THE STUDY (AFTER-CARE)
ON THE ENERGY CONSERVATION PROJECT
IN THE KINGDOM OF THAILAND

TEXTBOOK FOR THE ENERGY AUDIT TECHNIQUES WORKSHOP

9. Energy Conservation in Industrial Furnace

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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.

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 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 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)
l = 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 balance 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 inner 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

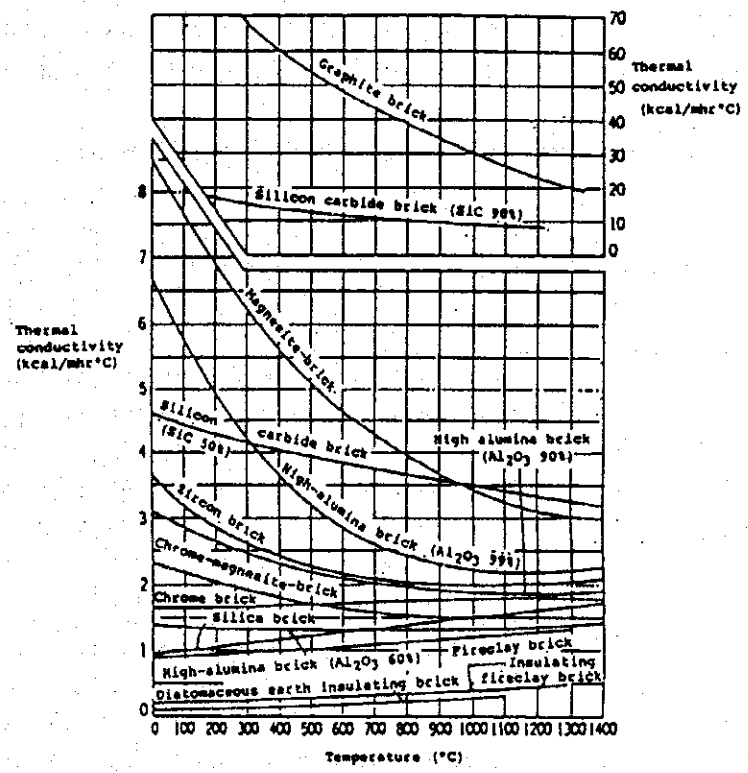
(1) Typical qualities of various firebricks (Table 1)

Table 1 Typical quality of refractory bricks

Material / Item		Fire clay			High alumina			Silica	Basic				Silicon carbide
		①	②	③	①	②	③		①	②	③	④	
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 expansion (%)		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

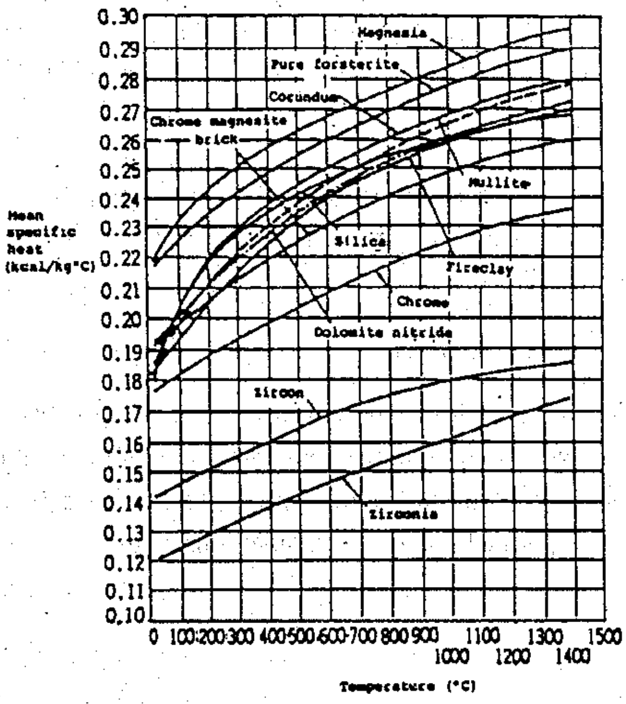
(2) Thermal conductivity of various firebricks (Figure 1)

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



(3) Mean specific heat of various firebricks (Figure 2)

Figure 2 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/cm²) 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 (kg/cm^2)	9	11	34	33	92	95
Modulus of rupture (kg/cm^2)	4	5	15	18	39	43
Thermal conductivity (kcal/mhr°C) at 350°C	0.12	0.13	0.16	0.17	0.19	0.23
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 (kg/cm^2)	14	14	28	35	63
Modulus of rupture (kg/cm^2)	7	7	17	20	25
Thermal conductivity (kcal/mhr°C) at 350°C	0.19	0.21	0.22	0.24	0.28
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 (kg/cm^2)		130	120	120 ≤	150
Modulus of rupture (kg/cm^2)		61	—	—	—
Thermal conductivity (kcal/mhr°C) at 350°C		0.47	0.51	0.55 ≥	0.60 ≥
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 (kg/cm^2)	16	15	30	29	80–200
Modulus of rupture (kg/cm^2)	10	9	17	15	
Thermal conductivity (kcal/mhr°C) at 350°C	0.14	0.15	0.17	0.19	0.30–0.35
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$_1$C)	—	—	—	—	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 (kg/cm^2)		65	184	10	22	45
Modulus of rupture (kg/cm^2)		33	72	9	17	28
Thermal conductivity (kcal/mhr°C) at 350°C		0.61	0.77	—	0.29	0.30
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

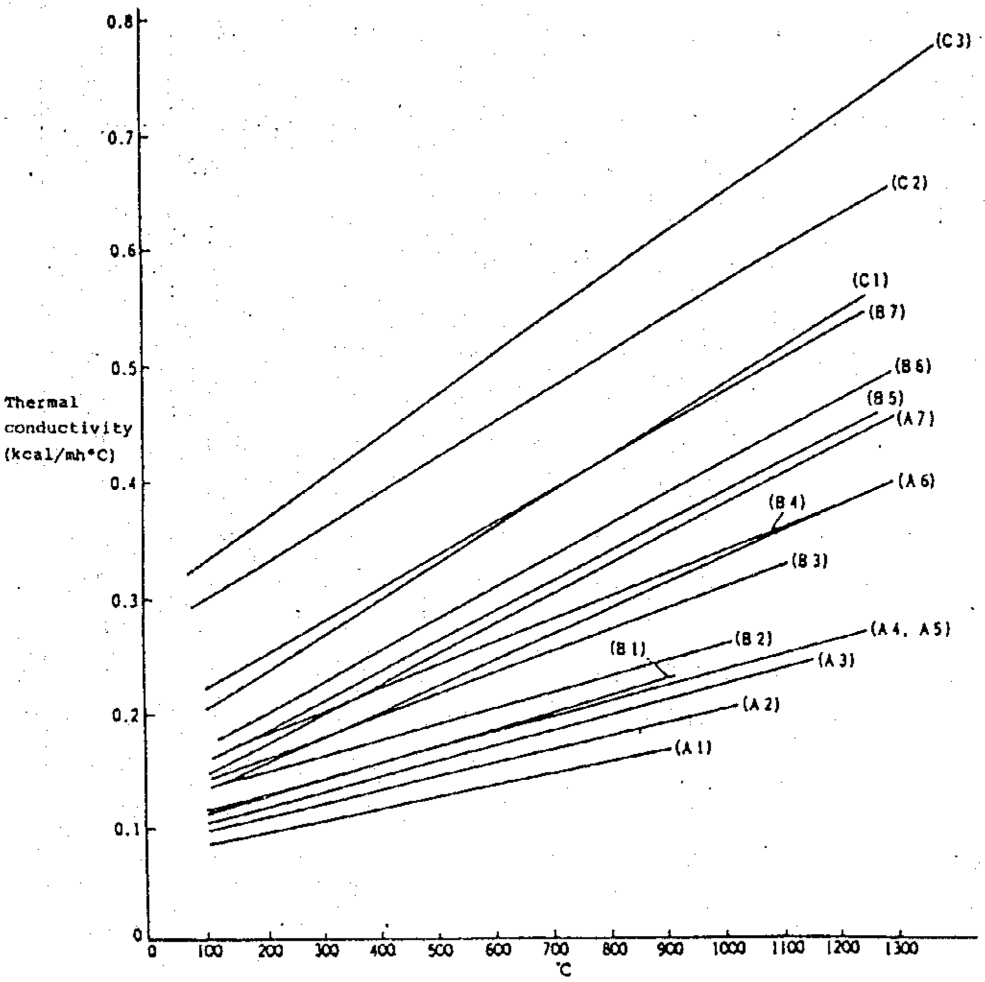
(4) Silicic acid insulating firebricks

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 (kg/cm^2)		42	40 or more	50
Modulus of rupture (kg/cm^2)		25	—	19
Thermal conductivity (kcal/mhr°C) at 350°C		0.32	0.4 or less	0.37
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 · 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 3 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]

Material / Item		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 (kgf/cm^2)	110°C – 24 h	450	200	260	250
	1000°C – 3 h	340	180	180	150
	1350°C – 3 h	450	200	300	300
	1500°C – 3 h	500	600	650	—
Modulus of rupture after heating (kgf/cm^2)	110°C – 24 h	80	40	60	50
	1000°C – 3 h	55	25	35	30
	1350°C – 3 h	40	40	50	65
	1500°C – 3 h	80	155	110	—
Thermal conductivity (kcal/mh°C)	at 260°C	0.93	0.65	0.64	0.52
	at 540°C	0.99	0.75	0.73	0.59
	at 800°C	1.04	0.86	0.80	0.63
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		Fireclay	
		①	②	①	②
Max. temperature for use (°C)		38	37	34–35	32
Execution required quantity (kg/m^3)		1800	1750	1650	1400
Linear change after heating (%)	110°C – 24 h	2900	2600	2300	2250
	1000°C – 3 h	–0.20	–0.55	–0.70	–0.70
	1350°C – 3 h	–0.25	–0.70	-0.55	-0.90
	1500°C – 3 h	+0.15	–0.75	0	–1.20
Crushing strength after heating (kgf/cm^2)	110°C – 24 h	+0.50	–0.65	–0.10	—
	1000°C – 3 h	170	90	40	45
	1350°C – 3 h	280	210	170	200
	1500°C – 3 h	600	440	320	320
Modulus of rupture after heating (kgf/cm^2)	110°C – 24 h	800	450	380	380
	1000°C – 3 h	35	30	10	5
	1350°C – 3 h	45	40	20	20
	1500°C – 3 h	120	100	40	40
Thermal conductivity (kcal/mh°C)	at 260°C	150	130	95	95
	at 540°C	1.21	1.15	0.84	0.81
	at 800°C	1.36	1.30	0.91	0.89
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 (kg/cm^2)	After drying	4.0	34	28	57	50	59	39	58	104
	After 500°C firing	3.0	31	28	43	26	40	--	--	--
	After max. temperature burning	3.0	28	30	55	179	1700°C 111	48	104	1400°C 135
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 (kcal/mh°C) at 350°C	500°C burned product	0.1	0.19	0.19	0.23	0.29	0.74	400°C 0.25	400°C 0.38	400°C 0.41
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	0.1	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 (kg/cm^2)	After 105°C drying	15	12	4.0	6.0	8.0
	After max. temperature burning	6	4	0.5	1.2	10.0
Cold crushing strength (kg/cm^2)	After 105°C drying	17	16	—	—	—
	After max. temperature burning	7	5	—	—	—
Heating shrinkage (%)	1000°C	0.6	0.4	1.2	1.3	—
	1200°C	1.0	—	—	—	0.6
	1300°C	—	0.6	—	—	—
	1400°C	—	—	—	—	1.3
	1500°C	—	—	—	—	2. 2
Thermal conductivity (kcal/mh°C) at normal temperature		0.15	0.14	0.069	0.071	0.16
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

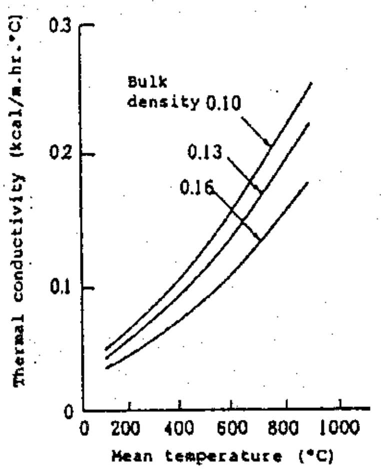
(1) Alumina silica fiber

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 4 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.

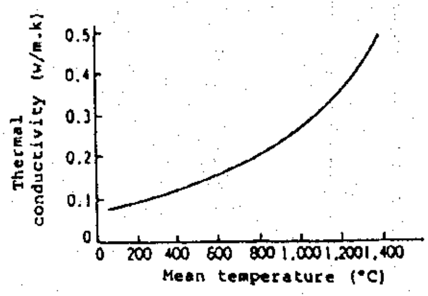
(2) Alumina fiber

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^{3}S^2
Young's modulus	1 × 104 MN/m^2
Specific modulus of elasticity	4 × 10 m^{2}S^2
Fiber diameter	3 μ (mean)
Surface area	3 m^2/g
Mohs's hardness	6
Composition	$A1_2O_3$ 95%, SiO_2 5%

Figure 5 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		
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.

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 16 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 17 Kinds and main physical properties of glass wool insulators

Material standard No. and name	Kind		Blulk density (kg/m^3)	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 18 Kinds and main physical properties of cattle hair felt

Material standard No. and name	Kind		Bulk density (kg/m^3)	Maximum working temperature (°C)	Tnermal 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		
		15 or more	130 or more	100		
	No.2	Less than 15	130 or more	100	0.053	0.042
		15 or more	130 or more	100	{0.046} or less	{0.036} or less
	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 19 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 20 Kinds and main physical properties of polystyrene 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)
JIS A 9511 (Polystyrene Foam Insulators)				(Average temperature 20±5°C)
	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 21 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)
JIS A 9512 (Water Repellent Perlite Insulators)				(Average temperature 20±5°C)
	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 22 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)
JIS A 9514 (Hard Urethane Foam Insulators)				(Average temperature 20±5°C)
	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

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.

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:

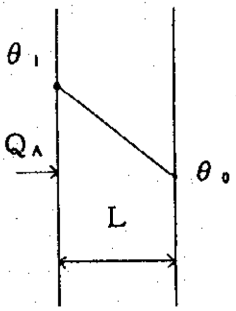
1) Conduction: This refers to a process in which heat moves as the sequential motion of molecules constituting materials, to the adjacent molecules. In a solid, heat is transferred always by conduction, and in a liquid or gas, heat is transferred by conduction as well as convection and radiation.

2) Convection: This refers to a process in which heat moves in a liquid together with the flowing portions of the liquid, and if temperatures difference 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.

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).

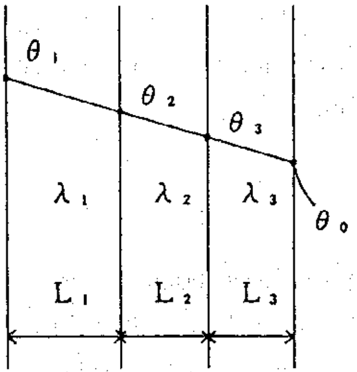


As illustrated, if the thickness of the solid wall is L m, the temperature at both the ends are θ_1 and θ_2, and the heat value transferred per unit area is Q_A kcal/m^{2}h, then we have

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

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.



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

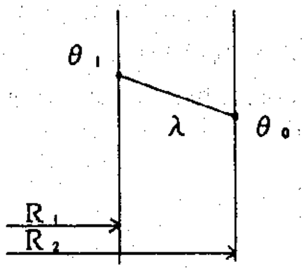
$$= \frac{\theta_1 - \theta_2}{\frac{L_1}{\lambda_1}} = \frac{\theta_2 - \theta_3}{\frac{L_2}{\lambda_2}} = \frac{\theta_3 - \theta_0}{\frac{L_3}{\lambda_3}} \cdots\cdots\cdots (3\text{-}2)$$

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

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

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



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

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

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

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,

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

In terms of unit outer surface area,

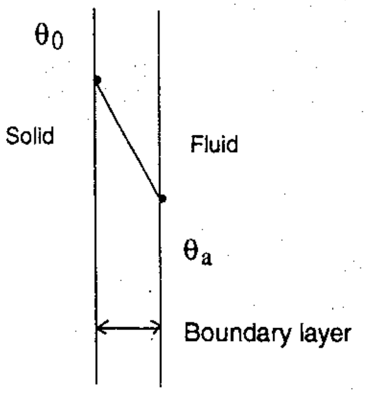
$$Q_A = \frac{(\theta_1 - \theta_0)}{\frac{r_{n+1}}{\lambda_1} l_n \frac{r_2}{r_1} + \frac{r_{n+1}}{\lambda_2} l_n \frac{r_3}{r_2} + \cdots + \frac{r_{n+1}}{\lambda_n} l_n \frac{r_{n+1}}{r_n}} \quad (\text{kcal/m}^2\text{h})$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3\text{-}7)$$

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

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

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/m²h°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 1.1 for plates facing down.

For the horizontal pipe

$$\alpha_e = 2.1\,\{(\theta_0 - \theta_g)/d\}^{0.25} \quad \text{(3-9')}$$

2) Forced convection by air

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

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

3) 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).

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

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

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:

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

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. 6 and 7.
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.

