
	Class B heat insulating board type 1	—	70	0.040 {0.034} or less
	Class B heat insulating board type 2b	—	70	0.034 {0.029} or less
	Class B heat insulating board type 2a	—	70	0.034 {0.029} or less
	Class B heat insulating board type 3	—	70	0.028 {0.024} or less
	Class B pipe cover type 1	—	70	0.040 {0.034} or less
	Class B pipe cover type 2	—	70	0.034 {0.029} or less
	Class B pipe cover type 3	—	70	0.028 {0.024} or less

2.4.6 Water repellent perlite insulators

If rocks made of natural glass with volatile ingredients solidly dissolved, such as perlite and obsidian are ground, arranged in grain size, and heated to higher than 1000°C, to be molten, and to have the volatile ingredients vaporized, they are foamed to form porous glass grains. Reinforcing fibers and a binder are added to the glass grains, and the mixture is molded by a press into an insulating product.

Table 22 Kinds and main physical properties of water repellent perlite insulators

Material standard No. and name	Kind	Bulk density (kg/m^3)	Maximum working temperature (°C)	Thermal conductivity W/m·K (kcal/m·h·°C)
				(Average temperature 20±5°C)
JIS A 9512 (Water Repellent Perlite Insulators)	Heat insulating board No. 1	250 or less	900	0.072 {0.062} or less
	Heat insulating board No. 2	180 or less	650	0.056 {0.048} or less
	Heat insulating board No. 1	250 or less	900	0.072 {0.062} or less
	Heat insulating board No. 2	180 or less	650	0.056 {0.048} or less

2.4.7 Hard urethane foam insulators

The insulators are obtained by foaming urethane resin as a high polymer by the expansion of carbonic acid gas or fluorocarbon. The insulators are very low in heat conductivity.

Table 23 Kinds and main physical properties of hard urethane foam insulators

Material standard No. and name	Kind	Bulk density (kg/m^3)	Maximum working temperature (°C)	Thermal conductivity W/m·K (kcal/m·h·°C)
				(Average temperature 20±5°C)
JIS A 9514 (Hard Urethane Foam Insulators)	Heat insulating board type 1 No. 1	45 or more	100	0.024 {0.021} or less
	Heat insulating board type 1 No. 2	35 or more	100	0.024 {0.021} or less
	Heat insulating board type 1 No. 3	25 or more	100	0.025 {0.022} or less
	Heat insulating board type 2 No. 1	45 or more	100	0.023 {0.020} or less
	Heat insulating board type 2 No. 2	35 or more	100	0.023 {0.020} or less
	Heat insulating board type 2 No. 3	25 or more	100	0.024 {0.021} or less
	Pipe cover No. 1	45 or more	100	0.024 {0.021} or less
	Pipe cover No. 2	35 or more	100	0.024 {0.021} or less
	Pipe cover No. 3	25	100	0.025 {0.022} or less

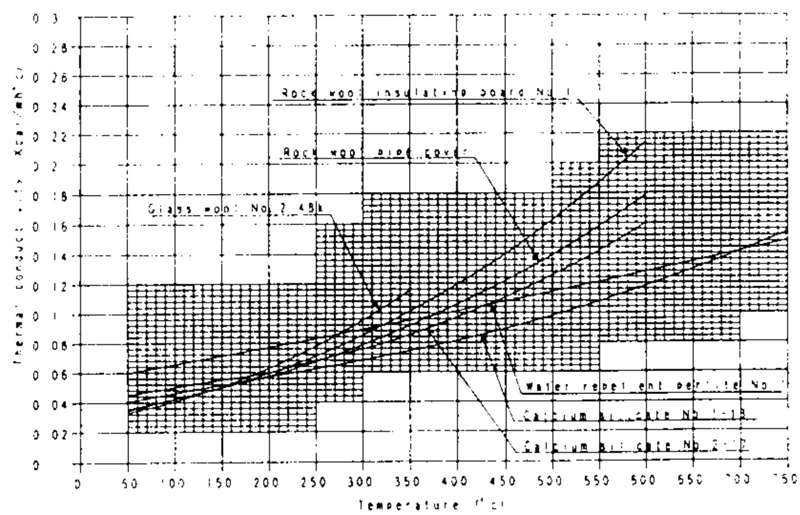


Figure 8 Thermal conductivity of heat insulating materials

2.4.8 Other heat insulators

Other insulators include asbestos insulators, diatomaceous earth insulators and magnesium carbonate insulators which had been specified in JIS. However, since they contain carcinogenic asbestos, their use was abolished, and they were deleted from JIS when the corresponding standards were revised.

Table 24 Characteristic of various refractories

Material	λ (W/m.K) at 1000 C	Bulk density (ton/m³)	Service temp (°C)
Steel (Low-carbon)	41 at 500° C	7.85	
Fire-brick (High-alumina)	2.79	2.95	SK40 (1920)
Fire-brick (Fire-clay)	1.28	2.10	SK34 (1750)
Insulating fire brick (JIS B4)	0.34	0.80	Less than 1200
Ceramic fiber (1400° C Blanket)	0.22	0.18	1400

Table 25 Thermal conductivity of various refractories

Material	Thermal conductivity
Steel (Low-carbon)	Very high (41 W/m.K at 500° C)
Fire-brick (High-alumina)	High (2.79 W/m.K at 1000° C)
Fire-brick (SK34)	High (1.26 W/m.K at 1000° C)
Insulating fire brick (JIS B4)	Low (0.34 W/m.K at 1000° C)
Ceramic fiber (1400 C Blanket)	Very low (0.22 W/m.K at 1000° C)

3. Furnace Wall Insulation Structure

Before examining the insulation structure of the furnace wall, the furnace operating condition must be thoroughly determined. The insulating system varies according to furnace temperature condition, state of the content (gas, solid, or fluid), contact with the content, and furnace body condition (fixed, rotated, or tilting). It is important to consider an insulating structure which can gain total economic effect while checking against "Criteria shown quantitatively concerning rationalization of energy use in a factory", determining the characteristics of the refractory and insulating material, utilizing insulating materials of lower heat conductivity, thoroughly examining the provision of high temperature insulating materials in the right places, and discriminating ones that satisfy the standard value from ones that does not.

3.1 Calculation of heat transfer

For examining the materials and thicknesses of the refractory materials or insulators constituting a furnace wall, and for calculating fuel consumption, etc., it is important for furnace design, to identify the temperature distribution, the dissipated heat value and the accumulated heat value by calculating heat transfer.

3.1.1 Mechanism of heat transfer

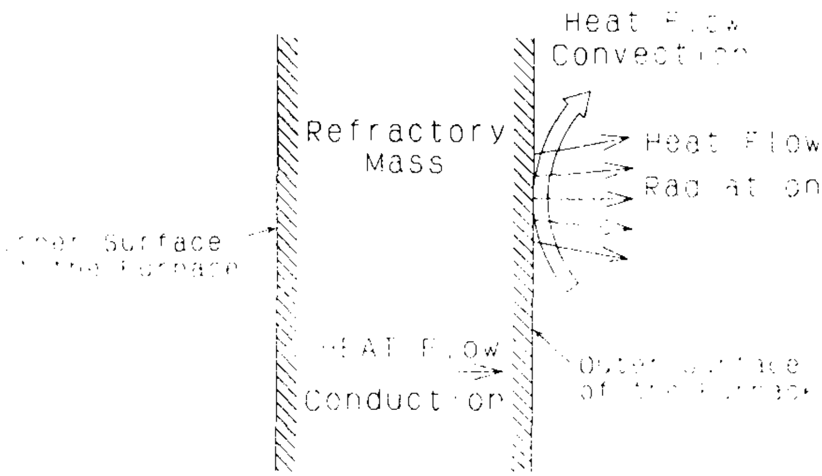
Heat transfer takes place in the following three processes:

1) Conduction: This refers to a process in which heat moves as the sequential motion of molecules constituting materials, to the adjacent molecules. In a solid, heat is transferred always by conduction, and in a liquid or gas, heat is transferred by conduction as well as convection and radiation.

2) Convection: This refers to a process in which heat moves in a liquid together with the flowing portions of the liquid, and if different temperatures occur in a liquid, flow occurs due to the difference in specific gravity, and such flow keeps occurring till the same temperature is reached in the entire liquid.

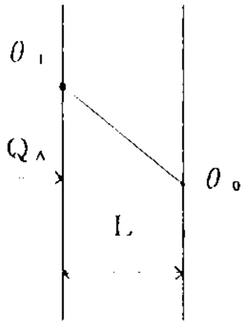
3) Radiation: Every object with heat radiates heat energy from its surface. If this heat energy (electromagnetic wave) is absorbed by another object, it is converted again into heat, to raise the temperature of the object. This heat movement process is called radiation.

Figure 9 Mechanism of heat flow



3.1.2 Basic formulae for heat transfer by conduction

In a steady state, the heat value moving in a solid wall by conduction is proportional to the heating surface area and the temperature difference, and inversely proportional to the heat moving distance (wall thickness).

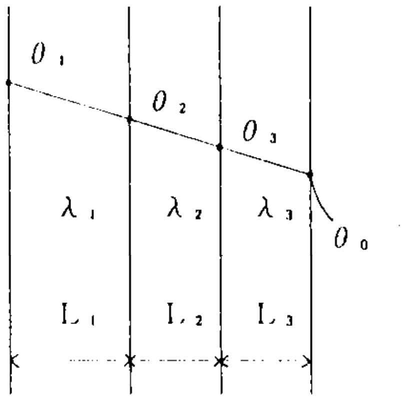


As illustrated, if the thickness of the solid wall is L m, the temperature at both the ends are θ_1 and θ_2, and the heat value transferred per unit area is Q_A kcal/m²h, then we have

$$Q_A = \lambda \frac{\theta_1 - \theta_0}{L} \quad (\text{Kcal/m}^2\text{h}) \cdots\cdots (3\text{-}1)$$

where λ is a proportional constant expressing the heat transfer condition, and is called thermal conductivity (kcal/mh°C).

The heat conduction in a multi-layer flat wall is expressed by the following formula, and the heat values through the respective layers are equal.



$$Q_A = \frac{\theta_1 - \theta_0}{\frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \frac{L_3}{\lambda_3}} \quad (\text{Kcal/m}^2\text{h})$$

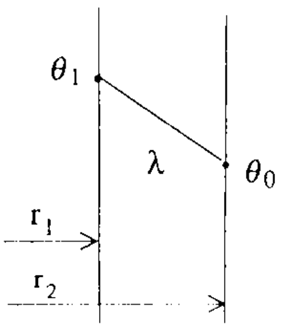
$$= \frac{\theta_1 - \theta_2}{\frac{L_1}{\lambda_1}} = \frac{\theta_2 - \theta_3}{\frac{L_2}{\lambda_2}} = \frac{\theta_3 - \theta_0}{\frac{L_3}{\lambda_3}} \cdots\cdots (3\text{-}2)$$

where $\frac{L}{\lambda}$ is called heat transfer resistance and expressed by R.

If the heat transfer resistance is used, the above formula can be expressed as

$$Q_A = \frac{\theta_1 - \theta_0}{R_1 + R_2 + R_3} \cdots\cdots (3\text{-}3)$$

The heat conduction in a cylindrical wall is expressed by the following formula per unit length.



$$Q_A = \frac{2\pi\lambda\,(\theta_1 - \theta_0)}{l_n\,(r_2/r_1)} \quad (\text{Kcal/mh}) \cdots\cdots (3\text{-}4)$$

To consider this formula in terms of unit outer surface area, let's divide it by outer surface area $2\pi r_2$. We have

$$Q_A = \frac{\lambda(\theta_1 - \theta_0)}{r_2\,l_n\,(r_2/r_1)} \quad (\text{Kcal/m}^2\text{h}) \cdots\cdots (3\text{-}5)$$

This corresponds to the heat transfer formula for a flat wall with the wall thickness L substituted by $r_2 \, l_n (r_2 / r_1)$.

Also for a multi-layer cylinder, similarly,

$$Q_A = \frac{2\pi(\theta_1 - \theta_0)}{\frac{1}{\lambda_1} l_n \frac{r_2}{r_1} + \frac{1}{\lambda_2} l_n \frac{r_3}{r_2} + \cdots + \frac{1}{\lambda_n} l_n \frac{r_{(n+1)}}{r_n}} \text{ (Kcal/mh)} \quad \text{(3-6)}$$

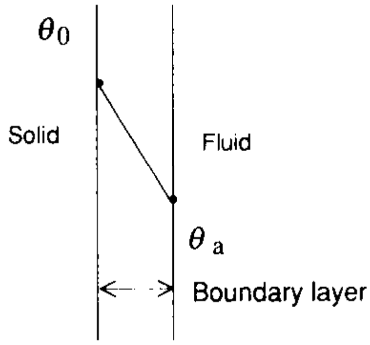
In terms of unit outer surface area,

$$Q_A = \frac{(\theta_1 - \theta_0)}{\frac{r_{(n+1)}}{\lambda_1} l_n \frac{r_2}{r_1} + \frac{r_{(n+1)}}{\lambda_2} l_n \frac{r_3}{r_2} + \cdots + \frac{r_{(n+1)}}{\lambda_n} l_n \frac{r_{(n+1)}}{r_n}} \text{ (Kcal/m}^2\text{h)} \quad \text{(3-7)}$$

3.1.3 Basic formulae for heat transfer by convection

When a fluid moves along a solid, the moving speed is lower at nearer to the wall surface due to the viscosity of the fluid, and becomes 0 at the wall surface.

A fluid flows in either turbulent flow or laminar flow. However, even turbulent flow has a portion near the wall surface, which becomes laminar flow and very low in flow velocity. It is called a boundary layer or laminar film.



The thermal transfer in the boundary layer owes to the heat conduction in the layer. The thickness of the boundary layer depends on the smoothness of the wall surface and the flow velocity and properties of the fluid.

If the thickness of the boundary layer is l and the thermal conductivity of the fluid is λ, then the heat value transmitted by convection can be expressed by

$$Q_c = \lambda / l \, (\theta_0 - \theta_a) \quad \text{(3-8)}$$

However, since it is difficult to decide the thickness of the boundary layer, λ / l is substituted by α_c which is called heat transfer coefficient (Kcal/m^{2}h°C).

For the value of α_c, various empirical formulae are proposed, but the following formulae are generally adopted.

1) Natural convection by air

$$\alpha_c = h_c (\theta_0 - \theta_a)^{0.25} \quad \text{(3-9)}$$

where h_c is a coefficient depending on the wall surface location and is 2.2 for vertical plates, 2.8 for plates facing up and 1.5 for plates facing down.

2) Natural comvection by air with horizontal cylinder like piping

$\alpha_c = 2.1\ ((\theta_0 - \theta_a) / d)^{0.25}$

where α is diameter of cylinder

3) Forced convection by air

$$\alpha_c = 6.122\ V_a^{0.775} + 4.41\ EXP(-0.6\ V_a) \quad \text{......(3-10)}$$

where V_a is the flow velocity of air (m/s).

4) In the case of water cooling

$$X = \theta_w + 0.1\ (\theta_0 - \theta_w)$$

$$\alpha_c = 2830\ (1 + 0.215\ X - 0.00007\ X^2)\ V_\omega^{(0.91-0.00115X)} \quad \text{......(3-11)}$$

where V_ω (m/s) is the flow velocity of water.

3.1.4 Basic formula for heat transfer by radiation

The heat value transmitted by radiation can be expressed by the following formula:

$$Q_R = 4.88\ \varepsilon \left\{ \left(\frac{273 + \theta_0}{100}\right)^4 - \left(\frac{273 + \theta_a}{100}\right)^4 \right\} \quad \text{......(3-12)}$$

This can be expressed by the radiative heat transfer coefficient as follows:

$$\alpha_R = Q / \Delta t = Q / (\theta_0 - \theta_a).$$

In formula (3-12), ε is called blackness or emissivity, and greatly depends on the material on the surface of the solid, being 0.95 for bricks and 0.8 to 0.95 for the painted surface of a metal.

3.1.5 Overall heat transfer

The heat transfer of a general industrial furnace wall can be considered as follows:

Inside of furnace →Inner surface of furnace wall:	Heat transfer by convection + radiation
Inside of furnace wall:	Heat transfer by conduction
Outer surface of furnace wall → Outside air:	Heat transfer by convection + radiation

Therefore, the heat transfer from the inside of a furnace to outside air is expressed as overall heat transfer by the following formula (multi-layer flat plate).

$$Q_r = \frac{\theta_g - \theta_a}{\frac{1}{\alpha_1} + \frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \cdots + \frac{L_n}{\lambda_n} + \frac{1}{\alpha_0}} \quad (\text{Kcal/m}^2\text{h}) \quad \text{......(3-13)}$$

However, since it is often difficult to accurately measure the temperature of the gas in a furnace compared to the temperature of the inner surface of a furnace wall, calculation is often effected assuming "Furnace internal gas temperature" = "Furnace wall inner surface temperature", disregarding the heat transfer coefficient in the furnace.

