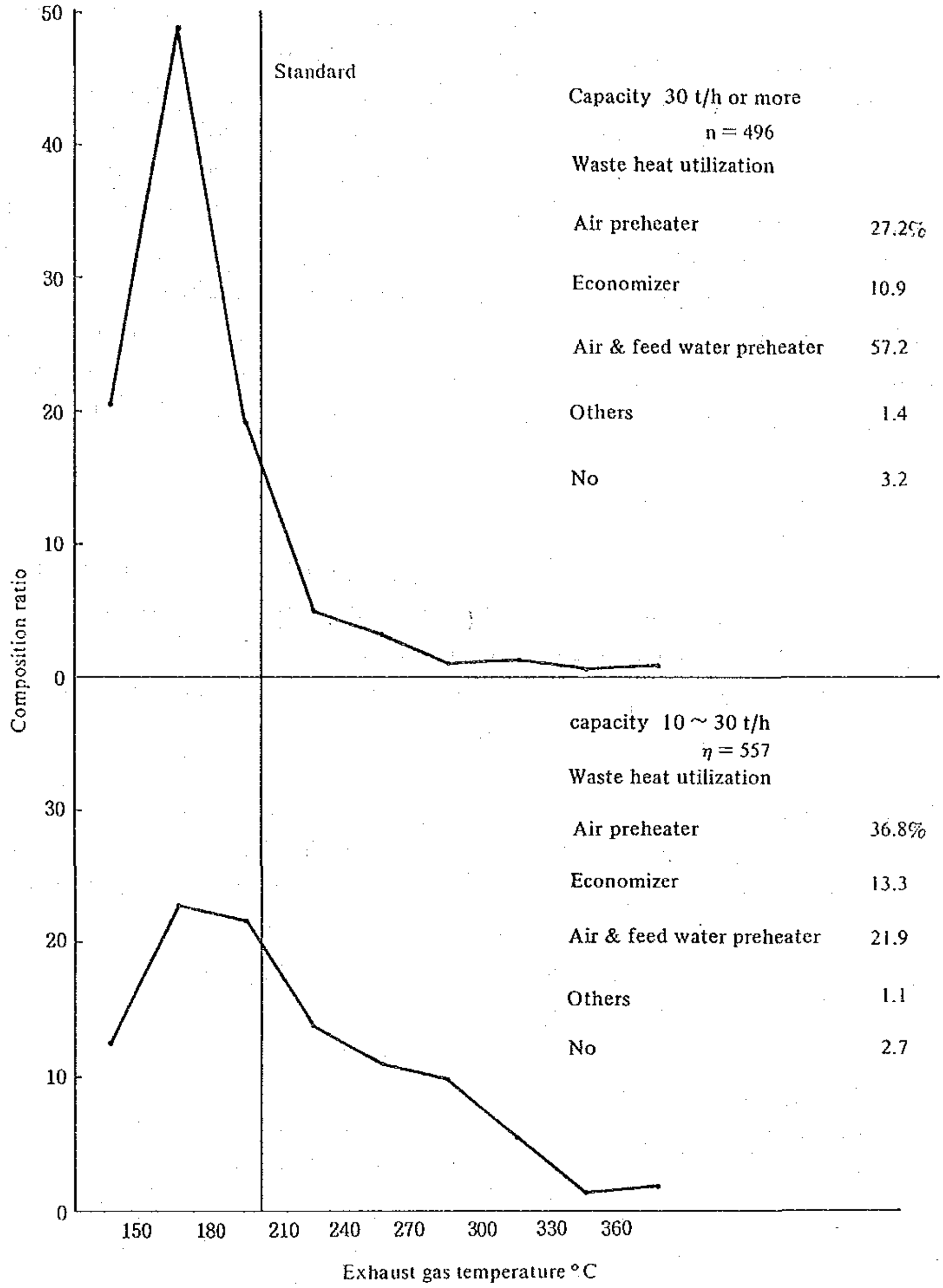


Fig. III-7-31 Boiler exhaust gas temperature distribution (1981)

The heat insulation reference of boilers is not shown in the Japanese standard but it is taken to be according to the Japanese Industrial Standards (JIS A9501). In JIS, it is provided to insulate heat with a thickness so that the sum of the fuel cost corresponded to the heat loss from the surface after the heat insulation and the annual amortization for the cost demanded to the heat insulation work is minimized. Namely, it is provided that the heat insulation thickness may be selected to cause the greatest economy according to fuel cost and working cost of insulation. (See Chapter of Steam.)

Partial heat release of boilers can be obtained, but to obtain an exact heat release in the whole is not always easy by reason of intricacy of the configuration. For standard, the surface temperature on the part contacted with steam should be set to 70° C in the temperature which is regarded to be economical in the existing condition without determining a rate of heat release.

1.7.4 Energy conservation of accessory

For a large scale boiler, an optimization of the capacity of blower and feed water pump should be taken. If most of the operation is under a low load, the number of revolutions should be controlled to reduce the contraction loss at the valve and the damper.

Dust attached on the air preheater and the fan should be cleaned periodically to prevent an increase of pressure loss and a reducing of the efficiency.

1.7.5 Operation

If the use of steam is limited to only day time, a one-through boiler of quick start-up operation is desirable, but for a flue smoke tube boiler, some consideration is needed not to advance the start-up time and to stop beforehand the termination of operation with choosing a time utilizable to the remaining pressure. When the boiler is stopped, the flue damper should be shut down to prevent cooling of the furnace.

1.7.6 Routine management

To advance the energy conservation of boilers, it must be settled first to provide required instruments and grasp the daily operating situations. Especially the relation between the evaporation and the fuel consumption, that is the evaporation multiple (see paragraph 1.5), should be observed. If a declining of the performance is recognized, its cause should be investigated immediately and an appropriate measure must be taken.

Table III-7-17 is a sample of operation records. These items must be recorded for the boiler management. The items such as the evaporation multiple, the feed water temperature, the exhaust gas temperature and O_2% in the exhaust gas should be prepared in chart to know a long-term tendency and these data make use of detection in its early stage of any abnormality. The indication of data is useful to promote the operator's interest to energy conservation.

Table III-7-17 Boiler Operating Daily Report

Manager	Chief operator	Early attendance	Day service	Night service

Date Weather Ambient temperature inside °C Outside °C

Every hour measured matters (Hours should be entered from the bottom to the upper.)	Hours	Pressure kg/cm²	Feed water temperature °C	Feed water quantity: Meter reading	Feed water quantity: Consumption lit.	Fuel oil quantity: Consumption lit.	Fuel oil quantity: Meter reading	Fuel oil temp.: Service tank °C	Fuel oil temp.: Heater outlet °C	Oil pressure: Primary kg/cm²	Oil pressure: Secondary kg/cm²	Exhaust gas temperature °C	Exhaust gas % CO_2	Furnace pressure mmAq	WB static pressure mmAq	Outlet static pressure mmAq	
					(A)	(B)											
					(Take care to the ratio. Example: 13:1)												
	Reading in previous day				Reading in previous day												

	Item	Result: Good	Result: No	Checker
Daily inspection	Relief valve			
	Water gage blowing			
	Automatic feedwater regulator			
	Low water level governor 1st step / 2nd step / 3rd step			
	Flame detector			
	Combustion state			
	Firing equipment			
	Feed water device			
	Automatic controller			
	Control interlocking devices			
Total	Feed water quantity (A)			lit./d
	Fuel oil quantity (B)			lit./d
	Evaporation multiple (A)/(B)			l/l
	Boiler efficiency			%
	Operating time			h
Fuel	Carry-over			l
	Today receiving quantity			l
	Stock			l

Reference

Boiler efficiency $\frac{Gs(i''-i')}{Lf.r.Hl} \times 100$

Gs = Evaporation kg/h ≑ Feed water quantity lit./h lit./d Blow quantity is reduced.

i'' = Specific enthalpy of generated steam Kcal/kg Dryness 98%

i' = Specific enthalpy of feedwater Kcal/kg

Lf = Fuel oil quantity lit./h. lit./d

r = Meter passing specific gravity Specific gravity converted with the meter passing temperature.

Hl = Hh − 6 × 9 × h Kcal/kg According to the Hh analysis table. h: Kerosine. Light oil. A grade fuel oil 13%. B grade fuel oil 12%. C grade fuel oil 11%

- Factor $\alpha = \frac{i''-i'}{r.\ Hl} \times 100$

  The factor can be calculated from the average pressure, feedwater temperature, fuel oil temperature, fuel oil specific gravity and low calorific value.

- Evaporation multiple = $\frac{Gs}{Lf} = \frac{\text{Feedwater quantity lit./h. lit./d}}{\text{Fuel oil quantity lit./h. lit./d}}$

- Boiler efficiency = $\frac{Gs}{Lf} \times \alpha\%$

- Steam unit price = $\frac{\text{Fuel unit price Bt/kl}}{\text{Evaporation ratio Ton/kl}}$ Bt/Ton

Boiler water blowdown	Blowing time	Pressure kg/cm²	Blowing quantity l
	Continuing blow		
	Total blowing quantity		

Cleaning agent	Chemical name	Input g.	Input hour

Chemicals pouring device	Previous day	Today	Pour

Water softener		
	Previous meter reading	l
	Today's meter reading	l
	Treating water quantity	ton
	Basic cycle	ton
	NaCl quantity	kg
	Hardness analysis	Good or no

Boiler water	Sampling	Pressure kg/cm²	State of boiler. Before and after blowing.
	Yes		
	No		

Water quality test				
Feed water	PH		—	
	Conductivity		μΩ/cm	
	Chloride ion		ppm	
	Hardness		ppm	
Boiler water	PH		—	
	Conductivity		μΩ/cm	
	Chloride ion		ppm	
	Hardness Phosphate ion		ppm	

Description)

1.7.7 Example

(1) Feed water preheating with waste heat in other processes (Petrochemical plant)

In an ethylene manufacturing process, the water used for cooling of the process fluid has been discharged at a temperature of 63° C with 1,500 t/h. The water has been cooled to 35° C in a cooling tower and has been used again for cooling.

On the other hand, the boiler in the adjoining plant has preheated air to 60° C in a preheater with steam to prevent a low temperature corrosion of the air preheater.

The persons in charge of both plants have taken notice of this point, arranged a pipe between both plants, installed a hot water system air preheater and disused the steam system preheater.

The results saved the steam for preheating of 13 t/h. The investment cost was 70 million yen. The saved cost of fuel was 330 million yen. The investment fund recovery period was 3 months.

(2) Improvement of boiler air ratio (Building material manufacturer)

The heat balance of a boiler (30 t/h) which burns fuel oil was as follows:

- Boiler efficiency 90%
- Exhaust gas loss 5%
- Steam loss for atomization 1%
- Heat release and others 4%

Various tests were carried out by changing the air ratio automatic controller to a manual operation in order to try to reduce the exhaust gas loss. The result proved to be possible to reduce from 2.5% of the conventional O_2% limit to 0.6%. As a result, O_2 has been reduced to 1.0% by replacing to a microcomputor control system which can cope with a load fluctuation and by installation of a zirconia system O_2 analyzer which is a low time delay.

Since the opening of the damper for the forced draft fan was a low degree of 10 to 20%, the revolution control by inverter was carried out.

As a result, fuel oil was reduced by 37.5 kl/year, power was reduced by 145×10^3 kwh/year, the merit was 5.15 million yen/year and the investment cost was recovered in about one year.

(3) Heat transfer improvement of smoke tube (See Fig. III-7-33)

A special steel turbulator was inserted in the smoke tube of a flue smoke tube boiler (6 kg/cm^2, 8.4 t/h) which burns fuel oil and the heat transfer was improved by giving a turbulent flow to the gas flow in the smoke tube. As a result, the boiler efficiency was improved from 88.5% to 90.5% and the fuel cost was saved by 4.3 million yen. The investment cost was 1.4 million yen and it was recovered in a short period.

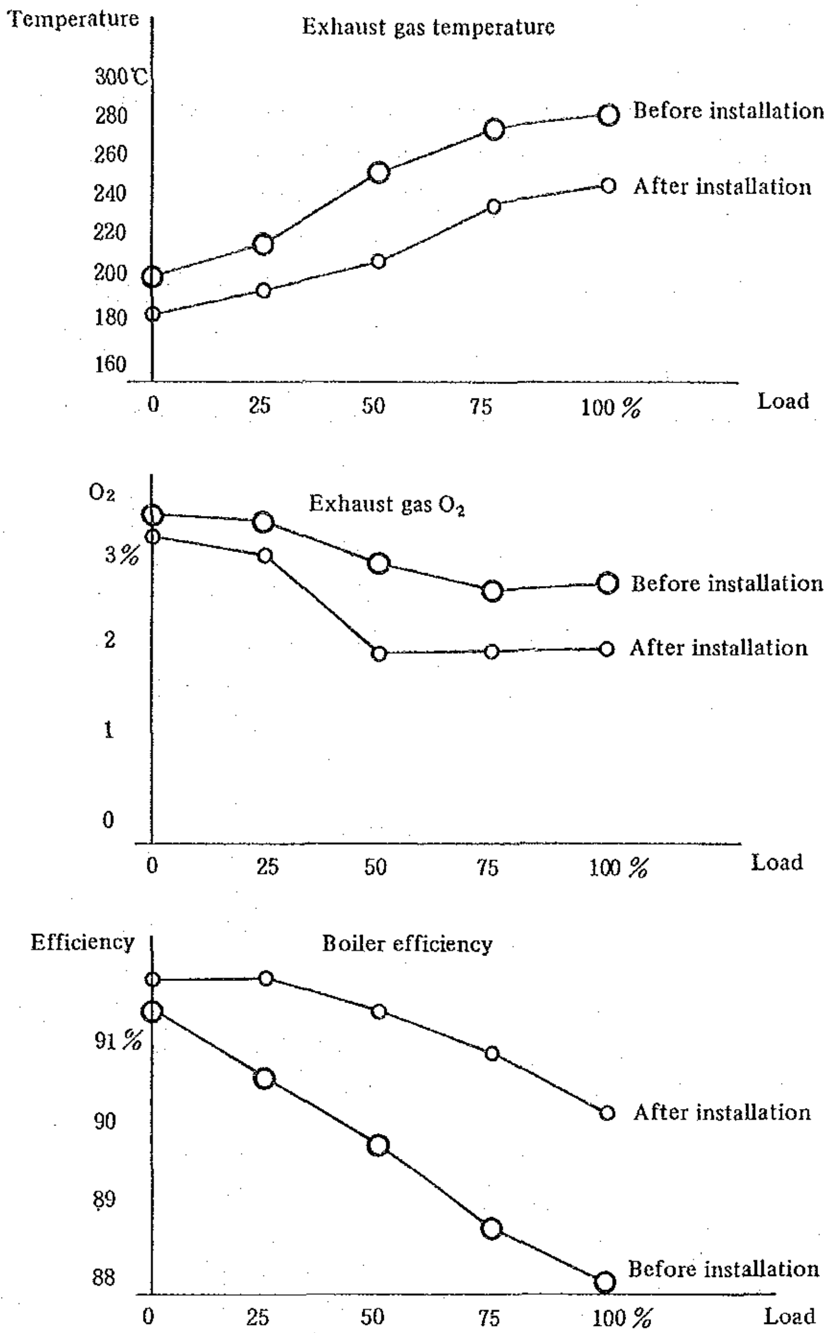


Fig. III-7-33 Comparison of before and after improvement

2. Utilization of steam

2.1 Utilization of steam

Steam is widely used in factories, buildings and so on as an energy source because of its excellent physical and chemical properties. Available utilization of steam with a thorough comprehension of its properties is related to an effective energy conservation.

The general characteristics of steam are as follows:

(1) Staturated steam is always in a constant relationship between the pressure and the temperature and by keeping steam in a constant pressure it is possible to set a constant temperature. (See Fig. III-7-34)

(2) Steam has a large latent heat of evaporation and the temperature is kept constant during evaporation (or condensation).

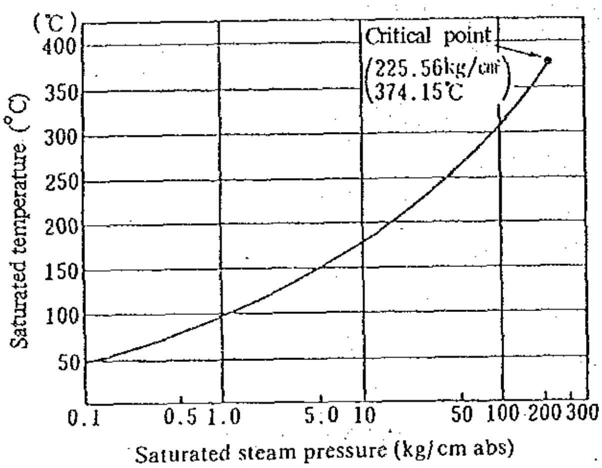


Fig. III–7–34
Relation between the saturated steam pressure and the saturated temperature

(3) The latent heat of evaporation of steam is larger with lower pressure and it is reduced as the pressure rises. (See Fig. III-7-35)

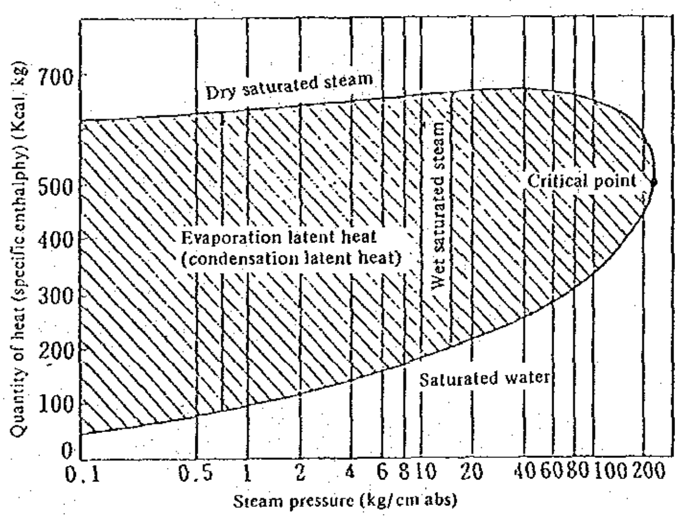


Fig. III–7–35 Relation between the saturated steam pressure and the quantity of heat.

(4) The heat transfer coefficient of steam in condensation is very large and so steam is particularly excellent as a heat transfer medium.

(5) Volume of the steam varies greatly after condensation and the specific volume of condensate is very small. Accordingly steam facilitates for easy handling.

(6) Steam is chemically stable and is a harmless substance.

2.2 Effectiveness of steam setting pressure

(1) Effectiveness of boiler steam pressure

When steam is used as indirect heating, the lower the steam pressure, the heat quantity (latent heat of condensation) released when steam condensates is larger. Therefore, the use of lower pressure steam allows saving of the fuel. Accordingly, the setting pressure of the boiler is required to reduce to a pressure corresponding to the temperature necessary as a heating source.