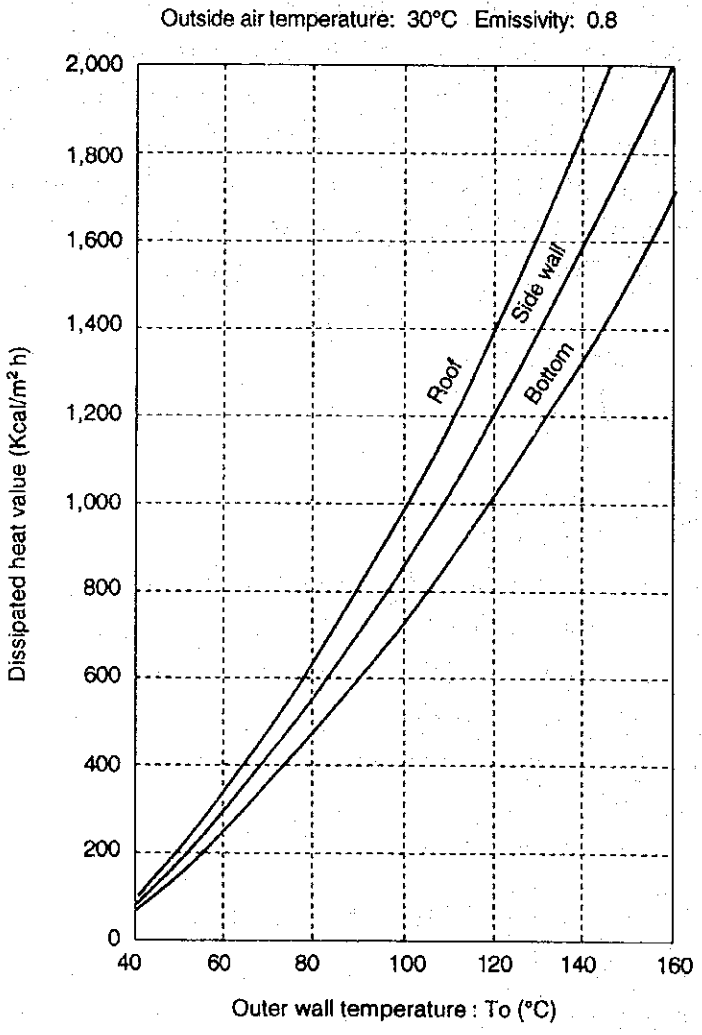
3.1.7 Standard value of furnace wall outer surface temperature

The furnace wall outer surface temperature of an industrial furnace is recommended by Standard for judgment to be not higher than the temperature shown in 23 for the furnace internal temperature concerned.

Table 23 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 6 Furnace wall outer surface temperature vs. dissipated heat value – 1



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

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

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

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

Symbols

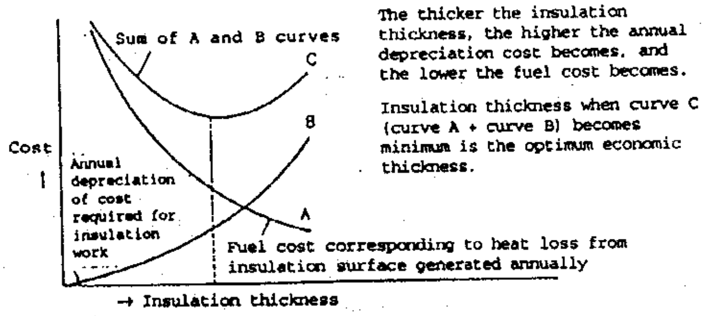
$L_1 \sim L_n$: Thickness of each refractory material constituting the furnace wall, m
$\rho_1 \sim \rho_n$: Density of each refractory material constituting the furnace wall, kg/m^3
$C_1 \sim C_n$: Specific heat of each refractory material constituting the furnace wall, kcal/kg°C
θ_1: Furnace wall inner 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 7 Relationship between insulation thickness and cost[11)]



The thicker the insulation thickness, the higher the annual depreciation cost becomes, and the lower the fuel cost becomes.

Insulation thickness when curve C (curve A + curve B) becomes minimum is the optimum economic thickness.

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.

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

$$F_1 = \frac{\pi}{4}\left(d_1{}^2 - d_0{}^2\right) aN \times 10^3 + bhQ \times 10^{-3} \cdots\cdots (3\text{-}18)$$

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

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

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

(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.

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

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

$$Q = \frac{\theta_0 - \theta_r}{\frac{X}{\lambda} + \frac{1}{\alpha}} \cdots\cdots (3\text{-}22)$$

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

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·h}
λ : Thermal conductivity of insulator (W/m·K) {kcal/m·h·°C}
α : Heat transfer coefficient of surface (W/m^2·K) {kcal/m^2·h·°C}
θ_0: Internal temperature (°C)
θ_r: Outside air temperature (°C)
*l*n: 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·K {10.32 kcal/m^2·h·°C}
Annual interest: 0.07
Years of use: 10 years
Construction price of insulator: 1.2 ($12000X_0^{-K}$ + 100) 10^3yen/m^2
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.

Heat value price: 5 yen/10^3W·h {5.81 yen/10^3kcal}
Annual hours of use: 3000 hours, 7300 hours

[Reference] Tables of Economical Insulation Thicknesses

Table 24 Insulation thicknesses and dissipated heat values of rock wool insulators

Rock wool pipe covers

(Insulation thickness in mm, dissipated heat value in W/m², and θ temperature in °C)

Thermal conductivity (W/m·K)			$-20°C \leq \theta < 100°C$ 0.031 4 + 0.000 174 θ $100°C \leq \theta \leq 600°C$ 0.038 4 + 7.13 × 10–5 · θ + 3.51 × 10^{-7} · θ^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	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	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 25 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)		$-20°C \le \theta < 100°C$ $0.033\,7 + 0.000\,151\,\theta$ $100°C \le \theta \le 600°C$ $0.039\,5 + 4.71 \times 10^{-5} \cdot \theta + 5.03 \times 10^{-7} \cdot \theta^2$	$-20°C \le \theta < 100°C$ $0.033\,7 + 0.000\,128\,\theta$ $100°C \le \theta \le 600°C$ $0.040\,7 + 2.52 \times 10^{-5} \cdot \theta + 3.34 \times 10^{-7} \cdot \theta^2$	$-20°C \le \theta < 100°C$ $0.036\,0 + 0.000\,116\,\theta$ $100°C \le \theta \le 600°C$ $0.041\,9 + 3.28 \times 10^{-5} \cdot \theta + 2.63 \times 10^{-7} \cdot \theta^2$	$-20°C \le \theta < 100°C$ $0.034\,9 + 0.000\,186\,\theta$ $100°C \le \theta \le 600°C$ $0.033\,7 + 1.63 \times 10^{-5} \cdot \theta + 5.03 \times 10^{-7} \cdot \theta^2$
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 26 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^2, and θ temperature in °C)

Themal conductivity (W/m·K)	$-20°C \le \theta \le 350°C$ $\quad 0.032\,8 + 8.44 \times 10–5 \cdot \theta + 5.84 \times 10–7 \cdot \theta^2$
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	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	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 27 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, and θ temperature in °C)

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

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

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	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	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 28 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, and θ temperature in °C)

Thermal conductivity (W/m·K)	$0°C \leq \theta \leq 200°C$ $0.046\,5 + 1.16 \times 10^{-4} \cdot \theta$ $200°C < \theta \leq 600°C$ $0.057\,0 - 9.36 \times 10–6 \cdot \theta + 3.74 \times 10^{-7} \cdot \theta^{1}$
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	$\frac{1}{2}$	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$	2	$2\frac{1}{2}$	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 29 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, and θ temperature in °C)

Themal conductivity (W/m·K) Annual hours of use (hour)			0°C ≤ θ ≤ 800°C $0.0632 + 1.26 \times 10^{-4} \cdot \theta + 2.67 \times 10^{-8} \cdot \theta^2$ 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	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 30 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/m², and θ temperature in °C)

Thermal conductivity (W/m·K)	0°C ≤ θ ≤ 600°C $0.048\,3 + 1.27 \times 10^{-4} \cdot \theta + 3.70 \times 10^{-8} \cdot \theta^2$
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	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	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.

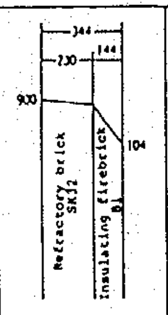
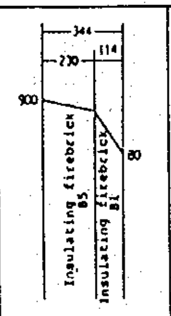
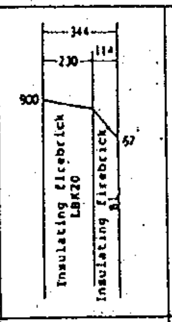
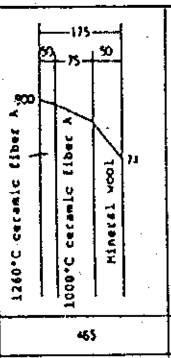
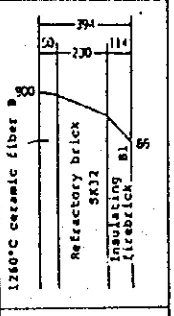
IT: Insulation thickness; DHV: Dissipated heat value

3.4 Typical Insulating Structures

3.4.1 General structure (example) and comparison of related specifications

Table 31 Furnace wall thickness: 344 mm; furnace wall surface temperature: 900°C 12)

Atmospheric temperature: 25°C
emissivity: 0.85

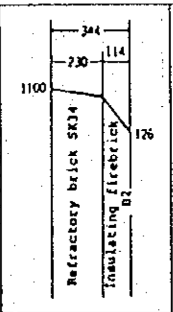
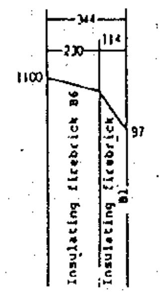
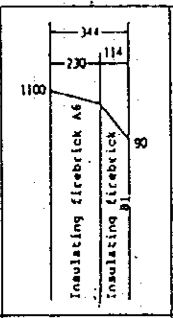
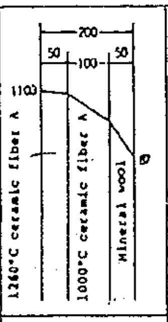
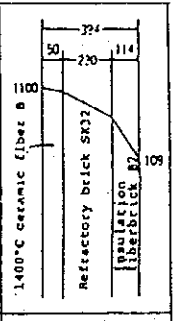
Furnace wall structure						
Emission calorific value Q (kcal/m²h)		868	538	380	465	615
Heat accumulation value H (kcal/m²)		91,310	33,990	20,190	2,880	71,180
Continuous operation 6000 h/year	Emission calorific value (kcal/m².year)	5,208 × 10³	3,228 × 10³	2,280 × 10³	2,790 × 10³	3,690 × 10³
	Rate (%)	100	62.0	43.8	53.6	70.9
	Fuel saving (kg/m².year)	–	360	532	440	276
*Batch operation 40weeks/year	Total heat loss (kcal/m².year)	7,428 × 10³	3,700 × 10³	2,461 × 10³	2,138 × 10³	5,523 × 10³
	Rate (%)	100	49.8	33.1	28.8	74.4
	Fuel saving (kg/m².year)	–	678	903	962	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 32 Furnace wall thickness: 344 mm; furnace wall surface temperature: 1100°C 12)

Atmospheric temperature: 25°C
emissivity: 0.85

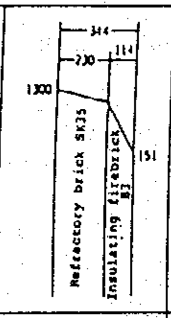
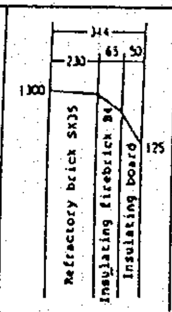
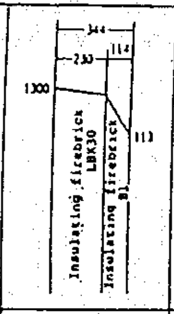
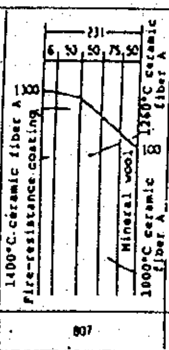
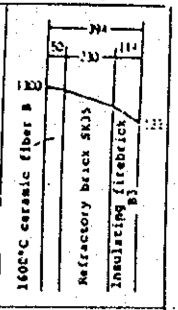
Furnace wall structure						
Emission calorific value Q (kcal/m²h)		1,188	771	677	623	946
Heat accumulation value H (kcal/m²)		111,830	48,000	36,970	4,110	95,860
Continuous operation 6000 h/year	Emission calorific value (kcal/m².year)	7,128 × 10³	4,626 × 10³	4,062 × 10³	3,738 × 10³	5,676 × 10³
	Rate (%)	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 (kcal/m².year)	9,641 × 10³	5,274 × 10³	4,422 × 10³	2,875 × 10³	7,950 × 10³
	Rate (%)	100	54.7	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 33 Furnace wall thickness: 344 mm; furnace wall surface temperature: 1300°C 12)

Atmospheric temperature: 25°C
emissivity: 0.85

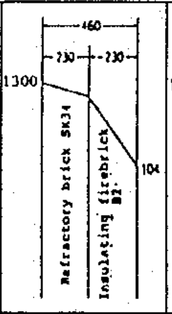
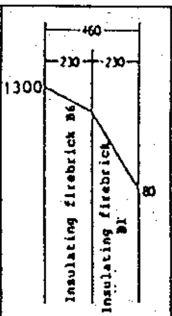
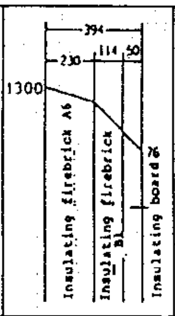
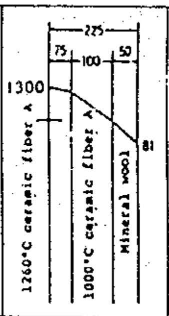
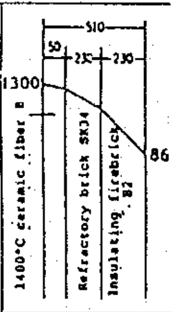
Furnace wall structure						
Emission calorific value Q (kcal/m²h)		1,653	1,188	985	807	1,335
Heat accumulation value H (kcal/m²)		131,630	138,510	57,550	10,980	114,770
Continuous operation 6000 h/year	Emission calorific value (kcal/m².year)	9.918×10^3	7.128×10^3	5.929×10^3	4.842×10^3	8.010×10^3
	Rate (%)	100	71.9	59.8	48.8	80.8
	Fuel saving (kg/m².year)	–	930	1,330	1,692	636
*Batch operation 40weeks/year	Total heat loss (kcal/m².year)	12.456×10^3	10.708×10^3	6.600×10^3	3.950×10^3	10.398×10^3
	Rate (%)	100	86.0	53.0	31.7	83.5
	Fuel saving (kg/m².year)	–	583	1,952	2,335	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 34 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 (kcal/m²h)		861	532	487	548	625
Heat accumulation value H (kcal/m²)		127,380	60,540	45,450	4,690	116,460
Continuous operation 6000 h/year	Emission calorific value (kcal/m².year)	5.166×10^3	3.192×10^3	2.922×10^3	3.288×10^3	3.750×10^3
	Rate (%)	100	61.8	56.6	63.6	72.6
	Fuel saving (kg/m².year)	–	459	522	437	329
*Batch operation 40weeks/year	Total heat loss (kcal/m².year)	8.841×10^3	4.736×10^3	3.937×10^3	2.527×10^3	7.377×10^3
	Rate (%)	100	53.6	44.5	29.1	83.4
	Fuel saving (kg/m².year)	–	955	1,140	1,458	340

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 8 Skid lining 13)

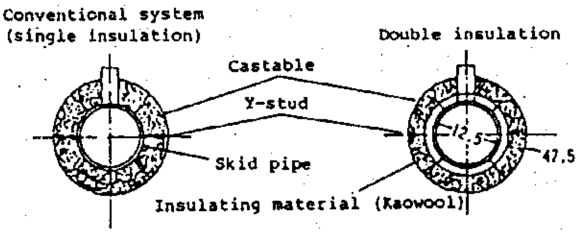
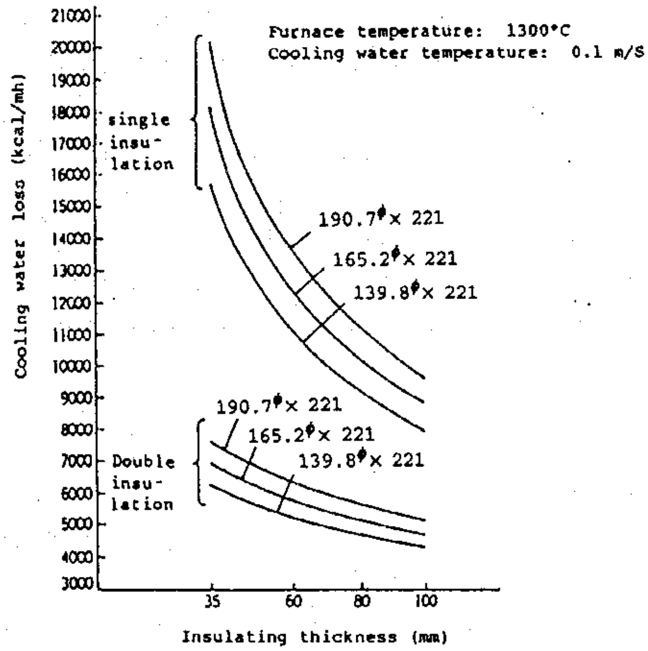


Figure 9 Water cooling heat loss comparison (calculated value) 14)



4. Energy Saving in Industrial Furnace

Tables 35 to 40 present the general thermal efficiency for various furnaces, from which it is understood that the current situation is not yet satisfactory in the sense of not only considerable difference in efficiency among furnaces but also average efficiency in general.

To this understanding, Table 41 suggests a number of factors to be envisaged for improvement. Measures as much as possible are desirably applied to a newly installed furnace. For existing furnace it is useful to study each factor that may deteriorate the efficiency and eventually to execute partial reconstruction.

4.1 Heat recovery from flue gas

4.1.1 Preheat of combustion air or fuel

In the most practical heat recovery method that relates to air preheat and fuel preheat, combustion air preheat is more widely adopted rather than fuel preheat. When preheating the fuel, care to safety and risk of thermal cracking should be taken, and fuel oil is never preheated with intention to energy saving except preheating for good atomization. Recuperator is a tool to exchange heat between exhaust gas and combustion air. It is made of metallic elements or ceramic elements through which sensible heat is transferred. Table 42 is the summary for available designs of recuperator. Figures 10 and 11 present arrangement of recuperator and examples respectively. (a) of Fig. 11 is concerned with large scale recuperator to be utilized in steel mill reheat furnace with heavy duty. In this, convective heat transfer is dominant. (b) of Fig. 11 is designed to apply to a higher exhaust gas temperature that enhances radiative heat transfer than in recuperator (a). (c) and (d) of Fig. 11 are composed by tile (ceramic) elements which enable to withstand a further high temperature.