In this case, the overall heat transfer is

$$Q_T = \frac{\theta_1 - \theta_a}{\frac{L_1}{\lambda_1} \cdots \frac{L_n}{\lambda_n} + \frac{1}{\alpha_0}} \quad (\mathrm{Kcal/m^2h}) \ \ldots\ldots\ldots\ldots (3\text{-}14)$$

In the case of a multi-cylinder,

$$Q_T = \frac{\theta_1 - \theta_a}{\frac{1}{\lambda_1} l_n \frac{r_2}{r_1} + \cdots \frac{1}{\lambda_n} l_n \frac{r_{n+1}}{r_n} + \frac{1}{\alpha_0}} \quad (\mathrm{Kcal/m^2h}) \ \ldots\ldots\ldots\ldots (3\text{-}15)$$

Symbols

θ_1: Furnace wall inner surface temperature, °C

$\theta_2 \sim \theta_n$: Temperature of each boundry of furnace wall, °C

θ_0: Furnace wall outer surface temperature, °C

θ_a: Outside air temperature, °C

θ_g: Furnace internal gas temperature, °C

θ_w: Cooling water temperature, °C

$\lambda_1 \sim \lambda_n$: Thermal conductivity at the average temperature of each refractory material, kcal/mh°C

$R_1 \sim R_n$: Heat transfer resistance of each refractory material

$L_1 \sim L_n$: Thickness of each refractory material, m

$r_1 \sim r_n$: Inner radius of each cylinder, m

V_a, V_W: Flow velocity in air cooling or water cooling, m/s

α_C: Convection heat transfer coefficient, kcal/m^{2}h°C

α_R: Radiation heat transfer coefficient, kcal/m^{2}h°C

Q_A: Heat value transferred by conduction, kcal/m^{2}h

Q_C: Heat value transferred by convection, kcal/m^{2}h

Q_R: Heat value transferred by radiation, kcal/m^{2}h

Q_T: Overall transferred heat value, kcal/m^{2}h

l_n: Natural logarithm

d: Outer diameter of pipe insulation

3.1.6 Calculation procedure

If the furnace internal gas temperature is equal to the furnace wall inner surface temperature as described before, the heat transfer of the furnace wall takes place as conduction from the inner surface to the outer surface of the furnace wall and as convection + radiation from the outer surface of the furnace wall to outside air. The respective heat values transferred are expressed by Q_A, Q_C and Q_R, and calculation is made using the following relation:

$$Q_T = Q_A = Q_C + Q_R \ \ldots\ldots\ldots\ldots (3\text{-}16)$$

Here comes the problem that the thermal conductivities of the refractory materials depend on the temperature, and in this case, we have two unknown values. So, we must resort to trial and error for calculation. Therefore, the following procedure is followed for calculation.

1) Based on the furnace internal temperature, θ_1, and the outside air temperature, θ_a, assume the temperatures of the respective boundaries, θ_2 to θ_n.
2) Find the average temperatures of the refractory materials from the assumed temperatures, and temporarily decide the thermal conductivities of the respective refractory materials, λ_1 to λ_n, from the average temperatures.
3) Find Q_C and Q_R based on the assumed furnace wall outside temperature.
   The approximate value of $Q_C + Q_R$ can be obtained by using Figs. 10 and 11.
4) $Q_A = Q_C + Q_R$. Hence, transform formula (3-2) as follows:

$$\theta_2 = \theta_1 - \frac{Q_A L_1}{\lambda_1}$$

$$\theta_3 = \theta_2 - \frac{Q_A L_2}{\lambda_2}$$

$$\theta_{n+1} = \theta_n - \frac{Q_A L_n}{\lambda_n}$$

   to find the temperatures of the respective boundaries, θ_2 to θ_n.
5) Repeat this assumption and calculation for comparison, till the temperatures of the boundaries obtained by calculation become close to the assumed temperatures. If the assumed temperatures are reasonable, the differences between the assumed values and the calculated values will become within 2° to 3°C after repetition of 4 or 5 times. Thus, the approximate temperatures of the respective boundaries and the approximate dissipated heat value can be obtained.

3.1.7 Standard value of furnace wall outer surface temperature

The furnace wall outer surface temperature of an industrial furnace is recommended by JIS to be not higher than the temperature shown in 2–3 for the furnace internal temperature concerned.

Table 26 Standard furnace wall outer surface temperature

Furnace temperature (°C)	Standard furnace outer surface temperature (°C)	
	Roof	Side wall
1,300	140	120
1,100	125	110
900	110	95
700	90	80

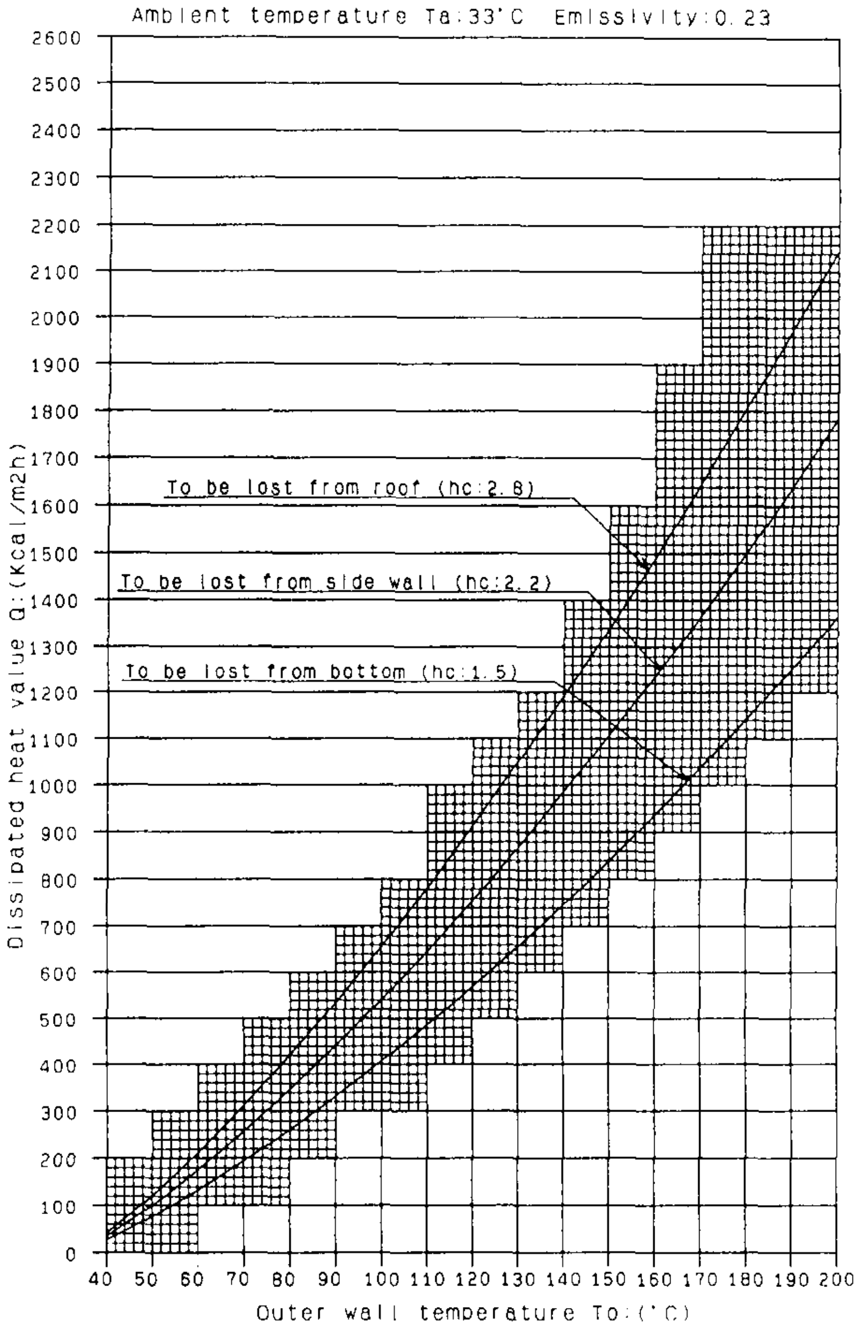


Figure 10 Furnace wall outer surface temperature vs. dissipated heat value — 1

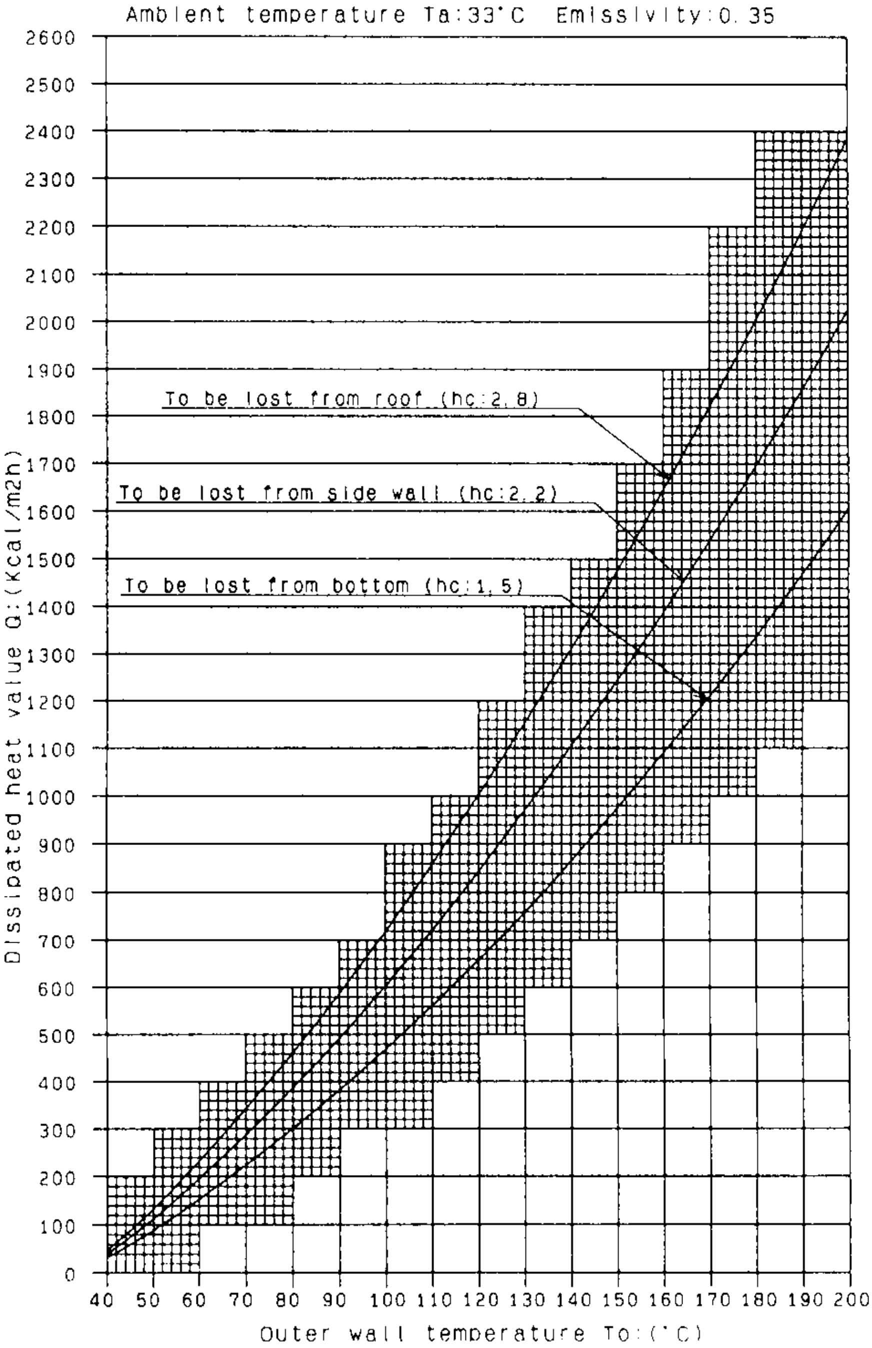


Figure 11 Furnace wall outer surface temperature vs. dissipated heat value — 2

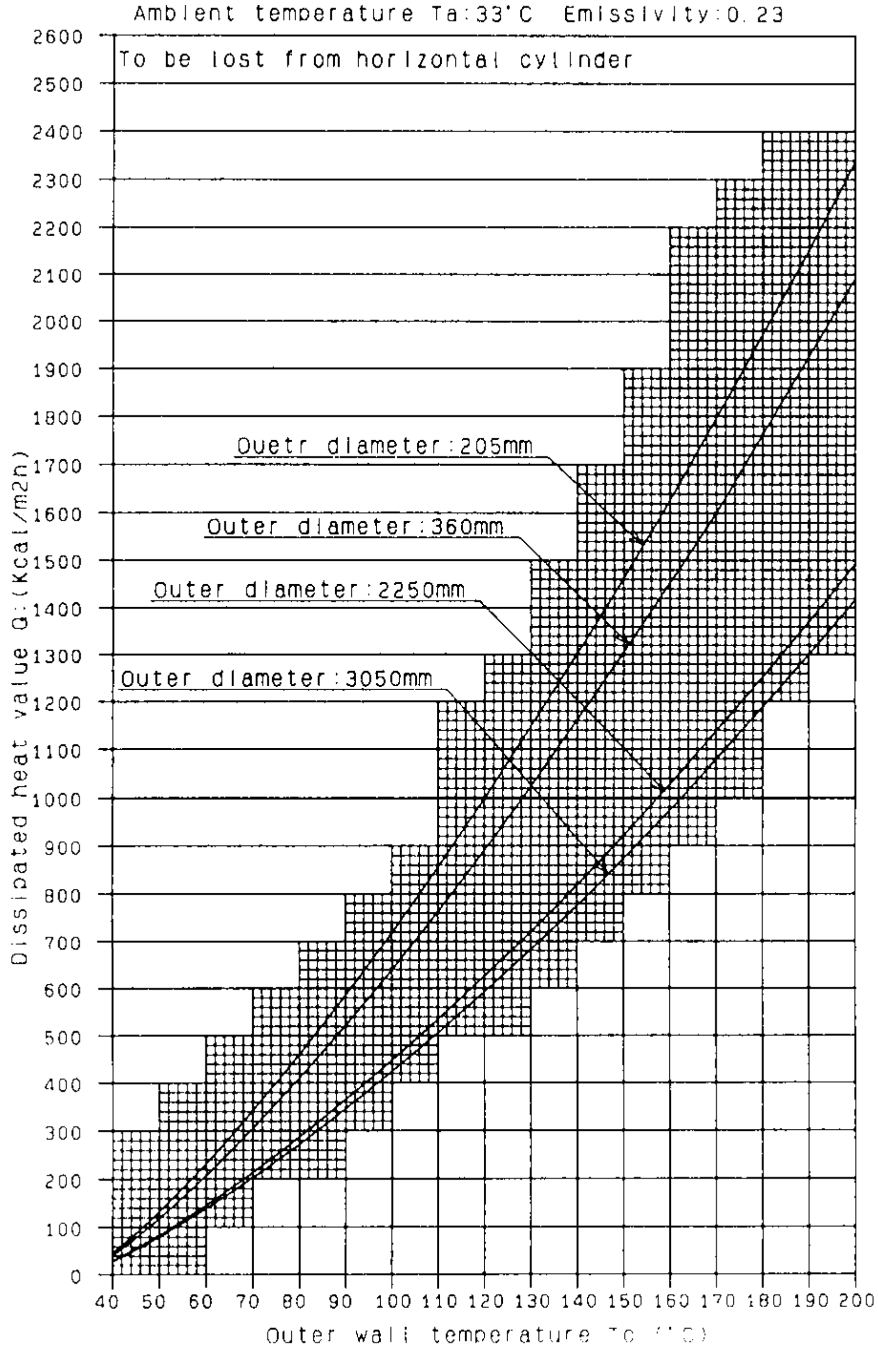


Figure 12 Furnace wall outer surface temperature vs. dissipated heat value — 3

3.2 Heat value accumulated in the refractory materials constituting a furnace wall

The accumulated heat value can be obtained from the following formula:

$$H = L_1\rho_1C_1\left(\frac{\theta_1 + \theta_2}{2} - \theta_s\right) + L_2\rho_2C_2\left(\frac{\theta_2 + \theta_3}{2} - \theta_s\right)$$

$$+ L_n\rho_nC_n\left(\frac{\theta_n + \theta_0}{2} - \theta_s\right) \quad (\text{Kcal/m}^2) \quad \ldots\ldots (3\text{-}17)$$

Symbols

$L_1 \sim L_n$: Thickness of each refractory material constituting the furnace wall, m

$\rho_1 \sim \rho_n$: Density of each refractory material constituting the furnace wall, kg/m^3

$C_1 \sim C_n$: Specific heat of each refractory material constituting the furnace wall, kcal/kg°C

θ_1: Furnace wall inner surface temperature, °C

θ_0: Furnace wall outer surface temperature, °C

$\theta_2 \sim \theta_n$: Temperature of each boundary of the furnace wall, °C

θ_s: Temperature of the furnace wall before heating, °C

3.3 Economical heat insulation thickness

In heat insulation work, a thicker heat insulator causes less heat value to be dissipated but requires a higher heat insulation work cost. Therefore, the economical heat insulation thickness should be selected to minimize the sum of "Heat Insulation Work Cost + Counter Value for the Dissipated Heat Value after Completion of the Work", considering the annual depreciation.

JIS A 9501 specifies the economical thicknesses of insulators used for heat insulation work, as follows.