In case of reduction of the steam pressure in an existing boiler, however, a proper pressure must be set in consideration of the limit of the minimum operating pressure of the boiler, the pressure loss of the steam piping and the capacity of the steam servicing equipment.

Example of fuel saving through the reduction of boiler steam pressure is shown in Table III-7-18.

Table III-7-18

Steam pressure (kg/cm^2G)	Saturation temperature (°C)	Specific enthalpy of steam (kcal/kg)	Condensation latent heat (kcal/kg)
7	169.6	660.8	489.5
5	158.1	657.9	498.6

If the steam pressure is reduced from 7 kg/cm^2G to 5 kg/cm^2G, the latent heat of condensation rises to approximately 9 kcal/kg from Table III-7-18. If an average steam consumption per month is taken as 5,400 metric tons, the steam consumption due to reduction of the steam pressure is

$$5{,}400 \times \frac{489.5}{498.6} \fallingdotseq 5{,}300 \text{ t/month}$$

If the calorific value of fuel is taken as 10,000 kcal/kg, the feed water temperature as 20° C and the boiler efficiency as 85%, The saving of fuel due to the reduction of steam pressure is as follows:

$$\frac{5{,}400 \times 10^3 \times (660.8 - 20)}{10{,}000 \times 0.85} - \frac{5{,}300 \times 10^3 \times (657.9 - 20)}{10{,}000 \times 0.85} = 9{,}347 \text{ kg/month}$$

Through reduction of steam pressure, there is also a merit of energy conservation due to decreasing of the diffusion heat from the boiler body and decreasing of heat loss of the blow-off.

(2) Pressure reducing effect of steam

When the minimum operating pressure of the boiler is limited or the high pressure steam in some steam servicing equipment is necessary, the high pressure steam is often reduced by a pressure reducing valve at the front of the low pressure steam servicing equipment.

Since pressure reduction through a pressure reducing valve is a kind of the throttling adiabatic expansion, the enthalpy of steam due to throttling does not change. If a high pressure steam is reduced through a pressure reducing valve, the dryness increases and an energy per unit weight, that is, heat utilized effectively by increasing of latent heat, increases. As a result of this, steam consumption can be saved.

An example of an increase of the heat quantity through pressure reducing is as follows:

If a steam 9 kg/cm^2G of steam pressure and 0.95 of dryness is reduced to 2 kg/cm^2G, the latent heat of saturated steam before pressure reduction is

$481.65 \times 0.95 = 475.57$ kcal/kg

and the enthalpy of wet steam is

$181.25 + 457.57 = 638.82$ kcal/kg.

The latent heat after pressure reduction is

$638.82 - 133.41 = 505.41$ kcal/kg.

Accordingly, the heat quantity due to pressure reduction is increased by

$505.41 - 457.57 = 47.84$ kcal/kg

In other words, the excessive heat quantity of $(47.84/457.57) \times 100 = 10.5\%$ is possible for utilization through pressure reduction. The dryness after pressure reduction results in the following:

$638.82 = 133.41 + X \times 517.9$

$X = 0.98.$

2.3 Steam transport

A steam piping from the boiler to the servicing equipment is required to satisfy the condition of minimum distance, minimum pipe diameter, minimum heat loss and minimum pressure drop as far as possible.

(1) Piping plan

The steam servicing condition in steam consuming equipment should be defined by the following items.

a. Servicing time and hours

b. Batch or continuance

c. Servicing pressure and quantity (average quantity and peak quantity)

With a plant plan of piping, the relation between the yard piping and the plant piping should be defined. The yard piping system diagram is shown in Fig. III-7-36. Decision of either the example 1 or 2 should be taken into consideration for various factors such as the area of factory, the length of yard piping, the time of expansion plant, the operating process of each plant, the initial cost and the heat loss. It is also required to investigate for an exclusive piping for the daytime and the night time, and a separation of the high pressure line and the low pressure line.

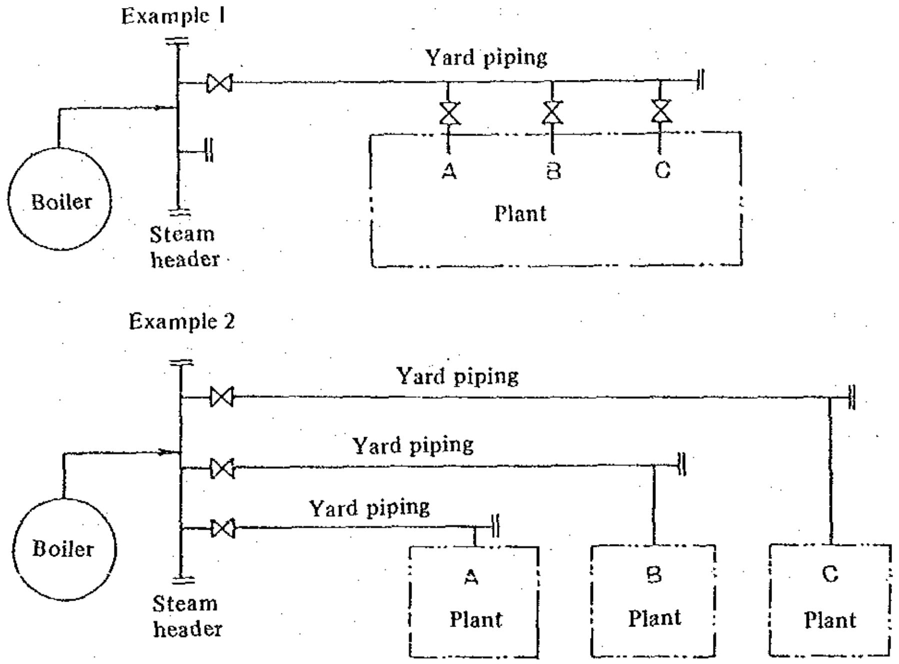


Fig. III–7–36 Yard piping system diagram

To take the piping from the yard piping into the plant, a main valve should be installed as shown in Fig. III-7-37 to lessen the influence on the work for the plant extension or to avoid heat loss by closing the main valve at a dead time. A pressure gauge and a flow meter must be installed. Also it is a method that a blind flange is mounted to some terminals of the header for future usage.

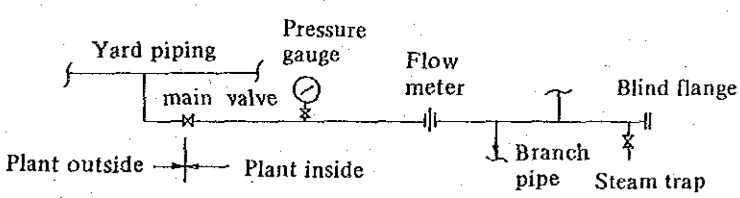


Fig. III–7–37 Plant battery limit schematic flow diagram

(2) Heat insulation of steam piping

In steam transport, part of the steam does not contribute for consuming at steam servicing equipment by heat dissipation from the pipe and is discharged as condensate with a large energy loss. Accordingly, the steam piping should be given a proper heat insulation to reduce heat loss.

A) Type and selection of heat insulating materials

a. Properties required of heat insulating materials

Heat insulating materials are classified roughly into an organic and an inorganic material. Both materials of organic and inorganic contain air bubbles in porous portion by the sponge structure, and show the insulation effect.

The thermal conductivity of insulating materials are:

(1) increases generally with the density;
(2) increases with absorption of moisture;
(3) increases with raising of the temperature.

b. Type of insulating materials

The insulating material used for steam piping is mostly an inorganic materials. Table III-7-19 shows the kinds and features of inorganic insulating materials.

c. Selection of heat insulating materials

Recently, as an heat insulation for the steam piping system, the calcium silicate, pearlite, rock wool or asbestos are generally applied. The important points for selection are as follows:

(1) Low thermal conductivity
(2) Small specific weight
(3) Low water absorption
(4) High strength and durability
(5) Withstands sufficiently against servicing temperatures
(but use below the safety servicing temperature).
(6) Good workability

B) Heat insulation works

Although an excellent heat insulation material is used, an incomplete works allows the heat insulation to worsen through intrusion of rainwater and the energy loss due to heat dissipation cannot be neglected. Care must be exercised for works.

a. Wroks

(1) Use a molded product as far possible.
(2) Consider the thermal expansion of pipes and the shrinkage of the heat insulating material.
The thermal expansion of piping and the shrinkage of the insulator cause some gaps. In case of two layers or more (if a required thickness is more than 75 mm, the works should be two layers as much as possible), the longitudinal and the lateral joints in each layer should be installed, in shifting, not to be put at the same part, and the joint should be packed with a compressed asbestos fiber (Fig. III-7-38).

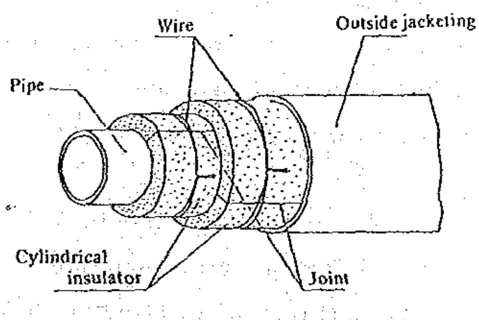


Fig. III-7-38 Case of cylindrical insulator

Table III–7–19 Heat insulator type and its feature

Heat insulator	Raw material and manufacturing process	Product	Property	Safety service temp.
Asbestos insulator	• Fiber shape formation of serpentinite or amphibole by subterranean heat and underground water. • Chrysotile asbestos of serpentinite is a thin white silklike and toughness fiber and is a good quality. • Amocite asbestos (brownish color) of amophibole is a longer, thick and brittle fiber and is unsuitable to yarn and fabric. There is blue asbestos in the same series.	• Long fiber is suitable to asbestos yarn and seat packing. Short fiber is for asbestos paper, asbestos plate and slate. • Asbestos insulation plate Asbestos insulation cylinder Asbestos insulation yarn Asbestos mat • Plate and ctlinder are molded by an inorganic adhesive.	Density: 0.23g/cm³ or less Thermal conductivity: 0.048~0.065 Kcal/m.h. °C	350~550 °C
Diatom earth insulator	• Aqueous rock formed by a heap of diatom remains. Recently not much use due to the development of an excellent insulator. • Diatom earth powder + reinforced binder (amocite asbestos fiber 3~5%)	• Water kneading insulator. Give a tackiness by addition of water in 160 to 200%. Coat it on reinforcement of a wire net. Slow drying.	Density (after drying): 0.45 to 0.55 g/cm³ Thermal conductivity (70°C): 0.08 to 0.09 Kcal/m.h.°C	Asbestos fiber: 500 °C or less Reinforcement of fibers for plastering: 250°C or less
Rock wool insulator	• Andesite, basalt, igneous rock, serpentinite, peridotite, chrolite-schist, slag of nikkel ore and manganese ore and limestone • Compound the above materials in a proper ratio, melt in a temperature of 1,500~1,600°C and form it to a thin fiber shape by blowing of compressed air/steam. SiO_2: 40–50%, Al_2O_3: 10~20%, CaO: 20~30% MgO: 3~7% Fe_2O_3: 2~5%	• Attacked by weak acid but not weathered. • Various shape products such as plate, cylinder, band and bracket. • Blacket is formed by set metal on both sides of the stratified rock wool and sew up with a wire. Good acoustic absorption effect.	Density: 0.10~0.38 g/cm³ Thermal conductivity (70°C): 0.039~0.048 Kcal/m.h.°C	Less 400~600°C
Glass wood insulator	• Manufactured by the similar manner to the rock wool.	• Plate, cylinder, bracket and band	Density: 0.008~0.096 g/cm³ Thermal conductivity (70°C): <0.042 Kcal/m.h.°C	Less 300~350°C
Calcium silicate insulator	• Add asbestos fiber into silicate power (mainly diatom earth) and slaked lime to reinforce, allow it to swell enough and mold in a metal moild to allow produce calcium silicate by steaming.	• Put on the market for a high temperature from 1952 and standardized in JIS in 1955. • Low price, good workability and durability. • Typical insulator used not only piping but a general machine.	Density: 1st class; less 0.22 g/cm³ 2nd class; less 0.35 g/cm³ Thermal conductivity (70°C): 1st class; <0.058 Kcal/,m.h.°C 2nd class; <0.053 Kcal/m.h.°C	Ca. 650°C
Perlite insulator	• Calcinate ignition rock such as pearlite or obsidian at 800~1,200°C in kiln. • White or gray white color fine particle and verly light particle having fine bubble. Not change in quality and not fade the color. Not absorb moisture in atmospher.	• Less 1 mm for moulding insulator • Blend asbestos fiber and inorganic adhesive, mold by press and dry. • Classified to 1st class and 2nd class. One of many excellent insulators.	Density: 1st class; less 0.2 g/cm³ 2nd class; less 0.3 g/cm³ Thermal conductivity: 1st class; <0.053 Kcal/m.h.°C 2nd class; <0.065 Kcal/m.h.°C	Ca. 650°C
Basic magnesium carbonate insulator (magnesium carbonate insulator)	• The conventional basic magnesium carbonate insulator has been compounded with basic magnesium carbonate of 85% and asbestos of 15%. The thermal conductivity is influenced by this ratio. The present insulator is blended with asbestos of 8% or more.	• Classified to magnesium carbonate water kneading insulator, plate and cylinder. • Convert to magnesium oxide by heating in a temperature of 300°C or more and shrinke extremely • Almost same properties as it of calcium silicate except for heat resistance. As present not used too much.		Less 250°C

(3) The valves, the flanges, and the hangers of pipes should be insulated.
The valve portions and the flange parts may sometimes not be insulated by reason of maintenance or inspection and complexity of the works, but these also should be insulated. Fig. III-7-39 shows the works of heat insulation for valves, Fig. III-7-40 shows the works of heat insulation for flange portions, and Fig. III-7-41 shows the works of a heat insulation for hangers.

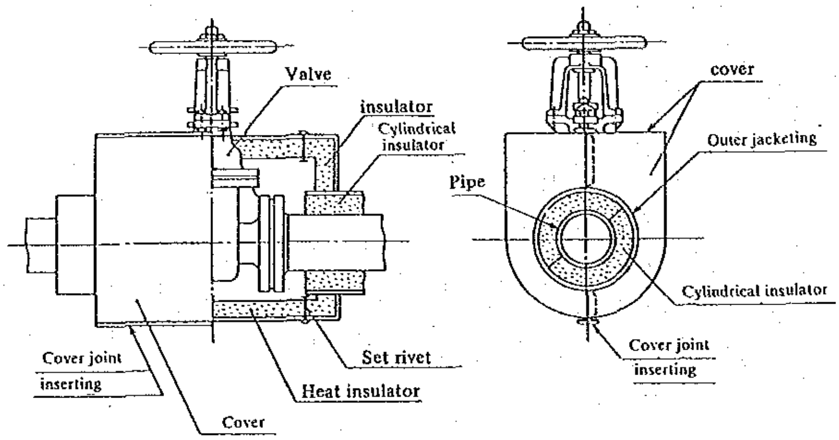


Fig. III-7-39 Insulation of valve

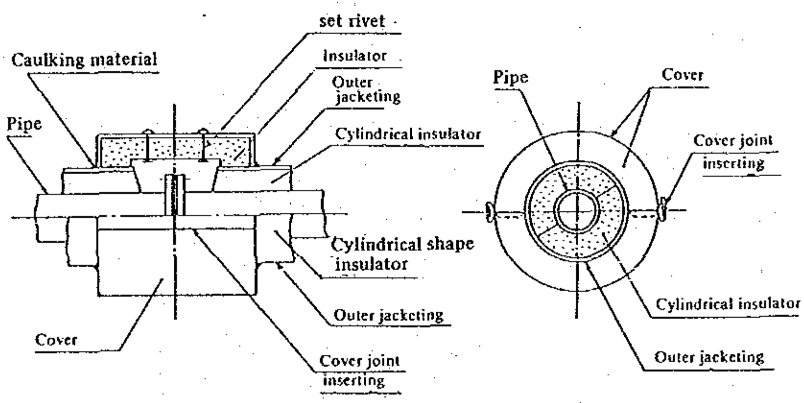


Fig. III-7-40 Insulation of flange

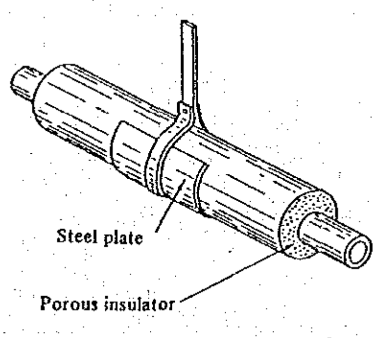


Fig. III-7-41 Installation of hanger

(4) Consideration of vibration

For heat insulation on the piping installed to vibrating equipment, an antivibration heat insulation should be selected and a fibrous heat insulating material is suitable for vibration absorption.

(5) Consideration of rainwater resistance and chemical resistance

To prevent the heat insulation against rainwater or corrosive chemicals, the heat insulating material should be covered with steel sheet, aluminium sheet or mastic gum.

When the heat insulating material absorbs moisture, because the thermal conductivity of water is approximately 0.5 kcal/ mh° C which is larger by about 10 times than that of the insulating material, heat loss increases. Care must be taken against moisture.

The mastic gum is a liquid or a paste containing asphalt or plastics as the main component and is excellent for workability, antirainwater and chemical resistance.

b. Maintenance and inspection of heat insulation

Since the heat-insulated sections deteriorate with age and are damaged, inspection is required. The inspection is sufficient by a visual check of the appearance and can be performed even in a daily inspection tour of the factory.

Special attention is as follows:

(1) Deformation and damage of the outerjacketing
(2) Decoloration of the outerjacketing and peeling of the painting
(3) Mark of steam leakage or falling of drops
(4) Shifting of the cover joint parts of outerjacketing or falling-off of the caulking.
(5) Gap between the hardware for hangers and supports and the outerjacketing for insulation.

If any abnormality is not found in the above points, the insulating performance is considered to be kept sufficiently.

If an abnormality is found, repairing is required at once.

c. Heat loss from the insulated pipe

A heat transfer in the pipe insulated as shown in Fig. III-7-42 is shown in Table III-7-20. The quantity of heat due to the heat transfer is expressed by the following equation.