It is interesting to note that these (c) and (d) are connected in series with (a) in practical cases. However, since leakage is likely to happen between ceramic elements in a long use due to peeling of mortar, care to keep pressure difference between air and exhaust gas as little as possible plays a decisive role to service life. (e) of Fig. 11 is a continuous accumulative heat exhanger in which accumulative wheel constantly rotates.

Figure 12 shows the control system that ensures good accuracy in maintaining the optimum energy saving rate when air preheat system has been introduced to the combustion system.

Following description relates to calculating energy saving rate when air or fuel is preheated. Referring to Fig. 13, available heat H is simply calculated by using calorific value of fuel F and flue gas sensible heat loss Q,

$$H = F - Q \text{ kcal/kg.fuel}$$

Now, taking into account of heat recovery PA and PF by air preheat and fuel preheat respectively and assuming their total P, it is expressed by

$$P = PA + PF \text{ kcal/kg.fuel}$$

Thus, corrected available heat H' becomes to be,

$$H' = F + P - Q = (F - Q) + P = H + P \text{ kcal/kg.fuel}$$

If the furnace necessitates x (kcal/h) as net heat, fuel consumption rate is $\frac{x}{H}$ (kg/h) when not preheated, and $\frac{x}{H+P}$ (kg/h) when preheated.

Hence, energy saving rate Sp is calculated as,

$$Sp = \frac{\frac{x}{H} - \frac{x}{H+P}}{\frac{x}{H}} = \frac{P}{H+P} \times 100\ \%$$

[Example]

Calculate flue gas heat loss Q (kcal/kg.fuel) and energy saving rate Sp (%) when firing kerosene at excess air ratio 1.2 with preheated air of 300°C used and the flue gas temperature from exit of furnace section is 900°C.

1. Theoretical combustion products from kerosene flame

CO_2	1.59 m^3N/kg.fuel
H_2O	1.56 m^3N/kg.fuel
SO_2	0/00 m^3N/kg.fuel
N_2	9.02 m^3N/kg.fuel

2. Excess air

O_2	$11.4^* \times 0.2 \times 0.21 = 0.48$ m^3N/kg.fuel
N_2	$11.4 \times 0.2 \times 0.79 = 1.80$ m^3N/kg.fuel

* theoretical air requirement for kerosene (m^3N/kg.fuel)

(1 + 2) is the eventual flue gas flow, and taking the data of average isopiestic specific heat shown in Table 43, Q is the total of;

CO_2	$1.59 \times 0.523 \times 900 = 748$
H_2O	$1.56 \times 0.387 \times 900 = 543$
N_2	$10.82 \times 0.331 \times 900 = 3{,}223$
O_2	$0.48 \times 0.351 \times 900 = 152$

Q = 4,666 kcal/kg.fuel

Knowing the lower calorific value of kerosene as 10,400 kcal/kg, H is calculated as

$$H = 10{,}400 - 4{,}666 = 5{,}734 \text{ kcal/kg.fuel}$$

Heat recovery P by air preheat is calculated as follows.

Combustion air flow:

$$11.4 \times 1.2 = 13.68 \text{ m}^3\text{N/kg.fuel}$$

Heat recovery

$$P = 13.68 \times 0.315 \times 300 = 1{,}293 \text{ kcal/kg.fuel}$$

Therefore,

$$Sp = \frac{P}{H + P} = \frac{1{,}293}{5{,}734 + 1{,}293} = 18.4\ \%$$

Figure 14 covers a range of air preheat level to facilitate estimation of the effect to energy saving.

4.1.2 Continuous steel slab reheat furance with hot cooling system, waste heat boiler and recuperator

Figures 15 and 16 illustrate one of the most advanced continuous slab reheat furnace that incorporates hot cooling system for skid pipes located in the furnace, together with recuperator for air preheat and waste heat boiler. Hot cooling system is to use hot watersteam mixture over 100°C instead of cold water in order to cool the skid pipes against heat radiation from furnace inside.

4.1.3 Heat recovery from heated works

In the glass industries, the furnace to be called glass lehr is used to heat the molded glass products up to 450° –600°C followed by soaking for a certain period and then gradual cooling process.

By this heat treatment, the mechanical strength of the products is improved, and at the same time coat or fluorescent matter on the glass surface is baked. Furnace section consists of heating, soaking, gradual cooling and fast cooling zones, through which works are transferred on the mesh belt continuously.

Until recent days, air injected into cooling zones to cool works down was exhausted as waste heat. Today, air is injected into cooling tube located in the cooling zones, and thus preheated air up to 200°C is provided to the burner, as shown in Fig. 17.

[Applied example]

Firing method : Direct fired
F'ce temperature : 550°C
Tonnage : 2,000 kg/h
Fuel consumption : 400,000 kcal/h before improvement
365,000 kcal/h after improvement
Energy saving rate : 9%

4.2 Excess air control

It is well known that stoichiometric combustion is ideal from economical point of view. However, from practical point of view it is quite common to add, a fractional air to the theoretical air requirement for complete combustion. This is a solution to incomplete mixing between air and fuel within a limited time. Air ratio is defined as ratio of actual combustion air flow to theoretical air requirement.

Namely,

$$\text{Air ratio} = \frac{\text{Actual combustion air flows } (\text{m}^3\text{N/kg.fuel})}{\text{Theoretical air requirement } (\text{m}^3\text{N/kg.fuel})}$$

For this, Table 44 shows the suggested guideline concerning excess air ratio, that is currently referred by most part of industries in Japan.

Table 45 presents the fuel saving rate achievable by optimization of air ratio, when firing Bunker A fuel oil. For example, fuel saving rate of 40% is achieved by reducing air ratio from 1.5 to 1.2, when furnace temperature is 1,300°C. Assuming available heat (kcal/kg.fuel) before and after excess air adjustment H_1 and H_2 respectively, it is generally true that H_2 is more than H_1, and fuel consumption rate for furnace thermal input x (kcal/h) decreases from $\frac{x}{H_1}$ to $\frac{x}{H_2}$ (kg/h).

Energy saving rate S_A is therefore expressed as

$$S_A = \frac{\frac{x}{H_1} - \frac{x}{H_2}}{\frac{x}{H}} = (1 + \frac{H_1}{H_2}) \times 100\ \%$$

H_1 and H_2 are defined as

$H_1 = F - Q_1$
$H_2 = F - Q_2$ (See 4.1.1)

4.3 Combined effect of preheat and excess air control

Presuming the fuel consumption rate 1, energy saving S_P (%) by air preheat and S_A (%) by excess air control, the fuel consumption rate when applying both measures is simply calculated as,

$$(1 - \frac{S_P}{100})(1 - \frac{S_A}{100})$$

and the integrated energy saving rate S_T is expressed as

$$S_T = \frac{1 - (1 - \frac{S_P}{100})(1 - \frac{S_A}{100})}{1}$$

$$= (S_P + S_A - \frac{S_P \cdot S_A}{100})\ \%$$

where

$$S_P = \frac{P}{H + P} \times 100\% \qquad \text{and}$$

$$S_A = (1 - \frac{H_1}{H_2}) \times 100\%$$

Therefore,

$$ST = \{1 - \frac{H_1 \cdot H}{H_2 (H + P)}\} \times 100\%$$

Here, because both measures to air preheat and to excess air ratio are taken for energy saving available heat H is identical with H_2.

Hence, S_T is summarized as,

$$ST = (1 - \frac{H_1}{H + P}) \times 100\%$$

Figure 18 presents the calculated results for the above equation concerning the integrated energy saving when firing Bunker B heavy fuel oil.

It must be recognized that air preheat level alters against changes in furnace load and furnace temperature, suggesting that a certain compensation system is necessary that works to keep air ratio unchanged. Figure 19 indicates how air ratio changes from 1.1 that was initially adjusted, when preheat level alters. To this solution, Fig. 12 shows the complete system, while Figs. 20 and 21 are concerned with more simple compensator that costs less but achieves less control accuracy.

4.4 Furnace pressure control

4.4.1 Necessity of furnace pressure control

(1) Pressure control for direct fired furnace

Here, a continuous steel slab reheat fuenace is described as an example.

Pusher furnace as shown in Fig. 22 (a) is of type where slabs are pushed forward through furnace inside. In contrast to this, walking beam furnace is of type where movable beam and stationary beam stand in the furnace and movable beam cycles the motion of upforward-down-backward by which slabs are tranferred toward furnace exit, as shown Fig. 22 (b).

Furnace undergoes the automatic control in pressure by a damper located in the flue duct. Detected pressure signal from the hearth line of furnace exit is supposed to actuate the above damper. From a point of view of energy saving, the hearth line pressure of + 0 mmH_2O is aimed at furnace inlet and the eventual hearth line pressure at furnace exit is preset with draft loss through furnace section taken into account. Typical draft loss lies within a range of 0.1 to 0.5 mmH_2O. Figure 23 shows the relationship between furnace pressure and air infiltration through furnace opening. It is indicated by the figure that setting the furnace bottom pressure at + 0 mmH_2O or a slightly positive is preferable. When the furnace pressure is controlled at a negative pressure, infiltrated air acts as an adversely affecting factor against both products quality and thermal efficiency. On the contrary, at an excessively high furnace pressure, hot combustion products tend to blow out through furnace opening, resulting in either overheat of furnace shell or thermal deficiency, and eventually penalty of shortened service life in refractories is involved.

Figure 24 presents the air infiltration rate as a function of furnace pressure while Fig. 25 suggests the recommended furnace pressure from the aspects of thermal efficiency and maintenance.

(2) Pressure control for batch type of heat treatment furnace

A positive furnace pressure is vital, desirably 10 to 20 mmH_2O, for heat treatment furnaces into which the atmosphere gas is supplied. Flow rate of atmosphere is thus manually controlled by adjustment of gas regulating valve. As air-seal enforcement, the furnace door is kept pushed tight to the furnace structure by air driven cylinder, between which the soft packing is used both to extend the service life and to accomplish better economy for running cost.

Also, a water seal device is employed on the atmosphere gas delivery pipe for the purpose of controlling the furnace pressure. In the heat treatment furnace which employs a gas recirculation fan, it is essential for keeping a constant furnace pressure to control the delivery flow of atmosphere gas in response to fan rotation by which the furnace pressure is possibly disturbed. To this end, water level of water seal device is raised to increase the delivery flow of gas at fan start-up, after which the level is restored when fan rotation has been stabilized.

(3) Furnace pressure control for continuous heat treatment furnace

Atmosphere gas is similarly provided also to, for example, a cold mill strip annealing furnace. In this, leakage of atmosphere gas from seal rollers employed at furnace inlet and outlet seems to be unavoidable. For the solution to this, additional gas of a certain amount is provided from various sections of furnace, resulting in that the furnace pressure remains controlled at 10 to 20 mmH_2O. In practice, the gas delivery flow is monitored and controlled depending upon the furnace operating conditions.

4.4.2 Control method of furnace pressure

(1) Pressure control in fuel fired furnace

There are natural draft type and forced draft type in fuel fired furnace. Control system comprises pressure detector (sensor), pressure transmitter, pressure controller unit, control damper located in flue duct and actuator. In the continuous furnace in which the doors for charge and discharge repeatedly open, the door motion behaves as a disturbing factor against control system. As a countermeasure to this the recent development concerning predicted control concept has been evaluated, where utilization of multifunction computing control capability of micro-DDC system has been found to serve as essential tool for in-advance control against fluctuation of operating condition.

(2) Computed control method for furnace pressure

In the multiple zone furnace for special steel alloy a recuperator is employed to each zone in order to achieve good fuel economy, and in addition requirement of even temperature distribution over the full furnace length arises. (See Fig. 26) To meet this requirement, damper opening in each flue duct is controlled by computing the real time firing rate as well as balance control among dampers. In an actual experience, the initially aimed purpose was accomplished by employing micro-DDS controller that computes flue gas volume of each section to determine the damper opening based on the output signals of fuel flow, air flow rate and furnace temperature.

(3) Special example for furnace pressure control

Glass melting furnace deals with caustic soda and silicic acid, and needs furnace pressure control for energy saving. Since the ordinary mechanical damper undergoes penalty of solidification of molten glass with resultant malfunction, air jet curtain is employed as pressure control device as shown in Fig. 27 (a). Figure 27 (b) shows the separately designed mechanical damper proposed to cope with the problem. Either device however retains disadvantage in response.

4.4.3 Damper mechanism and actuator

Butterfly type and slide type are widely used as mechanical damper, and should be carefully designed so as to withstand high temperature and thermal stress as well as to ensure acceptable response as a component in control loop.

These aspects become particularly important for the furnace the doors of which frequently open and close. Figure 28 (a) shows a slide damper driven by combination of pulley, wire and power cylinder.

Investment is in inverse proportion to response time that is improved by employing a high power cylinder and a heavy counter-weight.

Figure 28 (b) shows a butterfly damper which is supported by thrust roller bearings as for weight and by radial roller bearings as for radial force generated by: differential pressure through valve vane. The latter damper therefore needs the less actuating power than the first one, and ensures the advantage over the other in response time and tightness. As actuating power source, the hydraulic method is recommended in sense of response time. Tables 46 and 47 summarize the characteristics of various dampers.

4.5 Energy saving from furnace design aspect

4.5.1 Effective furnace length and shape of continuos furnace

Walking beam reheat furnace is described as representative example. Design review started with the effective furnace length to reduce fuel consumption rate. It is undoubted that the sensible heat of flue gas accounts for majority of heat loss, and that therefore diminishing this part of loss dominates the eventual reduction of fuel consumption. Based upon the study, the work heating load of 500 to 600 kg/m^{2}h as shown in Fig. 29 is today regarded as the optimized value, from which the effective furnace length is determined.

This, in turn, implies that the length has become 1.5 to 1.8 times as long, compared to the design basis over 900 kg/m^{2}h taken before oil crisis period. Although the extended furnace length impacts the increased investment, the improved fuel economy ensures the pay-back period within two or three years.

Fuel consumption rates indicated in Fig. 29 are compared for the reheat furnace with skid pipe double insulated, and there fuel consumption rate is 400×10^3 kcal/ton when designed at 900 kg/m^{2}h in heating load compared to 340×10^3 kcal/ton when designed at

600 kg/m^{2}h However, excessively reduced heating load below 400 kg/m^{2}h rather indicates increase in fuel consumption.

Figure 30 illustrates the comparison in effective length of walking beam reheat furnace erected before and after oil crisis period. The remarkable difference is that a moder reheat furnace incorporates the preheat zone without any burner installed, the length of which reaches 25% of total effective length.

4.5.2 Application of ceramic fiber to steel slab continuous reheating furnace

(1) Background of steel slab rolling continuous reheating furnace and needs for furnace material

1) Further strengthening of energy-saving measures is needed.

2) Because of continuous casting of steel slab, not charge (600°–1,000°C) is now the mainstream, but cold charge is still used depending on the grade of steel Therefore, the reheating furnace is required to handle both hot and cold charge.

3) Slab extracting temperatures in the continuous reheating furnace range from low temperature settings of 900 to 1,000°C depending on the grade of rolled steel. The furnace material must be selected on the basis of the high temperature extracting conditions.

4) The reheating furnace is required to readily change and follow up the temperature settings according to the grade of steel slab under either cold or hot charge operating conditions.

5) It is likely that in the case of a steel making plant only one unit of slab rolling continuous reheating furnace is used in the preprocessing process for the continuous casting machine. In such a case, it is not possible to stop the furnace.

4.5.3 Historical change of furnace design for catenary type

Figure 31 shows historical change of furnace design for catenary type. This type of furnace is used for continuous galvanizing line or continuous annealing and pickling line of stainless steel.

At first furnace is divided to two parts by support roller because of protecting roller from high temperature. And then by means of water cooled roller furnace was integrated into one.

And next to this it was put no burner zone as waste gas radiation zone. In addition to above it was also put convectional preheating zone with waste gas recirculation fan.

Finally recuperator and waste gas boiler was equipped.

Figure 32 shows update continuous anneal line. This furnace also equipped waste gas recirculating preheat zone.

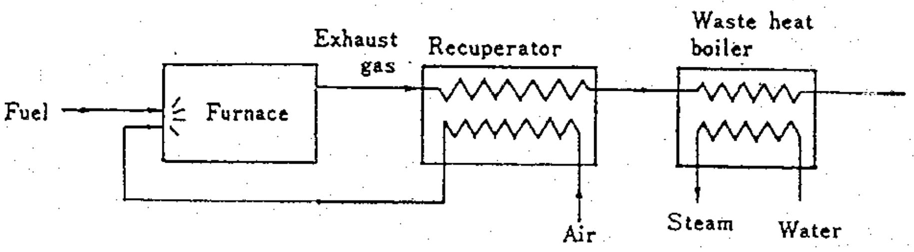
Figure 33 shows update annealing and picking line. Of course it is equipped radiational and convectional preheating zone, and in addition to that floater is useed instead of roller to reduce the water cooling loss.

4.5.4 Batch type annealing furnace with H_2 atmosphere

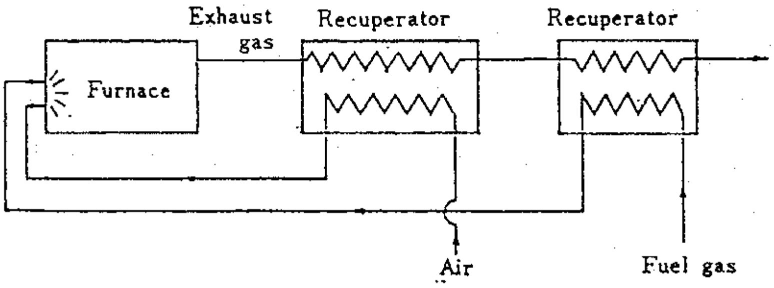
Batch type annealing furnace which is generally called bell type annealing furnace is usually operated under N_2 atmosphere. But thermal conductivity of hydrogen is greater than of nitrogen. So using hydrogen as treating atmosphere instead of nitrogen makes total energy during annealing lower.