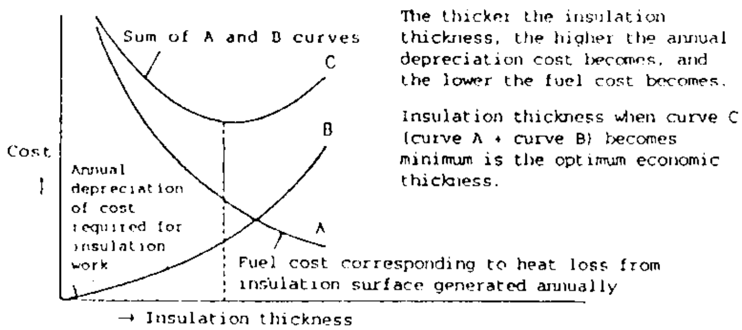


Figure 13 Relationship between insulation thickness and cost [11)]

3.3.1 Formulae for calculating the thickness of insulator used for heat insulation work, and dissipated heat value (economical heat insulation thickness)

The formulae for calculating the dissipated heat value are the same as formulae 3-14 and 3-15, though different in symbols used.

(1) Pipe

In the case of a pipe, the thickness of the insulator used and the dissipated heat value are calculated from the following formulae.

In the case of a pipe, the thickness of the insulator used and the dissipated heat value are calculated from the following formulae.

Thickness of insulator: The thickness of the insulator should be calculated from the following formulae, to minimize the value of F_1.

$$F1 = \frac{\pi}{4}(d_1^2 - d_0^2)\, aN \times 10^3 + bhQ \times 10^{-3} \quad \text{.......(3-18)}$$

$$X = \frac{d_1 - d_0}{2} \quad \text{.......(3-19)}$$

Dissipated heat value: The dissipated heat value should be calculated from the following formula.

$$Q = \frac{2\pi(\theta_0 - \theta_r)}{\frac{1}{\lambda} \ln \frac{d_1}{d_0} + \frac{2}{\alpha d_1}} \quad \text{.......(3-20)}$$

(2) Flat surface

The thickness of the insulator used for a flat surface and the dissipated heat value should be calculated from the following formulae.

Thickness of insulator: The thickness of the insulator should be calculated from the following formula, to minimize the value of F_2.

$$F_2 = XaN \times 10^3 + bhQ \times 10^{-3} \quad \text{.......(3-21)}$$

Dissipated heat value: The dissipated heat value should be calculated from the following formulae.

$$Q = \frac{\theta_0 - \theta_r}{\frac{X}{\lambda} + \frac{1}{a}} \quad \text{.......(3-22)}$$

$$N = \frac{n(1+n)^m}{(1+n)^m - 1} \quad \text{.......(3-23)}$$

where

F_1: Annual total cost of heat insulation for pipe (yen/m)

F_2: Annual total cost of heat insulation for flat surface (yen/m^2)

a : Construction price of insulator (10^3 yen/m^3)

b : Heat value price (yen/10^3 W·h) {yen/860 kcal}

n : Annual interest

m : Years of use

N : Depreciation rate

d_1: Outer diameter of insulator (m)

d_0: Inner diameter of insulator (based on outer diameter of pipe) (m)

h : Annual hours of use

X : Thickness of insulator (m)

Q : Dissipated heat value (in case of pipe) (W/m) {kcal/m·h}
(in case of flat surface) (W/m^2) {$kcal/m^2 \cdot h$}

λ : Thermal conductivity of insulator (W/m·K) {kcal/m·h·°C}

α : Heat transfer coefficient of surface ($w/m^2 \cdot K$) {$kcal/m^2 \cdot h \cdot °C$}

θ_0: Internal temperature (°C)

θ_r: Outside air temperature (°C)

θ_s: Surface temperature after heat or cold insulation (°C)

ln: Natural logarithm

3.2.2 Economical insulation thicknesses and dissipated heat values

Economical insulation thicknesses and dissipated heat values for the following conditions are shown in Tables 24 to 30 for reference.

Outside air temperature (room temperature):	20°C
Heat transfer coefficient of surface:	12 $W/m^2 \cdot K$ {10.32 $kcal/m^2 \cdot h \cdot °C$}
Annual interest:	0.07
Years of use:	10 years
Construction price of insulator:	1.2 ($12000X_0^{-K}$ + 100) $10^3 yen/m^3$

where X_0: Thickness of insulator (mm)

K: Constant

The value for the outer diameter of the pipe concerned is selected from the following:

15A	~	20A	K = 1.09
25A	~	50A	K = 1.13
65A	~	150A	K = 1.17
200A	~	300A	K = 1.21
350A	~	Flat surface	K = 1.28

However, if the thickness of insulator is 150 mm or more, 150 mm should be used for calculating the construction price.

[Reference] Tables of Economical Insulation Thicknesses

Table 27 Insulation thicknesses and dissipated heat values of rock wool insulators

Rock wool pipe covers

(Insulation thickness in mm, dissipated heat value in W/m, and θ temperature in °C)

Thermal conductivity (W/m·K) $-20°C \leq \theta < 100°C$ $0.031\,4 + 0.000\,174\,\theta$

$100°C \leq \theta \leq 600°C$ $0.038\,4 + 7.13 \times 10^{-5} \cdot \theta + 3.51 \times 10^{-7} \cdot \theta^2$

Annual hours of use (hour) 3 000

Pipe inside temperature (°C)	Nominal designation of pipe* A	15	20	25	32	40	50	65	80	100	125	150	200	250	300	350	400	450	500	550	600
	B	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4	5	6	8	10	12	14	16	18	20	22	24
100	IT	25	25	25	25	30	30	35	35	40	40	40	45	45	45	50	50	50	50	50	50
	DHV	16	19	22	25	25	28	30	34	37	44	50	57	69	80	81	91	101	111	121	131
150	IT	25	30	35	35	35	40	45	45	50	50	55	55	60	60	60	65	65	65	65	65
	DHV	29	31	32	37	40	43	46	51	57	67	71	88	98	113	124	130	145	159	173	187
200	IT	35	35	40	45	45	45	50	55	60	60	65	65	70	70	75	75	75	80	80	80
	DHV	38	43	45	48	52	60	65	68	77	89	95	117	131	151	157	176	194	202	219	237
250	IT	40	40	45	50	50	55	60	60	65	70	70	80	80	85	85	85	90	90	90	90
	DHV	50	56	59	64	69	74	92	90	102	111	126	140	165	181	198	222	234	256	278	299
300	IT	45	45	50	55	60	60	70	70	75	80	80	90	90	95	95	100	100	100	105	105
	DHV	63	70	75	81	83	94	99	110	123	136	153	171	201	222	242	259	286	312	325	351
350	IT	50	55	60	65	65	70	75	80	85	90	90	95	100	105	110	110	110	115	115	115
	DHV	77	83	89	96	103	112	123	131	147	162	182	213	240	265	279	311	342	360	390	420
400	IT	55	60	65	70	70	75	85	85	90	95	100	105	110	115	120	120	125	125	130	130
	DHV	94	100	108	117	125	136	145	159	179	198	214	250	283	313	330	366	390	425	445	479
450	IT	60	65	70	74	80	85	90	95	100	105	110	115	125	125	130	135	135	140	140	140
	DHV	112	120	129	140	145	158	174	185	208	230	249	291	320	364	385	414	455	481	520	558
500	IT	65	70	80	85	85	90	100	100	110	115	120	125	135	140	140	145	150	150	150	150
	DHV	132	142	148	161	171	187	201	219	240	265	288	336	370	409	445	480	512	557	601	645
550	IT	70	75	85	90	95	100	105	110	120	125	130	140	145	150	150	150	150	150	150	150
	DHV	155	166	174	189	196	213	236	251	276	304	330	376	425	470	510	564	618	671	706	758
600	IT	80	85	90	95	100	105	115	120	125	135	140	150	150	150	155	155	160	165	165	165
	DHV	175	188	202	220	228	249	268	285	322	347	376	429	495	561	594	657	702	745	803	861

Note*: The nominal designation of pipe is in conformity with JIS G 3452 (Carbon Steel Pipes for Piping).

Remark: The thicknesses of this table are expressed in 5 mm steps, and do not always agree with the thicknesses of the products actually sold.

IT: Insulation thickness; DHV: Dissipated heat value

Table 28 Insulation thicknesses and dissipated heat values of rock wool insulators

Rock wool heat insulating boards Nos. 1, 2 and 3, and felt

(Insulation thickness in mm, dissipated heat value in W/m^2, and θ temperature in °C)

Thermal conductivity (W/m·K)		$-20°C \le \theta < 100°C$ $0.0337 + 0.000151\,\theta$ $100°C \le \theta \le 600°C$ $0.0395 + 4.71 \times 10^{-5} \cdot \theta + 5.03 \times 10^{-7} \cdot \theta^2$	$-20°C \le \theta < 100°C$ $0.0337 + 0.000128\,\theta$ $100°C \le \theta \le 600°C$ $0.0407 + 2.52 \times 10^{-5} \cdot \theta + 3.34 \times 10^{-7} \cdot \theta^2$	$-20°C \le \theta < 100°C$ $0.0360 + 0.000116\,\theta$ $100°C \le \theta \le 600°C$ $0.0419 + 3.28 \times 10^{-5} \cdot \theta + 2.63 \times 10^{-7} \cdot \theta^2$	$-20°C \le \theta < 100°C$ $0.0349 + 0.000186\,\theta$ $100°C \le \theta \le 600°C$ $0.0337 + 1.63 \times 10^{-5} \cdot \theta + 3.84 \times 10^{-7} \cdot \theta^2$
Annual hours of use (hour)		3,000	3,000	3,000	3,000
Internal temperature (°C)	Kind	Heat reserving board No. 1	Heat reserving board No. 2	Heat reserving board No. 3	Felt
100	IT	60	55	60	60
	DHV	54	57	54	58
150	IT	75	75	75	80
	DHV	78	74	76	80
200	IT	90	90	90	95
	DHV	99	92	94	106
250	IT	110	105	105	115
	DHV	115	108	110	126
300	IT	125	120	120	135
	DHV	137	125	125	147
350	IT	145	130	130	150
	DHV	155	147	146	174
400	IT	150	150	145	155
	DHV	192	160	162	215
450	IT	160	150	150	–
	DHV	226	196	190	–
500	IT	180	160	155	–
	DHV	249	223	221	–
550	IT	200	175	170	–
	DHV	275	245	240	–
600	IT	220	190	185	–
	DHV	302	269	260	–

Remark: The thicknesses of this table are expressed in 5 mm steps, and do not always agree with the thicknesses of the products actually sold.

IT: Insulation thickness; DHV: Dissipated heat value

Table 29 Insulation thicknesses and dissipated heat values of glass wool insulators

Glass wool pipe cover and heat insulating board No. 2 48 K

(Insulation thickness in mm, dissipated heat value in W/m for pipe in W/m² for flat surface, and θ temperature in °C)

Themal conductivity (W/m·K)	$-20°C \le \theta \le 350°C$ $0.0282 + 7.2584 \times 10{-}5 \cdot \theta + 5.0224 \times 10{-}7 \cdot \theta^2$
Annual hours of use (hour)	3 000

Pipe inside temperature (°C)	Nominal designation of pipe* A	15	20	25	32	40	50	65	80	100	125	150	200	250	300	350	400	450	500	550	600	Flat surface
	B	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4	5	6	8	10	12	14	16	18	20	22	24	
100	IT	25	25	25	25	30	30	35	35	35	40	40	45	45	45	50	50	50	50	50	50	55
	DHV	16	18	21	24	24	27	29	33	40	42	48	55	66	77	78	87	97	107	117	126	56
150	IT	25	30	30	35	35	40	45	45	50	50	50	55	60	60	60	65	65	65	65	65	75
	DHV	29	30	34	36	39	42	45	50	56	65	74	86	95	110	121	127	141	155	169	183	75
200	IT	35	35	40	45	45	45	50	55	60	60	65	65	70	70	75	75	75	80	80	80	90
	DHV	38	43	45	49	53	60	66	69	77	89	96	118	132	152	158	177	196	203	221	238	98
250	IT	40	40	45	50	50	55	60	65	70	70	75	80	80	85	85	90	90	90	95	95	110
	DHV	52	58	62	66	72	77	85	90	101	116	125	146	172	189	206	220	243	266	276	298	117
300	IT	45	50	55	60	60	60	65	70	75	75	80	85	95	95	100	100	105	105	105	110	130
	DHV	68	72	77	83	83	90	97	107	113	133	146	158	208	239	251	279	296	323	350	363	137
350	IT	50	55	60	65	70	70	80	80	85	90	95	100	105	110	115	115	120	120	120	125	145
	DHV	86	92	99	107	110	124	132	145	164	181	195	228	258	285	300	334	355	387	419	436	164

Remark: The thicknesses of this table are expressed in 5 mm steps, and do not always agree with the thicknesses of the products actually sold.

IT: Insulation thickness; DHV: Dissipated heat value

Table 30 Insulation thicknesses and dissipated heat values of calcium silicate insulators

Calcium silicate pipe cover and heat insulating board No. 1-13

(Insulation thickness in mm, dissipated heat value in W/m for pipe in W/m^2 for flat surface, and θ temperature in °C)

Thermal conductivity (W/m·K) $0°C \le \theta \le 300°C$ $0.040\,7 + 1.28 \times 10^{-4} \cdot \theta$

$300°C < \theta \le 800°C$ $0.055\,5 + 2.05 \times 10–5 \cdot \theta + 1.93 \times 10^{-7} \cdot \theta^2$

Annual hours of use (hour) 3 000

Pipe inside temperature (°C)	Nominal designation of pipe* A	15	20	25	32	40	50	65	80	100	125	150	200	250	300	350	400	450	500	550	600	Flat surface
	B	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4	5	6	8	10	12	14	16	18	20	22	24	
100	IT	25	25	25	30	30	30	35	35	40	40	45	45	50	50	50	50	55	55	55	55	60
	DHV	19	21	25	26	28	32	35	39	43	50	52	65	72	84	92	104	106	117	128	138	61
150	IT	25	30	35	35	40	40	45	45	50	55	55	60	60	65	65	65	65	70	70	70	80
	DHV	32	34	35	41	41	47	51	57	64	69	78	91	108	118	129	145	160	165	180	195	80
200	IT	35	35	40	45	45	50	55	55	60	60	65	70	70	75	75	80	80	80	80	80	95
	DHV	41	46	49	52	56	61	66	74	83	96	102	119	141	154	169	180	199	218	237	255	100
250	IT	40	40	45	50	50	55	60	65	65	70	75	80	80	85	85	90	90	90	90	90	110
	DHV	52	58	62	67	72	78	85	90	106	116	125	146	172	189	207	221	244	267	277	299	117
300	IT	45	45	50	55	60	60	65	70	75	80	80	85	90	95	95	100	100	100	105	105	125
	DHV	63	71	75	81	84	95	104	110	124	137	154	180	203	223	244	261	288	314	328	353	133
350	IT	50	50	55	60	65	70	75	75	80	85	90	95	100	105	105	110	110	110	115	115	135
	DHV	75	83	89	97	99	108	119	131	148	163	176	206	233	257	280	301	331	361	377	406	153
400	IT	55	55	60	65	70	75	80	85	90	95	95	105	110	110	115	120	120	120	125	125	150
	DHV	87	97	104	112	116	126	139	148	167	184	206	233	263	301	317	341	374	408	428	460	168
450	IT	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	125	130	130	135	135	150
	DHV	104	111	119	129	134	146	161	170	192	212	230	269	304	336	355	394	419	457	479	515	200
500	IT	60	65	70	75	80	85	90	95	100	105	110	120	125	130	135	135	140	140	145	145	160
	DHV	118	126	136	147	152	166	183	195	220	242	263	298	337	373	394	437	466	507	533	572	221
550	IT	65	70	75	85	85	90	100	100	110	115	120	125	135	140	140	145	150	150	150	150	170
	DHV	133	142	153	161	172	188	202	220	242	267	289	338	372	412	447	482	515	560	604	649	243
600	IT	70	75	80	90	90	94	105	110	115	120	125	135	140	145	150	150	150	150	150	150	185
	DHV	149	160	172	182	194	211	227	241	272	300	326	371	419	464	491	543	595	647	698	749	258
650	IT	75	80	85	95	95	100	110	115	120	130	130	135	145	150	150	150	155	155	160	160	200
	DHV	166	178	192	203	216	236	254	270	305	328	328	356	406	520	564	623	666	723	761	817	274
700	IT	80	85	95	100	100	110	115	120	130	135	140	150	150	150	155	160	165	165	170	170	210
	DHV	185	198	209	227	241	257	283	301	332	366	397	453	523	593	628	678	725	786	828	888	298
750	IT	85	90	100	105	105	115	125	130	135	145	150	150	150	155	165	170	170	175	180	180	225
	DHV	205	220	232	251	267	285	308	328	369	399	432	514	594	657	681	736	804	853	899	964	316
800	IT	90	95	105	110	115	120	130	135	145	150	150	155	160	165	175	180	180	185	190	190	240
	DHV	227	243	257	278	290	315	341	363	401	441	488	568	642	711	738	797	870	924	975	1,043	335

Remark: The thicknesses of this table are expressed in 5 mm steps, and do not always agree with the thicknesses of the products actually sold.