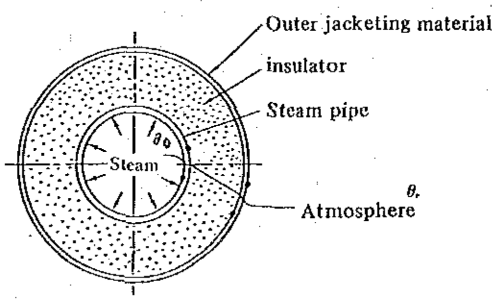


Fig. III–7–42 Insulated pipe

Table III–7–20 Heat transfer from steam in tube

NO.	Place	Heat transfer way
1	From steam to steam tube	A part of steam heat transfers to steam tube by convection.
2	In steam tube	Transfer form tube inside to tube outside by thermal conduction.
3	From steam tube to insulator	The heat reached to the outside surface of steam tube transfers immediately to the inside surface of insulator because of absence of fluid (water or air etc.).
4	In insulator	Transfer from the inside surface of insulator to the outside by thermal conduction. The transfered heat is influenced substantially by the property and thickness of insulator.
5	From insulator to outerjacketing	Heat reached to the outside surface of insulator transfers immediately to the inside surface of outerjacket.
6	In outerjacket	Transfer the heat from the inside surface of outerjacket to the outside surface through thermal conduction.
7	From outerjacket to atmosphere	Transfer the heat by convection and radiation (convective heat transfer through updraft or wind and radiant heat transfer to wall or object around the steam tube)

$$Q = \frac{1}{R}(\theta_o - \theta_r)$$

$$R = \frac{1}{2\pi}\left(\frac{2}{d_1 \alpha} + \frac{1}{\lambda}\ln\frac{d_1}{d_0}\right)$$

Here, R: Thermal resistance (mh° C/kcal)

θ_o, θ_r: Steam temperature, atmospheric temperature (° C)

d_I, d_O: Inside diameter of heat insulation (Outside idiameter of steam pipe), Outside diameter of heat insulation (m)

α: Heat transfer coefficient of surface (kcal/m^{2}h° C)

λ: Thermal conductivity of heat insulator (kcal/mh° C)

Q: Quantity of dissipating heat (kcal/mh)

d. Economical thickness of heat insulation

The heat insulation is the first step of energy conservation, but an economical optimization must be judged from the relation between the gain of energy recovered due to heat insulation and the cost spent for heat insulation.

An economical thickness of heat insulation is obtainable through the determination of a thickness that the sum(C) of the annual heat loss (A) due to the quantity of dissipating heat from the surface of heat insulation and the annual depreciation cost of the heat insulating construction (B) decreases to a minimum. This relation is shown in Fig. III-7-43.

The calculation equation of an economical thickness of heat insulators is as follows:

$$\frac{d_1}{2}\ln\frac{d_1}{d_0} + \frac{\lambda}{\alpha} = 10^{-3}\sqrt{\frac{b \cdot h \cdot \lambda(\theta_o - \theta_r)}{aN}}$$

Here,

$$N = \frac{n(1+n)^m}{(1+n)^m - 1}$$

Here, d_1: Outside diameter of heat insulation (m)
d_2: Inside diameter of heat insulation (m)
λ: Thermal conductivity of heat insulating material (kcal/mh° C)
α: Heat transfer coefficient of surface (kcal/mh° C)
b: Cost of heat quantity (¥/1,000kcal)
a: Works cost of heat insulation (1,000¥/m^3)
h: Annual servicing hours (h)
n: Annual rate of interest
m: Servicing years (years)
ln: Napierian logarithm
θ_o: Internal temperature (° C)
θ_r: Room temperature (° C)

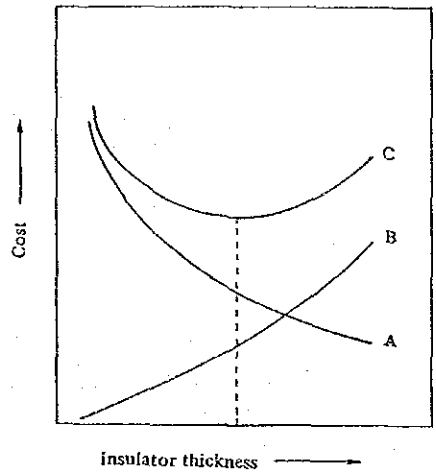


Fig. III–7–43
Relation between the insulation thickness and the cost

e. Heat insulation thickness of steam piping, loss of release heat and heat insulation efficiency

The heat insulation efficiency—dissipated heat after heat insulation to dissipated heat of bare pipe—is shown in Fig. III-7-44 and Fig. III-7-49.

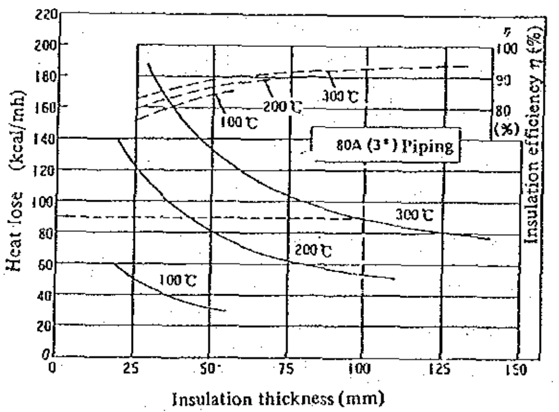


Fig. III–7–44 80A (3B) Piping

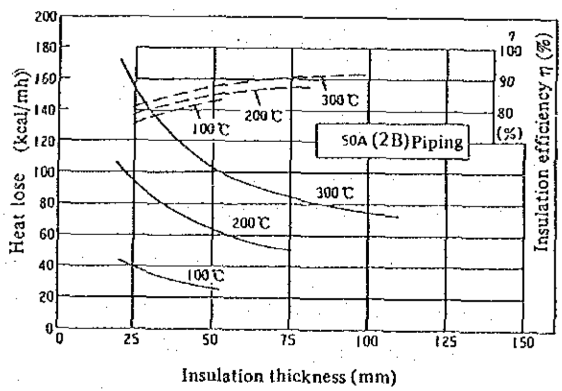


Fig. III–7–45 50A (2B) Piping

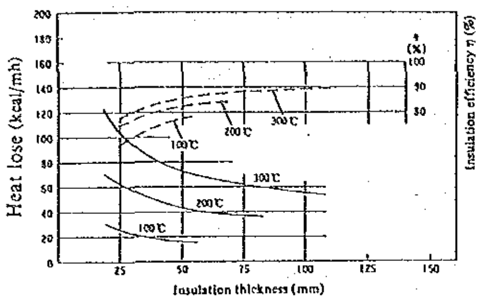


Fig. III-7-46 25A (1B) Piping

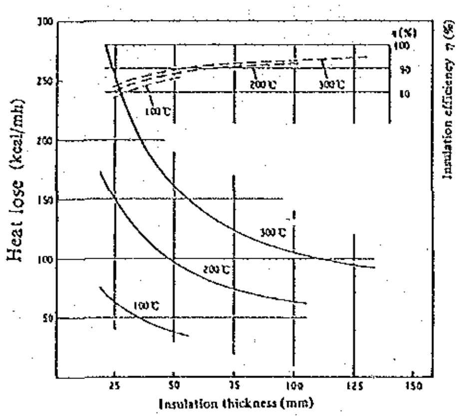


Fig. III-7-47 100A (4B) Piping

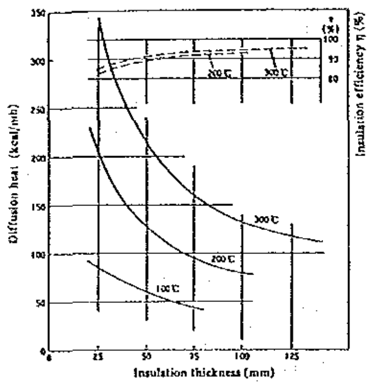


Fig. III-7-48 150A (6B) Piping

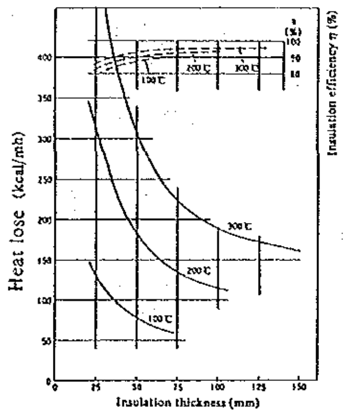


Fig. III-7-49 250A (10B) Piping

Heat insulation efficiency = $(Q_O - Q)/Q_O$

Q_O: Dissipated heat of bare pipe

Q: dissipated heat after heat insulation

<Example of Fig. III-7-44>

When a heat insulation thickness of 100 mm is worked on 80 mm (3B) piping at a steam temperature of 300°C, obtain the dissipating heat quantity and the heat insulation efficiency. (Answer) Draw a horizontal line from the intersectional point of 300°C curve and obtain the dissipated heat quantity of the ordinate (90 kcal/mh). To obtain the heat insulation efficiency, draw a perpendicular line from the intersectional point of 300°C, draw a horizontal line in a right direction from the intersectional point of the dotted curve of 300°C and read the ordinate efficiency scale (93%).

2.4 Steam traps

When steam is fed into a steam servicing equipment, the potential heat of steam is conducted to the subject for heating. As a result, the whole quantity of steam forms a condensate through condensation. The steam servicing equipment shows the maximum heating effect when the steam space is filled completely with steam. With a residence of condensate in the steam space, the effective heating surface area decreases and the heating effect of the equipment lowers. Accordingly, to maintain the equipment capacity at a maximum, the generated condensate should be discharged as soon as possible.

A steam trap is applied for this purpose.

(1) Classification and characteristic

The three most important functions of steam traps are described below.

- Discharge quickly the generated condensate.
- Do not leak steam.
- Discharge non-condensable gas such as air.

At the present time, many steam traps have been manufactured.

These are classified roughly into the following three types by their operating principles.

A) Mechanical steam traps

B) Thermostatic steam traps

C) Thermodynamic steam traps

Each type has various models and their classifications and characteristic are shown in Table III-7-21.

Table III–7–21 Classification and characteristic of steam trap

Large classification	Operation principle	Middle classification	Characteristic
Mechanical	Utilize the density difference between the steam and the condensate.	Lever float type Free float type Open backet type Inverted backet type Free ball backet type	The presence of condensate drives directly a trap valve. It is not necessary to wait a temperature drop of the condensate for actuation. The actuation is quick and secure and has a high reliability.
Thermostat check	Utilize the temperature difference between the steam and the condensate	Bimetal type Bellows type (steam expansion type)	Actuation does not depend on directly the presence of condensate. Since actuation is done through the medium of temperature, response is slow. Accordingly the actuation cycle is longer. A large air exhaust capacity.
Thermo-dynamic	Utilize the difference of thermodynamic property between the steam and the condensate.	Impulse type (orifice type) Disc type	The configuration is small and the reliability is next to the mechanical. The trap back pressure is limited to less 50% of the inlet pressure.

A) Mechanical steam traps

These types of traps function by openning and closing the valve by motions of the backet or the float due to the difference of the densities between steam and condensate.

a. Lever float type trap

This type is a trap to open or close the valve through the lever, utilizing the buoyance of a closed float (See Fig. III-7-50). Deformation due to abrasion or shock of the lever mechanism might cause warpage or incompetency of the valve seat.

b. Free float type trap

The float itself serves as valve to open or close the valve port (See Fig. III-7-51). This trap has a high reliability because there is little mechanical trouble. It has a continuous discharging characteristic of condensate.

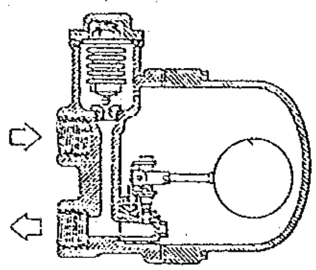


Fig. III–7–50

Float with lever type trap

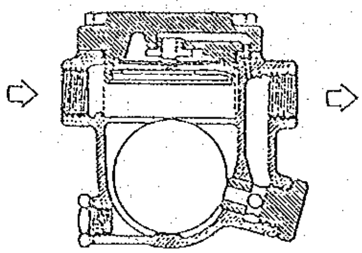


Fig. III–7–51

Free float type trap

c. Open backet type trap

The trap is equipped with a valve on the valve stick which is fixed in the center of the upward opened backet (See Fig. III-7-52).

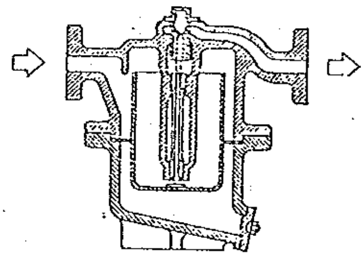


Fig. III–7–52 **Open backet type trap**

d. Inverted backet type trap

The trap has a hanging mechanism of a downward opening backet by the lever and the valve mounted to the lever opens or closes the orifice located in the upper (See Fig. III-7-53). Deformation or abrasion of the lever might cause trouble.

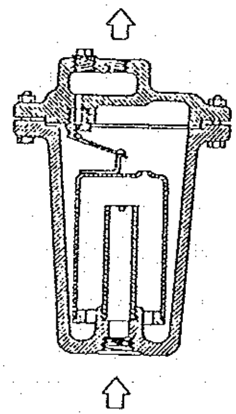


Fig. III–7–53 **Inverted backet type trap**

e. Free ball backet type trap

The trap does not have the lever as in the inverted backet type trap and its actuating principle is the same as the inverted backet type trap (Fig. III-7-54). The backet is a globe and its outer surface actuates as a valve. The trap actuates intermittently for a small quantity of condensate and discharges continually condensate for a large quantity.

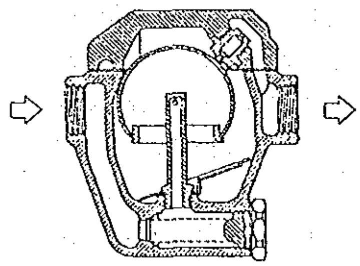


Fig. III–7–54 Free ball backet type trap

B) Thermostatic steam traps

The condensate is at a saturation temperature of steam just after the generation of condensate. After that, the temperature is reduced by dissipated heat to cause a temperature difference. This temperature difference is utilized for opening or closing of the valve.

a. Bimetal type trap

The power generated by bimetal is in a linear relation to the temperature. This relation is utilized for opening and closing of the valve. But the steam pressure has not a linear relation to the temperature and so the servicing pressure range of the trap is restricted (See Fig. III-7-55).

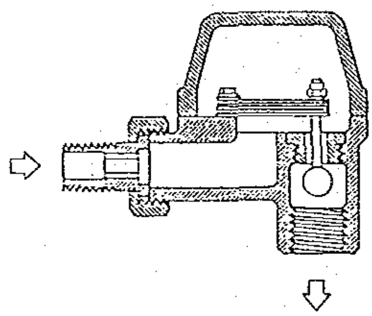


Fig. III–7–55 Bimetal type trap (strip type)

b. Bellows type trap

A low boiling point liquid is sealed in an expandible hermetically sealed enclosure and the valve can be opened or closed through utilization of expansion and contraction of the enclosure due to the change of the liquid vapor pressure by temperature variation (See Fig. III-7-56).

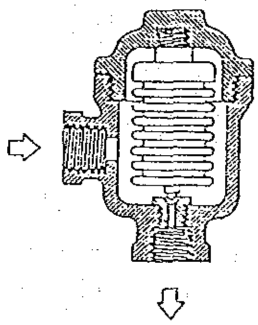


Fig. III–7–56 Bellows type trap

C) Thermodynamic steam traps

The valve can be opened or closed utilizing the difference of the thermodynamic properties between the condensate and the steam.

The trap performance is restricted by the pressure such that the trap's back pressure is less than 50% of the inlet pressure. If the pressure goes to 50% or more, the trap results in a blow-off condition and is impossible to actuate normally.

a. Impulse type trap

It is a trap utilized with fluid characteristics (when the condensate passes the orifice, some pressure drop is caused.) (Fig. III-7-57). Although the trap has an advantage of smaller size compared to other types, it has disposition of easy trouble, because it has mechanism some steam leaks when valve opens and precision fitting part.

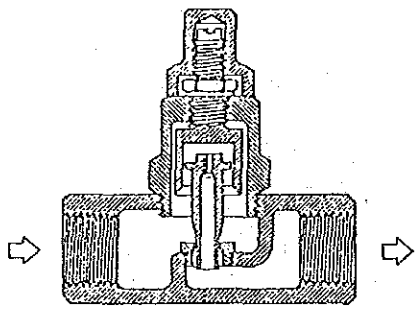


Fig. III–7–57 Impulse type trap

b. Disc type trap

The trap is equipped with a variable pressure chamber having a disc valve between the inlet and the outlet port and the disc valve opens or closes through the pressure change in the variable pressure chamber (See Fig. III-7-58).

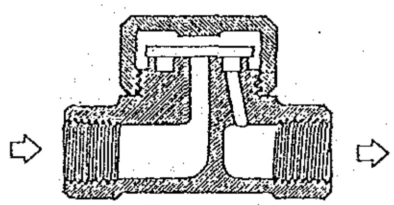


Fig. III–7–58 Disc type trap

The trap has a simple structure of only a disc valve in the moving part and can actuate in a wide pressure range without adjustment. But since its actuation depends on the ambient temperature and is not based on an existence of condensate, the trap actuates in spite of no existence of condensate in case of rain and causes some heat loss.

(2) Selection of a steam trap

For selection of a steam trap, the following items should be investigated:

a. Condensate load of steam servicing equipment and load characteristics.

b. Steam condition: Pressure, temperature and saturated steam or superheated steam.

c. Back pressure condition: Discharge to atmospheric or recovery of condensate.

d. Maintenance condition: Long servicing life with little trouble. Easy disassembly and inspection.

e. Body material

Item "a" of the above items is especially important. When the equipment is in continuous operation, the load variation during operation is generally small. On the other hand, in a batch system, the operation starts and stops several times in a day and much air and condensate must be discharged at every starting-up. Besides, the starting hour is required to be shortened as much as possible from the viewpoint of productivity. While the steam pressure rises with the progress of the process, the quantity of condensate decreases.

Accordingly, although a load variation exists, the trap must discharge quickly the condensate and must have a sufficient discharge ability.

Next, an important issue is disorder of the trap. If the trap continues blow-off, it results in a larger quantity of steam loss than that in normal operation. If block trouble is caused, a huge steam loss may arise because of operation with unavoidable using of the bypass valve. A disorder of the trap, however, is mostly the abrasion of the parts and is a mechanical one. The trouble lessens with the simpler structure of the trap. Therefore, a trap of a structure as simple as possible should be selected.

When condensate is recovered, since the trap is applied with back pressure, a mechanical trap-whose actuation is not affected by the back pressure-should be used.

(3) *Installation procedure of steam traps*

For installation of traps, the following points should be considered.

a. The steam trap does not have the power to push out condensate as in a pump. Condensate is pushed out by steam pressure.