Figure 34 shows typical H_2 batch annealing furnace.

Figure 10 Layout examples of waste heat recovery by recuperator

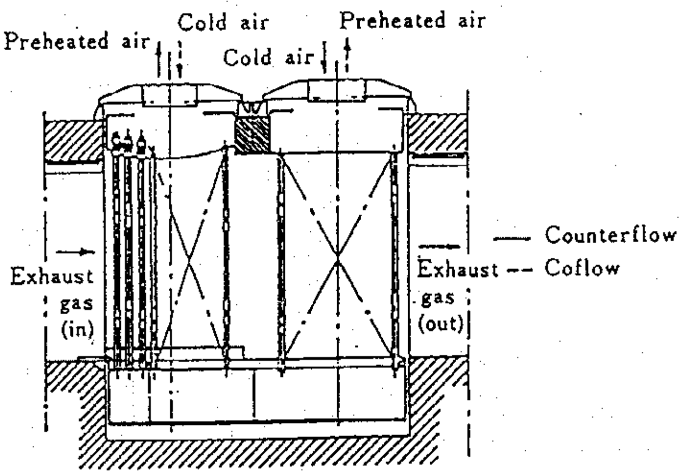


(a) Preheating of combustion air and generation of steam by waste heat boiler

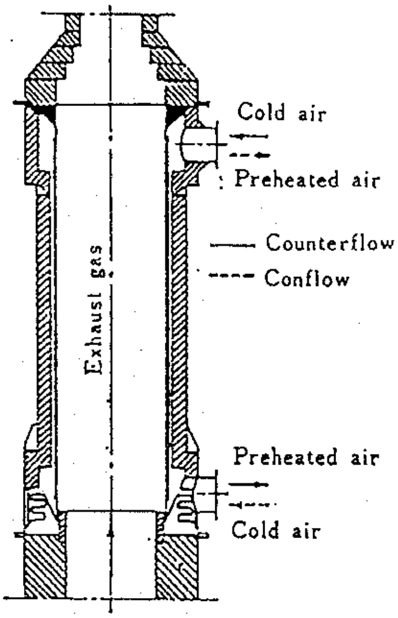


(b) Preheating of combustion air and fuel

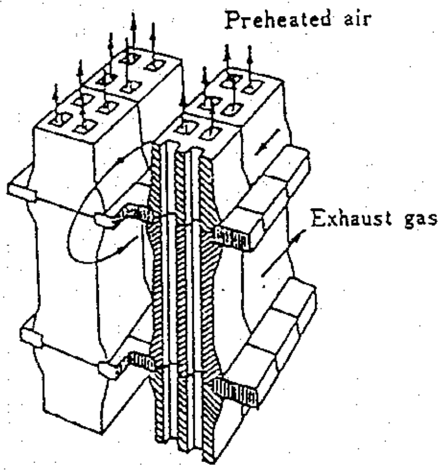
Figure 11 Example of recuperators



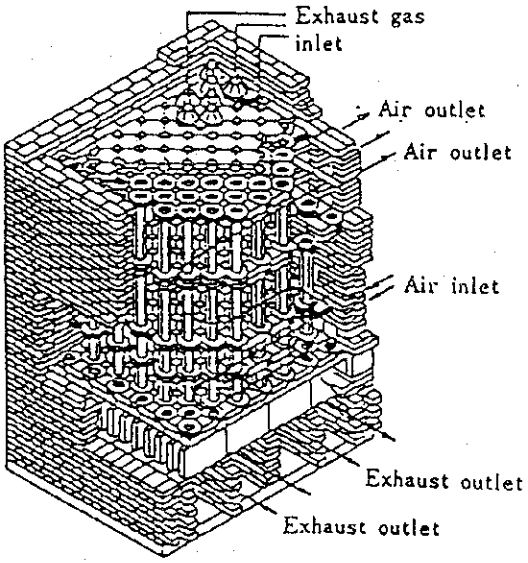
(a) Tube type recuperator



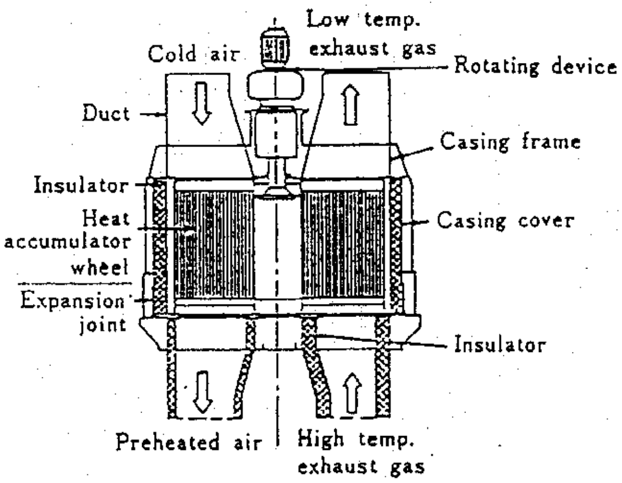
(b) Radiation type recuperator



(c) Stein tile recuperator



(d) Armco type tile recuperator



(e) Heat wheel

Figure 12 Air fuel ratio control system for the case preheating combustion air

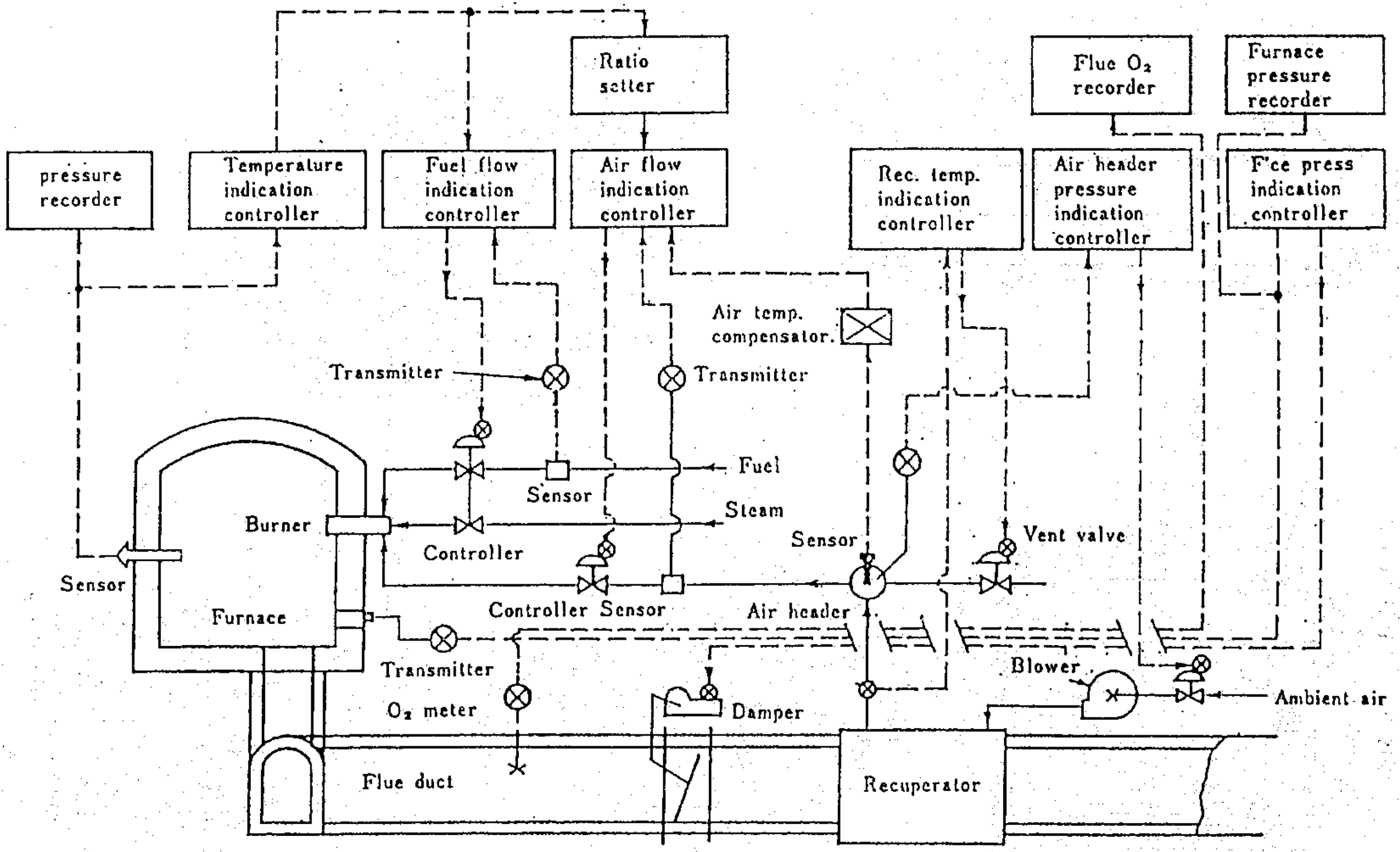


Figure 13 Basic conceptual diagram of waste heat utilization

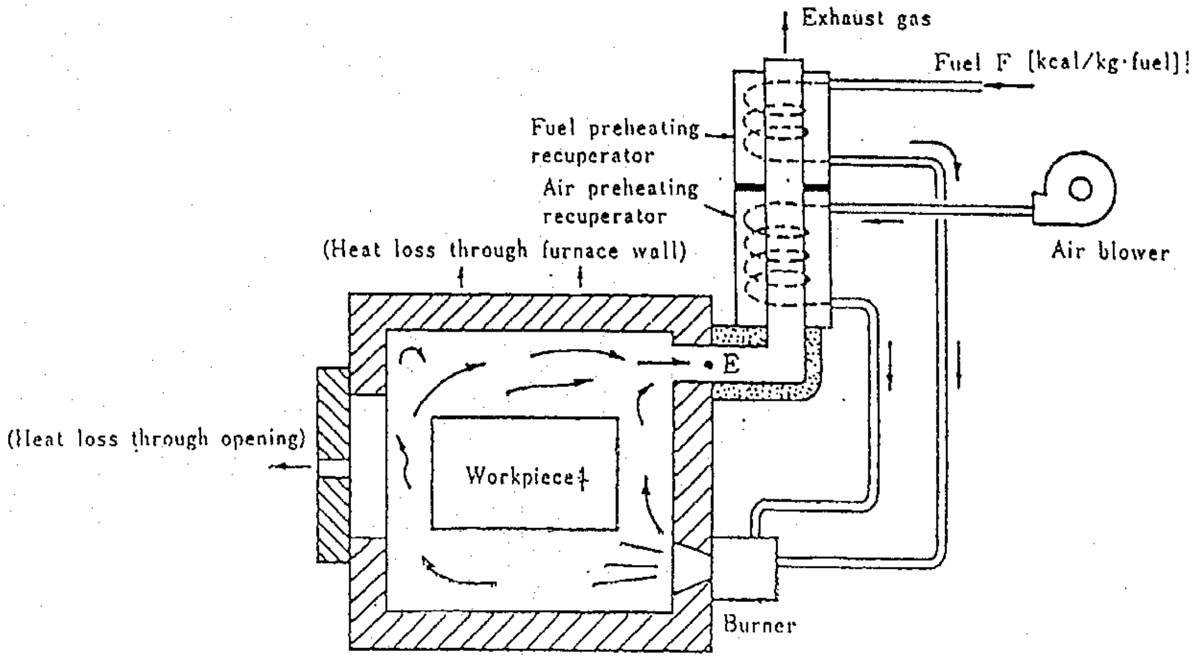


Figure 14 Fuel saving rate through air preheating

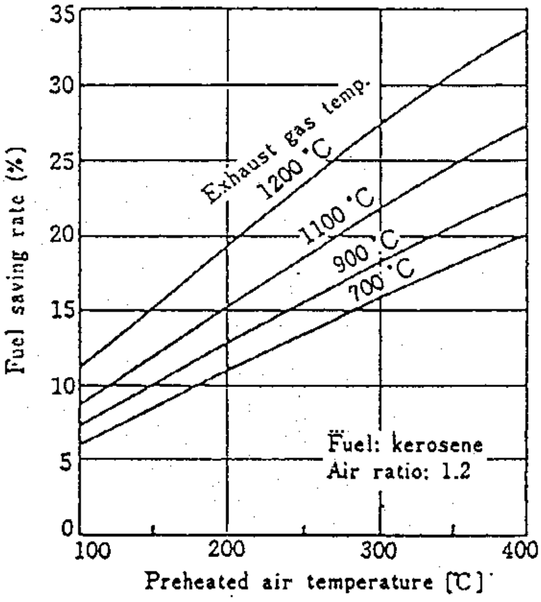


Figure 15 System diagram of hot cooling system

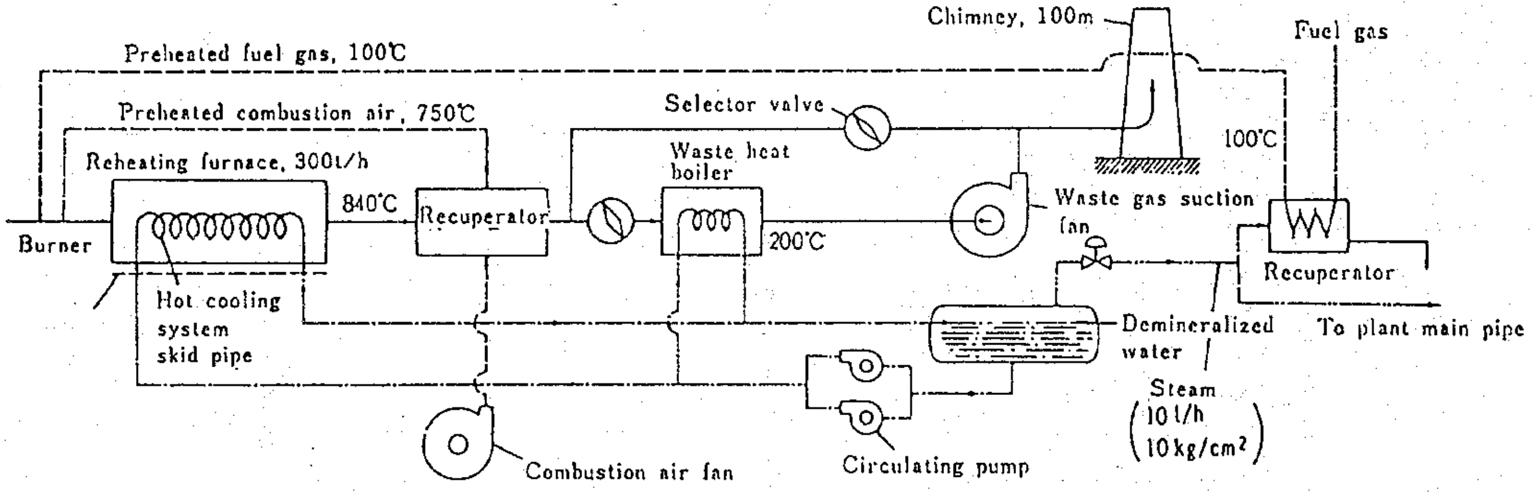
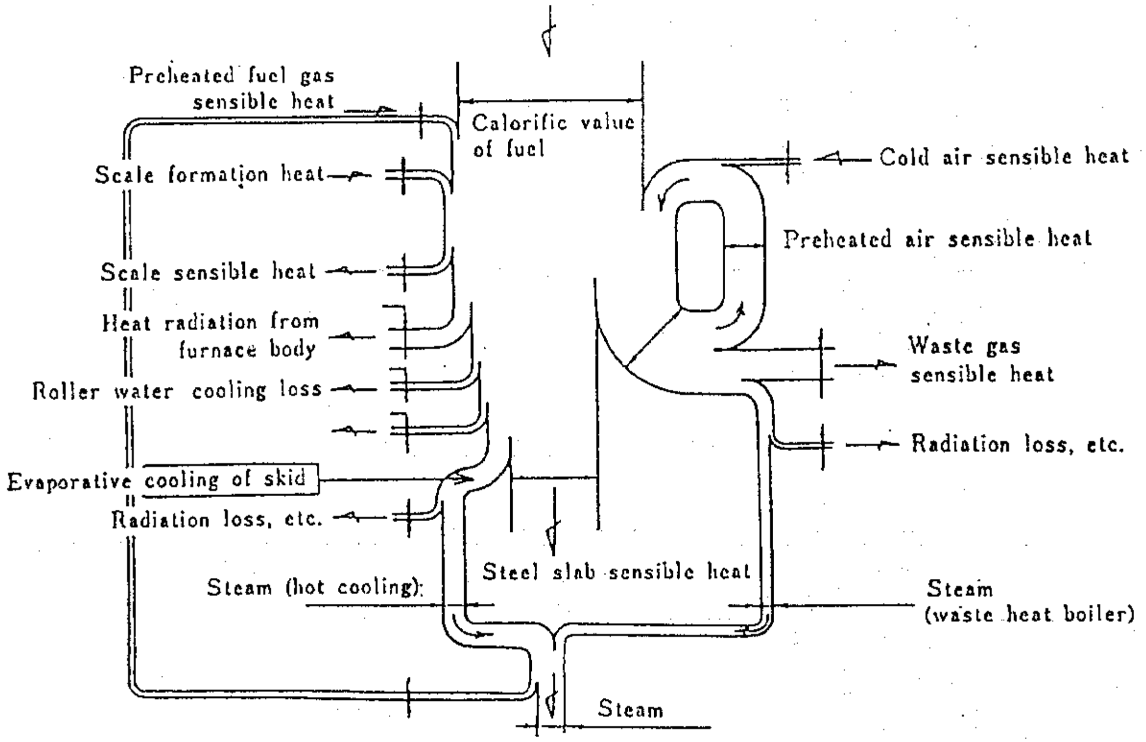


Figure 16 WB type reheating furnace heat balance (calculated value)