IT: Insulation thickness; DHV: Dissipated heat value

Table 31 Insulation thicknesses and dissipated heat values of calcium silicate insulators

Calcium silicate pipe cover and heat insulating board No. 2-17

(Insulation thickness in mm, dissipated heat value in W/m for pipe in W/m² for flat surface, and θ temperature in °C)

Thermal conductivity (W/m·K) $0°C \le \theta \le 200°C$ $0.046\,5 + 1.16 \times 10^{-4} \cdot \theta$

$200°C < \theta \le 600°C$ $0.057\,0 - 9.36 \times 10–6 \cdot \theta + 3.74 \times 10^{-7} \cdot \theta^{1}$

Annual hours of use (hour) 3 000

Pipe inside temperature (°C)	Nominal designation of pipe* A	15	20	25	32	40	50	65	80	100	125	150	200	250	300	350	400	450	500	550	600	Flat surface
	B	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4	5	6	8	10	12	14	16	18	20	22	24	
100	IT	25	25	25	30	30	35	35	40	40	45	45	50	50	50	55	55	55	55	55	55	65
	DHV	21	23	27	28	31	32	38	39	47	50	58	66	79	92	94	105	117	128	140	152	62
150	IT	30	30	35	40	40	40	45	50	50	55	55	60	65	65	70	70	70	70	70	70	80
	DHV	32	37	38	41	44	51	56	58	69	75	85	99	110	128	148	165	180	180	196	211	87
200	IT	35	35	40	45	45	50	55	55	60	65	65	65	75	75	80	80	80	85	85	85	100
	DHV	44	49	52	56	61	65	72	79	89	97	110	128	144	166	173	193	214	223	242	261	102
250	IT	40	45	50	50	55	55	60	65	70	70	75	80	85	85	90	90	95	95	95	95	115
	DHV	55	59	63	71	73	83	91	96	108	125	134	157	177	203	212	237	250	274	297	320	121
300	IT	45	50	55	55	60	65	70	70	75	80	85	90	95	95	100	100	105	105	105	110	130
	DHV	60	72	77	88	90	98	108	119	134	147	159	186	210	240	252	281	298	325	353	365	138
350	IT	50	55	60	65	65	70	75	80	85	90	90	100	105	105	110	110	115	115	120	120	145
	DHV	81	87	93	101	108	117	130	137	155	171	191	216	244	279	294	327	347	379	396	426	155
400	IT	55	60	65	70	70	75	85	85	90	95	100	110	115	115	120	125	125	125	130	130	150
	DHV	96	103	110	119	128	139	148	163	184	203	219	248	281	320	338	364	400	435	456	491	185
450	IT	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	135	140	140	140	155
	DHV	112	120	129	140	145	158	174	185	209	231	250	292	330	365	386	416	456	482	521	560	217
500	IT	65	70	75	80	85	90	95	100	110	115	120	125	130	135	140	145	145	150	150	150	170
	DHV	130	139	150	163	169	184	203	216	237	261	283	331	374	414	438	472	548	548	592	635	238
550	IT	70	75	80	90	90	95	105	110	115	120	125	135	140	145	150	150	150	150	150	150	185
	DHV	150	161	173	183	195	212	228	243	274	302	328	373	422	467	494	547	599	651	702	754	260
600	IT	75	80	90	95	100	105	110	115	125	130	135	145	150	150	150	155	155	160	160	165	200
	DHV	172	184	194	210	218	238	263	279	308	339	368	420	474	537	583	629	688	730	787	824	284

Remark: The thicknesses of this table are expressed in 5 mm steps, and do not always agree with the thicknesses of the products actually sold.

IT: Insulation thickness; DHV: Dissipated heat value

Table 32 Insulation thicknesses and dissipated heat values of water repellent perlite insulators

(a) Water repellent perlite pipe cover and heat insulating board No. 1

(Insulation thickness in mm, dissipated heat value in W/m for pipe in W/m^2 for flat surface, and θ temperature in °C)

Themal conductivity (W/m·K): $0°C \le \theta \le 800°C$ $0.063\,2 + 1.26 \times 10^{-4} \cdot \theta + 2.67 \times 10^{-8} \cdot \theta^2$

Annual hours of use (hour): 3 000

Pipe inside temperature (°C)	Nominal designation of pipe* A	15	20	25	32	40	50	65	80	100	125	150	200	250	300	350	400	450	500	550	600	Flat surface
	B	1/2	3/4	1	1 1/4	1 1/2	2	2 1/2	3	4	5	6	8	10	12	14	16	18	20	22	24	
100	IT	25	25	30	30	35	35	40	40	45	45	50	55	55	55	60	60	60	60	60	60	70
	DHV	26	30	31	36	36	42	45	50	56	65	69	80	95	110	113	127	141	155	169	183	75
150	IT	30	35	40	40	45	45	50	55	55	60	60	65	70	70	75	75	75	80	80	80	90
	DHV	41	44	46	53	54	61	67	70	84	91	104	121	135	156	162	181	201	209	227	245	101
200	IT	40	40	45	50	50	55	60	65	65	70	75	80	80	85	85	90	90	90	95	95	110
	DHV	53	59	63	68	73	80	87	92	109	119	129	150	177	195	213	227	251	274	285	307	121
250	IT	45	45	50	55	60	60	70	70	75	80	85	90	95	95	100	100	105	105	105	105	125
	DHV	67	75	80	87	89	101	107	118	133	146	158	184	208	239	251	279	296	323	350	377	142
300	IT	50	55	60	65	65	70	75	80	85	90	90	100	105	105	110	110	115	115	115	115	145
	DHV	82	87	94	101	109	118	130	138	156	172	193	217	246	281	296	329	350	381	413	429	157
350	IT	55	60	65	70	70	75	85	85	90	95	100	105	110	115	120	120	125	125	130	130	150
	DHV	96	103	111	120	128	140	149	164	185	204	221	258	292	322	340	378	402	438	459	494	186
400	IT	60	65	70	75	75	80	90	95	100	105	110	115	120	125	130	130	135	135	140	140	155
	DHV	111	119	128	139	149	162	173	184	208	229	249	290	329	363	384	426	454	494	519	557	216
450	IT	65	70	75	80	85	90	95	100	105	110	115	125	130	135	140	140	145	145	150	150	165
	DHV	127	136	146	159	165	179	198	210	237	262	284	284	365	404	428	473	505	549	578	620	239
500	IT	70	75	80	85	90	95	100	105	115	120	125	130	140	145	145	150	150	150	150	150	180
	DHV	143	153	165	179	186	202	223	237	261	288	312	365	402	445	483	521	571	620	669	719	254
550	IT	75	75	85	90	95	100	105	110	120	125	130	140	145	150	150	150	150	155	155	155	195
	DHV	159	175	184	199	207	226	249	265	292	322	349	398	450	498	540	597	653	692	747	802	269
600	IT	75	80	90	95	100	105	115	120	125	130	135	145	150	150	150	155	160	160	165	165	205
	DHV	180	193	203	221	229	250	270	287	323	357	387	441	498	564	612	660	706	766	807	865	291
650	IT	80	85	95	100	105	110	120	125	130	140	145	150	150	155	160	165	165	170	175	175	220
	DHV	198	212	224	243	243	275	297	316	356	384	417	485	560	620	657	710	776	823	868	930	305
700	IT	85	90	100	105	110	115	125	130	140	145	150	150	155	160	170	170	175	180	180	185	230
	DHV	216	232	244	265	276	300	325	346	381	420	456	542	612	677	703	775	829	880	948	994	326
750	IT	90	95	105	110	115	120	130	135	145	150	150	155	160	165	175	180	185	185	190	190	245
	DHV	235	252	266	288	300	327	353	376	415	457	506	589	665	736	764	826	884	957	1010	1081	340
800	IT	95	100	110	115	120	125	135	140	150	150	150	160	170	175	185	185	190	195	200	200	255
	DHV	254	272	288	312	325	354	383	407	450	505	558	637	705	780	812	894	957	1016	1072	1147	361

Remark: The thicknesses of this table are expressed in 5 mm steps, and do not always agree with the thicknesses of the products actually sold.

IT: Insulation thickness; DHV: Dissipated heat value

Table 33 Insulation thicknesses and dissipated heat values of water repellent perlite insulators

Water repellent perlite pipe cover and heat insulating board No. 2

(Insulation thickness in mm, dissipated heat value in W/m for pipe in W/m², for flat surface and θ temperature in °C)

Thermal conductivity (W/m·K)	$0°C \le \theta \le 600°C$ $0.0483 + 1.27 \times 10^{-4} \cdot \theta + 3.70 \times 10^{-8} \cdot \theta^2$
Annual hours of use (hour)	3 000

Pipe inside temperature (°C)	Nominal designation of pipe*																							
		A	15	20	25	32	40	50	65	80	100	125	150	200	250	300	350	400	450	500	550	600	Flat surface
		B	½	¾	1	1¼	1½	2	2½	3	4	5	6	8	10	12	14	16	18	20	22	24	
100	IT		25	25	25	30	30	35	35	40	40	45	45	50	50	50	55	55	55	55	55	55	65
	DHV		21	24	28	29	32	34	40	41	49	53	60	59	83	96	96	110	122	134	146	159	65
150	IT		30	30	35	40	40	45	45	50	55	55	55	60	65	65	70	70	70	70	70	75	85
	DHV		34	38	40	43	47	50	58	61	68	79	90	104	116	134	139	156	172	189	206	210	87
200	IT		35	40	45	45	50	50	5	60	60	65	70	75	75	80	80	80	85	85	85	85	100
	DHV		46	49	52	59	60	69	76	79	94	103	111	129	167	167	183	205	215	236	256	276	108
250	IT		40	45	50	50	55	60	65	65	70	75	75	85	85	90	90	95	95	95	100	100	115
	DHV		59	62	67	76	77	84	92	102	115	126	142	159	187	206	225	241	265	290	302	325	128
300	IT		45	50	55	60	60	65	70	75	80	80	85	90	95	100	100	105	105	110	110	110	130
	DHV		72	76	82	88	95	103	114	120	135	155	167	196	221	244	266	285	314	330	358	386	146
350	IT		50	55	60	65	65	70	80	80	85	90	95	100	105	110	110	115	115	120	120	120	145
	DHV		85	91	97	105	113	123	130	143	162	178	193	225	255	281	306	329	362	382	413	445	162
400	IT		55	60	65	70	75	75	85	85	95	100	100	110	115	120	120	125	125	130	130	130	150
	DHV		98	105	113	123	127	143	152	167	183	201	255	255	288	319	347	373	410	433	469	504	190
450	IT		60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	135	140	140	140	155
	DHV		113	121	130	141	146	159	175	186	210	232	251	293	332	367	388	418	458	485	524	563	218
500	IT		65	70	75	80	85	90	95	100	105	110	115	125	130	135	140	140	145	150	150	150	170
	DHV		127	136	147	159	165	180	199	211	238	263	285	324	366	406	429	475	507	537	580	622	233
550	IT		70	75	80	85	90	95	100	105	115	120	125	135	140	145	150	150	150	150	150	150	180
	DHV		143	153	165	179	185	202	223	237	261	288	312	355	402	445	471	521	570	620	669	718	254
600	IT		75	80	85	90	95	100	110	110	120	125	130	140	145	150	150	150	150	150	155	160	195
	DHV		159	170	183	199	207	225	243	264	291	321	348	396	448	496	538	595	652	690	745	780	268

Remark: The thicknesses of this table are expressed in 5 mm steps, and do not always agree with the thicknesses of the products actually sold.

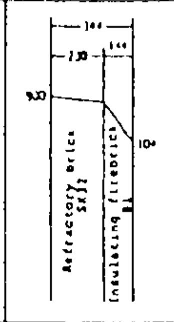
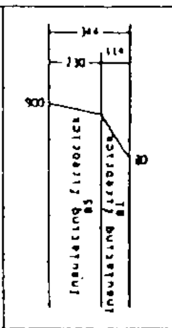
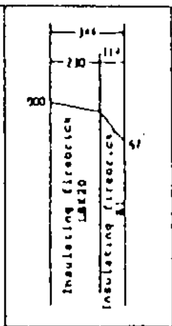
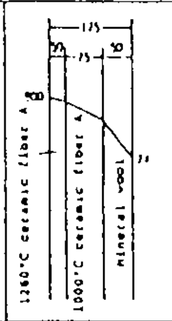
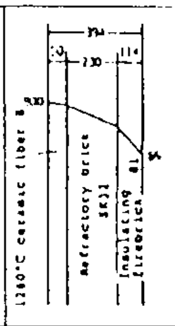
IT: Insulation thickness; DHV: Dissipated heat value

3.4 Typical insulating structures

3.4.1 General structure (example) and comparison of related specifications

Table 34 Furnace wall thickness: 344 mm; furnace wall surface temperature: 900°C 12)

Atmospheric temperature: 25°C
emissivity: 0.85

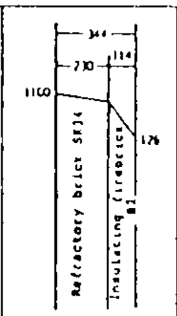
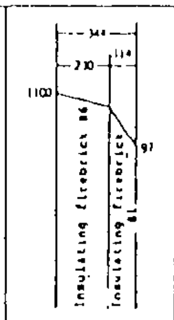
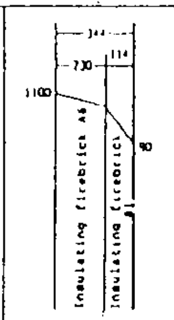
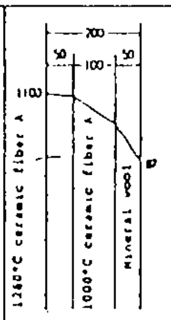
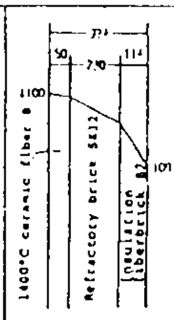
Furnace wall structure						
Emission calorific value Q(KJ/m²h)		3,633	2,252	1,591	1,946	2,574
Heat accumulation value H(KJ/m²)		382,224	142,282	84,515	12,055	297,959
Continuous operation 6000 h/year	Emission calorific value (KJ/m² · year)	21.801×10^3	13.512×10^3	9.544×10^3	11.679×10^3	15.446×10^3
	Rate (%)	100	62.0	43.8	53.6	70.9
	Fuel saving (kg/m².year)	-	360	537	440	276
*Batch operation 40weeks/year	Total heat loss (KJ/m² · year)	31.094×10^3	15.488×10^3	10.302×10^3	8.950×10^3	23.119×10^3
	Rate (%)	100	49.8	33.1	28.8	74.4
	Fuel saving (kg/m².year)	-	678	903	967	346

Note: Ceramic fiber suffix A indicates blanket. Ceramic fiber suffix B indicates block.

* Operation days = 5 days/week, operation hours = 1 batch, steady state = 15 h/day, 75 h/week, temperature rise stop = 9 h/day, 45 h/week, cooling down = 2 days

Table 35 Furnace wall thickness: 344 mm; furnace wall surface temperature: 1100°C 12)

Atmospheric temperature: 25°C
emissivity: 0.85

Furnace wall structure						
Emission calorific value Q(KJ/m²h)		4,973	3,227	2,834	2,607	3,960
Heat accumulation value H(KJ/m²)		468,120	200,928	154,547	17,204	401,270
Continuous operation 6000 h/year	Emission calorific value (KJ/m² · year)	29.838×10^3	19.364×10^3	17.004×10^3	15.647×10^3	23.760×10^3
	Rate (%)	100	64.9	57.0	52.4	79.6
	Fuel saving (kg/m².year)	-	582	713	788	338
*Batch operation 40weeks/year	Total heat loss (KJ/m² · year)	40.357×10^3	23.961×10^3	18.510×10^3	12.035×10^3	33.279×10^3
	Rate (%)	100	59.4	45.9	29.8	82.4
	Fuel saving (kg/m².year)	-	1,016	1,214	1,573	393

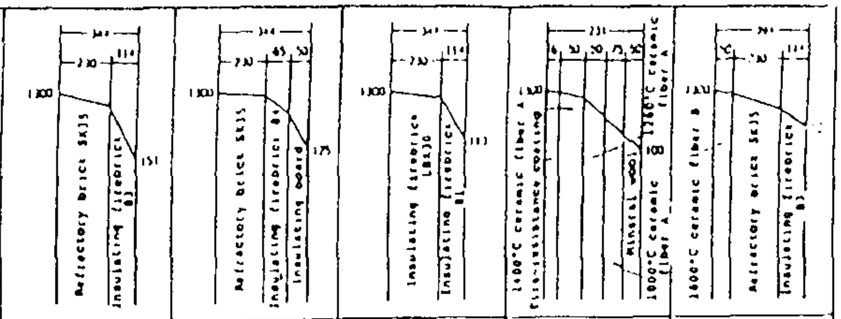
Note: Ceramic fiber suffix A indicates blanket. Ceramic fiber suffix B indicates block.