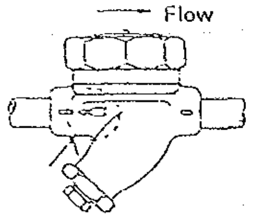
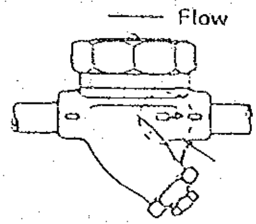
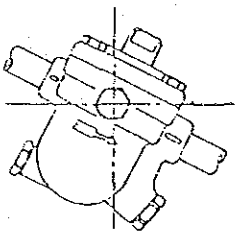
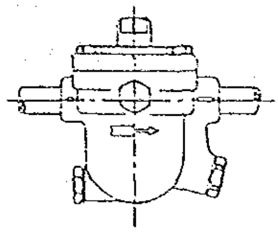
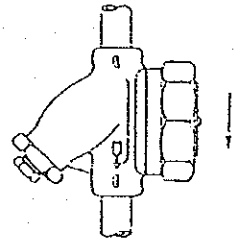
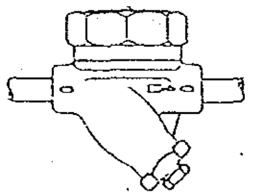
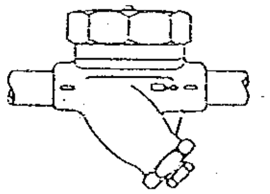
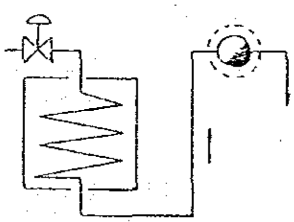
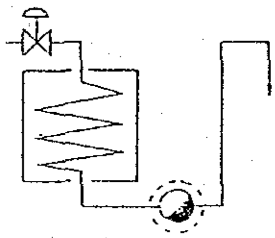
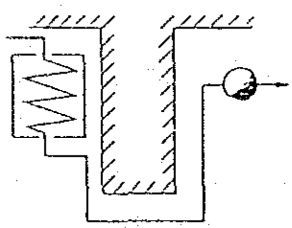
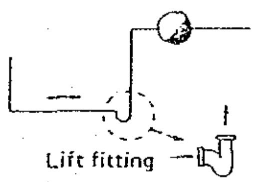
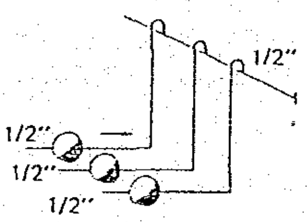
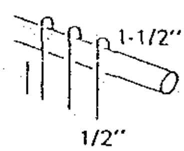
b. If condensate does not enter into a steam trap, it can not work; consequently, the piping from the condensate exhausting point in the equipment to the steam trap should be installed in a gravity flow.

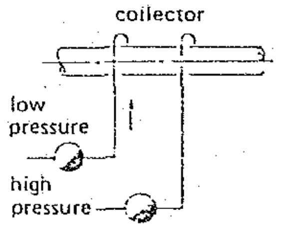
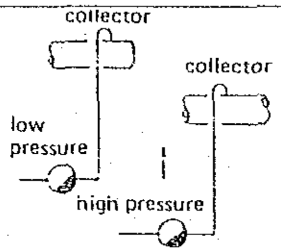
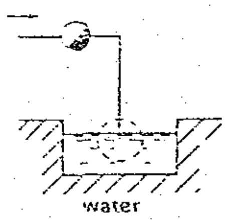
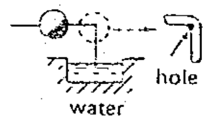
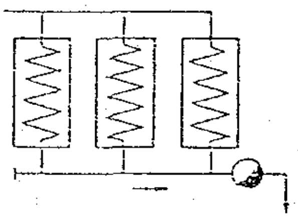
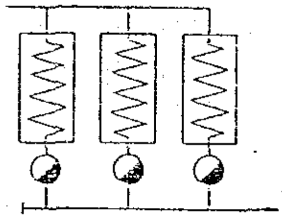
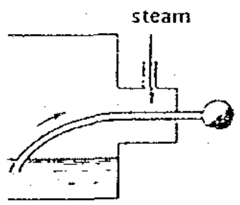
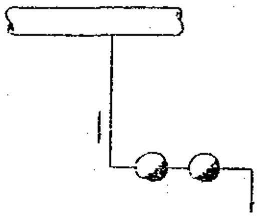
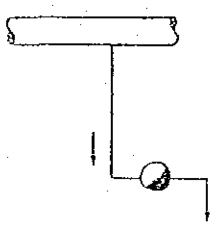
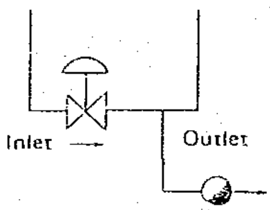
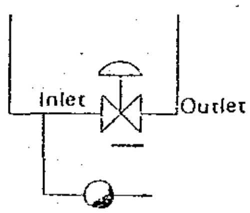
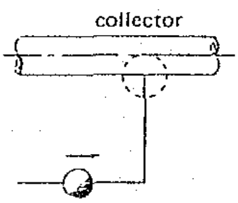
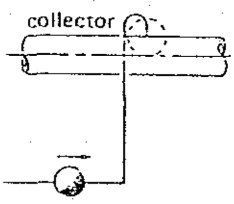
These are important rules for installation of steam traps. On the basis of these rules, some good and worse examples are shown in Fig. III-7-59.

(4) Maintenance of steam traps

A) Inspection

Steam traps are consumables and their function declines after a period of use to be scarcely fit for use. The life of steam traps is uncertain. Steam traps should always be checked carefully and if any trouble is found, they must be replaced with good one, or put in good condition by repairing.

WRONG INSTALLATION	DESCRIPTION	CORRECT INSTALLATION
	Steam trap should be fitted in the direction of flow. All steam traps bear on the body stamp or mark showing flow direction.	
	Free float type steam trap should be fitted horizontally.	
	Thermodyne steam traps have no limitation as to position. It can be fitted vertically.	
	Never use an inlet pipe smaller than trap size. Steam locking and air binding are apt to occur when inlet pipe is too small.	
	Never install steam trap at a higher level than the drainage point. The inlet pipe should be one that allows water to flow into the trap by gravity.	
	If the trap has to be installed at level higher than the draining point, use a lift-fitting.	
	Size of collector must be larger than trap size. The collector should have a sectional area above sum of those for all traps connected to it.	

WRONG INSTALLATION	DESCRIPTION	CORRECT INSTALLATION
	Condensate discharged through two traps which operate at different pressures should not be collected to a common collector.	
	Outlet pipe should not be submerged into trenches. Provide small hole to break vacuum.	
	Each steam unit should always have individual steam trap. (Individual trapping) To fit one trap to several steam equipment is a bad practice. (Group trapping)	
	In siphon type cylinder, steam locking is liable to occur.	
	Double trapping is a bad practice. An efficient one trap is enough.	
	Steam trap must be fitted at the inlet side to discharge condensate before the regulating valve.	
	To collect condensate, the trap outlet pipe must not be connected to the bottom of collector.	

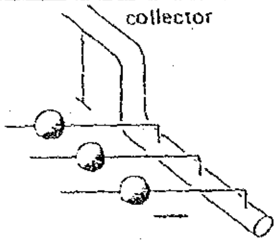
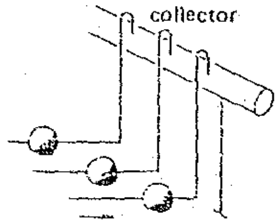
WRONG INSTALLATION	DESCRIPTION	CORRECT INSTALLATION
	Collector should not have a riser. The head of condensate in the collector exerts on the traps as a back pressure.	

Fig. III–7–59 Good example and worse example of installation (I)

The inspection is divided into periodic inspection and daily inspection.

The intervals of periodic inspection should be decided in consideration of the inspection effect and cost. The inspection effect is expressed as steam consumption per unit production (steam consumption rate). For periodic inspection, the following items must be prepared:

a. Steam trap plot plan
b. Steam trap register book
c. Steam trap check list (See Table III-7-22)

Daily inspection must be carried out to maintain the condition at the finishing time of the periodic inspection as far as possible and should be done to not worsen the steam consumption rate.

B) Inspection method

a. Visual inspection

When condensate is discharged from a steam trap into the atmosphere, or when a side glass is mounted in the outlet of the steam trap, visual inspection is available.

b. Auditory inspection

This inspection is a method by listening to the actuating sound by a stethoscope, but much experience is necessary.

c. Touch inspection

Grip the inlet pipe and the outlet pipe of the steam trap with hands wearing gloves and make sure of the actuating condition through the temperature difference.

d. Instrument measuring inspection

This inspection is a method to measure the actuating sound by an ultrasonic measuring instrument and can be simply checked without experience.

C) Disorder of steam traps

The disorder of steam traps are classified into the following four groups. With this clue to go upon, a trouble spot can be found.

a. Blockage

Blockage means that opening the valve of the steam trap is impossible. Such steam traps do not discharge condensate and air, and are also cold. When the outlet of the discharge pipe is open to atomosphere, blockage can be easily confirmed.

Table III–7–22 List of check results of steam traps

Plant:

	Block		
	Trap No.		
Applications	Main		
Applications	Boiler		
Applications	Heater		
Applications	Dryer		
Applications	General heating		
Applications	Tracing		
Applications	Heating		
Applications	Others		
	Pressure		
	Recovery		
	Indoor		
	Manufacturer		
	Model		
	Size		
	Installation Date		
	Working hrs/day		
Conditions	Good	0	
Conditions	Blowing	1	
Conditions	Leaky Valve	2	
Conditions	Leakage thru packing	3	
Conditions	Leakage thru body	4	
Conditions	Capacity shortage	5	
Conditions	Blockage	6	
Conditions	Shut-down	7	
Causes	Worn valve		
Causes	Defective body		
Causes	Foreign material caught		
Causes	Incorrect selection		
Causes	Wrong Installation		
Causes	Air binding		
Causes	Steam locking		
Causes	Incorrect adjustment		
Causes	Others		
	Remedy		
Former Conditions	Last Inspection		
Former Conditions	Before-last Inspection		
	Violation		
	Replaced trap		

Date

b. Continuing blow-off

Continuing blow-off means that it is impossible to close the valve of the steam traps. Such traps continue to discharge a large quantity of steam with condensate. In this case, since the steam servicing equipment is operated and its production is not obstructed, this disorder is apt to be left as it is. But, because a large quantity of steam is wasted, the daily inspection should lay emphasis on detection of this trouble.

c. Steam leakage

Although the trap works, steam leakage is too much compared to normal actuation. From the viewpoint of energy conservation, this is a problem similar to the continuing blow-off.

d. Insufficient discharge

Although the trap works, condensate stays in the equipment due to the poor discharging ability.

2.5 Condensate recovery

(1) Significance of condensate recovery

Heat utilized actually in the steam servicing equipment is only the latent heat out of the total quantity of heat. The sensible heat of steam, namely the quantity of heat of condensate, is almost wasted. The heat content of condensate amounts to approximately 20 to 30% of the total heat content of steam as shown in Fig. III-7-60. If this heat content of condensate is recovered 100% and utilized effectively, the fuel consumption can be saved by approximately 20 to 30%. This will result in large energy conservation.

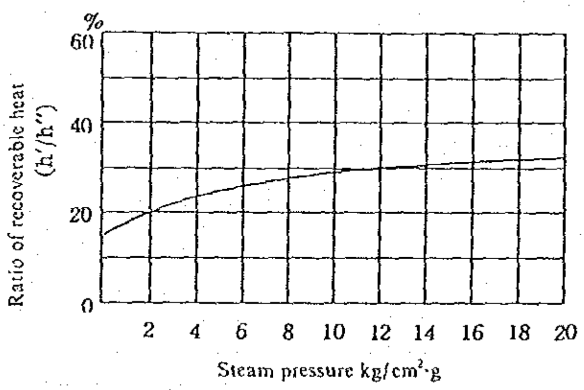


Fig. III–7–60

Ratio of recoverable heat

(Enthalpy of condensate/Enthalpy of saturated steam)

(2) Utilization of recovered condensate.

The recovered condensate is generally utilized as feed water of the boiler. Consideration of the pressure and the quantity of condensate and the layout of the steam equipment is necessary to more effectively recover the condensate. The utilization of condensate is classified into the following three methods.

A) Direct utilization

The condensate discharged from the steam trap is recovered directly to the boiler

or the feed water tank by a condensate recovery pump (See Fig. III-7-61).
(Fig. III-7-61)

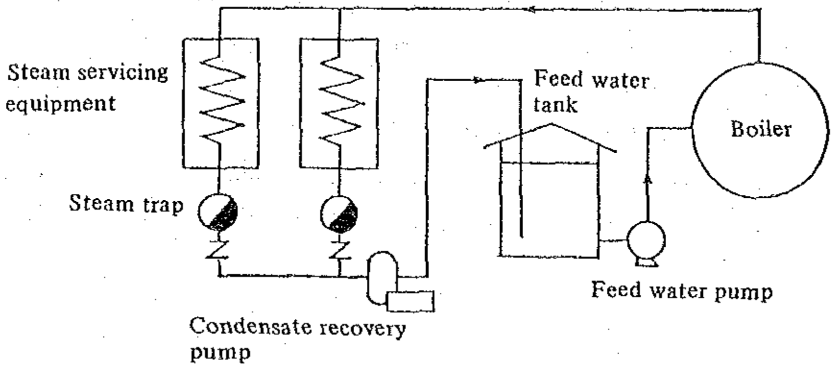


Fig. III–7–61 Direct utilization to feed water tank

B) Indirect utilization

If condensate is contaminated, only the potential heat of condensate should be recovered by heat exchange to other fluids in the heat exchanger (Fig. III-7-62).

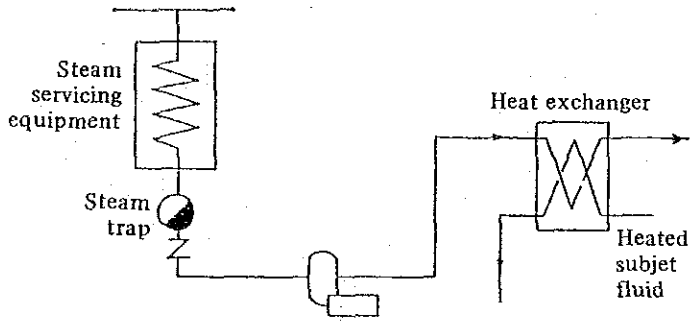


Fig. III–7–62 Indirect utilization through heat exchanger

C) Utilization of flash steam

If the pressure of condensate is high, it is effective that the condensate be recovered into the flash tank and a part of it be utilized as low pressure steam (See Fig. III-7-63).

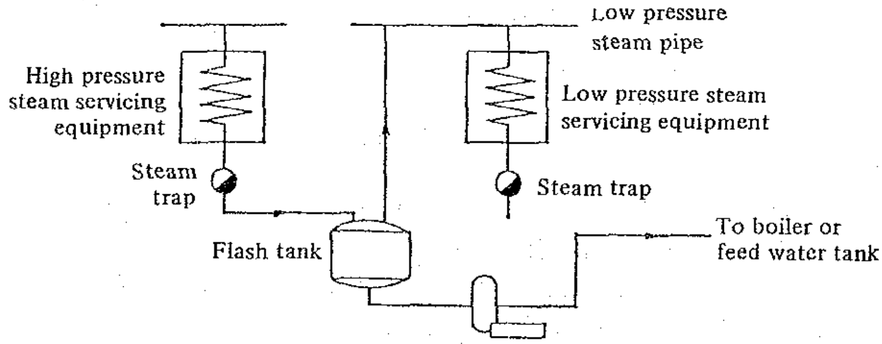


Fig. III–7–63 Flash steam utilization

(3) Condensate recovery method

Recovery of condensate from the generating source to re-utilization has the following three methods depending on the pressure of condensate and the recovery distance. These methods have characteristics respectively.

A) Method by only steam trap

Condensate can be recovered to a flash tank or a condensate tank by the steam pressure acting on the steam trap. This can be applied to the case of a short distance between the condensate generating place and the utilizing place (See Fig. III-7-64).

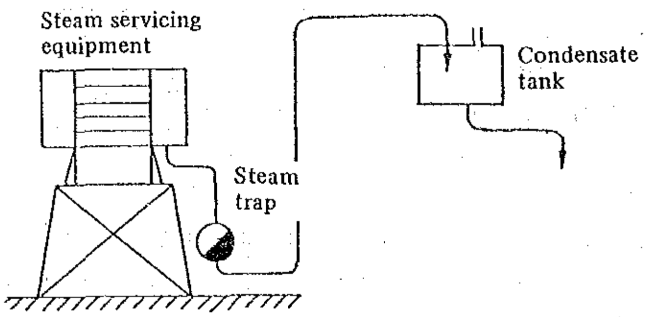


Fig. III–7–64 **Recovery by steam trap only**

B) Method by centrifugal pump

The condensate discharged from the steam trap is once gathered in a condensate tank and then is sent pressurized by a centrifugal pump. This is applied to the case when the steam traps are installed in a wide area. Each condensate tank is installed by an area or by a process and then the condensate is recovered by sending it pressurized by a pump in a central tank (See Fig. III-7-65).

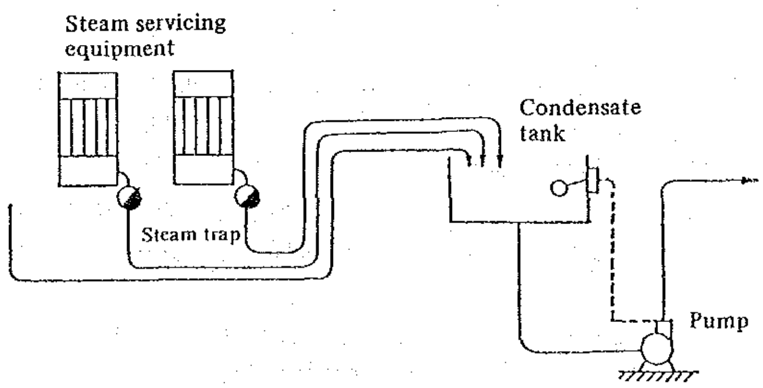


Fig. III–7–65 **Recovery by centrifugal pump**

In this case, care must be used for ensuring the water head of the pump, a level control of condensate, and a pump capacity as well as a back pressure limit of the steam trap. Especially when the temperature in the tank is 80° C or more, a positive water head of 4 to 5 m is required to prevent a cavitation of the pump

C) Method by condensate recovery pump

Recently, a condensate recovery pump, which combines with an ejector to make up for the weak points of cetrifugal pump, has been used. Since the suction side of this pump is operated under a pressurized condition, no cavitation is caused and its positive water head is sufficient with about one meter. In the case of a closed system of the condensate recovery line, even a condensate of about 180° C can be sent pressurized with a large effect of energy conservation (Fig. III-7-66).