Heating capacity: 300t/h
Fuel consumption: 12.1 × 10^4kcal/t (2.0 × 10^4kcal/t for steam)
Fuel: COG (5,000kcal/Nm^3)
Steel slab charge temperature: 770℃ average
Steel slab discharge temperature: 1,250℃

Figure 17 Heating curve in glass lehr

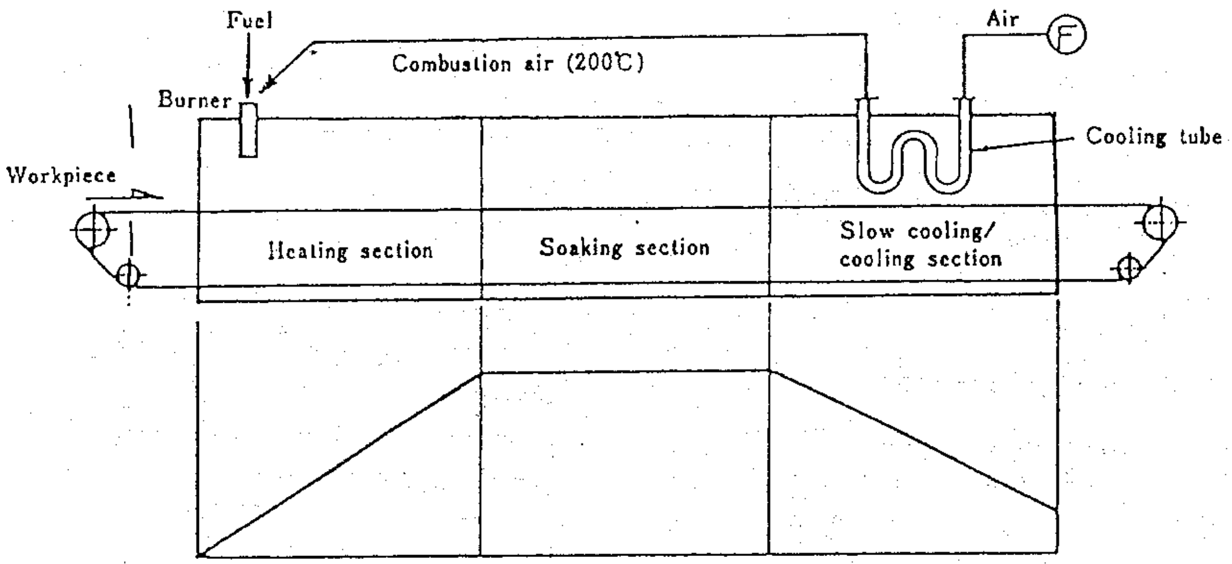


Figure 18 Overall fuel saving rate through combustion air preheating and air ratio correction (Fuel oil B)

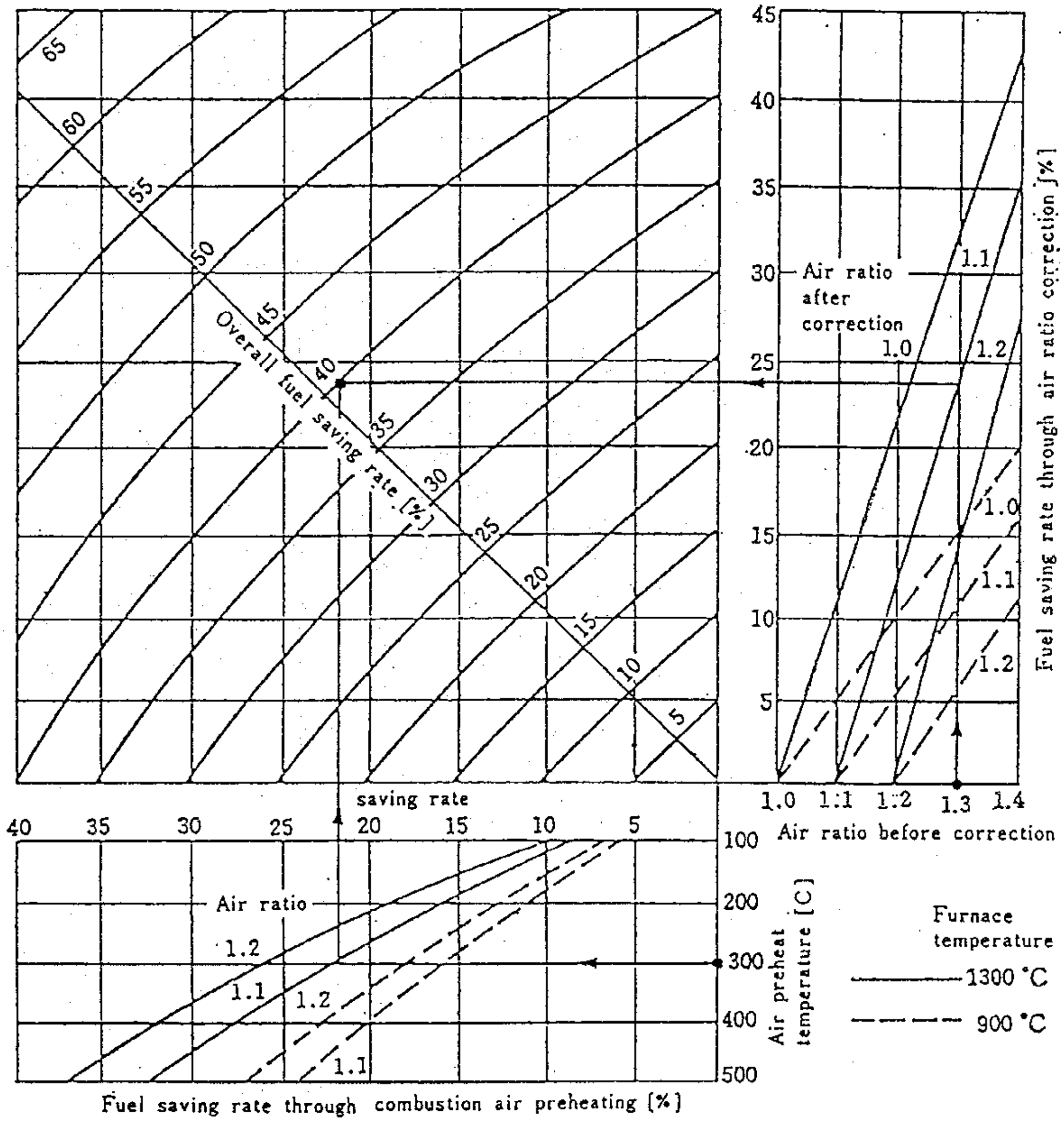


Figure 19 Air ratio variation against combustion air temperature variation

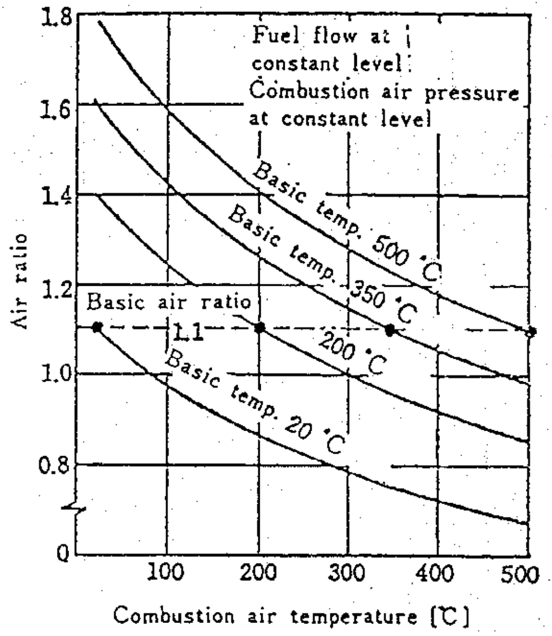


Figure 20 System diagram of proportioning oil burner piping with air preheat compensator

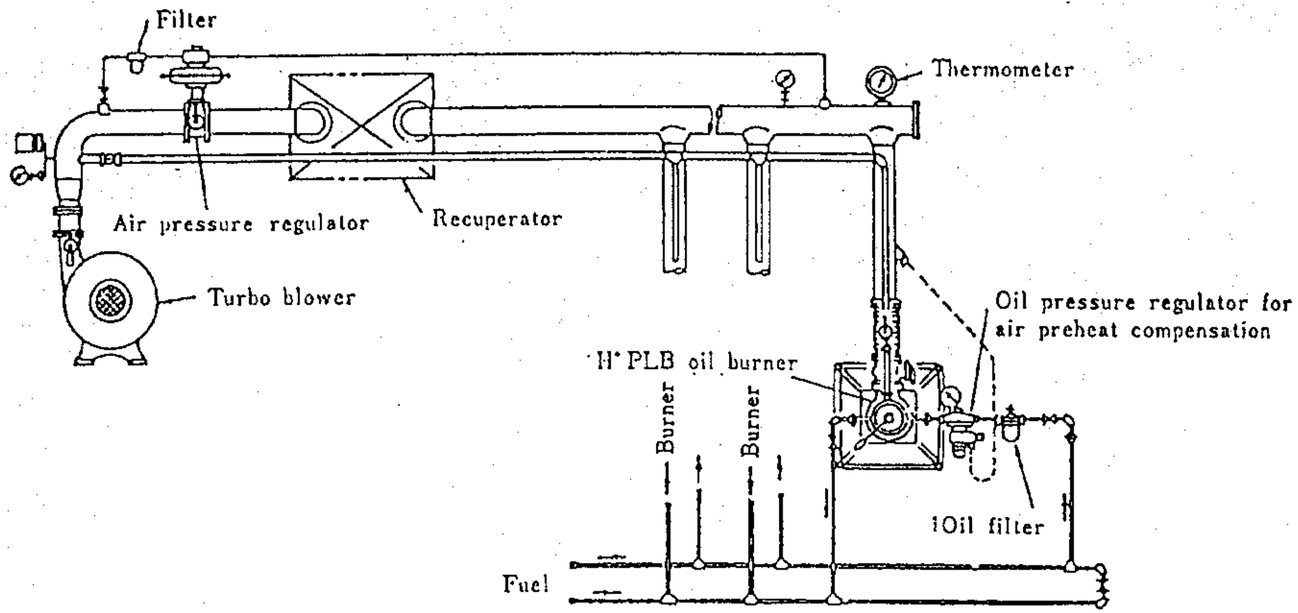


Figure 21 System diagram of gas burner piping with air preheat conpensator

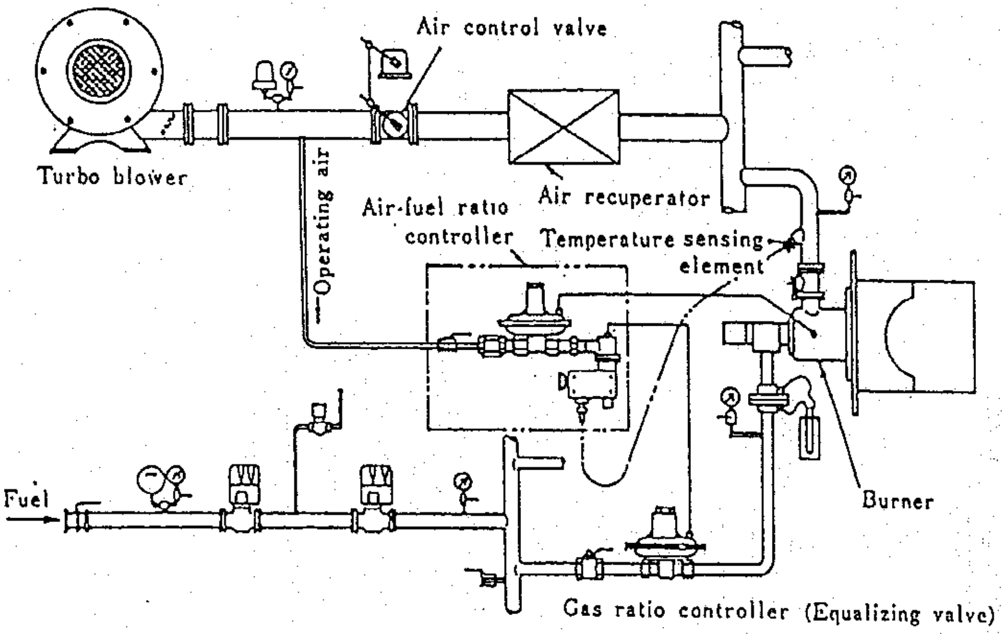
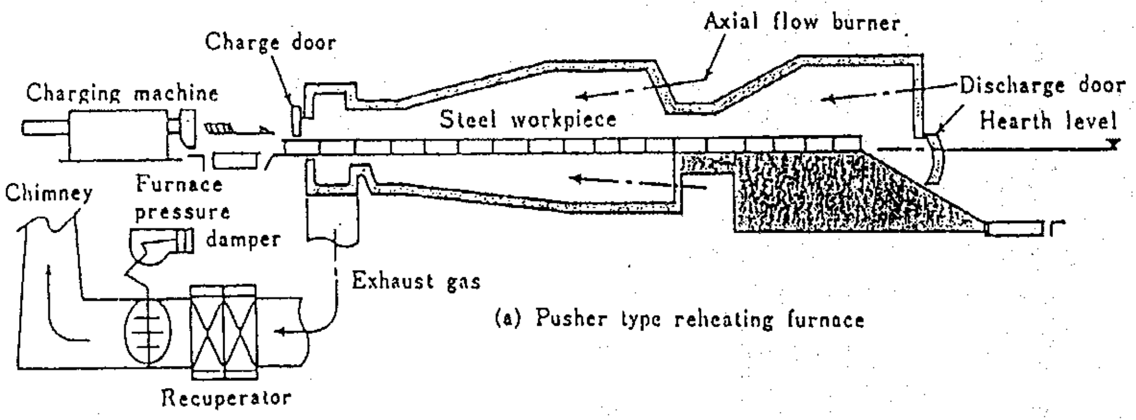
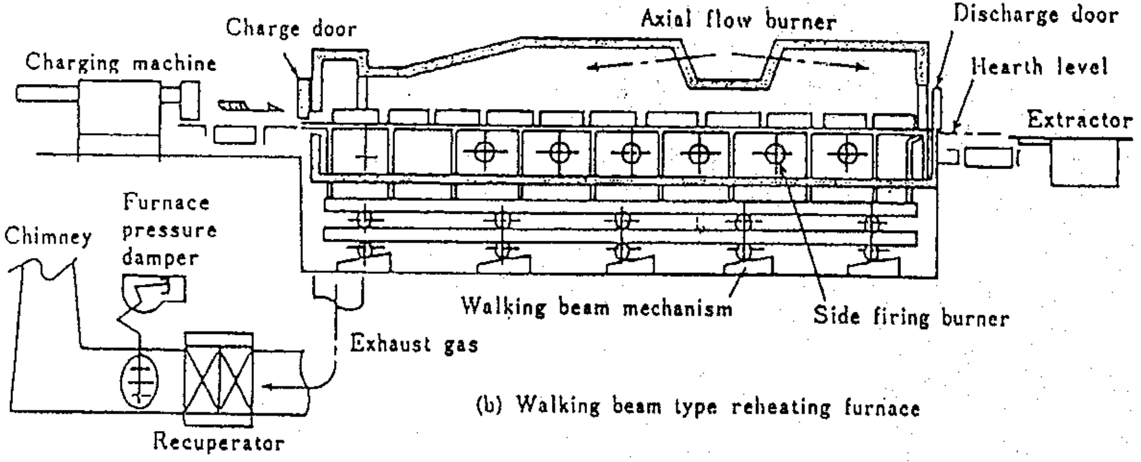


Figure 22 Furnace pressure control



(a) Pusher type reheating furnace



(b) Walking beam type reheating furnace

Figure 23 Air ingress during reheating furnace opration

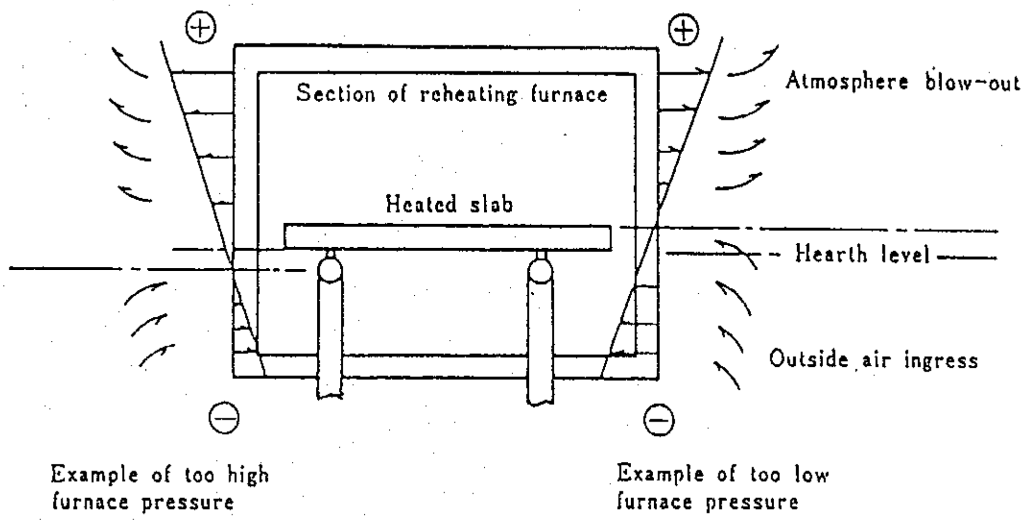
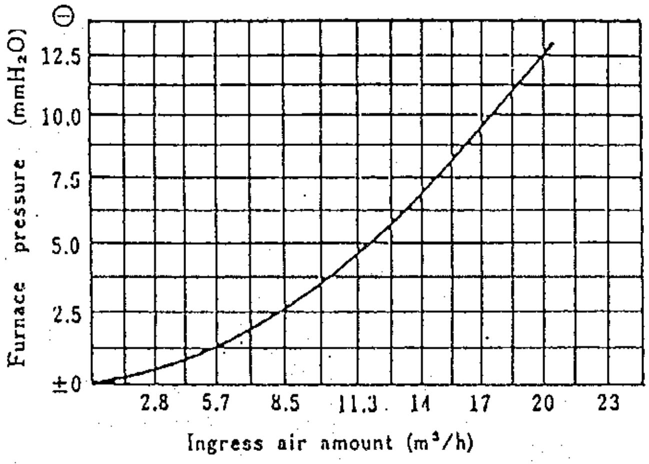
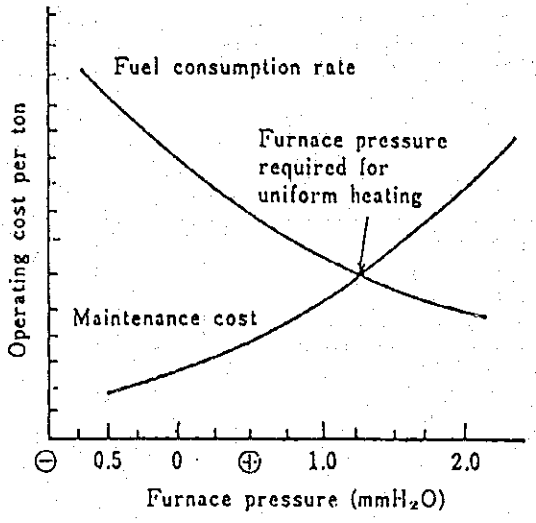