* Operation days = 5 days/week, operation hours = 1 batch, steady state = 15 h/day, 75 h/week, temperature rise stop = 9 h/day, 45 h/week, cooling down = 2 days

Table 36 Furnace wall thickness: 344 mm; furnace wall surface temperature: 1300°C [12)]

Atmospheric temperature: 25°C
emissivity: 0.85

Furnace wall structure



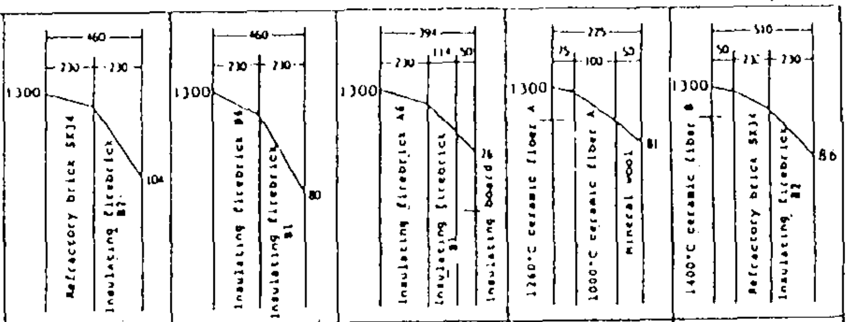
Emission calorific value Q (KJ/m².h)		6,919	4,973	4,115	3,378	5,588
Heat accumulation value H (KJ/m²)		551,008	579,803	440,904	45,963	480,427
Continuous operation 6000 h/year	Emission calorific value (KJ/m² · year)	41.517×10^3	29.838×10^3	24.794×10^3	20.290×10^3	33.580×10^3
	Rate (%)	100	71.9	59.8	48.8	80.8
	Fuel saving (kg/m².year)	–	930	1,110	1,492	636
*Batch operation (weeks/year)	Total heat loss (KJ/m² · year)	53.141×10^3	44.824×10^3	27.628×10^3	16.535×10^3	43.518×10^3
	Rate (%)	100	86.0	52.0	31.1	81.5
	Fuel saving (kg/m².year)	–	583	1,952	2,535	626

Note: Ceramic fiber suffix A indicates blanket. Ceramic fiber suffix B indicates block.
* Operation days = 5 days/week, operation hours = 1 batch, steady state = 15 h/day, 75 h/week, temperature rise stop = 9 h/day, 45 h/week, cooling down = 2 days

Table 37 Furnace wall thickness: 460 mm; furnace wall surface temperature: 900°C [12)]

Atmospheric temperature: 25°C
emissivity: 0.85

Furnace wall structure



Emission calorific value Q (KJ/m².h)		3,604	2,227	2,039	2,294	2,616
Heat accumulation value H (KJ/m²)		533,212	253,420	190,254	19,632	487,502
Continuous operation 6000 h/year	Emission calorific value (KJ/m² · year)	21.625×10^3	13.362×10^3	12.235×10^3	13.784×10^3	15.696×10^3
	Rate (%)	100	61.8	56.6	63.6	72.6
	Fuel saving	–	459	527	417	329
*Batch operation (weeks/year)	Total heat loss (KJ/m² · year)	37.008×10^3	19.825×10^3	16.480×10^3	14.764×10^3	30.880×10^3
	Rate (%)	100	53.6	44.5	39.9	83.4
	Fuel saving (kg/m².year)	–	955	1,140	1,458	345

Note: Ceramic fiber suffix A indicates blanket. Ceramic fiber suffix B indicates block.
* Operation days = 5 days/week, operation hours = 1 batch, steady state = 15 h/day, 75 h/week, temperature rise stop = 9 h/day, 45 h/week, cooling down = 2 days

3.4.2 Water-cooling skid heat loss comparison

The water-cooling skid pipe insulating system is shown here. When heat from the water cooling part is double insulated, in the case of walking beam furnace of a large water cooling area, a fuel saving of almost 10% can be achieved.

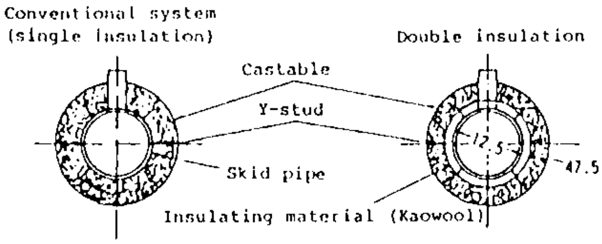


Figure 14 Skid lining [13)]

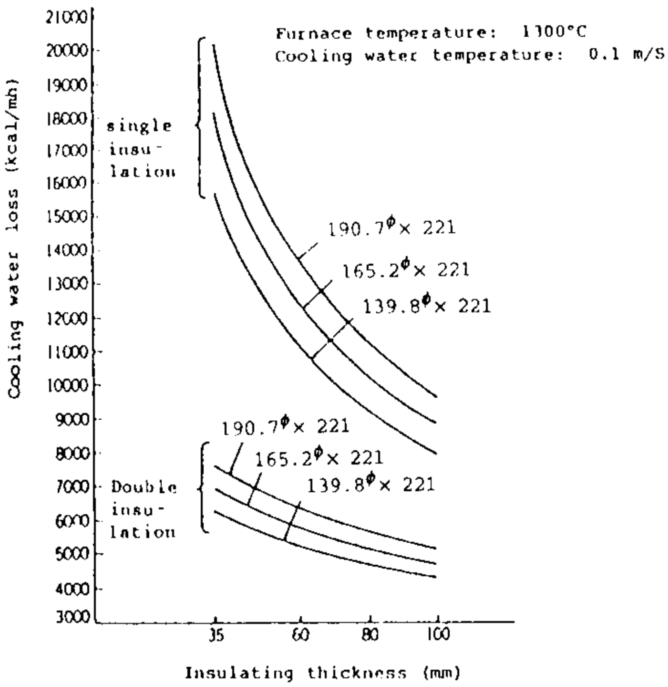
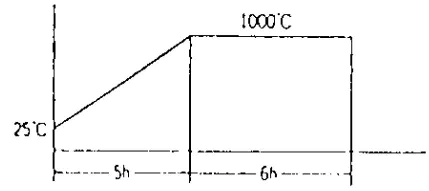


Figure 15 Water cooling heat loss comparison (calculated value) [14)]

4. Energy Saving Insulating Structure Execution (example)

4.1 Car bottom type heat treatment furnace

Table 38 Car bottom type heat treatment furnace[15]

		Insulating firebrick furnace		Kaowool lining furnace	
Treatment purpose		Casting heat treatment			
Internal furnace effective dimensions		600 W x 600 H x 1,000 L (mm)			
Amount of treatment (incl. jig)		340 kg/time			
Heating condition					
Output		36 kW (100)		27 kW (75)	
Power consumption		245 kWh (100)		167 kWh (68)	
Atmospheric gas		None			
Insulation measure	Roof (mm)	LBK-28	115	Ceramic fiber blanket	75
		Calcium silicate temperature retaining board	150	Calcium silicate temperature retaining board	100
				Slag wool	100
		Total	265	Total	275
	Side surface (mm)	LBK-28	115	Ceramic fiber blanket	62.5
				Special calcium silicate temperature-retaining board	65
		Calcium silicate temperature-retaining board	175	Calcium silicate temperature-retaining board	150
		Total	290	Total	277.5
	Car bottom (mm)	LBK-28	130	Ceramic fiber board	20
		Calcium silicate temperature-retaining board	150	CI Cl	115
				Calcium silicate temperature-retaining board	130
		Total	280	Total	265

(Note) 1 Heating of batch type is via electric heater.

4.2 Roller hearth type continuous heating furnace for quenching

Table 39 Roller hearth continuous hardening furnace[15)]

		Before modification		After modification	
Treatment purpose		Hardening of counter-sunk spring			
Internal furnace dimensions		340 W x 600 H x 3,000 L (mm)			
Amount of treatment		45.5 kg/h			
Treatment temperature		830°C			
Output		35 kW		35 kW	
Power consumption (kWh/month)		17,102		13,718	
Atmospheric gas		RX gas			
Insulation measure	Roof (mm)	LBK-23	115	Ceramic fiber board	50
		LBK-20	115	Special calcium silicate temperature retaining board	65
				Calcium silicate temperature-retaining board	50
		Silica board	50	Slag wool	65
		Total	280	Total	230
	Side surface (mm)	LBK-23	115	Ceramic fiber board	50
		LBK-20	115	Special calcium silicate temperature-retaining board	65
		Silica board	50	Calcium silicate temperature-retaining board	115
		Total	280	Total	230
	Hearth (mm)	LBK-23	65	LBK-23	115
		LBK-20	65	Special calcium silicate temperature-retaining board	50
		LBK-20	65	Calcium silicate temperature-retaining board	25
		Total	195	Total	190

(Note) 1. LBK-23 and LBK-20 are insulating firebrick of bulk specific gravity 0.55 and 0.50 respectively.
2. Silica board is calcium silicate temperature-retaining board #2.
3. Heating by continuous furnace is via electric heater.

4.3 Skid pipe double layer insulation

To minimize heat loss due to skid cooling water, the skid pipe is wrapped with ceramic fiber, and further castable is then put on.

Table 40 Skid double layer insulation result[16)]

	Conventional	Double layer insulation
Cooling water inlet temperature (°C)	24.8	25.0
Cooling water outlet mean temperature (%)	31.9	31.3
Cooling water flowrate (t/hr)	785	700
Cooling water loss calorific value (W)	6.483×10^3	5.129×10^3
Loss calorific value reduction rate (%)	—	21

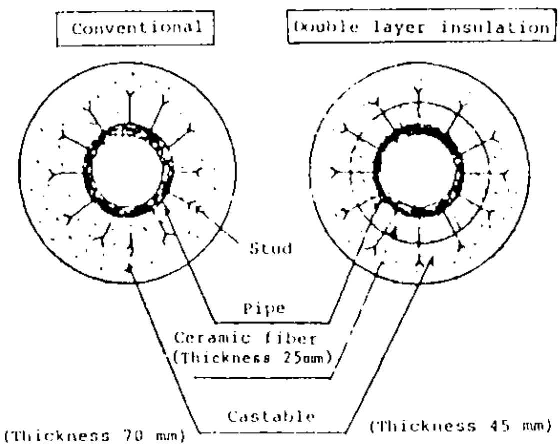


Figure 16 Skid pipe sectional view [16)]

5. Introduction of Industrial Furnaces for Which Refractory Materials and Insulating Materials Are Used

5.1 Furnace for steel production

5.1.1 Blast furnace

This furnace melts iron ores and produces pig iron. The operating temperature is extremely high (appr. 2,300°C at the entrance of hot air). It is cooled by water in consideration of its durability. Noninsulating refractory materials of high heat conductivity are used.

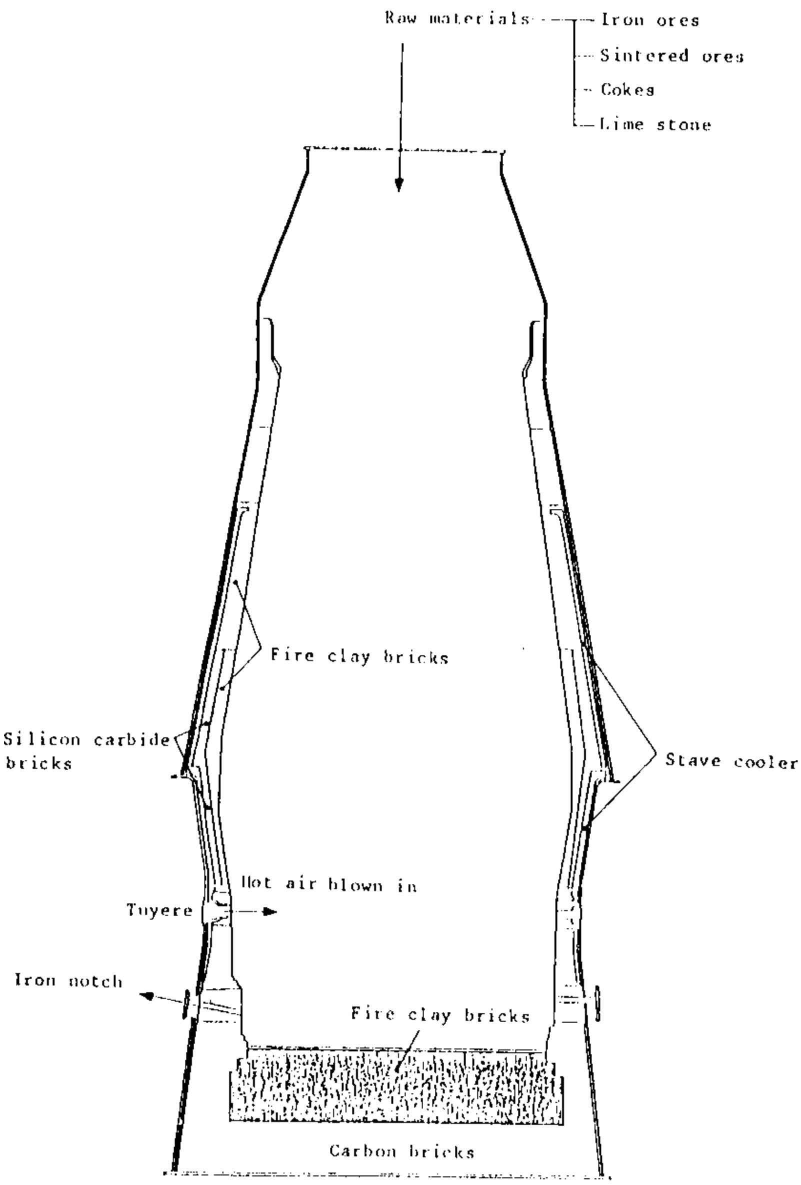


Figure 17 Blast furnace

5.1.2 Converter

This furnace produces steel by refining the pig iron produced in a blast furnace. Its operating temperature is extremely high (1,600°–1,700°C) like a blast furnace. It has melt steel in it. Refractory materials which are selected in consideration of the durability are used.

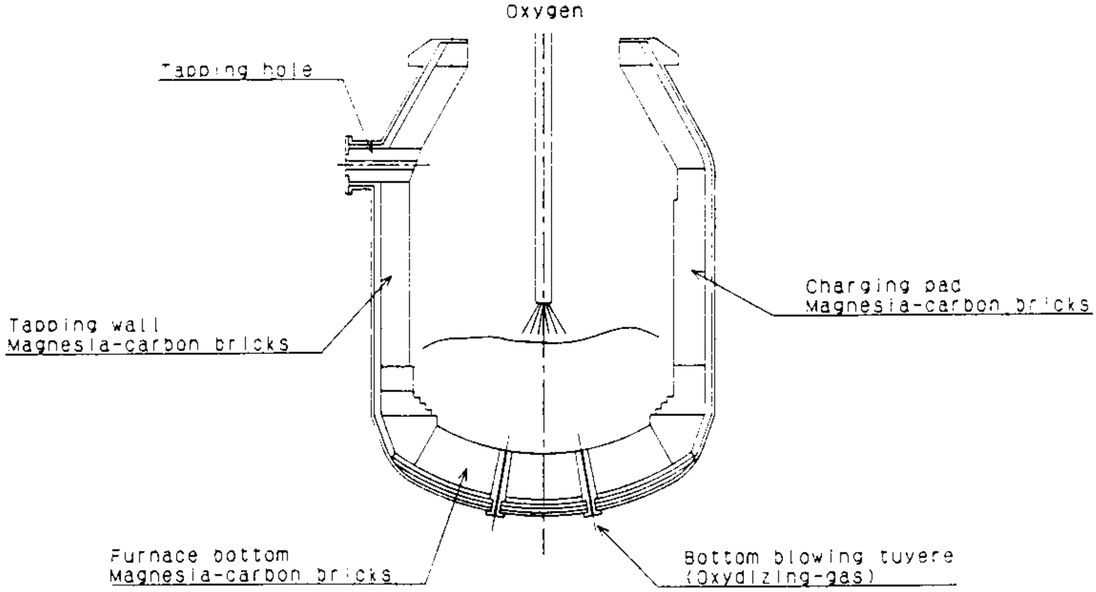


Figure 18 Converter

5.13 Reheating furnace

This furnace reheats pieces of steel (slab, bloom, billet etc.) to a target temperature (appr. 1,250°C) for hot rolling. The temperature in the furnace is 1,200°–1,300°C and its energy consumption is large. As one of the means of energy conservation the insulation is intensified by various methods in order to decrease the heat loss by diffusion.

a) Heat loss ratio of reheating furnace (Example)

Table 41 An example for the heat loss ratio

	Rate
Heat content of steel (Bloom, slab)	40.2
Heat loss carried out of furnace by products of combustion	44.6
Heat loss by water cooling	6.9
Heat loss from furnace walls	6.0