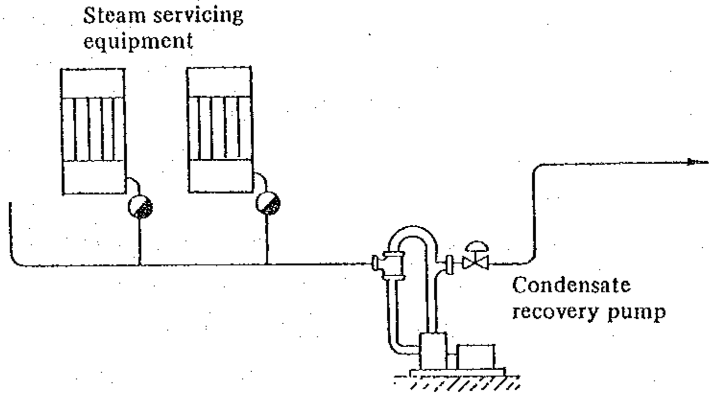


Fig. III–7–66 Recovery by condensate recovery pump

For this method, a mechanical steam trap should be applied.

(4) Consideration for condensate recovery

A) Selection of steam traps

Keeping the highest heating efficiency in steam servicing equipment is an important problem related to production as a problem prior to the condensate recovery. In a condition of application of back pressure to the steam trap and pressure fluctuation, a mechanical steam trap having little trouble should be selected.

B) Condensate treatment

The recovered condensate may be considered as pure distilled water because practically only a very small amount of various impurities are dissolved in it. Can the recovered condensate itself be used as boiler feed water? If it is impossible to use, what is the condensate treatment method? Or, for a severe contaminated condensate, is heat quantity alone recovered? These questions should be investigated.

pH control of condensate

The pH of condensate declines due to dissolution of carbon dioxide. In consequence, this increases the total iron concentration in the condensate. At the time of condensate recovery, some chemicals are required to be poured into the condensate to control the dissolved oxygen and the pH.

C) Condensate recovery piping

If piping systems for different steam pressures are installed, the condensate recovery pipings must be installed by a steam pressure system.

Since the recovery piping accompanied with flash steam is a two-phase flow of steam and condensate, it should be designed for the maximum flow rate within 15 m/s and a large pressure loss and water hammer should be prevented.

D) Design of the total system

The condensate recovery system is a series of closed systems from the boiler through the steam servicing equipment to return to the boiler again. Therefore, the recovery system should be designed as a whole instead of a design for every equipment.

(5) Utilization of flash steam

In the paragraph about utilization of recovery condensate, it is described to recover the high pressure condensate into the flash tank and to utilize a part of the condensate as low pressure steam. However, since this method actually has various problems, its economical effect should be investigated.

a. When the condensate quantity discharged from the steam trap is extremely small, the flash steam is also small and is scarcely worth using. There are many steam traps which discharge a small quantity of condensate in a factory. The total of these condensates result in a fair amount. But it is necessary to manage to gather these small quantity condensates with a cost as small as possible.

b. Although a fair amount of condensate can be gathered and flash steam can be obtained from these, an user of it may not be found. Before flash steam is recovered, its usage should be previously decided.

c. The distance between the place generating condensate and the servicing place of flash steam is desired to be short. Because the flash steam is of a low pressure, the pressure loss is required to be minimized. If the distance is long, the piping increases in diameter and the piping cost becomes rather expensive, its merit may be offset. For this case, the utilization of flash steam must be given up.

Fig. III-7-67 shows the example using flash steam. The example is used with a flash steam in the front stage of air heater.

When a steam of 8 kg/cm^2G is used by 2,500 kg/h and condensate is discharged into a flash tank of 0.5 kg/cm^2G of internal pressure, the quantity of flash steam is generated with 12.3% (wt.) by Table III-7-23 and a steam quantity of 307.5 kg/h is obtained.

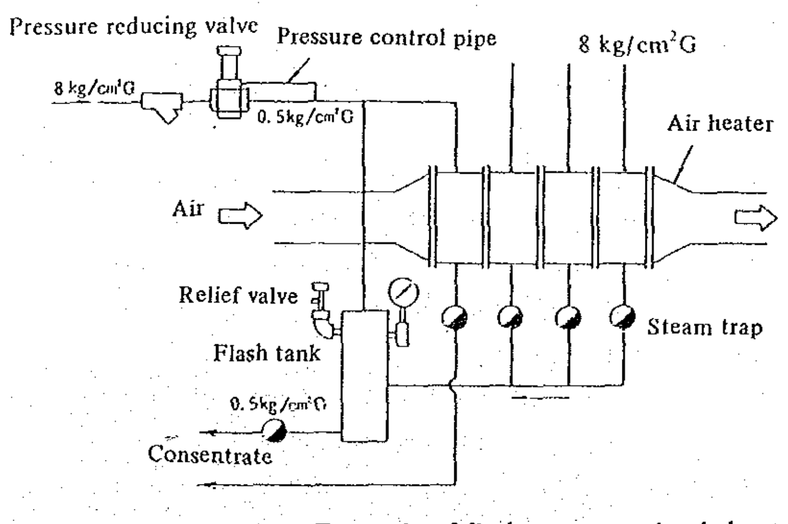


Fig. III-7-67 Example of flash steam use in air heater

Table III–7–23 Flash steam generating rate (wt. %)

Pressure in high pressure side (kg/cm^2G)	Low pressure side (kg/cm^2 G)															
	0	0.3	0.5	1	1.5	2	3	4	5	6	8	10	12	14	16	18
1	3.7	2.5	1.7	–	–	–	–	–	–	–	–	–	–	–	–	–
2	6.2	5.0	4.2	2.6	1.2	–	–	–	–	–	–	–	–	–	–	–
3	8.1	6.9	6.1	4.5	3.2	2.0	–	–	–	–	–	–	–	–	–	–
4	9.7	8.5	7.7	6.1	4.8	3.6	1.6	–	–	–	–	–	–	–	–	–
5	11.0	9.8	9.1	7.5	6.2	5.0	3.1	1.4	–	–	–	–	–	–	–	–
6	12.2	11.0	10.3	8.7	7.4	6.2	4.3	3.0	1.3	–	–	–	–	–	–	–
8	14.2	13.1	12.3	10.8	9.5	8.3	6.4	4.8	3.4	2.2	–	–	–	–	–	–
10	15.9	14.8	14.2	12.5	11.2	10.1	8.2	6.6	5.3	4.0	1.9	–	–	–	–	–
12	17.4	16.3	15.5	14.0	12.7	11.6	9.8	8.2	6.9	5.7	3.5	1.7	–	–	–	–
14	18.7	17.6	16.9	15.4	14.1	13.0	11.2	9.6	8.3	7.1	5.0	3.2	1.5	–	–	–
16	19.0	18.8	18.1	16.6	15.3	14.3	12.4	10.9	9.6	8.4	6.3	4.5	2.9	1.4	–	–
18	21.0	19.9	19.2	17.7	16.5	15.4	13.6	12.1	10.8	9.6	7.5	5.7	4.1	2.7	1.3	–
20	22.0	20.9	20.2	18.8	17.5	16.5	14.7	13.2	11.9	10.7	8.7	6.9	8.3	3.8	2.5	1.2

A flash tank is a sort of pressure vessel to recover flash steam from the condensate. The flash tank capacity is decided on the basis of this large flash steam generating volume (m^3/s). When the flash steam goes up in the tank, reasonable velocity of the flash steam may be required not to involve condensate. The inside diameter of the tank should be decided to be a rising speed of steam of 1 to 2 m/s. But as a variation of the operating condition may carry out entrainment, a separator should be mounted to the steam outlet pipe.

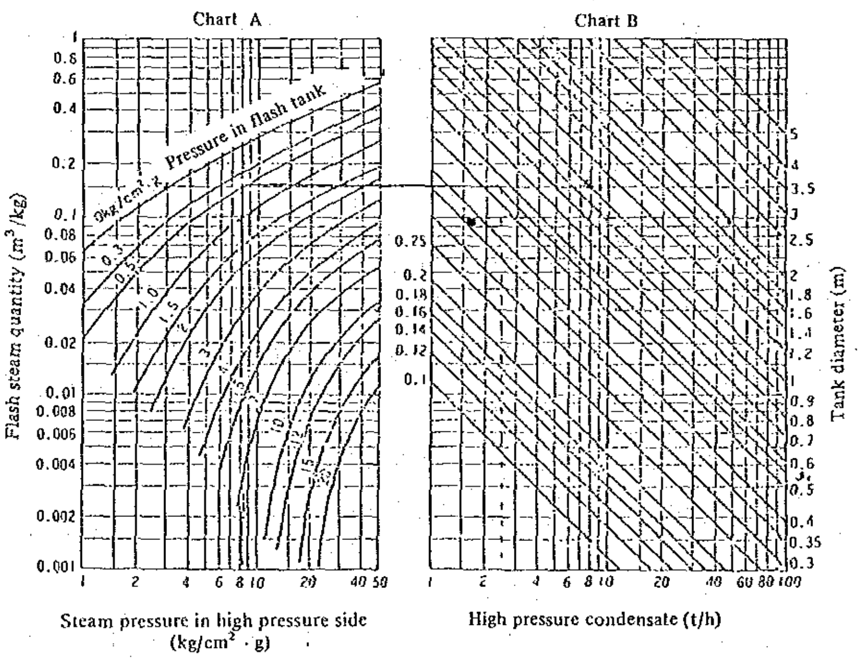


Fig. III–7–68 Chart of flash tank diameter

Fig. III-7-68 shows a chart to decide the inside diameter of the flash tank.

Obtain the inside diameter of the tank through the example shown in Fig. III-7-67.

Obtain the intersection of the steam pressure of 8 kg/cm^{2}G in the high pressure side and the internal pressure of 0.5 kg/cm^{2}G in the flash tank from the chart A. Move horizontally to chart B and obtain the intersection with a high pressure condensate quantity of 2.5 t/h. The diameter of the tank is obtainable as 0.55m. If the tank capacity is 40 liters or more, a safety valve must be installed so that the pressure in the tank does not become excessive by a variation of the supplied condensate quantity and the flash steam demand.

(6) Utilization of thermocompressors

The structure of thermocompressors is composed of three basic parts, body, a steam nozzle and diffuser as shown in Fig. III-7-69. When a driving steam is expanded through the steam nozzle, a supersonic jet having an extremely low static pressure is generated. When its speed is reduced by the diffuser, the pressure is recovered. That is, when a low pressure steam is sucked into the Venturi throat section, it becomes high pressure steam. Fig. III-7-70 shows an example of a chemical plant. The bottom liquid in a stripping tower is introduced to a flash tank and the low pressure of a generated flash steam is raised to a proper pressure by the thermocompressor to save additional steam.

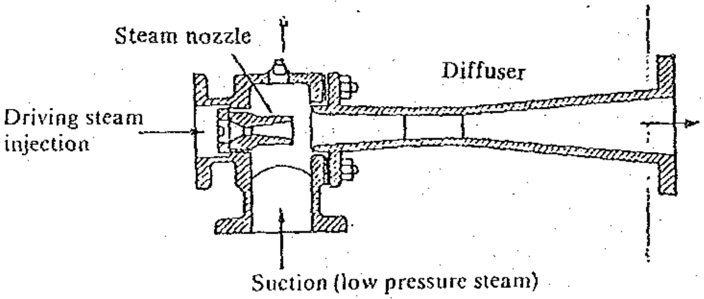


Fig. III–7–69 Thermocompressor

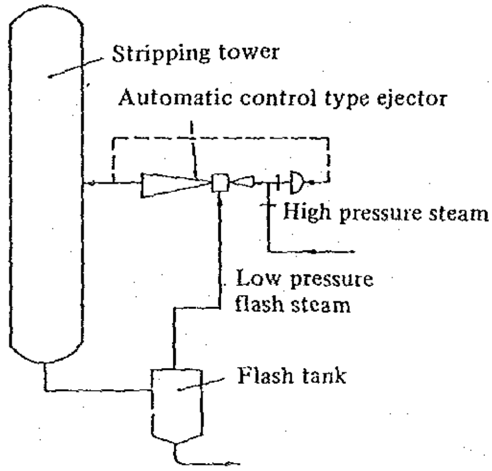


Fig. III–7–70 Example of thermocompresser use for stripping tower

2.6 Utilization of direct heating by steam

Direct heating by steam has the following two methods:

(1) Direct heating in a closed vessel.

(2) Heat by direct blowing steam to liquid.

The direct heating method has advantages such as simple and low cost equipment, quick work, and a constant temperature.

(1) Direct heating in a closed vessel

A direct heating vessel such as an autoclave and a steamer is mounted with an airtight door and is applied to treat a settled quantity of goods in batch.

In the case of the steam direct heating, a constant temperature is accurately obtained by adjustment of steam pressure. This is suitable to heating in the case that a product quality may deteriorate at higher than a certain temperature or a process requiring a very narrow temperature range.

But, the relation that the steam temperature depends on the pressure holds true only in the case when air is not contained in the steam. In an air containing steam, the temperature is a saturation temperature equivalent to the partial pressure of steam in the mixture and is lower than the saturation temperature of steam alone. Therefore, *sufficient air elimination is required at the start up. For reference, the relation between* the air mixing ratio and the steam temperature is shown in Table III-7-24.

Table III-7-24 Relation between the air mixing ratio and steam temperature (°C)

Steam Pressure kg/cm^2 / Air mixing ratio %	2	3	5	9
0	119.6	132.9	151.1	174.5
10	116.3	129.3	147.2	169.6
20	112.7	125.5	142.9	165.3
40	104.3	116.3	132.9	154.0

(2) Direct steam blow heating method

A direct steam blowing operation is often carried out in some processes such as when hot water is required or when heating of a raw material solution. For steam blowing, there are various methods, such as installation of a silencer to the tip of steam pipe, *or a steam blowing pipe with a number of small holes (See Fig. III-7-71 and Fig.* III-7-72).

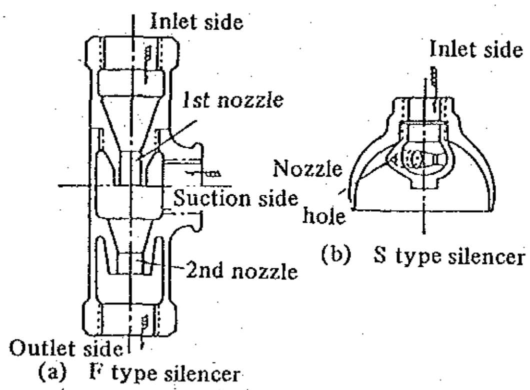


Fig. III-7-71 Silencer

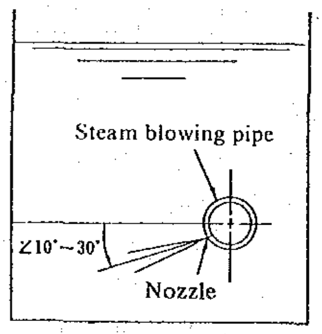


Fig. III-7-72
Steam blowing angle from nozzle

Either method is important to condense effectively the steam blown in the liquid and to devise not to leak the live steam to atomosphere, and great consideration is necessary.

a. Reduce the velocity of steam bubbles blowed into liquid.

b. Give a longer time to condensate the steam bubbles. Select a proper depth and location, and install a blow nozzle downward at an angle of 10° to 30° to the level (See Fig. III-7-72).

c. Install the blow nozzle under a large water head.

d. Because the heat exchange from the steam bubble to the liquid is done on the contact surface, the blow nozzle size should be designed to form a number of small bubbles in order to increase the surface area of steam bubbles.

e. Reduce the blowing pressure of steam. A low pressure is advantageous with small steam bubbles. Since the steam blowing pipe is always inserted in the liquid bath, a stop of steam supply brings about vacuum in the pipe and causes backflow of the liquid into the pipe. A preventing measure for this is required. Install a check valve operable in a very low pressure to the pipe as shown in Fig. III-7-73. When the steam side comes in a vacuum, the valve opens by a pressure difference to atmospheric pressure, the vacuum is destroyed and the backflow of liquid can be prevented.

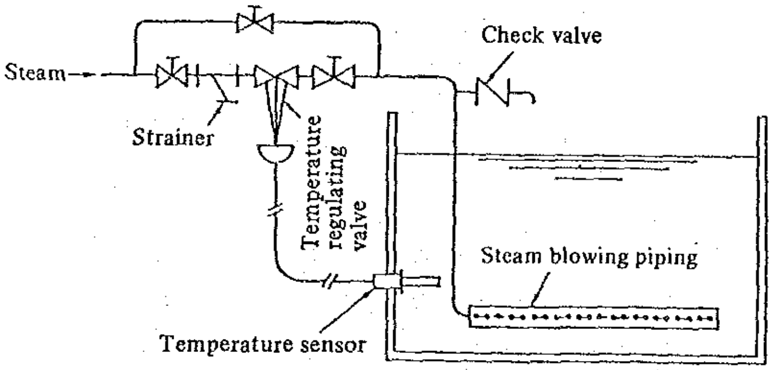


Fig. III–7–73 Steam direct blow-in heater

2.7 Utilization of heat pumps

In the food, textile and chemical industries, large amounts of a hot waste water are generated at a relatively low temperature and are discarded without effective utilizing means. If the heat quantity of hot waste water is recovered by heat pumps, the recovered heat quantity has a possibility of being re-utilized in most processes to reduce steam consumption.

(1) Type and principle of heat pumps

Heat pumps used for industry are classified as follows;

Compression type heat pump

Absorption type heat pump

Either heat pump, in principle, performs heat absorption and dissipation utilizing the phase change of the medium.

A) Compression type heat pump

The fundamental elements are shown in Fig. III-7-74. This heat pump is composed of an evaporator as a heat exchanger in the low temperature section, and compressor and a condenser as a heat exchanger in the high temperature section, and expansion valve.

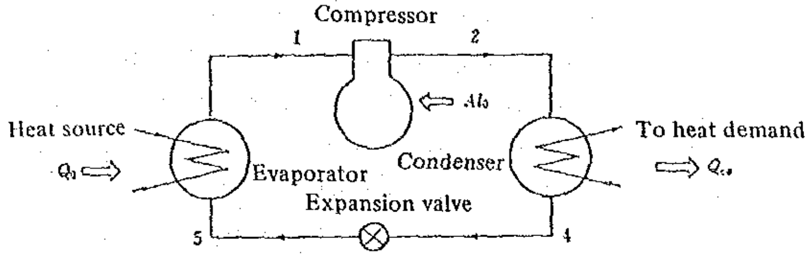


Fig. III–7–74 Vapor compression type heat pump cycle

The heating medium circulates in the system with repeat of the change in evaporation → compression → condensation → expansion → evaporation. Freon is generally used as a heating medium.

The quantity of heat Q_o taken in the low temperature side is added with the energy Al_o spent to pressurize it and a larger quantity of heat Q_{co} than the quantity of heat absorbed in the low temperature is released. The above phase change is shown in Fig. III-7-75 with expression as a phase diagram of the heating medium. The figures of each dot in the diagram correspond to the places of figures shown in Fig. III-7-74.