Figure 24 Furnace pressure vs. ingress air amount



(Air ingress through 25.4mm square opening)

Figure 25 Optimum furnace pressure in view of fuel consumption rate and furnace maintenance



Measuring point: furnace ceiling
(1.5m from hearth level)

Figure 26 Continuous reheating furnace with furnace pressure arithmetic control system

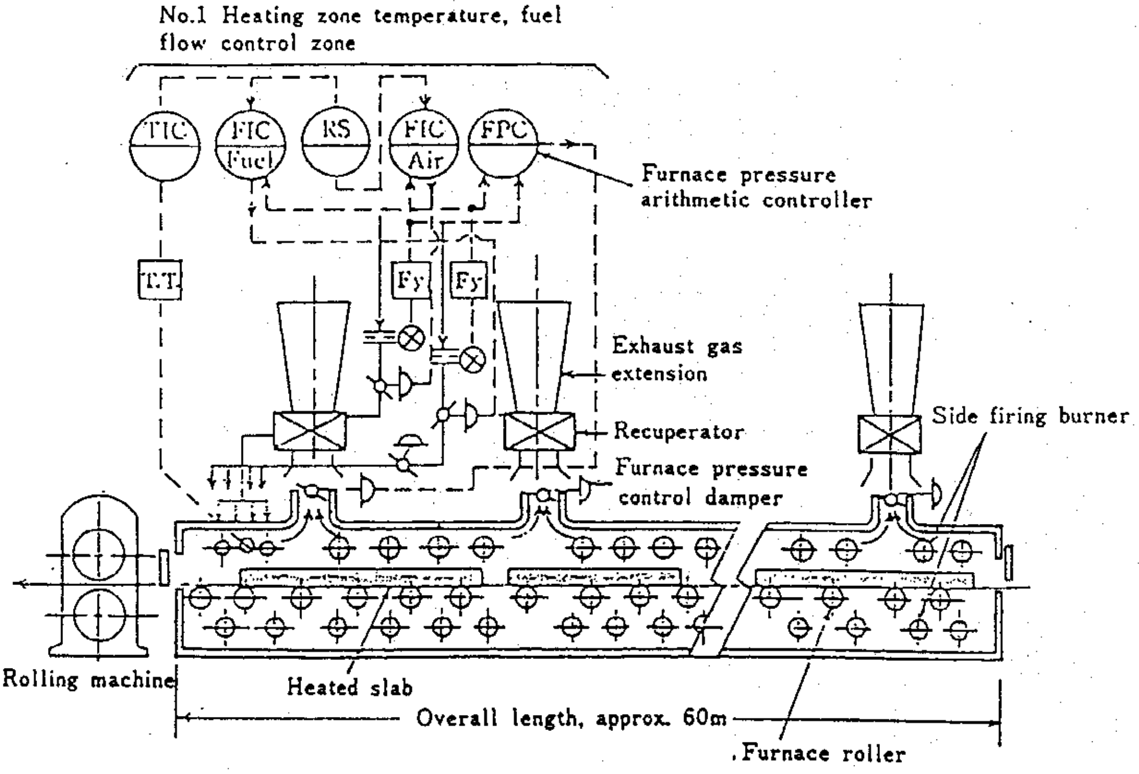
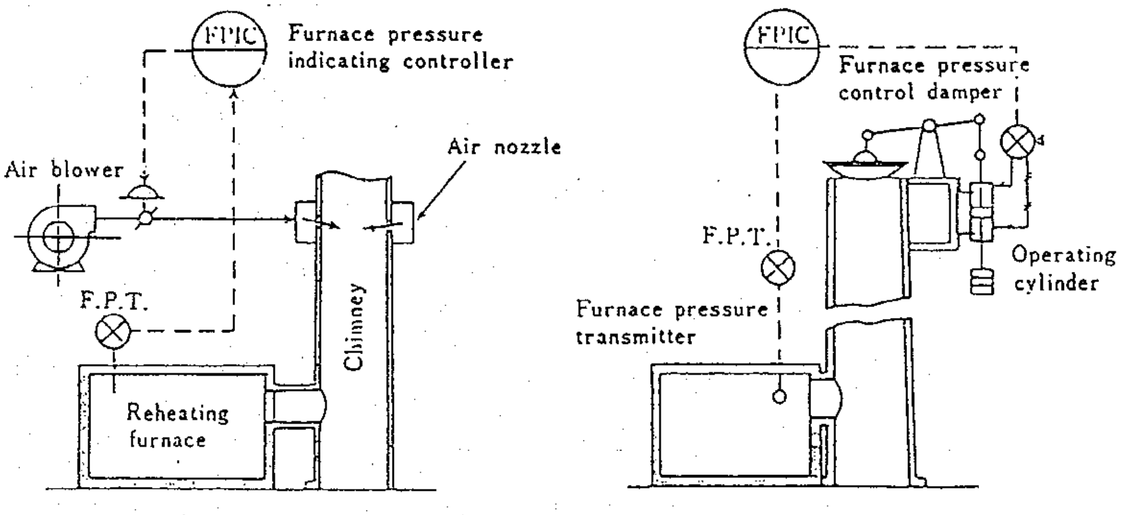
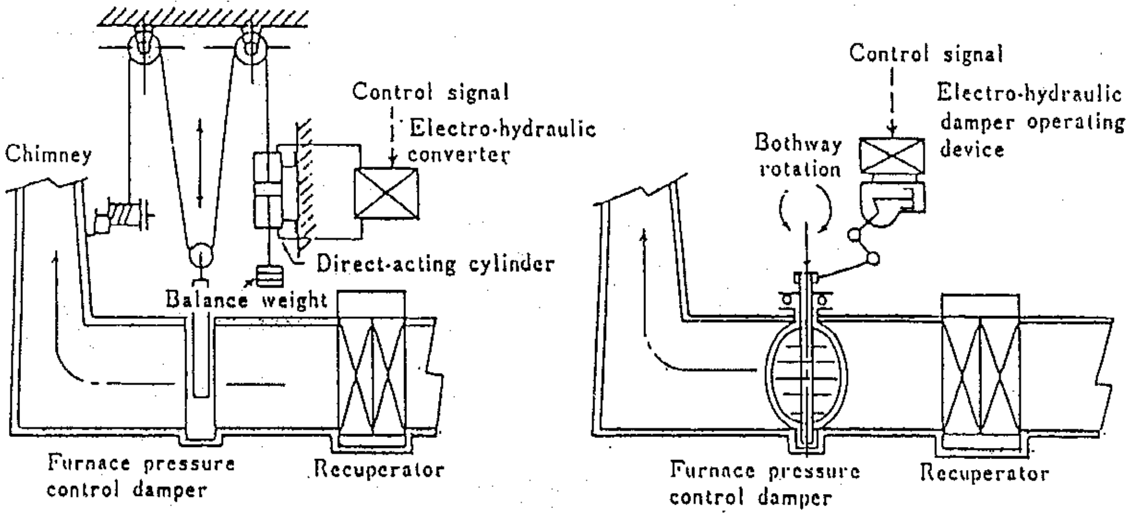


Figure 27 Damper for pressure control



(a) Air curtain type (b) Poppet valve type

Figure 28 Damper configuration



(a) Suspended slide damper (b) Rotary (butterfly) type damper

Figure 29 Hearth coverage and fuel consumption of WB furnace provided with double insulation method

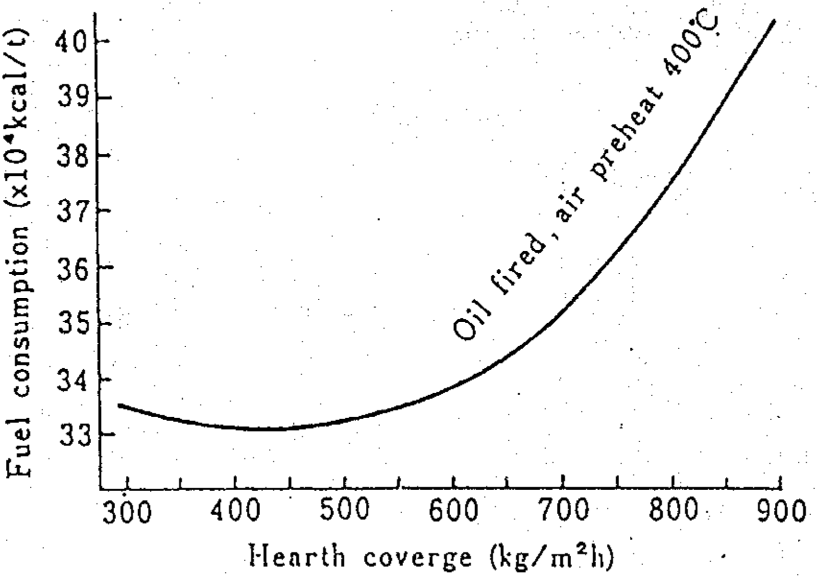
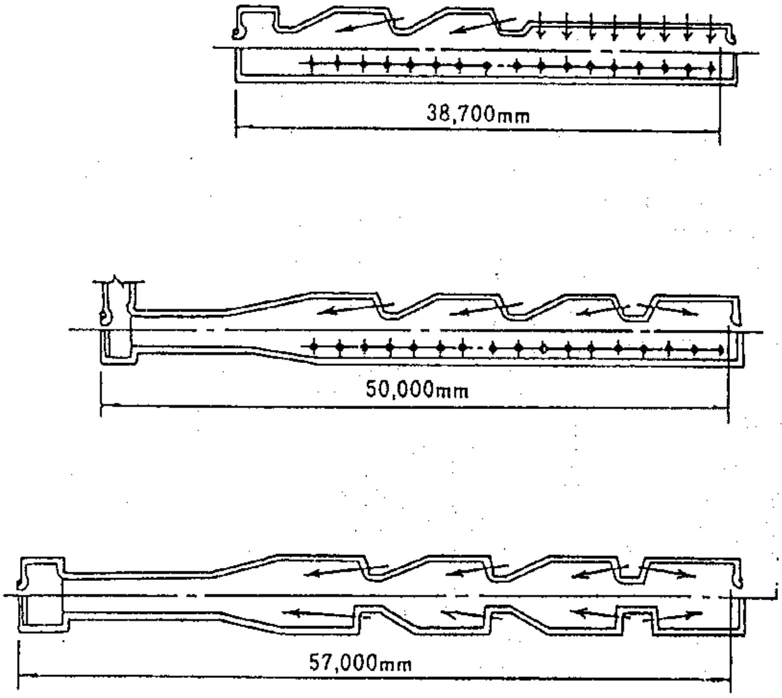


Figure 30 Example of hearth coverage (effective furnace length)



Hot strip mill
420 t/h
890 Kg/m^{2}h
45×10^4Kcal/t
450°C Air, preheating/heating zone: heavy oil/soaking zone: mixed gas
Heating/soaking zone: mixed gas
Start of operation: June 1971

Hot strip mill
300 t/h
650 Kg/m^{2}h
35×10^4Kcal/t
400°C Air, Heavy oil
Start of operation: Jan. '81

Hot strip mill
300 t/h
600 Kg/m^{2}h
36×10^4Kcal/t
500°C Air, Mixed gas
Start of operation: Apr. '79

Figure 31 Historical change of furnace desigh for catenary type

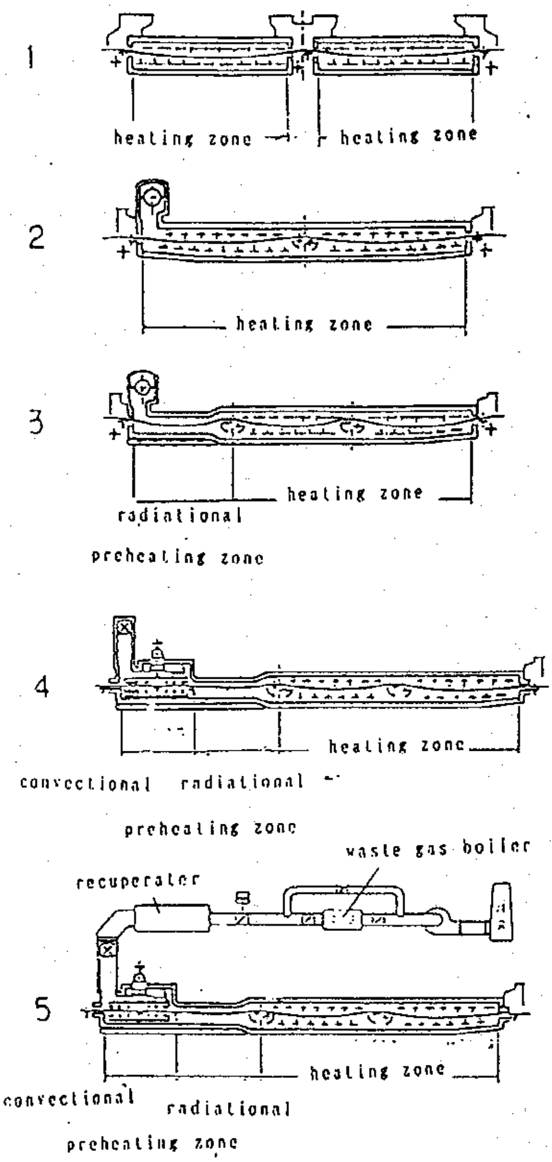
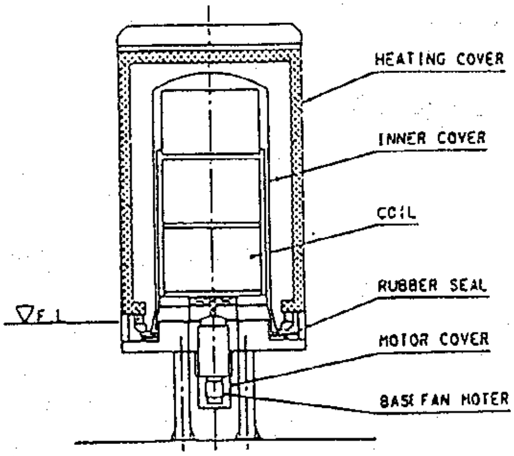