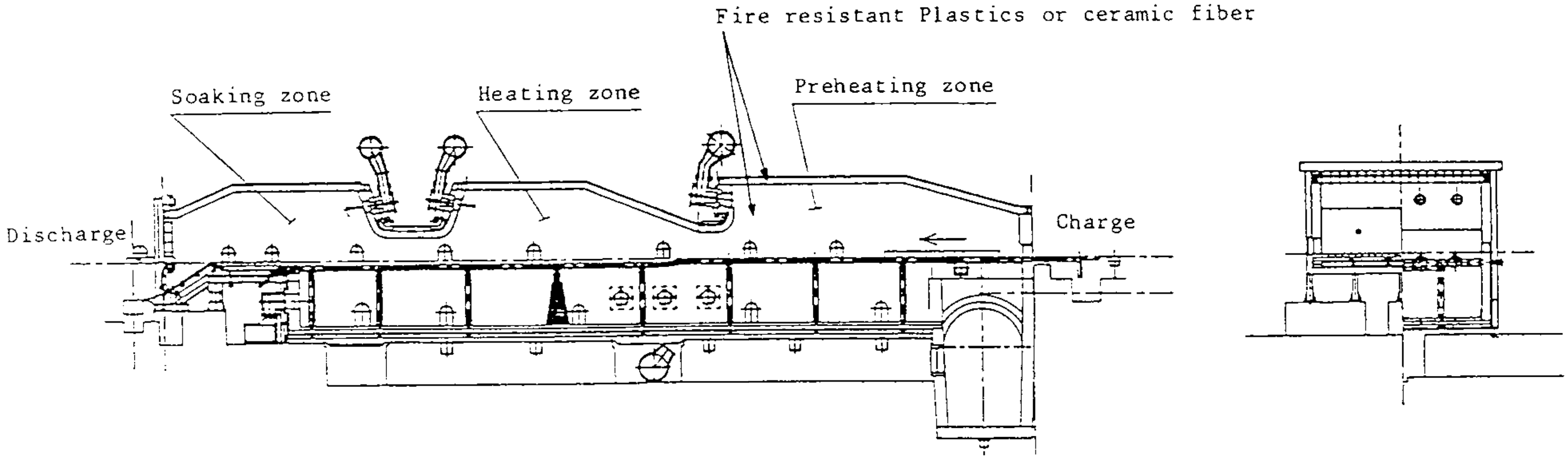


Figure 19 Reheating furnace

b) Insulating structures of reheating furnace

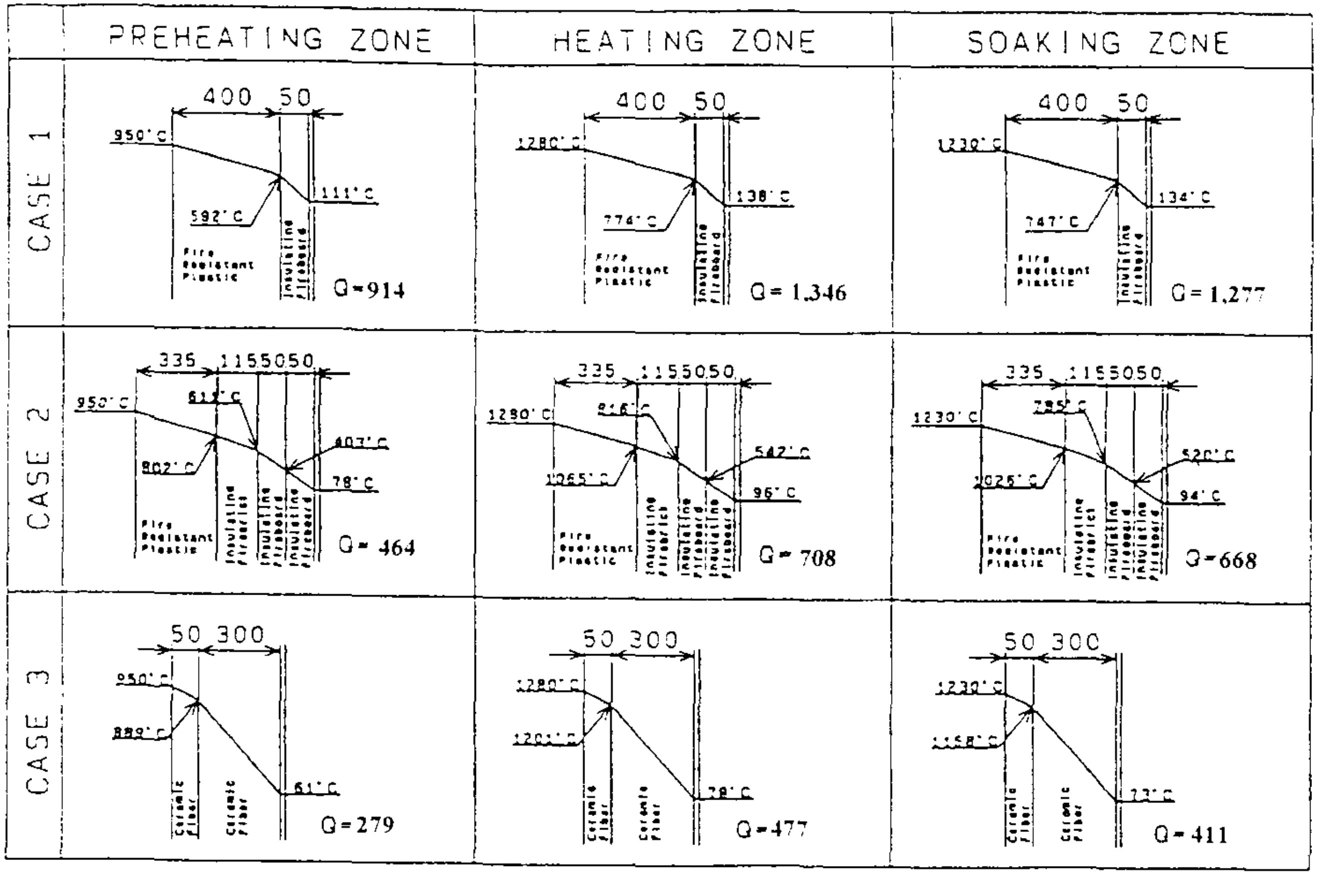


Figure 20 Reheating furnace (Slide wall)

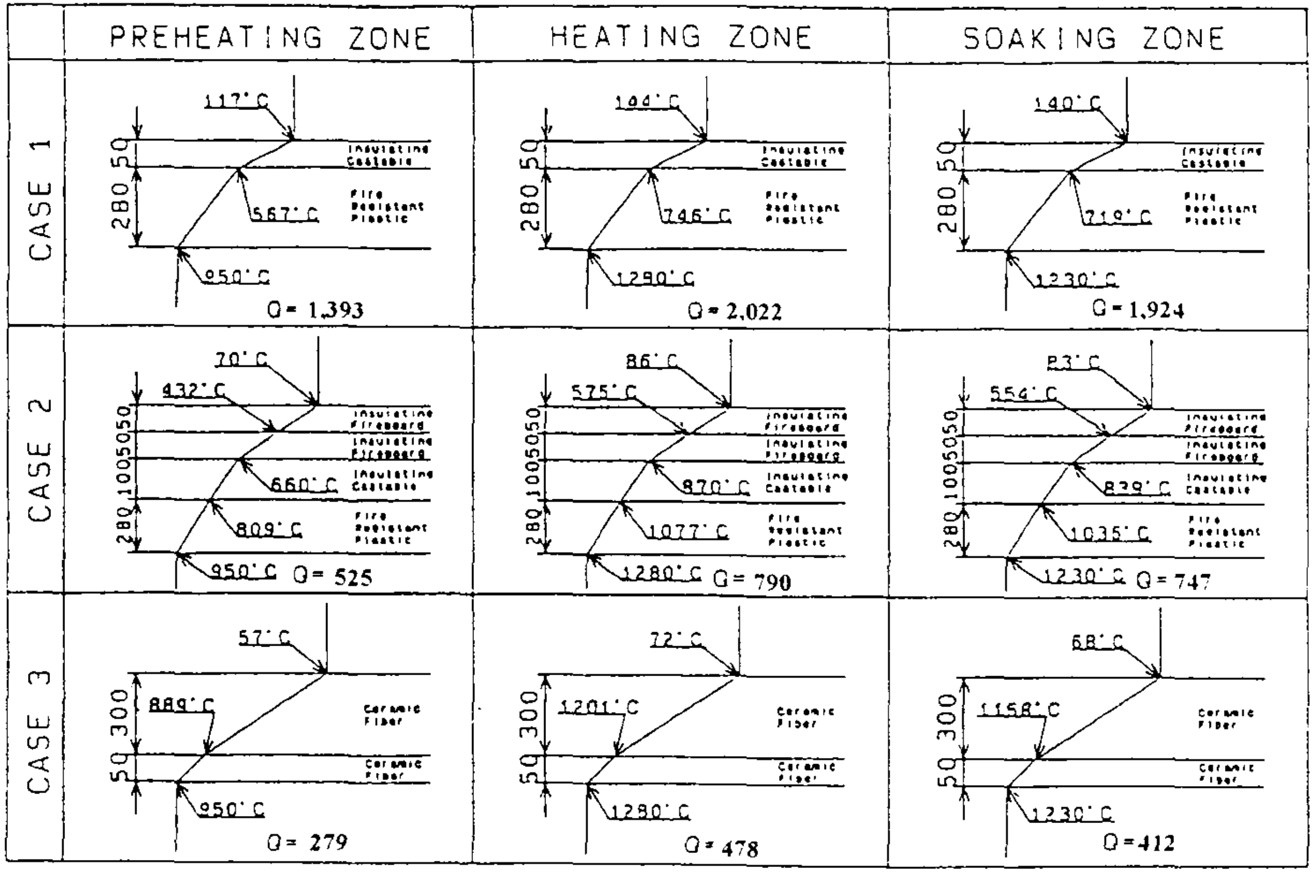


Figure 21 Reheating furnace (Ceiling)

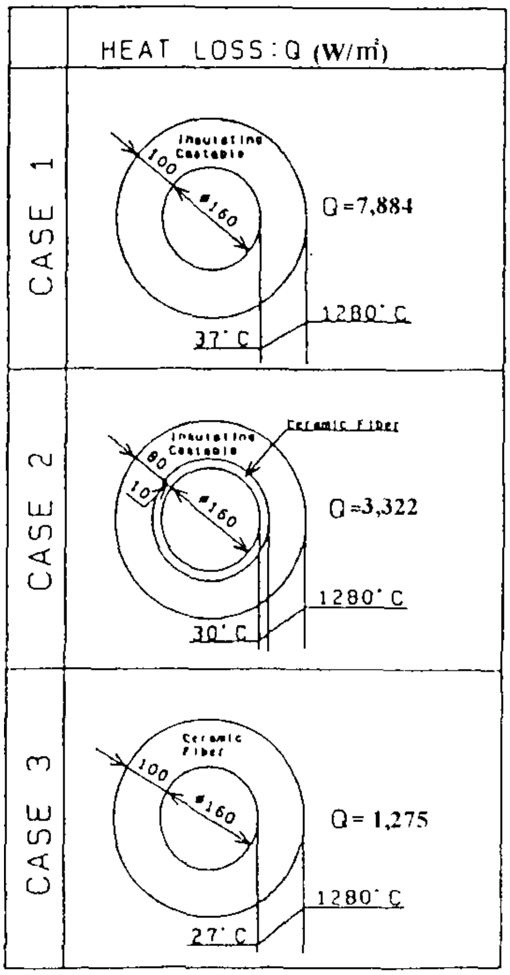


Figure 22 Reheating furnace (Skid pipe)

5.2 Furnace for producing non-ferrous metals (copper, lead, zinc, etc.)

5.2.1 Copper reverberatory furnace

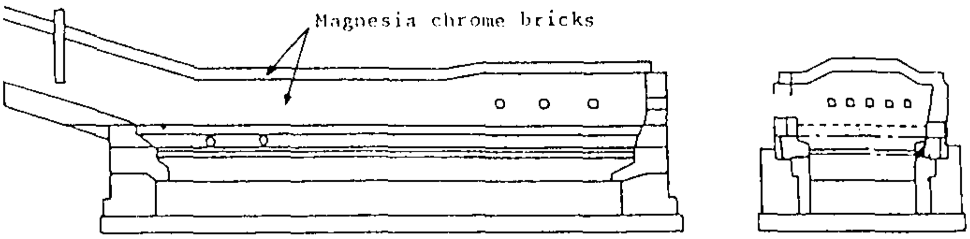


Figure 23 Copper reverberatory furnace

5.3 Furnace for producing ceramics (cement, glass, refractories, etc.)

5.3.1 Cement rotary kiln

This furnace calcinates powder materials consisting of calcareous material, argillaceous material, siliceous material, iron oxide material etc. in a specified ratio to the semi-molten state (appr. 1,450°C). Semi-molten black grains are called clinker. Cement is produced by adding an adequate amount of plaster to clinker and powdering it.

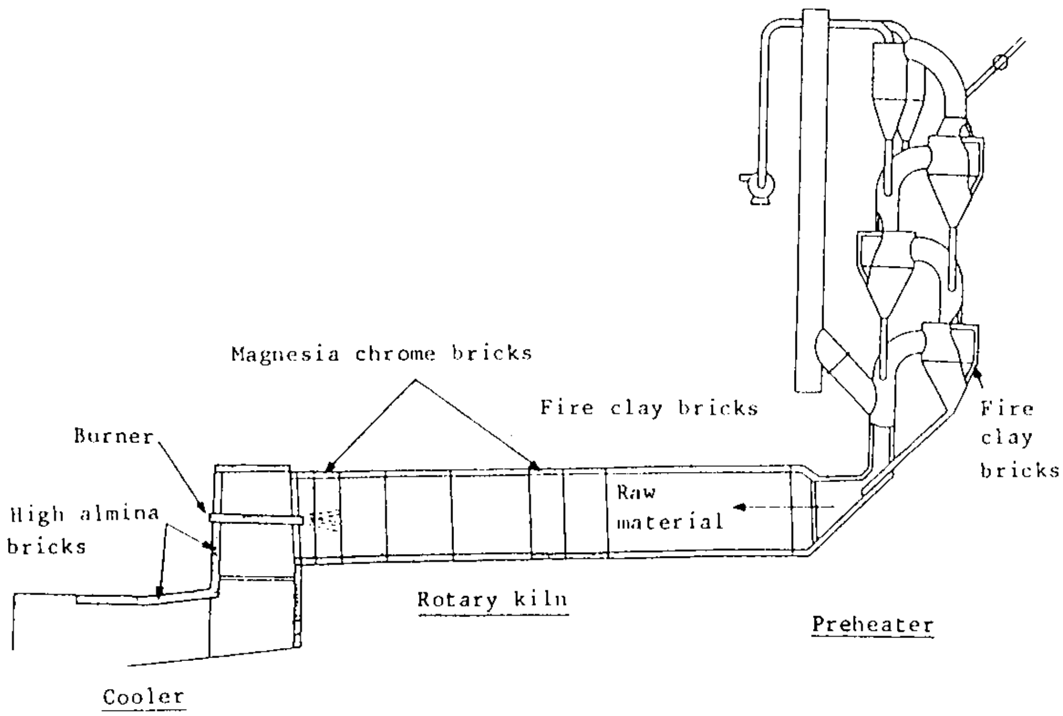


Figure 24 Cement rotary kiln

5.3.2 Heat loss ratio of cement rotary kiln (Example)

Table 42 An example for the heat loss ratio

	Rate
Heat required for sintering of clinker	52 4
Heat loss carried out of cooler by exhaust gas	16.0
Sensible heat of exhaust gas from kiln or preheater	19.7
Heat loss from furnace walls and by dust etc.	9.1

5.3.3 Insulation structure of cement rotary kiln

Since a rotary kiln rotates during operation, it is hard to use insulating materials between the firebrick lining and the shell. In this example, heat diffusion is decreased by using a composite material consisting of firebrick and insulating material.

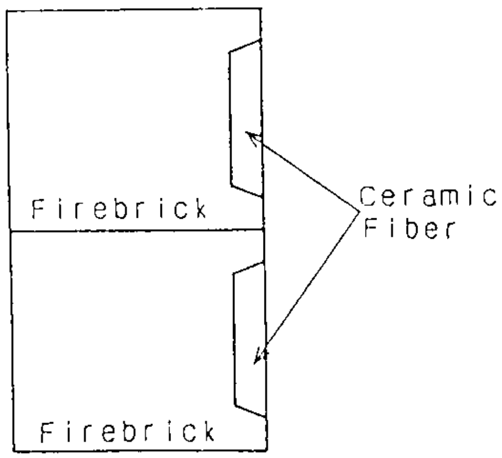


Figure 25

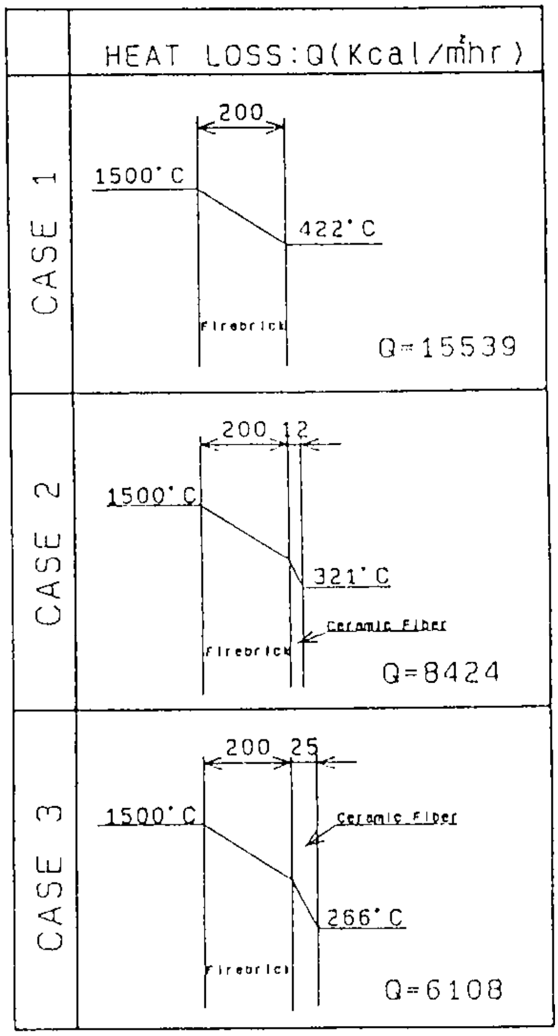


Figure 26 Cement rotary kiln

5.4 Furnace for chemical industry and others

Refractory materials and insulating materials are used also for furnaces of chemical industry (cokes, oil refining, ethylene production etc.) and furnaces for environmental maintenance (City refuse incinerator, industrial waste incinerator etc.)