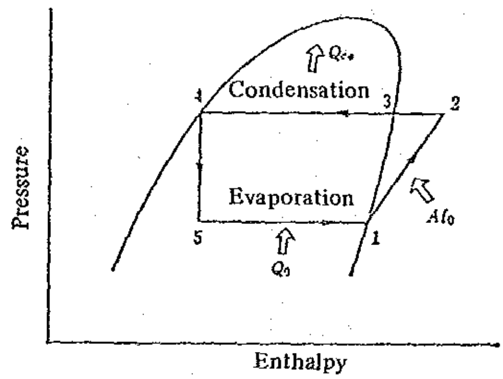


Fig. III–7–75 Heat pump cycle on Mollier chart

B) Absorption type heat pumps

There is a 1st class and 2nd class in the absorption heat pumps. Either pump takes quantity of heat from the outside through evaporation and condensation of the heating medium and releases them as quantity of heat at high temperature. In order that the heating medium vapor may move to the high pressure section without use of a compressor, LiBr is used as an absorbent with water as heating medium.

a. The 1st Class absorption type heat pump

The fundamental elements are shown in Fig. III-7-76. The quantity of heat Q_E transferred from the heat source enters in the evaporator and water evaporates. This steam is absorbed by the LiBr concentrated solution in the absorber to release the quantity of heat Q_A. The LiBr diluted solution which is diluted by absorption of water is fed to a generator by a pump as the absorption ability declines. In the generator, water in the LiBr diluted solution evaporates by the quantity of heat Q_G in a high temperature of the outside steam etc. The LiBr concentrated solution brought back to the original concentration returns again to the absorber and continues an absorbing action.

The steam evaporated in the generator is fed to the condenser, releases the quantity of heat Q_C to the outside and the steam itself condensates. The condensated water returns again to the evaporator and repeats the cycle. A heat exchanger is equipped in the interval between the generator and the absorber and saves the quantity of heat required in the generator. Fig. III-7-77 shows the cycle on the Dühring diagram. ϵ_1 and ϵ_2 express the concentrations of diluted solution and concentrated solution respectively.

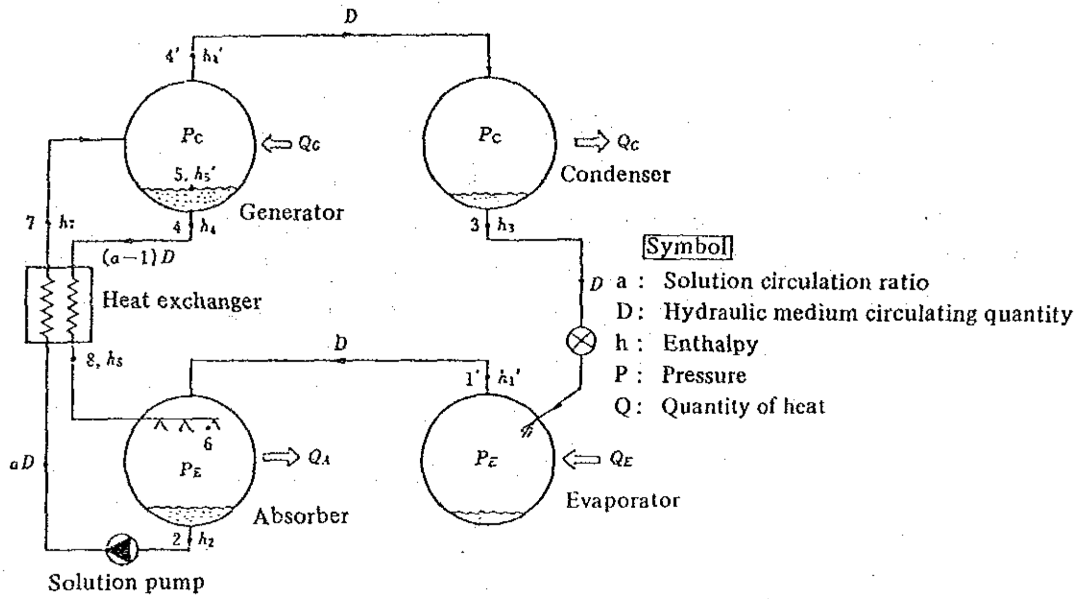


Fig. III−7−76 Flowsheet of absorption heat pump (LiBr-Water 1st type)

b. The 2nd Class absorption type heat pump

The hot waste water as a heat source is fed to the evaporator and the generaotr and a lower temperature water out of the hot waste water is fed to the condenser and a high temperature water is obtained in the absorber. Fig. III-7-78 shows the flowsheet and Fig. III-7-79 shows the cycle on the Dühring diagram.

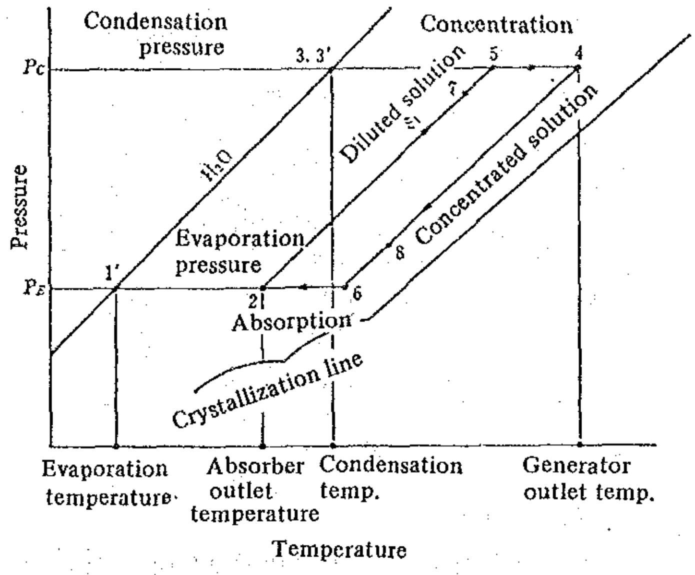
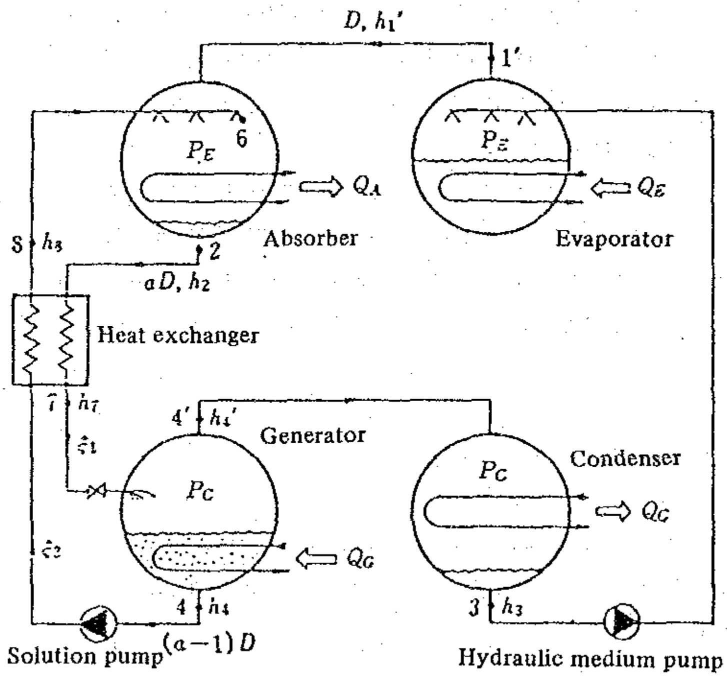


Fig. III–7–77 1st absorption heat pump cycle on Dühring diagram



Example of cycle

Item		Inlet	Outlet
Hot water in absorber	(°C)	95	100
Heat source of evaporator	(°C)	70	65
Heat source of generator	(°C)	70	65
Cooling water of condenser	(°C)	6	8
1' point temperature	(°C)	60	
2 point temperature	(°C)	108	
3 point temperature	(°C)	10	
4 point temperature	(°C)	58	

Symbol

a : Solution circulation ratio
D : Hydraulic medium circulating quantity
h : Enthalpy
P : Pressure
Q : Quantity of heat
ϵ : Concentration

Fig. III–7–78 2nd type absorption heat pump flowsheet

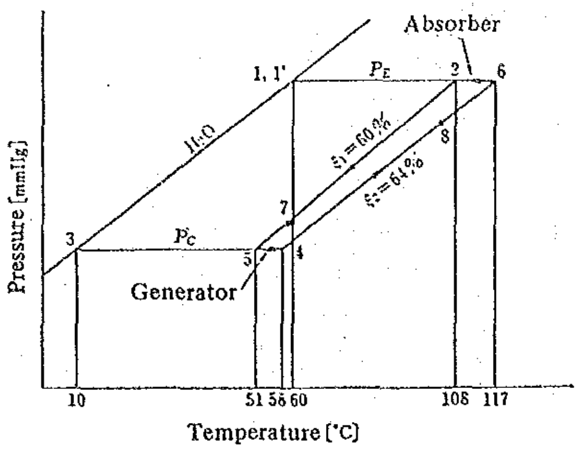


Fig. III–7–79
Cycle of 2nd type absorption heat pump on Dühring diagram

In these figures, the values in each section to obtain the high temperature water of 100° C from the hot waste water of 70° C are expressed.
The 2nd Class heat pump obtains a quantity of heat utilized effectively only from the absorber, unlike the 1st Class heat pump, and the whole heat energy to permit the equipment to operate is taken from the waste heat.

(2) Application example of heat pumps

A) Application example of compression type heat pump in chemical industries

Hot water of 81° C is produced by a compression type heat pump using the hot waste water fed from the top condenser of the distillation column as a heat source and is used as a heat source of the reboiler. Fig. III-7-80 shows the flow.

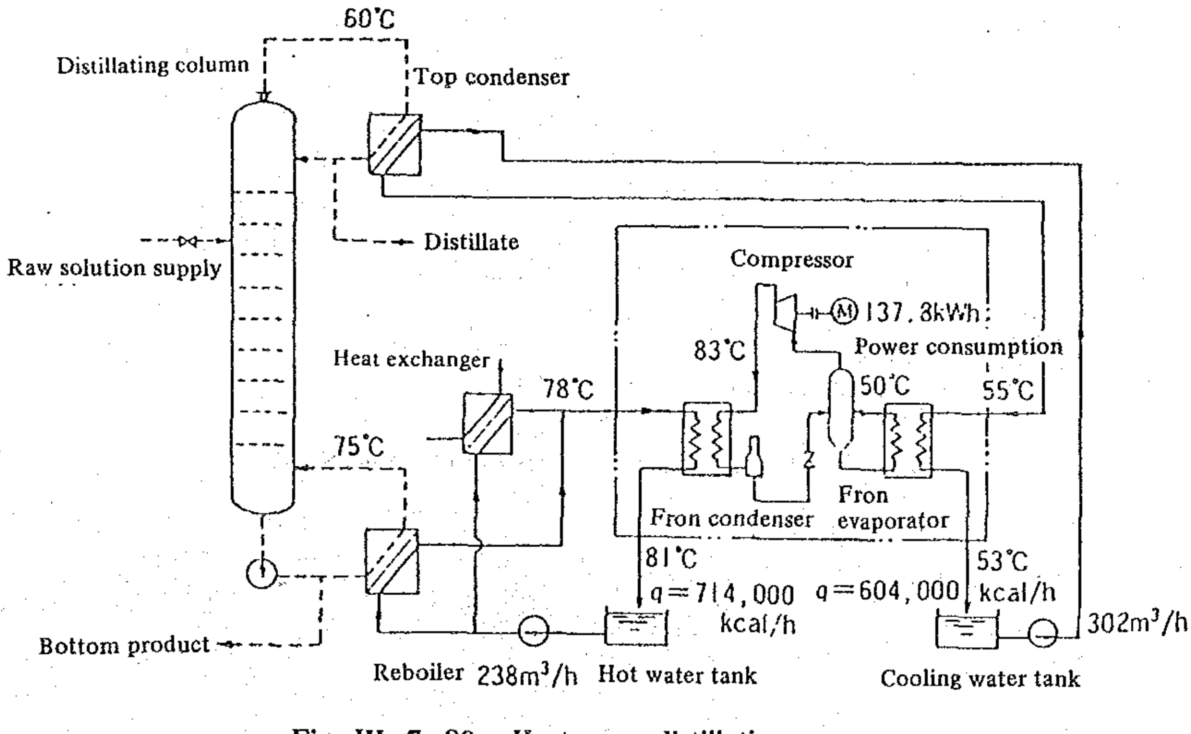


Fig. III–7–80 Heat pump distillation

Cooling water of 53° C is fed to the top condenser to absorb the condensation heat of the overhead gas. When the cooling water rises to 55° C and it is again cooled to 53° C, the heat quantity is taken by the heat pump, the hot water of 78° C rises to 81° C to supply to the reboiler and the heat is utilized for evaporation heating of the bottom liquid.

In comparison to the conventional steam heating, the use of heat pumps brought about the possibility of a running cost of 40% in the utilization of boilers.

B) Application example of the 1st Class heat pump in textile industries

The flowsheet is shown in Fig. III-7-81. The characteristics of this system are to supply hot water to the dye house and to cool it in the knitting factory. The air conditioning load is utilized as a heat source of the heat pump.

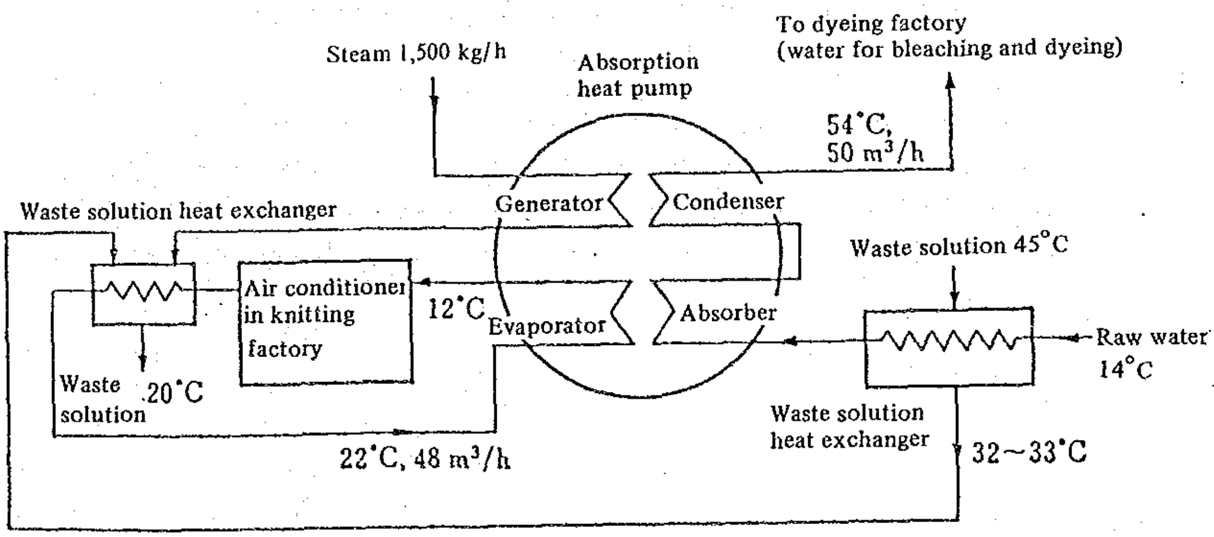


Fig. III–7–81 Absorption heat pump flowsheet in textile dyeing plant

But since the cooling load fluctuates by season or hour quantity of, heat is recovered as hot waste water and condensate as well as the cooling load.

The heat source for driving is steam, and it supplies heat quantity to the generator and a circulating water of 22° C is cooled to 12° C in the evaporator and is fed to the air conditioning system.

Hot water for the process is heated to 54° C by passing in a series of the absorber and condenser, and sent to the dye house.

The system utilizes, at the same time, two functions of cooling and heating of the heat pump character. This system is the most effective application.

C) Application example of the 2nd Class absorption type heat pump in chemical factories

The example for utilization of the compression type heat pump in order to recover the heat in the waste heat of the distillation column is described in the previous paragraph. Here, an application example of the 2nd Class absorption type heat pump is introduced. The flowsheet is shown in Fig. III-7-82.

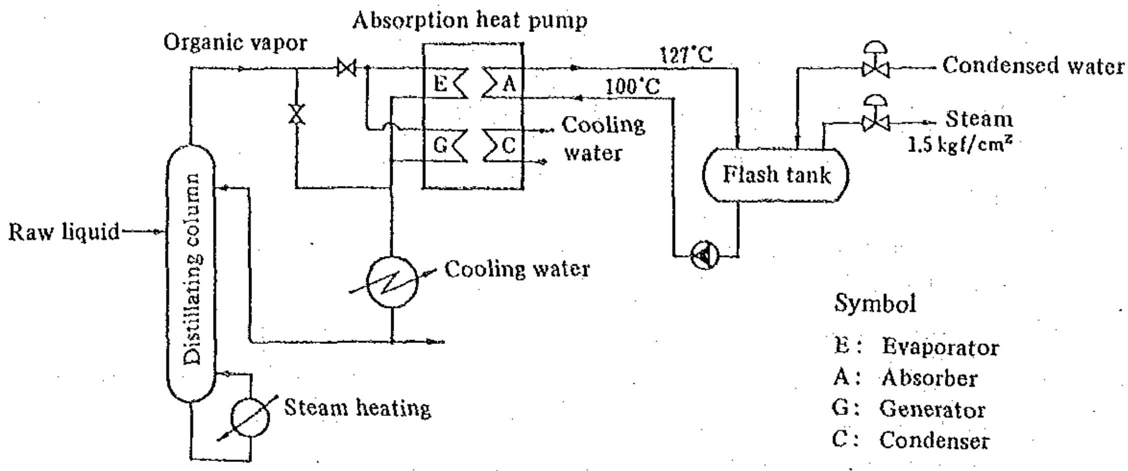


Fig. III–7–82 **Flowsheet of 2nd type heat pump utilized with exhaust heat of distillating column**

An organic vapor (80° C) taken out of the top of the distillation column is passed to the evaporator and the generator separately. When normal cooling water is passed to the condenser, a higher temperature water (127° C) than the heat source is obtainable from the absorber. This high temperature water is fed to the flash tank to generate a steam of 1.5 kg/cm^{2}G and 125° C which is used as a process steam.

III. Guideline for Rationalization of Energy Use

8. Electricity

Contents

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Of the electrical equipments which are most common to various industrial fields such as ceramic, glass, paper, textile, metal, plastic, chemical and food, the items closely related to energy conservation are classified as follows:

8.1 Electric power management
8.2 Transformers
8.3 Motors
8.4 Compressors
8.5 Blowers (fan and blower)
8.6 Lighting
8.7 Electric heating
8.8 Air conditioning

Although some of these items may not be closely related to some factories, the engineers in charge are requested to read through all the items in case of future equipment expansion.

8.1 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 standpoint of improvement of the load factor.

8.1.1 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 with measuring instruments at important points so that the electric power consumption rate in each plant may be measured and checked periodically.

(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.

(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.

8.1.2 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)

$$P = E\,I\cos\phi \quad \cdots\cdots (2)$$

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 (See Fig. III-8-1 and Fig. III-8-2).