Figure 32 H_2 type batch annealing furnace



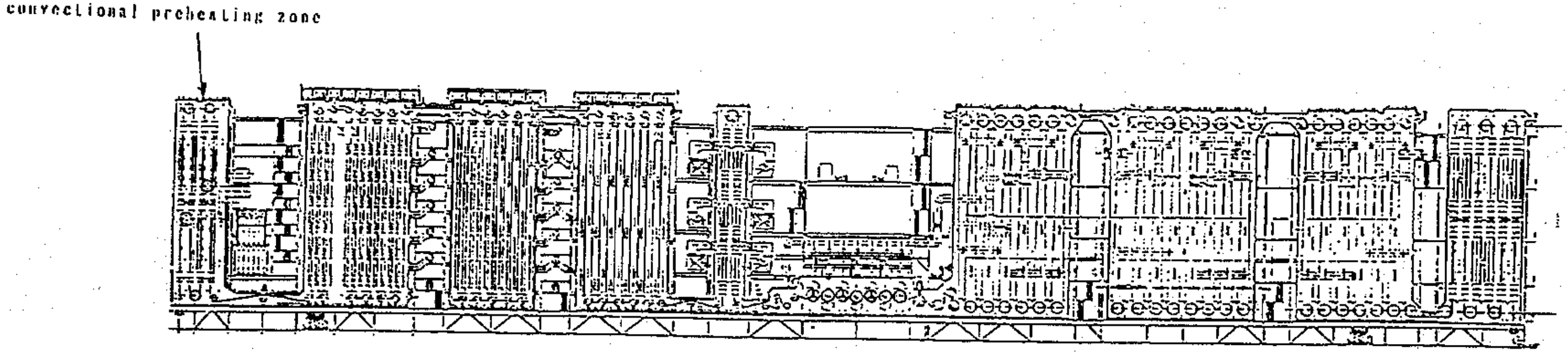


Figure 33 Update continuous annealing line

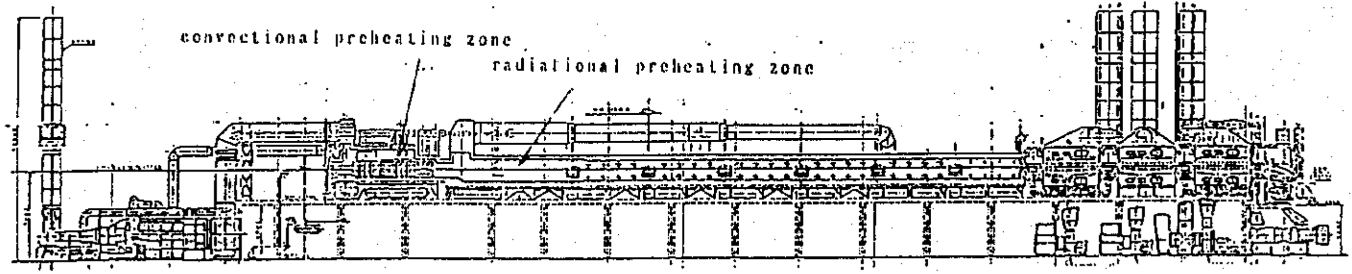


Figure 34 Update annealing and pickling line for stainless steel

Figure 35 Thermal efficiency of industrial furnaces

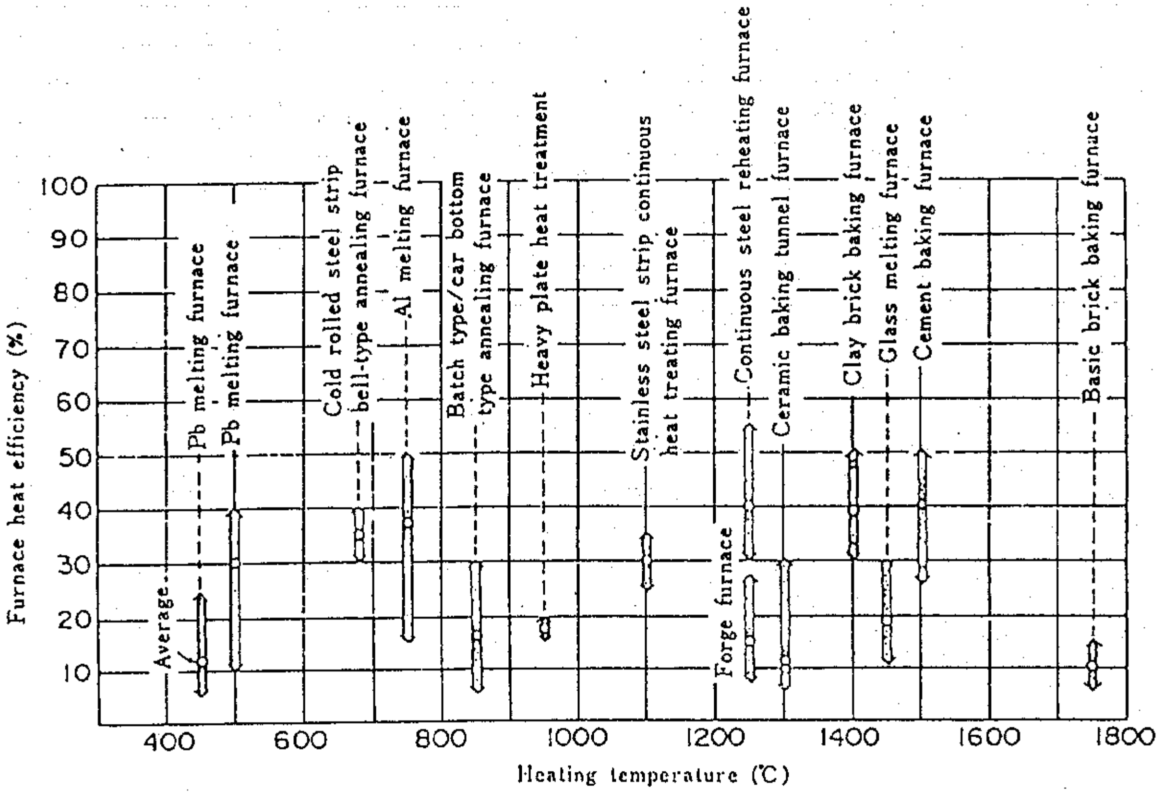
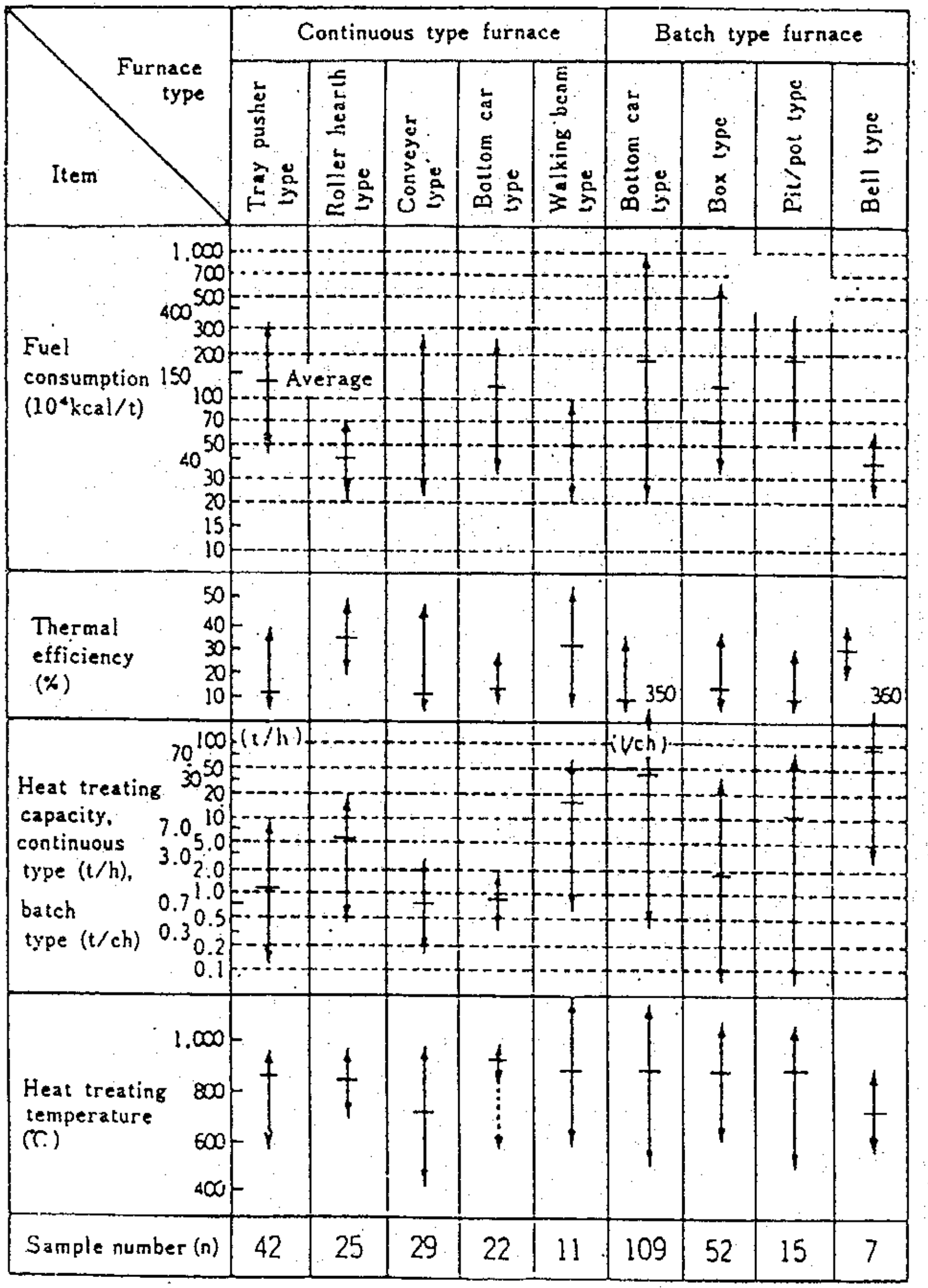


Table 36 Fuel consumption and thermal efficiency of heat treating furnace



Furnace type	Tray pusher type	Roller hearth type	Conveyer type	Bottom car type	Walking beam type	Bottom car type	Box type	Pit/pot type	Bell type
	Continuous type furnace					Batch type furnace			
Sample number (n)	42	25	29	22	11	109	52	15	7

Table 37 Heating capacity and actual fuel consumption of steel slab continuous reheating furnace

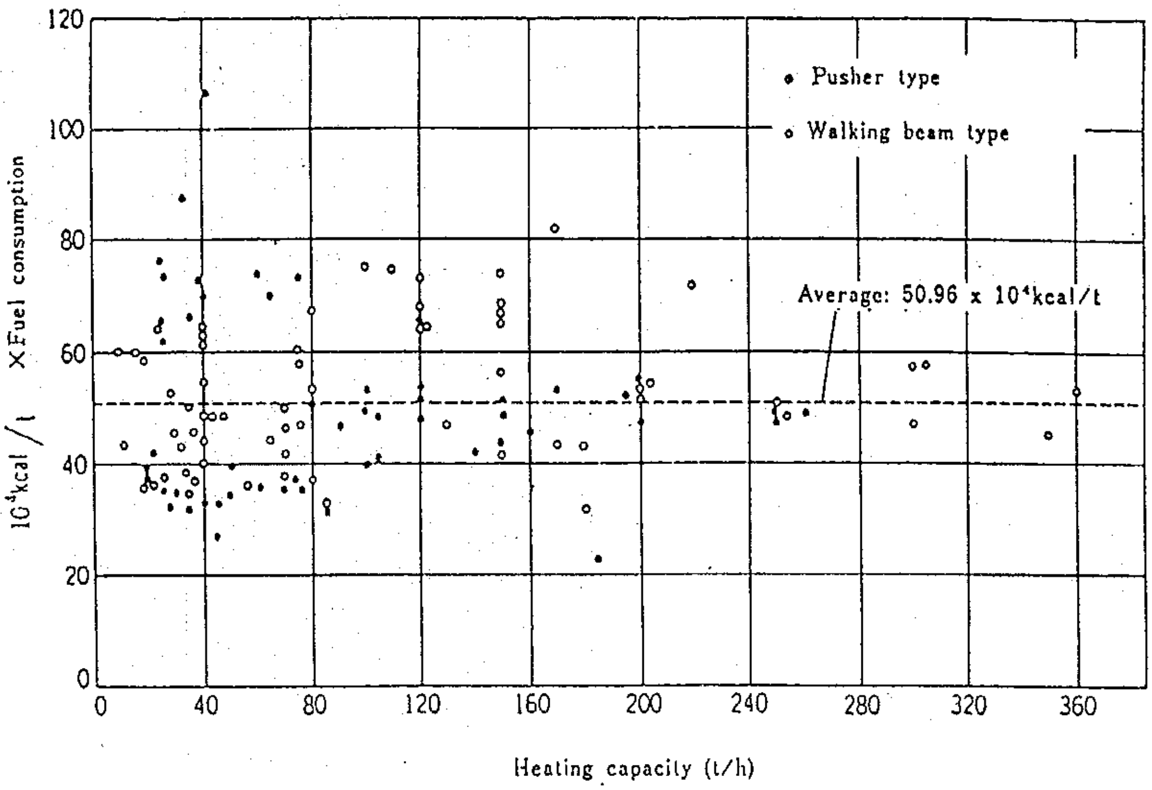


Table 38 Fuel consumption and thermal efficiency in forge furnace

Plant	Kind of forging	Fuel consumption litre/t(product)	Heat efficiency %
A	Closed die forging	340	8.3
B	〃	355	8.5
C	〃	240	12.5
D	〃	270	11.0
E	〃	205	14.6
F	〃	238	12.6
G	Open die forging	240	8.9
H	〃	380	5.6

Table 39 Fuel consumption of melting furnace

Kind of furnace	Number of furnaces	Fuel consumption (10^4kcal/t)		Melting capacity (t/d)	Melting temperature (℃)	Fuel
		Average	Range			
Aluminum melting furnace	43	134.7	81~216	6~ 200	(Tap hole) 630~900	Heavy oil,
Copper melting furnace (continuous type)	8	88.9	57~140	36~1,320	1,100~1,300	Heavy oil,
〃 (quarter type)	4	74.8	55~100	5~1,296	1,000~1,200	Heavy oil,
Glass melting furnace (plate, bottle, electric)	101	272.8	132~700	10~ 430	1,400~1,650	Heavy oil, light oil, kerosene, LPG

Note: Only cold charge is used for aluminum melting

Table 40 Fuel consumption of tunnel kiln

Kind of furnace		No. of furnaces	Fuel consumption (10^4 kcal/t)		Capacity (Product) (t/h)	Temp. (℃)	Fuel
	Temp [℃]		Average	Range			
Tunnel kiln for fire brick	970~1,200	28	99.5	36~330	5~ 72	970~1,200	Heavy oil
	1,250~1,550	70	142.2	75~576	2~ 72	1,250~1,550	Heavy oil, LPG, Kerosene
	1,600~1,850	24	373.3	150~710	8~ 49	1,600~1,850	Heavy oil, Kerosene
Tunnel kiln for tile		50	213.2	64~505	2~220	1,000~1,330	Heavy oil, Diesel oil

Table 41 Factor of energy-saving measures

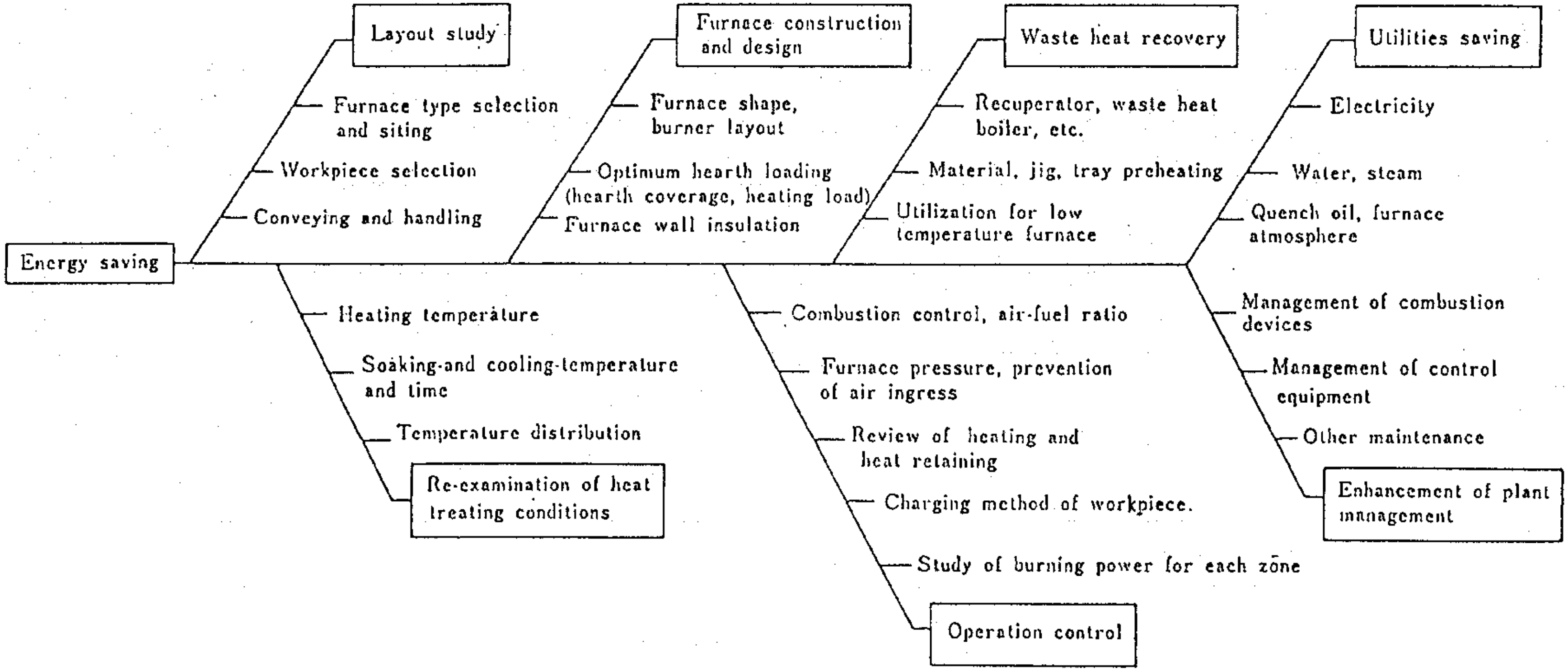


Table 42 Outline of air preheater

Type				Exhaust gas temp. limit	Preheated air temp.	Applied furnace
Recuperator	Metallic recuperator	Flue type	Convection type, multi-tube type, etc.	1,000℃ max.	300~600℃	Reheating furnace, heat treating furnace, other industrial furnaces
		Chimney type	Radiation type (radiation + convection type)	1000~1300℃		
	Ceramic (tile) recuperator		Armco type Stein type	1200~1400℃	400~700℃	Soaking furnace, glass oven
Regenerator	Conventional type			1000~1600℃	600~1300℃	Coke oven, hot blast furnace, glass oven (melter)
	Rotary regenerating type			600℃ max.	100~300℃	Boiler, hot blast furnace, Oil refinery heater

Table 43 Average isopiestic specific heat of gas

Temp. (°C)	H_2	N_2	O_2	CO	H_2O	CO_2	SO_2	Air
0	0. 305	0. 311	0. 312	0. 311	0. 341	0. 387	0. 424	0. 310
100	0. 307	0. 311	0. 315	0. 312	0. 344	0. 412	0. 445	0. 311
200	0. 309	0. 312	0. 320	0. 313	0. 348	0. 432	0. 464	0. 312
300	0. 309	0. 313	0. 325	0. 315	0. 352	0. 450	0. 481	0. 315
400	0. 310	0. 316	0. 330	0. 318	0. 537	0. 466	0. 494	0. 318
500	0. 311	0. 319	0. 334	0. 321	0. 363	0. 480	0. 507	0. 321
600	0. 312	0. 321	0. 339	0. 325	0. 369	0. 493	0. 518	0. 324
700	0. 313	0. 325	0. 343	0. 329	0. 375	0. 504	0. 527	0. 328
800	0. 314	0. 329	0. 347	0. 332	0. 381	0. 515	0. 535	0. 331
900	0. 316	0. 331	0. 351	0. 335	0. 387	0. 523	0. 542	0. 334
1, 000	0. 317	0. 334	0. 354	0. 338	0. 393	0. 532	0. 548	0. 338
1, 100	0. 319	0. 338	0. 356	0. 341	0. 400	0. 540	0. 554	0. 340
1, 200	0. 321	0. 340	0. 359	0. 344	0. 406	0. 547	0. 559	0. 343
1, 300	0. 323	0. 342	0. 362	0. 346	0. 411	0. 553	0. 563	0. 345
1, 400	0. 325	0. 345	3. 361	0. 348	0. 418	0. 559	0. 567	0. 348
1, 500	0. 326	0. 347	0. 366	0. 351	0. 423	0. 565	0. 570	0. 350
1, 600	0. 328	0. 350	0. 368	0. 353	0. 428	0. 570	0. 573	0. 353
1, 700	0. 330	0. 351	0. 370	0. 355	0. 433	0. 575	0. 576	0. 354
1, 800	0. 332	0. 353	0. 372	0. 357	0. 439	0. 579	0. 579	0. 356
1, 900	0. 334	0. 354	0. 374	0. 358	0. 443	0. 583	0. 581	0. 358
2, 000	0. 336	0. 356	0. 376	0. 360	0. 448	0. 587	0. 583	0. 359