5.4.1 City refuse incinerator

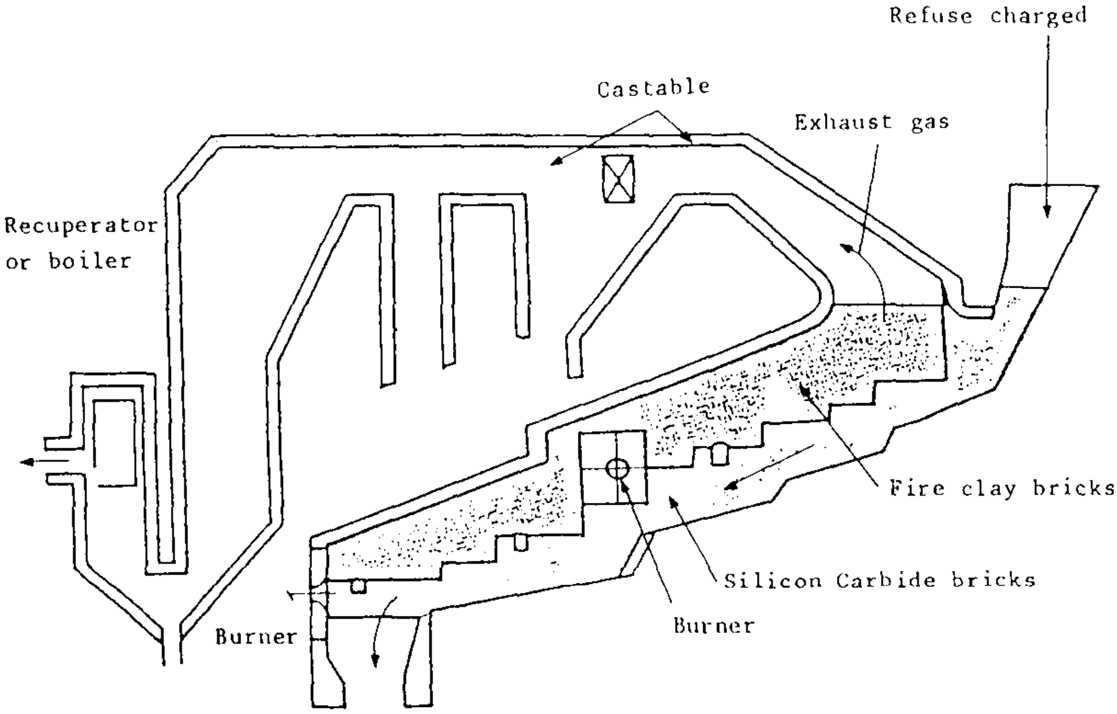


Figure 27 Incinerator

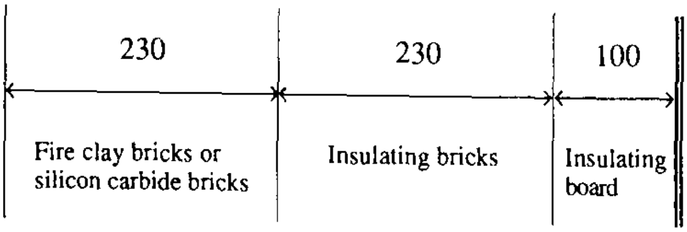


Figure 28 Incinerator side wall lining

6. Working Methods of Various Insulating Materials

6.1 Refractory bricks and insulating bricks

Refractory bricks and insulating bricks shall be fixed by mortar joint (2–3 mm).

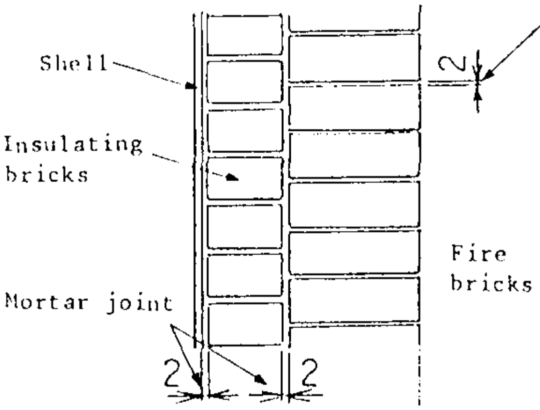


Figure 29 Brick work on side wall

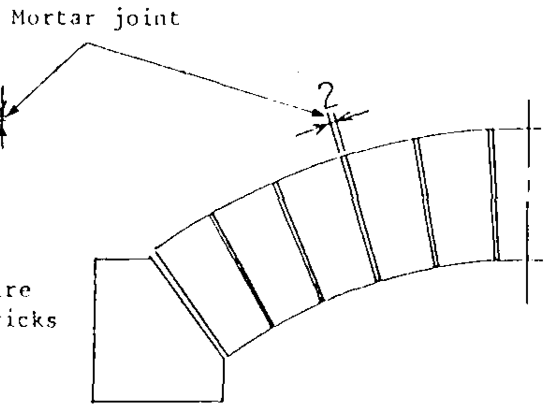


Figure 30 Brick work on ceiling arch

6.2 Monolithic refractory and insulating material

6.2.1 Castable refractories

Casting method, gunning method, trowel method etc. are available.

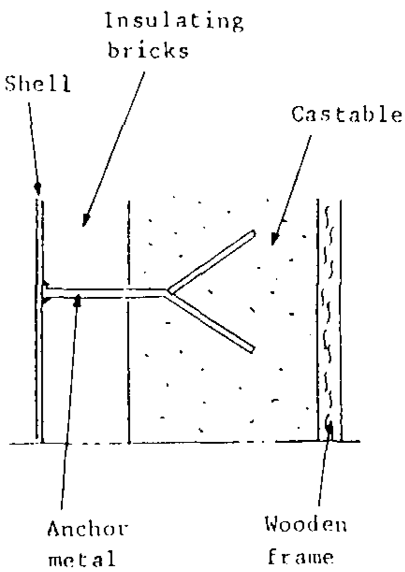


Figure 31 Casting method

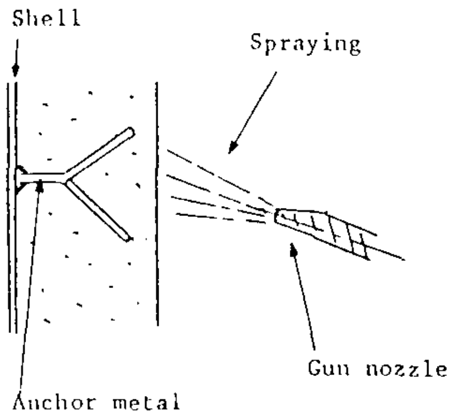


Figure 32 Gunning method

6.2.2 Plastic refractories

Slices are rammed with a rammer.

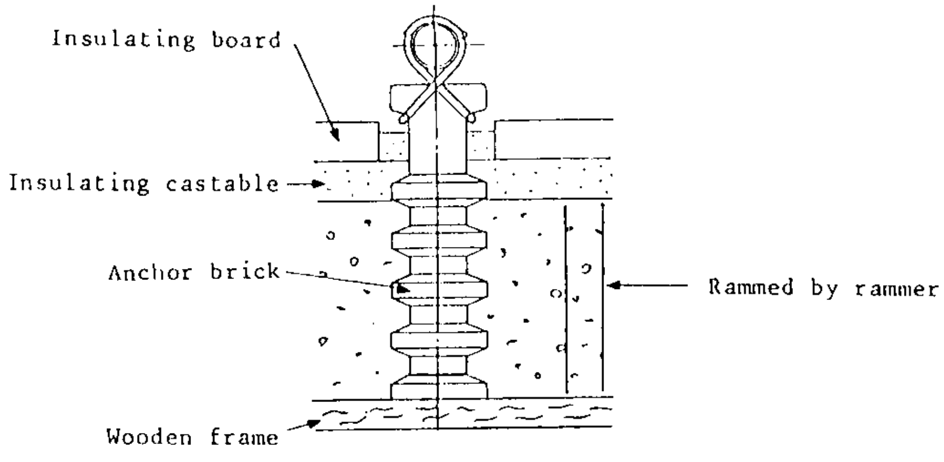


Figure 33 Ceiling insulation

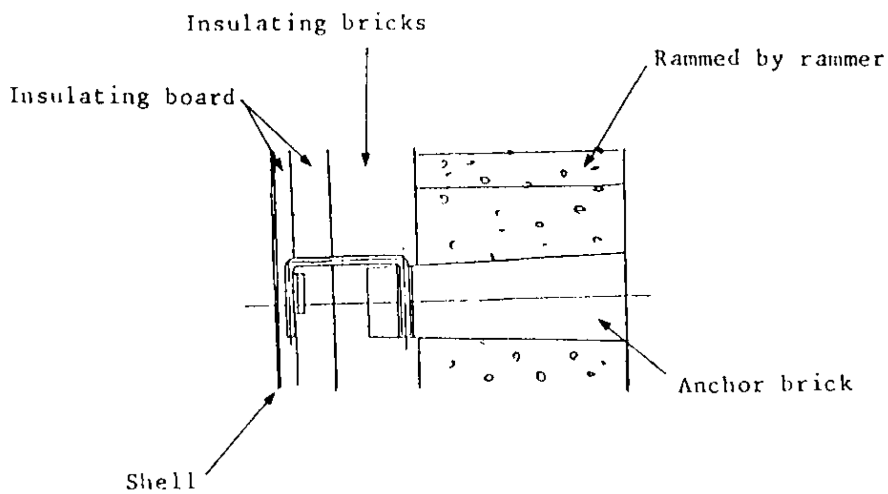


Figure 34 Side wall insulation

6.3 Ceramic fiber

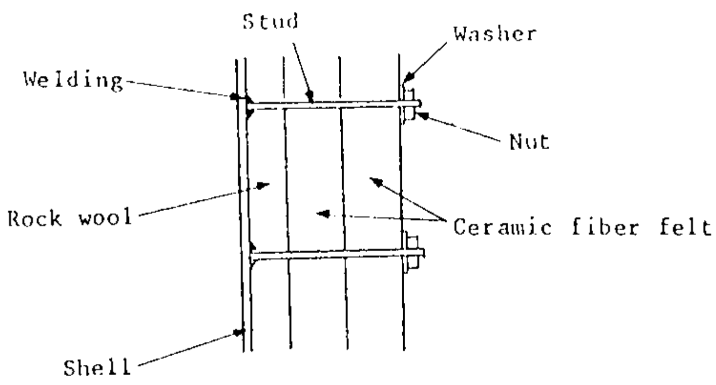


Figure 35 Laminated lining

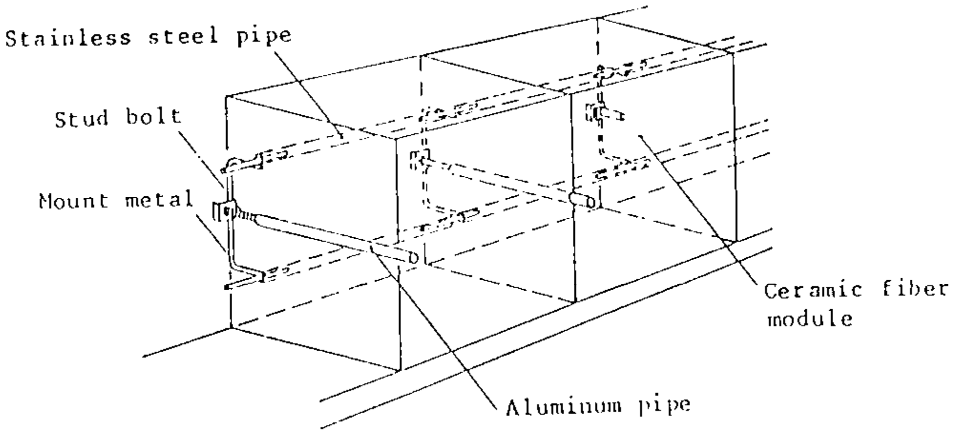


Figure 36 Module (block) lining

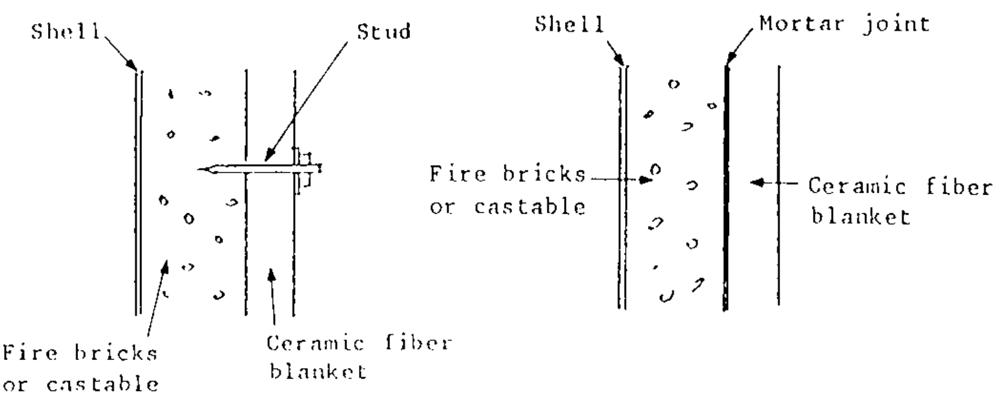


Figure 37 Veneering method

6.4 Heat insulation of pipes

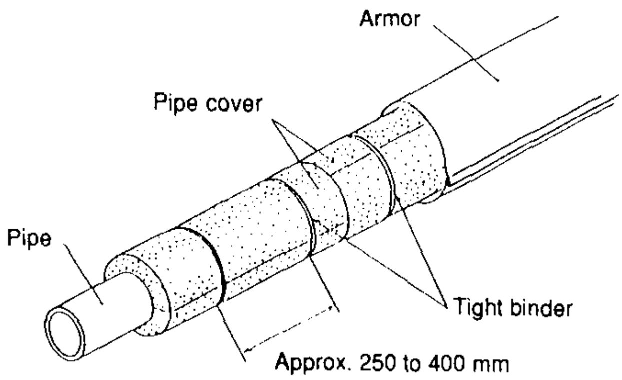


Figure 38 Heat insulation of straight pipe (single layer)

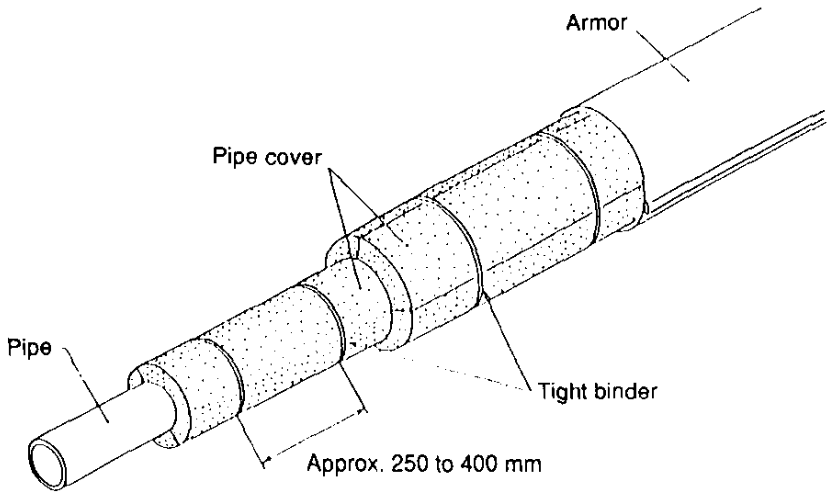


Figure 39 Heat insulation of straight pipe (double layer)

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CASE STUDY OF ECCJ FACTORY
(Heat Insulation)

Present Condition of Heat Insulation at ECCJ Factory 1/2

Facility		Portion	Inner Temp. (℃)	Material of Insulation	Thickness of Insulation(mm)	Surface Temp. (℃)	Surface Area(m^2)	Dissapation Heat per unit Area(Kcal/m^2h)	Dissapation Heat (Kcal/h)	Operating Time(h/year)	Heat loss (kcal/y)
No.1 Boiler		Cylindrical wall	175	Not specified	50	150(given)	54.7	1584	86.645		
		Vertical wall	175	Not specified	50	150(given)	13.2	1810	23.895	12x25x12=	
		Total							110.540	3.600	$3.98x10^8$
No.2 Boiler		Cylindrical wall	175	Not specified	50	150(given)	31.7	1635	51.830		
		Vertical wall	175	Not specified	50	150(given)	6.9	1810	12.490	24x25x12=	
		Total							64.320	7.200	$4.63x10^8$
Heatinge Furnace		Cylindrical wall	950	SK33+JISB6	115+115=230	134	62.6	1362	85.260		
		Vertical wall	950	SK33+JISB6	115+115=230	135	2.3	1500	3.450	24x25x12=	
		Total							88.710	7.200	$6.39x10^8$
Steam Piping	OD= 12" (320mm)	Broken Insulation	175	Missing		175	10.0	2676	26.760		
		Sound Insulation	175	Glasswool	20	63	101.8	237	24.130		
	OD= 6" (165mm)	Sound Insulation	175	Glasswool	20	60	64.4	232	14.900	24x25x12=	
		Total							65.790	7.200	$4.74x10^8$
Dryer (2 Unit)		Roof	82	Glasswool	20	45	102	82	8.360		
		Vertical wall	82	Glasswool	20	47	230	79	18.170		
		Bottom	82	Glasswool	20	50	102	73	7.450	12x25x12=	
		Total per 1 Unit							33.980	3600	$1.22x10^8$