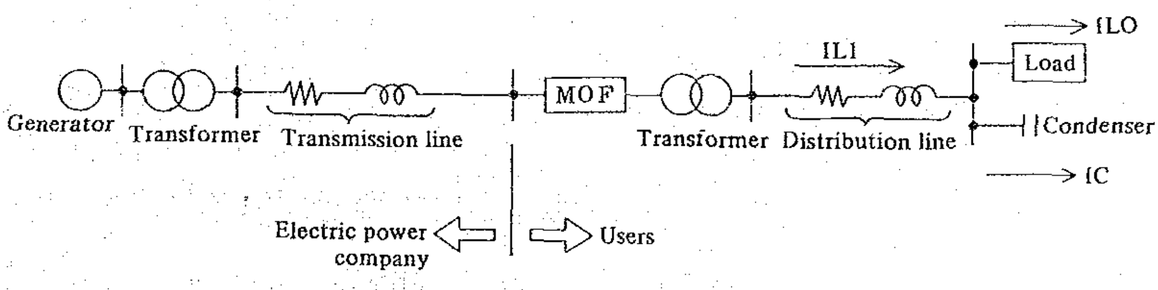


Fig. III–8–1 Diagram of electric power system

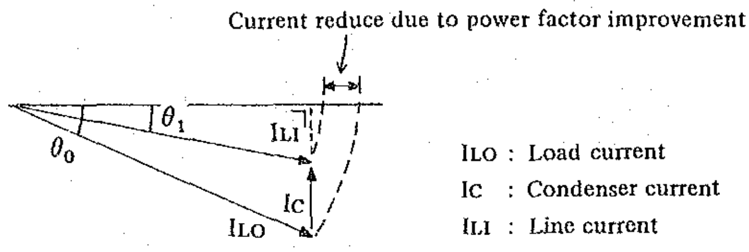
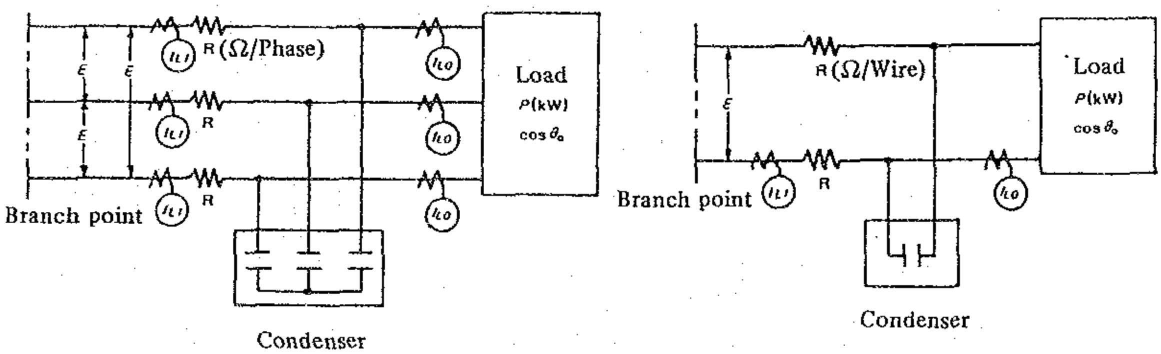


Fig. III–8–2 Reduced line current due to power factor improvement

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 with a phase-advancing capacitor to improve the power factor in Fig. III-8-3 is determined by the following equations:



(a) In the case of 3 phase circuit (b) In the case of single phase circuit

Fig. III–8–3

A) Equation for three phase circuit

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

Where

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

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

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

Hence,

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

In equation (5), substituting

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

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

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

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

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

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

Hence,

$$P_L = 2 \times \frac{P^2}{E^2} \times \left(\frac{1}{\cos^2 \theta_0} - \frac{1}{\cos^2 \theta_1}\right) \times R \times 10^{-3}\ (kW) \quad \cdots\cdots (9)$$

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

$$= 2 \times (I_{LO} \times \cos \theta_0)^2 \times k_1 \times R \times 10^{-3}\ (kW) \quad \cdots\cdots (11)$$

Where

P (kW) : Load power

I_{LO} (A): Load current

I_{LI} (A): Line current

E (kV): Line voltage

$\cos \theta_0$: Present power factor

$\cos \theta_1$: Power factor after improvement

And

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

This coefficient can be determined from Table III-8-1 and Fig. III-8-4 by knowing present power factor $\cos \theta_0$.

Table III–8–1 Coefficient k_1

Present load power factor ($\cos\theta_1$)	Target improved power factor ($\cos\theta_1$)																								
	0.75	0.76	0.77	0.78	0.79	0.80	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00
0.50	2.222	2.269	2.313	2.356	2.398	2.438	2.476	2.513	2.548	2.583	2.616	2.648	2.679	2.709	2.738	2.765	2.792	2.819	2.844	2.868	2.892	2.915	2.937	2.959	2.980	3.000
51	2.067	2.113	2.158	2.201	2.242	2.282	2.321	2.357	2.393	2.427	2.461	2.493	2.523	2.553	2.582	2.610	2.637	2.663	2.688	2.713	2.737	2.760	2.782	2.803	2.824	2.845
52	1.920	1.967	2.012	2.055	2.096	2.136	2.174	2.211	2.247	2.281	2.314	2.346	2.377	2.407	2.456	2.464	2.491	2.517	2.542	2.566	2.590	2.613	2.635	2.657	2.678	2.698
53	1.782	1.829	1.873	1.916	1.958	1.997	2.036	2.073	2.108	2.145	2.176	2.208	2.239	2.269	2.298	2.325	2.352	2.379	2.404	2.428	2.452	2.475	2.497	2.519	2.540	2.560
54	1.652	1.698	1.743	1.786	1.827	1.867	1.905	1.942	1.978	2.012	2.045	2.077	2.108	2.138	2.167	2.195	2.222	2.248	2.273	2.298	2.321	2.344	2.367	2.388	2.409	2.429
55	1.528	1.574	1.619	1.662	1.703	1.745	1.782	1.819	1.854	1.889	1.922	1.954	1.985	2.014	2.045	2.071	2.098	2.124	2.150	2.174	2.198	2.221	2.243	2.265	2.285	2.306
56	1.411	1.457	1.502	1.545	1.586	1.626	1.665	1.702	1.737	1.772	1.805	1.857	1.868	1.897	1.926	1.954	1.981	2.007	2.033	2.057	2.081	2.104	2.126	2.148	2.168	2.189
57	1.300	1.347	1.391	1.434	1.476	1.515	1.554	1.591	1.626	1.661	1.694	1.726	1.757	1.787	1.815	1.843	1.870	1.896	1.922	1.946	1.970	1.995	2.015	2.037	2.058	2.078
58	1.195	1.241	1.286	1.329	1.370	1.410	1.448	1.485	1.521	1.555	1.589	1.621	1.651	1.681	1.710	1.738	1.765	1.791	1.816	1.841	1.865	1.888	1.910	1.931	1.952	1.973
59	1.095	1.141	1.186	1.229	1.270	1.310	1.349	1.386	1.421	1.456	1.489	1.521	1.552	1.581	1.610	1.638	1.665	1.691	1.717	1.741	1.765	1.788	1.810	1.832	1.852	1.873
60	1.000	1.046	1.091	1.134	1.175	1.215	1.254	1.291	1.326	1.361	1.394	1.426	1.457	1.486	1.515	1.543	1.570	1.596	1.622	1.646	1.670	1.693	1.715	1.737	1.757	1.778
61	0.910	0.956	1.001	1.044	1.085	1.125	1.165	1.200	1.236	1.270	1.305	1.335	1.366	1.396	1.425	1.453	1.480	1.506	1.531	1.556	1.579	1.602	1.625	1.646	1.667	1.687
62	0.824	0.870	0.915	0.958	0.999	1.039	1.077	1.114	1.150	1.184	1.217	1.249	1.280	1.310	1.339	1.367	1.394	1.420	1.445	1.470	1.493	1.516	1.539	1.560	1.581	1.601
63	0.742	0.788	0.833	0.876	0.917	0.957	0.995	1.032	1.068	1.102	1.135	1.167	1.198	1.228	1.257	1.285	1.312	1.338	1.363	1.388	1.411	1.434	1.457	1.478	1.499	1.520
64	0.664	0.710	0.755	0.798	0.839	0.879	0.917	0.954	0.990	1.024	1.057	1.089	1.120	1.150	1.179	1.207	1.234	1.260	1.285	1.310	1.333	1.356	1.379	1.400	1.421	1.441
65	0.589	0.636	0.680	0.723	0.765	0.804	0.843	0.880	0.915	0.950	0.983	1.015	1.046	1.076	1.104	1.132	1.159	1.185	1.211	1.235	1.259	1.282	1.304	1.326	1.347	1.367
66	0.518	0.564	0.609	0.652	0.693	0.733	0.772	0.808	0.844	0.878	0.912	0.944	0.975	1.004	1.033	1.061	1.088	1.114	1.139	1.164	1.188	1.211	1.233	1.254	1.275	1.296
67	0.450	0.496	0.541	0.584	0.625	0.665	0.704	0.740	0.776	0.810	0.844	0.876	0.906	0.936	0.965	0.993	1.020	1.046	1.071	1.096	1.120	1.143	1.165	1.186	1.207	1.228
68	0.385	0.431	0.476	0.519	0.560	0.600	0.638	0.675	0.711	0.745	0.779	0.811	0.841	0.871	0.900	0.928	0.955	0.981	1.006	1.031	1.055	1.078	1.100	1.121	1.142	1.163
69	0.323	0.369	0.414	0.457	0.498	0.538	0.576	0.613	0.649	0.683	0.716	0.748	0.779	0.809	0.838	0.866	0.893	0.919	0.944	0.969	0.992	1.015	1.038	1.059	1.080	1.100
70	0.263	0.310	0.354	0.397	0.439	0.478	0.517	0.554	0.589	0.624	0.657	0.689	0.720	0.749	0.778	0.806	0.833	0.859	0.885	0.909	0.933	0.956	0.978	1.000	1.021	1.041
71	0.206	0.252	0.297	0.340	0.381	0.421	0.460	0.497	0.532	0.566	0.600	0.632	0.663	0.692	0.721	0.749	0.776	0.802	0.828	0.852	0.876	0.899	0.921	0.943	0.963	0.984
72	0.151	0.198	0.242	0.285	0.327	0.367	0.405	0.442	0.477	0.512	0.545	0.577	0.608	0.638	0.667	0.694	0.721	0.748	0.773	0.797	0.821	0.844	0.866	0.888	0.909	0.929
73	0.099	0.145	0.190	0.233	0.274	0.314	0.352	0.389	0.425	0.459	0.492	0.524	0.555	0.585	0.614	0.642	0.669	0.695	0.720	0.745	0.768	0.791	0.814	0.835	0.856	0.877
74	0.048	0.095	0.140	0.182	0.224	0.264	0.302	0.339	0.375	0.409	0.442	0.474	0.505	0.535	0.564	0.592	0.619	0.645	0.670	0.694	0.718	0.741	0.763	0.785	0.806	0.826
75	—	0.046	0.091	0.134	0.175	0.215	0.254	0.291	0.326	0.361	0.394	0.426	0.457	0.486	0.515	0.543	0.570	0.596	0.622	0.646	0.670	0.693	0.715	0.737	0.757	0.778
76	—	—	0.045	0.088	0.129	0.169	0.207	0.244	0.280	0.314	0.347	0.379	0.410	0.440	0.469	0.497	0.524	0.550	0.575	0.600	0.623	0.646	0.668	0.690	0.711	0.731
77	—	—	—	0.045	0.084	0.124	0.162	0.199	0.235	0.269	0.303	0.335	0.365	0.395	0.424	0.452	0.479	0.505	0.530	0.555	0.579	0.602	0.624	0.645	0.666	0.687
78	—	—	—	—	0.041	0.081	0.119	0.156	0.192	0.226	0.260	0.292	0.322	0.352	0.381	0.409	0.436	0.462	0.487	0.512	0.536	0.559	0.581	0.602	0.623	0.644
79	—	—	—	—	—	0.040	0.078	0.115	0.151	0.185	0.218	0.250	0.281	0.311	0.340	0.368	0.395	0.421	0.446	0.471	0.494	0.517	0.539	0.561	0.582	0.602
80	—	—	—	—	—	—	0.038	0.075	0.111	0.145	0.178	0.210	0.241	0.271	0.300	0.328	0.355	0.381	0.406	0.431	0.454	0.477	0.500	0.521	0.542	0.563
81	—	—	—	—	—	—	—	0.037	0.073	0.107	0.140	0.172	0.203	0.233	0.262	0.290	0.317	0.343	0.368	0.392	0.416	0.439	0.461	0.483	0.504	0.524
82	—	—	—	—	—	—	—	—	0.036	0.070	0.103	0.135	0.166	0.196	0.225	0.253	0.280	0.306	0.331	0.355	0.378	0.402	0.424	0.446	0.467	0.487
83	—	—	—	—	—	—	—	—	—	0.034	0.068	0.100	0.130	0.160	0.189	0.217	0.244	0.270	0.295	0.320	0.344	0.367	0.389	0.410	0.431	0.452
84	—	—	—	—	—	—	—	—	—	—	0.033	0.065	0.096	0.126	0.155	0.183	0.210	0.236	0.261	0.285	0.309	0.332	0.354	0.376	0.397	0.417
85	—	—	—	—	—	—	—	—	—	—	—	0.032	0.063	0.093	0.122	0.150	0.176	0.203	0.228	0.252	0.276	0.299	0.321	0.343	0.364	0.384
86	—	—	—	—	—	—	—	—	—	—	—	—	0.031	0.061	0.090	0.118	0.144	0.171	0.196	0.220	0.244	0.267	0.289	0.311	0.332	0.352
87	—	—	—	—	—	—	—	—	—	—	—	—	—	0.030	0.059	0.087	0.114	0.140	0.165	0.189	0.213	0.236	0.258	0.280	0.301	0.321
88	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.029	0.057	0.084	0.110	0.135	0.160	0.183	0.206	0.229	0.250	0.271	0.291
89	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.028	0.055	0.081	0.106	0.131	0.154	0.177	0.200	0.221	0.242	0.262
90	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.027	0.053	0.078	0.103	0.127	0.149	0.172	0.193	0.214	0.235
91	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.026	0.051	0.076	0.100	0.123	0.145	0.166	0.187	0.208
92	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.025	0.050	0.073	0.096	0.119	0.140	0.161	0.181
93	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.024	0.048	0.071	0.093	0.115	0.136	0.156
94	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.024	0.047	0.069	0.091	0.111	0.132
95	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.023	0.045	0.067	0.088	0.108
96	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.022	0.044	0.065	0.085
97	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.022	0.043	0.063
98	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.021	0.041
99	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.020

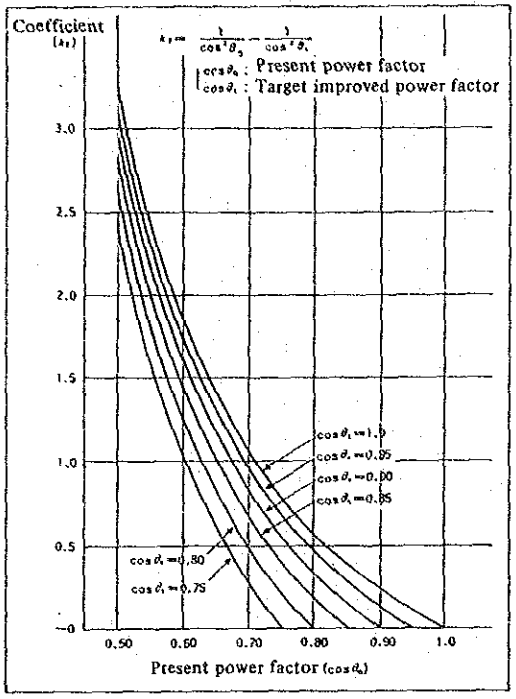


Fig. III–8–4 Coefficient (k_1)

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 III-8-2.

Table III–8–2 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 ($\cos\theta_0$)	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)	m 500	0.60	131 A	87.3 A	82.7 A	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

Note: 1. $\cos\theta_1$ in the table indicates power factor after improvement.

2. Reduction of loss (PL) is determined by equation (7). However, coefficient, k_1 has the following values from Table III-8-1.

$\cos\theta_0$	$\cos\theta_1$	k_1
0.60	0.90	1.543
	0.95	1,670
0.70	0.90	0.806
	0.95	0.933

(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. III-8-5 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.

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

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

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

Where,

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

Coefficient, k_1 is determined by Table III-8-1 or Fig. III-8-4 as shown above.

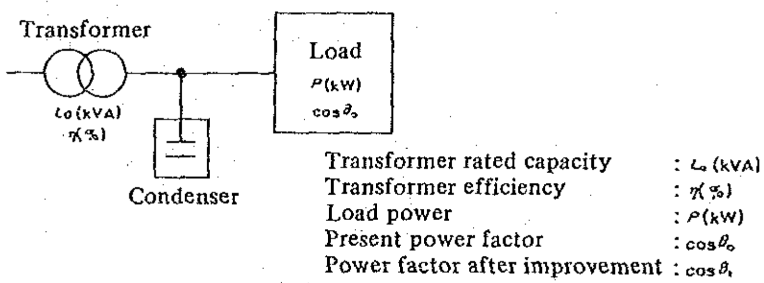


Fig. III–8–5 Reduction effect of transformer loss

Also, k_2 is determined from Table III-8-3 or Fig. III-8-6 by investigating transformer efficiency η, load power P, rated capacity of transformer L_0.

Table III–8–3 Coefficient k_2

$\frac{P}{L_o}$	Transformer efficiency η (%)											
	96.75	97.0	97.25	97.50	97.75	98.0	98.25	98.50	98.75	99.0	99.25	99.50
	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$	$\times10^{-3}$
0.40	4.30	3.96	3.62	3.28	2.95	2.61	2.28	1.95	1.62	1.29	0.97	0.64
0.45	5.44	5.01	4.58	4.15	3.73	3.31	2.89	2.47	2.05	1.64	1.22	0.81
0.50	6.72	6.19	5.66	5.13	4.60	4.08	3.56	3.05	2.53	2.02	1.51	1.01
0.55	8.13	7.49	6.84	6.21	5.57	4.94	4.31	3.69	3.06	2.44	1.83	1.22
0.60	9.67	8.91	8.14	7.39	6.63	5.88	5.13	4.39	3.65	2.91	2.18	1.45
0.65	11.35	10.45	9.56	8.67	7.78	6.90	6.02	5.15	4.28	3.41	2.55	1.70
0.70	13.17	12.12	11.09	10.05	9.02	8.00	6.98	5.97	4.96	3.96	2.96	1.97
0.75	15.12	13.92	12.73	11.54	10.36	9.18	8.02	6.85	5.70	4.55	3.40	2.26
0.80	17.20	15.84	14.48	13.13	11.79	10.45	9.12	7.80	6.48	5.17	3.87	2.57
0.85	19.42	17.88	16.34	14.82	13.30	11.80	10.30	8.80	7.32	5.84	4.37	2.91

Note 1: Calculated from $k_2 = (\frac{100}{\eta} - 1) \times \frac{4}{5} \times (\frac{P}{L_o})^2$

2: Assumed as full-load loss of transformer: copper loss = 1 : 0.8.