Table 44 Standard air ratio

(1) Boiler

Classification		Load [%]	Standard air ratio			
			Solid fuel	Liquid fuel	Gaseous fuel	Blast furnace gas, other by-product gas
Electric utility use		75 ~100	1.2 ~1.3	1.05 ~1.1	1.05 ~1.1	1.2
Others	Evaporation over 30t/h	75 ~100	1.2 ~1.3	1.1 ~1.2	1.1 ~1.2	1.3
	Evaporation over 10t/h and below 30t/h)	75~ ~100	—	1.2 ~1.3	1.2 ~1.3	—
	Evaporation below 10t/h	75 ~100	—	1.3	1.3	—

(2) Industrial furnace

Classification	Standard air ratio
Melting furnace for metal casting	1.3
Steel slab continuous reheating furnace	1.25
Metal reheating furnace other than steel slab continuous reheating furnace	1.3
Continuous heat treating furnace	1.3
Gas generator and gas reheating furnace	1.4
Petroleum refinery furnace	1.4
Pyrolyzer and reformer	1.3
Cement baking furnace	1.3
Alumina baking furnace and lime baking furnace	1.4
Continuous glass melting furnace	1.3

Table 45 Calculated values of S_A (fuel oil A) %

Furnace temperature [°C]	Air ratio before correction	Air ratio after correction				
		1.40	1.30	1.20	1.10	1.00
700	1.70	11.6	14.9	17.9	20.8	23.4
	1.60	7.72	11.1	14.3	17.3	20.1
	1.50	3.86	7.43	10.7	13.8	16.7
	1.40	—	3.76	7.27	10.5	13.5
	1.30	—	—	3.65	7.01	10.1
	1.20	—	—	—	3.48	6.74
	1.10	—	—	—	—	3.38
900	1.70	18.7	23.5	27.7	31.5	34.9
	1.60	12.5	17.6	22.2	26.3	29.9
	1.50	6.23	11.7	16.6	21.0	25.0
	1.40	—	5.94	11.3	16.0	20.2
	1.30	—	—	5.66	10.7	15.2
	1.20	—	—	—	5.29	10.1
	1.10	—	—	—	—	5.06
1100	1.70	30.8	37.3	42.6	47.1	51.0
	1.60	20.6	28.0	34.1	39.3	43.7
	1.50	10.3	18.6	25.6	31.4	36.4
	1.40	—	9.43	17.3	23.8	29.4
	1.30	—	—	8.67	15.9	22.1
	1.20	—	—	—	7.91	14.7
	1.10	—	—	—	—	7.36
1300	1.70	55.0	61.9	67.1	70.9	74.0
	1.60	36.7	46.5	53.6	59.1	63.4
	1.50	18.3	31.0	40.2	47.3	52.9
	1.40	—	15.7	27.2	35.9	42.7
	1.30	—	—	13.7	23.9	32.1
	1.20	—	—	—	11.9	21.3
	1.10	—	—	—	—	10.7

Table 46 Types and characteristics of furnace pressure control damper

Type Characteristic	(1) Suspended type (slide type)	(2) Rotary type (butterfly type)	(3) Poppet valve type	(4) Air nozzle type
1. Control characteristic	Better flow characteristic than (2) in low flow range. Response speed is slow with pulley and rope linkage method.	Same characteristic as butterfly type valve	Flow variation is big with valve lift. Control range is narrow.	Response is inferior as compared to (1),(2) and (3).
2. Necessary considerations in high temperature operation	Valve and sliding grooves cause great friction loss. Thermal distortion of valve is likely to cause valve sticking in sliding grooves. Water cooling should be considered.	In manufacturing of valve, consideration must be given to thermal distortion and expansion. Shaft needs water or air cooling.	Same as (2)	No great problem, but thermal shock of air blow nozzle must be considered.
Power for damper operation, etc.	Extremely big driving cylinder is required for faster operating speed. Quick response speed is not possible because of heavy damper weight. Hydraulic cylinder driving is preferable.	Driving torque is small because damper shaft is supported by external rolling bearing. Horizontal support of damper is not desirable because it causes bending moment of damper weight to be applied to the shaft. (small damper excepted)	Linkage is located in low temperature area. Forced lifting and lowering of the valve is possible by driving cylinder. Driving power is small next to (2).	Only small power is required to drive air nozzle blow control valve.
Equipment cost (in order of cost from left to right)	High			Low

Table 47 Driving units for damper and their features

	Item	Electro-hydraulic system	Pneumatic cylinder	Motor-driven system
1	Operating power	Big output with compact unit	Bigger unit is required than hydraulic system.	The unit can be made relatively compact.
2	Response	Quick. Effective for damper with big inertia.	Substantially slower than hydraulic system. Uufit for damper with big inertia.	Quick. (with servo motor used)
3	Operating speed	Quick	Slow	Quick (servo motor output increases)
4	Maintenance	Inferior to the other two systems in that hydraulic oil needs maintenance.	Easy	Easy
5	Contingency measures for power failure	Can stop at current position at power failure. To move to full open or close position, accumulator or direct current backup power supply is required.	Cannot readily stop at current position at power failure. To move to full open or close position, receiver tank or backup power supply is required.	Stops at current position at power failure. To move to full open or close position, separate power supply is required.
6	Equipment cost	High	Low	Medium
7	Backup power supply	Accumulator. Direct current uninterruptive power supply	Receiver tank Direct current uninterruptive power supply	Separate power supply
8	Adaptability to automatic control system	(1) (Excellent)	(3) With small, light weight damper, adaptability is good.	

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THE STUDY (AFTER-CARE)
ON THE ENERGY CONSERVATION PROJECT
IN THE KINGDOM OF THAILAND

TEXTBOOK FOR THE ENERGY AUDIT TECHNIQUES WORKSHOP

10. Energy Conservation in Electric Equipment Operation

March 1994

Japan International Cooperation Agency (JICA)

The Energy Conservation Center, Japan (ECCJ)

1. ENERGY CONSERVATION IN ELECTRIC EQUIPMENT OPERATION

1. ELECTRIC POWER MANAGEMENT

For electric power conservation, it is necessary to manage the electric power from both electric energy and maximum electric power aspects.

It is important to manage the electric energy from the following two aspects:

(1) Improvement of the electric power consumption rate

(2) Improvement of the power factor

and for the maximum electric power, it is important to manage from the stand point of improvement of the load factor.

1.1 Improvement of the Electric Power Consumption Rate

To generally improve the electric power consumption rate, it is important to get a reasonably clear picture of the transition in this consumption rate, classify each production process and each raw material and associate them with changes in the processing method and for technical improvement. It is also essential to determine the target value for the electric power consumption rate in each production process, work out a plan starting from a portion which can be improved and carry it out.

Important items to improve the electric power consumption rate are concretely described as follows:

(1) Placement of measuring instruments

Provide measuring instruments at important points so that the electric power consumption for each hour may be measured and checked periodically. It is necessary to grasp the load condition, maximum electric power and electric power consumption rate from the results of measurement. If there is any problem, it must be solved quickly.

(2) Electric power management

Optimize voltage and capacity in each distribution line and endeavour to introduce high-efficiency electric equipment, operate them efficiently and reduce troubles.

(3) Equipment management

Optimize capacity for the production equipment, intend to introduce and operate high-efficiency production equipment, and endeavour to prevent troubles by completing maintenance and control. Special attention should be paid to troubles with the electric equipment since they are liable to cause the suspension of operation, equipment damage and accident resulting in injury or death.

(4) Process control

Rationalize the operation processes and improve the layout.

(5) Quality control

Establish an overall company cooperative system for quality control and endeavour to reduce defective ratio.

(6) Participation by all employees

Enhance consciousness for increased productivity and cost, and positively promote for the establishment of a work improvement suggestion system and for thoroughness of QC circle activities.

1.2 Improvement of the Power Factor

When AC electric power is provided to a load, the electric power at this point is generally less than the product of the voltage and current. In this case, the ratio of the two is called "Power factor", and is expressed by the following equation:

$$\text{Power factor} = \frac{P}{E \cdot I} \times 100\% \quad \cdots\cdots (1)$$

where P: Electric power (W)
E: Voltage (V)
I : Current (A)

$$P = EI \cos\phi \quad \cdots\cdots (2)$$

ϕ: Phase difference between voltage and current

$$I = \frac{P}{E \cos \phi} \quad \cdots\cdots (3)$$

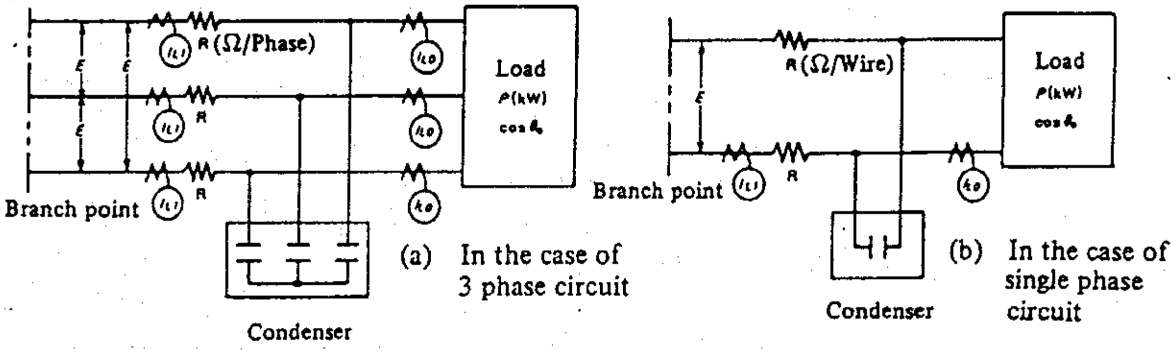
Then, the current to get a specified output should be increased as being inverse proportion to the power factor. A phase-advancing capacitor is generally provided to improve this power factor. The energy conservation effect due to this is obtained by reducing all of the surplus current and resistance loss of the distribution line or the transformer.

Effects obtained by improvement of the power factor are described below:

(1) Reduction effect of Distribution Line Loss

Since power loss in the distribution line is given by (Line current)^2 × (Line resistance), reduced distribution line loss (P_L) to be obtained by providing a phase-advancing capacitor to improve the power factor in Fig. 1 is determined by the following equations:

Figure 1 Reduction Effect of Distribution Loss



(a) In the case of 3 phase circuit

(b) In the case of single phase circuit

A) Equation for three phase circuit

$$P_L = 3 \times (I_{LO}{}^2 - I_{LI}{}^2) \times R \times 10^{-3} (\text{kW}) \quad \cdots\cdots (4)$$

where

Before improvement

$$I_{LO}{}^2 = \left(\frac{P}{\sqrt{3} \times E \times \cos\theta_0}\right)^2 = \frac{P^2}{3E^2} \bullet \frac{1}{\cos^2\theta_0}$$

After improvement

$$I_{LI}{}^2 = \left(\frac{P}{\sqrt{3} \times E \times \cos\theta_1}\right)^2 = \frac{P^2}{3E^2} \bullet \frac{1}{\cos^2\theta_1}$$

$$I_{LO}{}^2 - I_{LI}{}^2 = \frac{P^2}{3E^2}\left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right)$$

Hence,

$$P_L = \frac{P^2}{E^2} \times \left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right) \times R \times 10^{-3} (\text{kW}) \quad \cdots\cdots (5)$$

In equation (5), substituting

$$\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1} = k_1$$

$$P_L = \frac{P^2}{E^2} \times k_1 \times R \times 10^{-3} (\text{kW}) \quad \cdots\cdots (6)$$

where,

$$\frac{P^2}{E^2} = 3\cos^2\theta_0 \cdot I_{LO}^2$$

Hence,

$$P_L = 3 \times (I_{LO} \times \cos\theta_0)^2 \times k_1 \times R \times 10^{-3}\ (kW) \quad \cdots\cdots (7)$$

B) Equation for single phase circuit

$$P_L = 2 \times (I_{LO}^2 - I_{LI}^2) \times R \times 10^{-3} (kW) \quad \cdots\cdots (8)$$

where

Before improvement

$$I_{LO}^2 = (\frac{P}{E\ \cos\theta_0})^2$$

After improvement

$$I_{LI}^2 = (\frac{P}{E\ \cos\theta_1})^2$$

$$I_{LO}^2 - I_{LI}^2 = \frac{P^2}{E^2}(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1})$$

Hence,

$$\begin{aligned} P_L &= 2 \times \frac{P^2}{E^2} \times (\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}) \times R \times 10^{-3} (kW) \quad \cdots\cdots (9) \\ &= 2 \times \frac{P^2}{E^2} \times k_1 \times R \times 10^{-3} (kW) \quad \cdots\cdots (10) \\ &= 2 \times (I_{LO} \times \cos\theta_0)^2 \times k_1 \times R \times 10^{-3} (kW) \quad \cdots\cdots (11) \end{aligned}$$

where

P (kW): Load power
I_{LO} (A) : Present load current
I_{LI} (A) : Line current after improvement
E (kV) : Line voltage
$\cos\theta_0$: Present power factor
$\cos\theta_1$: Power factor after improvement

C) Calculation example

Reduced loss in the model system of three phase distribution line is calculated by using the preceding equation (7), as is shown in Table 1.

Table 1 Calculation Example of Reduction Effect of Loss in 3 Phase Distribution Line due to Power Factor Improvement

Resistance value of distribution line and cable R: (Size of electric wire)	Length of wiring l	Present power factor ($\cos q_0$)	Present load current	Load current after improvement		Reduction of loss in wiring	
				$\cos\theta_1 = 0.90$	$\cos\theta_1 = 0.95$	$\cos\theta_1 = 0.90$	$\cos\theta_1 = 0.95$
Ω/km 0.20 (100sq or equivalent)	500 m	0.60	131A	87.3A	82.7A	2.87 kW	3.10 kW
		0.70	131	102	96.5	2.04	2.30
0.13 (150sq) or equivalent	500	0.60	219	146	138	5.18	5.61
		0.70	219	170	161	3.68	4.26
0.10 (200sq) or equivalent	500	0.60	262	175	165	5.74	6.21
		0.70	262	104	193	4.08	4.72
0.08 (250sq) or equivalent	500	0.60	306	204	193	6.25	6.76
		0.70	306	238	225	4.44	5.14
0.06 (325sq) or equivalent	500	0.60	350	233	221	6.12	6.62
		0.70	350	272	258	4.35	5.04

(2) Reduction effect of transformer loss

Generally speaking power loss in transformers consists of "Iron loss" which occurs in iron core, and "Copper loss" which occurs in coil, of which "Copper loss" is greatly affected by the power factor.

A) Equation

Reduced transformer loss (P_t) when the power factor is improved by a phase-advancing capacitor on the secondary side of the transformer as shown in Fig. 2 is determined by the following equations:

However, it is assumed that total load loss of transformers: Copper loss = 1:0.8.

The equations are the same for both single and three phase.

$$P_t = (\frac{100}{\eta}-1)\times\frac{4}{5}\times(\frac{P}{L_0})^2\times(\frac{1}{\cos^2\theta_0}-(\frac{1}{\cos^2\theta_1})\times L_0\ (kW) \quad \cdots\cdots (12)$$

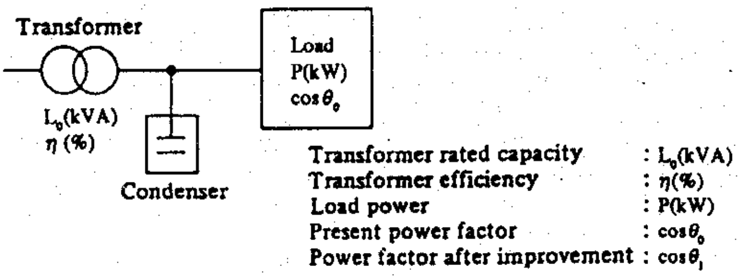
$$= (\frac{100}{\eta}-1)\times\frac{4}{5}\times(\frac{P}{L_0})^2\times k_1\times L_0 (kW) \quad \cdots\cdots (13)$$

$$= k_2\times k_1\times L_0\ (kW) \quad \cdots\cdots (14)$$

where,

$$k_2 = (\frac{100}{\eta}-1)\times\frac{4}{5}\times(\frac{P}{L_0})^2$$

Figure 2 Reduction Effect of Transformer Loss



B) Calculation example

The calculation example of reduced transformer loss using preceding equation (14) is shown in Table 2.

Table 2 Calculation Example of Reduction Effect of Transformer Loss

Transformer specification	L_0=300kVA η=98%			L_0=500kVA η=98.5%			L_0=1,000kVA η=99%		
P/L_0	0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7
$\cos\theta_0 \rightarrow \cos\theta_1$	kW	kW	kW	kW	kW	kW	kW	kW	kW
0.60 → 0.90	1.89	2.72	3.70	2.35	3.39	4.61	3.12	4.49	6.11
0.60 → 0.95	2.04	2.95	4.01	2.55	3.67	4.99	3.37	4.86	6.61
0.70 → 0.90	0.99	1.42	1.93	1.23	1.77	2.41	1.63	2.35	3.19
0.70 → 0.95	1.14	1.65	2.24	1.42	2.05	2.79	1.88	2.72	3.69