Present Condition of Heat Insulation at ECCJ Factory 2/2

Facility	Operating period	Portion	Inner Temp (℃)	Material and Thickness of Insulation(mm)	Surface Temp.(℃)	Surface Area(m²)	Dissapation Heat per unit Area(Kcal/m²h)	Time/cycle(h)	Dissapation Heat/cycle	Operating cycle/year	Heat loss (Kcal/y)
Dyeing machine (Bath)	Heat up to dyeing	Cylindrical wall	(90+33)/2=	Nothing	61.5	9.33	193	60/60	1801		
		Vertical wall	61.5	Nothing	61.5	2.74	209	60/60	573	3x25x12=	
		Total							2374	900	2.137x10⁶
	Dyeing	Cylindrical wall	90	Nothing	90	9.33	454	40/60	2824		
		Vertical wall		Nothing	90	2.74	491	40/60	897	3x25x12=	
		Total							3721	900	3.349x10⁶
	Heat up to fixing	Cylindrical wall	(75+33)/2=	Nothing	54	9.33	134	20/60	417		
		Vertical wall	54	Nothing	54	2.74	144	20/60	132	3x25x12-	
		Total							549	900	4.491x10⁵
	Fixing	Cylindrical wall	75	Nothing	75	9.33	310	20/60	964		
		Vertical wall		Nothing	75	2.74	336	20/60	307	3x25x12=	
		Total							1271	900	1.144x10⁶
	Softaing	Cylindrical wall	45	Nothing	45	9.33	69	20/60	215		
		Vertical wall		Nothing	45	2.74	74	20/60	68	3x25x12=	
		Total							283	900	2.547x10⁵
	Total per 1 Unit								8198		7.378x10⁶

Note: Inner temperature of boiler and steam piping is derived from a saturation temperature of steam under 8 Kg/Cm²G
The quantity of disapation heat is caluculated under following conditions.
Ambient air temperature : 33℃
Emissivity of cold surface : Steel shell -0.85
Stainless steel shell -0.35
Surface of insulation -0.23
Condition of convection : Natural convection by air
Thermal conductivity : SK33 -fixed as 1.4 Kcal/mh℃
B6 -fixed as 0.25 Kcal/mh℃
Glasswool -fixed as 0.045 Kcal/mh℃

Improvement Plan of Heat Insulation at ECCJ Factory 1/4

Facility	Portion	Inner Temp. (℃)	Existing Insulation Material	Existing Insulation Thickness (mm)	Additional Insulation Material	Additional Insulation Thickness (mm)	Surface Temp. (℃)	Dissapation Heat per unit Area (Kcal/m²h)
No.1 Boiler	Cylindrical wall ID-2800mm	175	Not specified	50	—	—	150	1584
					Glasswool	15	80	272
					Glasswool	25	68	187
					Glasswool	50	55	105
					Glasswool	75	49	73
					Glasswool	100	46	56
	Vertical wall	175	Not specified	50	—	—	150	1810
					Glasswool	15	74	291
					Glasswool	25	63	197
					Glasswool	50	51	110
					Glasswool	75	47	76
					Glasswool	100	44	59
No.2 Boiler	Cylindrical wall ID-2000mm	175	Not specified	50	—	—	150	1635
					Glasswool	15	78	276
					Glasswool	25	66	189
					Glasswool	50	54	105
					Glasswool	75	48	73
					Glasswool	100	45	56

Improvement Plan of Heat Insulation at ECCJ Factory 2/4

Facility	Portion	Inner	Existing Insulation		Additional Insulation		Surface	Dissapation Heat per
		Temp. (℃)	Material	Thickness(mm)	Material	Thickness(mm)	Temp. (℃)	unit Area(Kcal/m²h)
Heating Furnace	Cylindrical wall ID=1200mm	950	SK33 + B6	115 + 115	——	——	134	1360
					Ceramicfiber	25	113	1003
					Ceramicfiber	50	100	787
					Ceramicfiber	75	90	643
					Ceramicfiber	100	82	540
	Vertical wall	950	SK33 + B6	115 + 115	——	——	135	1500
					Ceramicfiber	25	118	1174
					Ceramicfiber	50	106	964
					Ceramicfiber	75	97	818
					Ceramicfiber	100	91	711
Steam piping	Cylindrical wall ID=320mm	175	Glasswool	20	——	——	63	237
					Glasswool	15	53	142
					Glasswool	30	48	100
					Glasswool	45	45	76
					Glasswool	60	44	61
	Cylindrical wall ID=165	175	Glasswool	20	——	——	60	232
					Glasswool	15	51	135
					Glasswool	30	46	92
					Glasswool	45	44	69
					Glasswool	60	42	54

Improvement Plan of Heat Insulation at ECCJ Factory 3/4

Facility	Portion	Inner Temp. (℃)	Existing Insulation Material	Existing Insulation Thickness(mm)	Additional Insulation Material	Additional Insulation Thickness(mm)	Surface Temp. (℃)	Dissapation Heat per unit Area(Kcal/m^2h)
Dryer	Roof	82	Glasswool	20	—	—	45	82
					Glasswool	15	42	52
					Glasswool	30	40	38
					Glasswool	45	38	30
	Vertical wall	82	Glasswool	20	—	—	47	79
					Glasswool	15	43	51
					Glasswool	30	41	37
					Glasswool	45	39	30
	Bottom	82	Glasswool	20	—	—	50	73
					Glasswool	15	45	48
					Glasswool	30	42	36
					Glasswool	45	41	29

Improvement Plan of Heat Insulation at ECCJ Factory 4/4

Facility	Operation Period	Portion	Inner Temp. (℃)	Existing Insulation Material	Existing Insulation Thickness(mm)	Additional Insulation Material	Additional Insulation Thickness(mm)	Surface Temp.(℃)	Dissapation Heat per unit Area(Kcal/m²h)
Dyeing machine	Heat up to dyeing	Cylindrical wall ID=1320mm	(90-33)/2= 61.5	—	—	Polyethylene foam	5	49	87
						Polyethylene foam	15	42	45
						Polyethylene foam	25	40	30
		Vertical wall	61.5	—	—	Polyethylene foam	5	49	91
						Polyethylene foam	15	42	46
						Polyethylene foam	25	39	31
	Dyeing	Cylindrical wall ID=1320mm	90	—	—	Polyethylene foam	5	65	196
						Polyethylene foam	15	51	98
						Polyethylene foam	25	46	66
		Vertical wall	90	—	—	Polyethylene foam	5	64	206
						Polyethylene foam	15	50	103
						Polyethylene foam	25	45	68
	Heat up to fixing	Cylindrical wall ID=1320mm	(75-33)/2= 54	—	—	Polyethylene foam	5	45	61
						Polyethylene foam	15	40	32
						Polyethylene foam	25	38	22
		Vertical wall	54	—	—	Polyethylene foam	5	45	64
						Polyethylene foam	15	40	33
						Polyethylene foam	25	38	22
	Fixing	Cylindrical wall ID=1320mm	75	—	—	Polyethylene foam	5	57	137
						Polyethylene foam	15	46	69
						Polyethylene foam	25	43	46
		Vertical wall	75	—	—	Polyethylene foam	5	56	143
						Polyethylene foam	15	46	71
						Polyethylene foam	25	42	48
	Softning	Cylindrical wall ID=1320mm	45	—	—	Polyethylene foam	5	40	32
						Polyethylene foam	15	37	17
						Polyethylene foam	25	36	12
		Vertical wall	45	—	—	Polyethylene foam	5	40	34
						Polyethylene foam	15	37	18
						Polyethylene foam	25	36	12

Note. Inner temperature of boiler and steam piping is derived from a saturation temperature of steam under 8 Kg/Cm²G

The quantity of disapation heat is calucuiated under following conditions

Ambient air temperature	33℃	
Emissivity of cold surface	Steel shell	-0.85
	Stainless steel shell	-0.35
	Surface of insulation	-0.23
Condition of convection	Natural convection by air	
Thermal conductivity	SK33	-fixed as 1.4 Kcal/mh℃
	36	-fixed as 0.25 Kcal/mh℃
	Ceramic fiber	-fixed as 0.15 Kcal/mh℃
	Glasswool	-fixed as 0.045 Kcal/mh℃
	Polyethylene foam	-expressed as folows $\lambda = 0.027 + 0.00016\theta$ Kcal/mh℃

REFERENCE MATERIAL

Technical Terms for Refractory 1/2

Term	Difinition
abrasion of refractories	wearing away of refractory surfaces by the scouring action of moving solids.
binder	a substance added to a granular material to give it workability and green or dry strength.
burning(firing) of refractories	the final heat treatment in a kiln to which refractory brick and sapes are subjected in the process of manufacture for the purpose of developing bond and other necessary physical and chemical properties
castable	a combination of refractory grain and suitable bonding agent that, after the addition of a proper liquid, is generally poured into place to form a refractory shape or structure which becomes rigid because of chemical action.
corrosion of refractories	destruction of refractory surfaces by the chemical action of external agencies.
erosion of refractories	wearing away of refractory surfaces by the washing action of moving liquids.
firebrick	any type of refractory brick specifically fireclay brick.
monolithic refractory	a refractory which may be installed in situ, without joints to form an integral structure.
mortar refractory	a finely ground preparation which becomes plastic and trowelable when tempered with water, and is suitable for laying and bonding refractory brick.
permanent linear change	the percent dimensional change in length(based on original length) of a refractory specimen free of externally applied stresses, after being subjected to a prescribed heat treatment.
plastic refract ory	a refractory material, tempered with water, that can be extruded and that has suitable workability to be pounded into place to form a monolithic structure.
porosity	the percentage of the total volume of a material occupied by both open and closed pores.
pyrometric cone equivalent(PCE)	the number of that Standard Pyrometric Cone whose tip would touch the supporting plaque simultaneously with a cone of the refractory material being investigated when tested in accordance with Test Method C24.2

Technical Terms for Refractory 2/2

Term	Difinition
refractories	nonmetallic materials having those chemical and physical properties that make them applicable for structures, or as components of systems, that are exposed to environments above 1000° F(538℃).
refractoriness	in refractories, the capability of maintaining a desired degree of chemical and physical identity at high temperatures and in the environment and conditions of use.
spalling of refractories	the cracking or rupturing of a refractory unit, which usually results in the detachment of a portion of the unit.
spalling of refractories, mechanical	the spalling of a refractory unit caused by stresses resulting from impact or pressure.
spalling of refractories structural	the spalling of a refractory unit caused by stresses resulting from differential changes in the structure of the unit.
spalling of refractories -thermal	the spalling of a refractory unit caused by stresses resulting from nonuniform changes of the unit produced by a difference in temperature.
thermal expansion	the reversible change in size of materials due to temperature changes.

Conversion Table of Seger Cone No. and Temperature

Seger Cone No.	Temperature ℃
1 a	1100
2 a	1120
3 a	1140
4 a	1160
5 a	1180
6 a	1200
7	1230
8	1250
9	1280
10	1300
11	1320
12	1350
13	1380
14	1410
15	1435
16	1460
17	1480
18	1500
19	1520
20	1530
26	1580
27	1610
28	1630
29	1650
30	1670
31	1690
32	1710
33	1730
34	1750
35	1770
36	1795
37	1825
38	1850
39	1880
40	1920
41	1960
42	2000

Examples of Energy Saving Practice Using Ceramic Fiber

No	Furnace	Operation	Existing lining	Improved lining	Benefit
1	Annealing	Continuous(1200°C)	Firebrick 480 mm	C.F+100mm	15% fuel saving
2	Heat treating	Continuous(980°C)	Firebrick 115 mm	C.F 50 mm	Heat loss is reduced by 27%
			I.F.B 115 mm	I.B 120 mm	
			I.B 25mm		
3	Reheating	Intermittent(1010°C)	Castable	C.F 304/150 mm	75% Reduction in fuel use
4	Forging	Intermittent(1290°C)	Firebrick	C.F 75 mm	30.5% Reduction in fuel use
				Plastic 267 mm	
				I.B 75 mm	
5	Aluminum reverberatory	Continuous	Castable	C.F	50% of Fuel Saving
6	Annealing	Intermittent(900°C)	I.F.B+I.B	C.F 152 mm	6hr of heat are saved every day
7	Ammonia reformer	Continuous(1038°C)	I.F.B	C.F +50 mm	13% of fuel saving
8	Reheating	Continuous(1288°C)	Firebrick 460 mm	C.F 230 mm	45% of fuel saving
9	Forging	Intermittent(1316°C)	Firebrick+I.F.B	C.F 230 mm	31% of fuel saving
10	Reheating	Continuous		C.F +75 mm	Efficiencies have risen by 12.8%
11	Heat treating	Intermittent	I.F.B	C.F 100 mm	44% of fuel saving
12	Reheating	Continuous(1316°C)	Castable	C.F +75 mm	13% of fuel saving
13	Porcelain	Intermittent(1500°C)		C.F +100 mm	Reduction in fuel consumption
14	Carburizing	Intermittent	Firebrick 460 mm	C.F 317 mm	47% of energy saving
15	Reheating	Continuous	Plastic	C.F +50 mm	14% of fuel saving
16	Forging	Intermittent(1371°C)	Firebrick	C.F 305 mm	Lower fuel consumption by 30%
17	Forging	Intermittent(1343°C)	Firebrick+I.B	C.F 305 mm	Heat up time is reduced to 1/2-1/3
18	Pusher type Heating	Continuous	Firebrick	C.F	66% of fuel saving
19	Porcelain enameling	Continuous	Firebrick	C.F 203 mm	10% increase in productivity
20	Porcelain enameling	Continuous	Firebrick	C.F 152 mm	40% of fuel saving
21	Porcelain enameling	Continuous(849°C)	Firebrick	C.F 203 mm	35% of fuel saving
22	Porcelain enameling	Intermittent	Castable 254 mm	C.F 203 mm	40% of fuel saving
23	Firing bone china	Intermittent(1223°C)	I.F.B 230mm+C.F 50mm	C.F 150 mm	23% of fuel saving
24	Firing refractories	Intermittent(1500°C)	Firebrick	C.F +50 mm	40% of fuel saving
25	Firing porcelain	Intermittent(1400°C)	Firebrick	C.F +50 mm	32% of fuel saving
26	Firing chinaware	Continuous(1371°C)	I.F.B	C.F +25 mm	35% of fuel saving
27	Firing Pottery	Intermittent(1177°C)	Firebrick 343 mm	C.F 152 mm	Firing time was reduced by 6hr
28	Annealing	Intermittent(900°C)	Firebrick	C.F 203 mm	50% of fuel saving
29	Reheating	Continuous	I.F.B 343 mm	C.F +75 mm	24% of fuel saving

Normal Total Emissivity[a] of Various Surfaces

Surface	Temperature* (°C)	Emissivity ε
Aluminum		
Well-polished surface	227 – 580	0.039 – 0.057
Rough surface	26	0.055
Oxidized surface	200	0.11
Roofing	38	0.216
Iron and steel		
Polished surface	430 – 980	0.144 – 0.377
Iron oxide	100	0.736
Oxidized steel	200 – 590	0.79
Rough oxidized steel sheet	38 – 370	0.94 – 0.97
Molten cast iron	1,300 – 1,400	0.29
Nickel and nickel alloys		
Electrolytic nickel (unpolished)	20	0.11
Oxidized nickel	650 – 1,250	0.59 – 0.86
Nichrome wire (shining)	49 – 1,000	0.65 – 0.79
Nichrome wire (oxidized)	49 – 500	0.95 – 0.98
Platinum band	930 – 1,480	0.12 – 0.17
Tungsten filament	3,300	0.39
Asbestos paper	38 – 370	0.93 – 0.945
Concrete tile	1,000	0.63
Red crude brick	21	0.93
Firebrick	590 – 1,000	0.80 – 0.90
Paints, lacquers and varnishes		
White enamel on rough iron surface	23	0.906
Black lacquer on iron surface	24	0.875
Oil paint	100	0.92 – 0.96
Aluminum paint, Al 26%	100	0.3
Paper (thin)	19	0.93
Gypsum, rough lime	10 – 88	0.91
Roofing	21	0.91
Water	0 – 100	0.95 – 0.963

a) Translation of Table A-23 (by H.C. Hottel) included in McAdams, Heat Transmission, 3rd Ed., McGraw-Hill, New York (1954)-produced with permission

* Where two sets of temperature and emissivity values are available, intervening sets of values can be obtained by interpolation.

Unit Conversion Table

Quantity	SI Unit	Conventional units		Remarks
Force	N	kgf		
	1	0.1019716		
	9.80665	1		
Torque Moment of force	N · m	kgf · m		
	1	0.1019716		
	9.80665	1		
Pressure	Pa	kgf/cm^2		
	1	1.019716×10^{-5}		
	9.80665×10^4	1		
	9.80665	10^{-4}		
Energy Work Heat Enthalpy	kJ	kW · h	kcal	
	1	1/3600	0.2388459	
	3600	1	859.8452	
	4.1868	1.163×10^{-3}	1	
Power Power rate Power output Heat flow	W	kgf · m/s		
	1	0.1019716		
	9.80665	1		
Heat flux (heat flow per unit area)	W/m^2	kcal/(m^2 · h)		
	1	1/1.163		
	1.163	1		
Heat conductivity	W/(m · K)	kcal/(m · h · °C)		
	1	1/1.163		
	1.163	1		
Heat transfer rate Heat transfer coefficient	W/(m^2 · K)	kcal/(m · h · °C)		
	1	1/1.163		
	1.163	1		
Heat capacity Entropy	kJ/K	kcal/°K		
	1	0.2388459		
	4.1868	1		
Specific internal energy Specific enthalpy Mass latent heat (latent heat)	kJ/kg	kcal/kgf		
	1	0.2388459		
	4.1868	1		
Specific heat Specific entropy (Mass entropy)	kJ/(kg · K)	kcal/(kgf · °C)		
	1	0.2388459		
	4.1868	1		