3: L_o : Transformer rated capacity (kVA) P : Load power (kW)

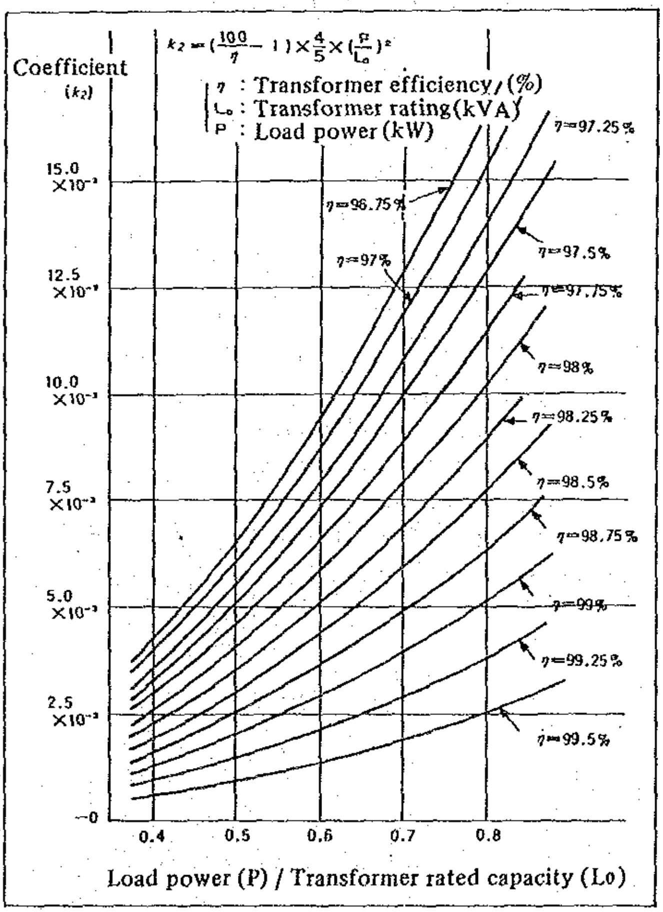


Fig. III–8–6 Coefficient (k_2)

B) Example of calculation

The calculation example of reduced transformer loss using preceding equation (14) is shown in Table III-8-4.

Table III–8–4 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

Note: 1. P : Load power (kW)
L_0: Transformer rated capacity (kVA)

2. Loss reduction (Pt) is determined from equation (14). However, coefficient, k_1 and k_2 have the following values from Table III–8–1 and Table III–8–3:

$\cos\theta_0$	$\cos\theta_1$	Coefficient k_1
0.60	0.90	1.543
	0.95	1,670
0.70	0.90	0.806
	0.95	0.933

P/L_0	Coefficient k_2		
	η = 98%	η = 98.5%	η = 99%
0.5	4.08×10^{-3}	3.05×10^{-3}	2.02×10^{-3}
0.6	5.88×10^{-3}	4.39×10^{-3}	2.91×10^{-3}
0.7	8.00×10^{-3}	5.97×10^{-3}	3.96×10^{-3}

(3) Effect by reducing bus voltage drop

A) Decreasing bus voltage drop and energy conservation

Since improving the power factor reduces the line current, voltage drop in the distribution line can be reduced, which is, to a large extent, energy conservation. That is, it is because the following various problems which occur, because of the voltage drop following operation of load, can be settled by improvement of the power factor.

a. Life of fluorescent and mercury lamps, etc. becomes short and the brightness lowers.

b. In electric heaters utilizing Joule heat, the operating efficiency lowers because heating capacity decreases in proportion to the square of the voltage.

c. In a constant load state, load current of induction motors increases, efficiency lowers and distribution line loss increases because motor torque decreases in proportion to the square of the voltage.

It should be noted that when more phase-advancing capacitors than required are operated in a light-load time zone such as on holidays, at night, etc., the bus voltage to the contrary rises excessively, thus resulting in shortened life of all electric equipments such as motors, lighting appliances as well as the capacitors themselves. Therefore, unnecessary capacitors must be released by means of an automatic control system, etc. as described later.

B) Equation

Voltage drop reduction value (namely, voltage buildup value) ΔV due to phase-advancing capacitors can be generally determined by the following equation:

$$\Delta V = \frac{Qc}{R.C.} \times 100(\%) \qquad (15)$$

Where R.C. : Short-circuit capacity of capacitor-connecting bus (kVA)

Q_c: Capacity of capacitor (kVA)

C) Example of calculation

Let us determine bus voltage buildup value ΔV, when 500 kVA phase-advancing capacitor is connected to a bus with short-circuit capacity of 125 MVA.

$$\Delta V = \frac{500\ (kVA)}{125 \times 10^3\ (kVA)} \times 100 = 0.4\ (\%)$$

(4) Increased surplus capacity for distribution equipment

Load on transformer and distribution equipment in distribution line through which line current passes in Fig. III-8-1 and Fig. III-8-2 will be less when the line current reduces due to the improved power factor. Namely, the equipment will have a margin in capacity. Therefore,

a. In the existing equipment, it is possible to increase the load without involving equipment expansion such as re-installation of the distribution line and increased transformer capacity,

b. For new equipment, cost can be saved because equipment with a smaller capacity is purchased.

How much load can be increased by improvement of the power factor in the existing distribution equipment varies with the power factor of the extension load in addition to the power factor before improvement ($\cos \theta_0$), and the power factor after improvement ($\cos \theta_1$).

For one thing, the ratio of extensible load capacity P_1 (kW), when the extension load power factor is identical with the load power factor after installation of the capacitor, to the existing load capacity P_0 (kW) is shown in Fig. III-8-7 Fig III-8-8 and Table III-8-5.

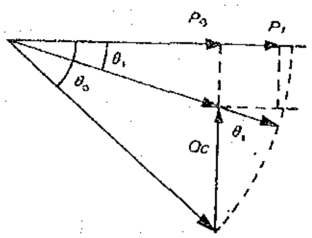


Fig. III–8–7
Increased surplus capacity for distribution equipment due to power factor improvement

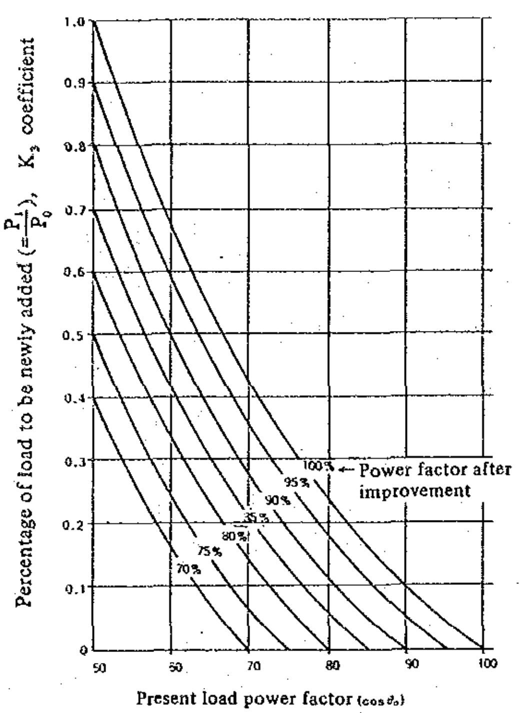


Fig. III–8–8

Table III–8–5 Coefficient K_3

Present power factor cos θ_0	Power factor after improvement cos θ_1						
	0.7	0.75	0.8	0.85	0.9	0.95	1.00
0.50	0.4	0.5	0.6	0.7	0.8	0.9	1
52	0.346	0.442	0.538	0.635	0.731	0.827	0.9231
54	0.296	0.389	0.481	0.574	0.667	0.759	0.8519
56	0.25	0.339	0.429	0.518	0.607	0.696	0.7857
58	0.207	0.293	0.379	0.466	0.552	0.638	0.7241
0.60	0.167	0.25	0.333	0.417	0.5	0.583	0.6667
62	0.129	0.210	0.290	0.371	0.452	0.532	0.6129
64	0.094	0.172	0.25	0.328	0.406	0.484	0.5625
66	0.061	0.136	0.212	0.288	0.364	0.439	0.5152
68	0.029	0.103	0.176	0.25	0.324	0.397	0.4706
0.70		0.071	0.143	0.214	0.286	0.357	0.4286
72		0.042	0.111	0.181	0.25	0.319	0.3889
74		0.014	0.081	0.149	0.216	0.284	0.3514
76			0.053	0.118	0.184	0.25	0.3158
78			0.026	0.090	0.154	0.218	0.2821
0.80				0.063	0.125	0.188	0.25
82				0.037	0.098	0.159	0.2195
84				0.012	0.071	0.131	0.1905
86					0.047	0.105	0.1628
88					0.023	0.080	0.1364
0.90						0.056	0.1111
92							
94							
96							
98							

Assuming in Fig III-8-7,

$$k_3 = \frac{P_1}{P_0}$$

Then,

$$\frac{P_0}{\cos\theta_0} = \frac{P_0 + P_1}{\cos\theta_1} = \frac{P_0 + k_3 \cdot P_0}{\cos\theta_1}$$

Hence,

$$P_0 (1 + k_3) = P_0 \cdot \frac{\cos\theta_1}{\cos\theta_0}$$

$$\therefore k_3 = \frac{\cos\theta_1}{\cos\theta_0} - 1 \quad \text{.......} \quad (16)$$

Example:

When a 100 kW load at a power factor of 70% is improved to 95% of the power factor, k = 0.36% from Fig III-8-8. That is, a load of 100 kW × 0.36 = 36 kW (power factor 95%) can be increased with the present equipment as it is.

(5) Reduced electric charge

At present, users who are receiving electric power from MEA must pay a penalty of 15Bt per kVAR when the maximum reactive power exceeds 63% of the maximum power. If the maximum power and the maximum reactive power appear at the same time, this is equivalent to about 85% of the power factor. Accordingly, improving the power factor in low power factor factories reduces the electric charge.

We have described effects due to installation of capacitors in above items (1) to (5) and will describe problems on selection of capacitor connection and automatic switching control below.

(6) Selection of capacitor connection

A) Connection and effect

There are many points to be considered when connecting a phase-advancing capacitor as shown in Fig. III-8-9.

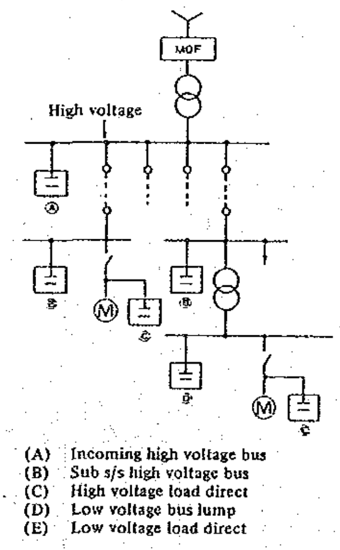


Fig. III–8–9 Connection points of phase advancing condenser

a. Receiving power factor improvement effects

This has almost nothing to do with the connecting point of phase-advancing capacitor.

b. Required capacitor capacity

Generally, since more phase-advancing capacitors are dispersed, the smaller their use ration (operating time) will be, the total capacity of required capacitors will be the larger. In Fig. III-8-9, when capacitors are centralized to (A), a required capacitor capacity may be calculated for all the leveled load in the compound, while when dispersed to (B) to (E), a capacitor capacity to meet load for a restricted area must be calculated.

c. Reduction effect of power loss

It is needless to say that the closer a capacitor is installed to the end of the distribution line, the greater the effect will be and, the longer the line length is, the greater the effect will be.

d. Increased equipment surplus capacity

Increased equipment surplus capacity due to installation of a phase-advancing capacitor takes place in the distribution line, cable and transformer inserted in a series between the capacitor connection and the receiving end. Therefore, the closer the capacitor is connected to the end, the greater the effect will be. However, even if the surplus capacity is increased, for example, it is no worse if there is no space to expand or no planning to increase load in the future.

It is necessary to widely consider this.

e. Reduction effect of voltage drop

Since reduction effect of voltage drop due to a phase-advancing capacitor is determined by power source impedance viewed from the connecting point, the effect will be larger when it is connected at the end.

The foregoing items are summarized in Table III-8-6.

Table III–8–6 Comparison between collective installation of power receiving station and decentralized installation of ends

Item	Collective installation of power receiving stations	Decentralized installation of ends
Reduction effect of basic charge	(the same)	(the same)
Total capacity of required condenser	Minimum	Generally maximum
Loss reduction effect of distribution line and transformer	Small	Large
Reduction effect of voltage drop	Small	Large
Maintenance and inspection	Simple	Troublesome
Initial cost	Small	Generally, large (especially for low voltage)

B) Determination of capacitor connection

To obtain the maximum energy conservation effect, phase-advancing capacitors should be connected to the end of all of them. However, taking into consideration other conditions such as investment effect, etc., the practical way to determine is as follows.

a. Directly connect to a load with comparatively large capacity (See Fig. III-8-9, (C), (E)).

b. Collectively install at concurrence load (See Fig. III-8-9, (B), (D)).

c. Connect the capacitor for improving receiving power factor to the receiving high voltage bus (Fig. III-8-9, (A)).

The above methods are considered and should be determined according to each user's conditions on a basis of this information.

(7) Automatic switching control of capacitors

Operating unnecessary capacitors causes the distribution line and transformer losses due to capacitor current in addition to the difficulty due to rises in the bus voltage, thus nullifying the energy conservation effect. Therefore, a switcing control will be required. Especially since capacitors installed at the end of the factory are considered difficult to control manually, it is recommended to use an automatic switching control. The automatic switching control mainly has the following four systems:

a. System to switch synchronizing to load on-off signal

b. System to switch according to increase or decrease in load current (Current control)

c. System to switch according to increase or decrease in line reactive power (Reactive power control)

d. System to switch by means of a time switch (Programmed control)

It is necessary to select a suitable system according to the load fluctuation pattern. One example of selection is shown in Fig. III-8-10.

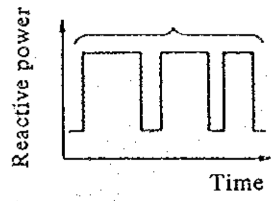
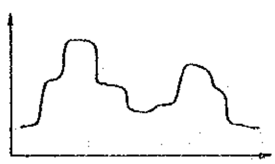
Load fluctuation pattern	(Same every day) 	(Changes every day) 
Applied control system	Reactive power control Current control Program control	Reactive power control

Fig. III–8–10

8.1.3 Improved load factor

Sinc the load factor is defined as shown in equation (17), it is important for improving load factor to restrain the maximum power in such a manner not to concentrate production in a specified time zone through appropriate factory management or through operation control.

$$\text{Load factor} = \frac{\text{Mean power (kW)}}{\text{Maximum power (kW)}} \times 100\ (\%) \quad \cdots\cdots (17)$$

Improving the load factor provides the following advantages:

(1) Since capacity for the receiving and distribution equipments, etc. can be effectively utilized, the equipment investment can be saved.

(2) It is possible to know operating conditions of the factory and machine equipments and to eliminate waste by checking the load curve and load factor.

(3) It is possible to reduce the contract demand and charge by lowering the maximum power.

When the maximum power is likely to exceed the contract demand after lowering it, a demand controller may be required. The demand controller usually consists of a monitor portion and a control portion; the monitor portion receives metering pulse from a watt hour meter and performs operations and judgements required for demand control, it also displays the present demand value and predicted demand value, and it performs alarm, control instructions and recording, etc. The control portion receives instruction from the monitor portion and stops and returns the predetermined load.

8.2 Transformers

For transformer energy conservation, it is necessary to pay attention to the following:

(1) Transformer efficiency

(2) When there are two or more transformers, operation with an efficient number of transformers.

(3) Selection of transformer taps

8.2.1 Selection of transformers

(1) Transformer efficiency is expressed by the following equation:

$$\eta = \frac{n\,p\,\cos\phi}{n\,p\cos\phi + W_i + n^2 W_c} \times 100\ (\%) \quad \cdots\cdots (1)$$

Where η: Efficiency (%)

n: Load factor

p: Rated capacity (kVA)

cos ϕ: Power factor

W_i: Iron loss

W_c: Copper loss

Although a transformer has dielectric and stray-load losses, in addition to the above iron and copper losses, they are difficult to measure and are minute, and as such will be ignored. Also, the ratio of copper loss W_c to iron loss W_i at rated load is called "Loss ratio α".

$$\alpha = \frac{W_c}{W_i} \quad \cdots\cdots (2)$$

The loss ratio is generally 2 to 5 as shown in Table III-8-7. However, it may exceed 10 in the energy conservation type transformers as described later.

Table III–8–7 Efficiency of 3 phase high voltage medium capacity transformer

Primary 6.6/3.3 kV, Secondary 400/200 V

	Company A				Company B			
	Efficiency (%)	Iron loss (kW)	Copper loss (kW)	Loss ratio	Efficiency (%)	Iron lossq (kW)	Copper loss (kW)	Loss ratio
300	98.2	0.9	4.6	5.1	97.9	2.2	4.2	1.9
500	98.27	1.3	7.5	5.8	98.1	2.7	7.0	2.6
750	98.36	2.0	10.5	5.3	98.2	3.2	10.6	3.3
1,000	98.52	2.5	12.5	5.0	98.2	3.5	14.8	4.2
1,500	98.62	4.5	16.5	3.7	–	–	–	–
2,000	98.69	6.0	20.5	3.4	98.3	7.3	27.3	3.7

From equation (1), the transformer efficiency is at maximum when $n = \sqrt{W_i/W_c}$, namely, output when the iron loss is equal to the copper loss at this point. One example of change in efficiency against output is illustrated in Fig. III-8-11.

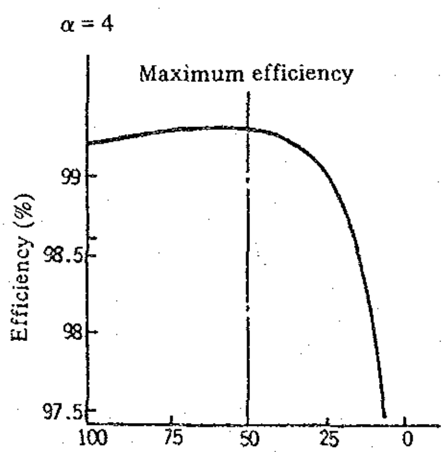


Fig. III–8–11 Transformer efficiency (Example)

Also, the transformer efficiency varies with the load power factor in equation (1) and lowering the power factor reduces the efficiency.

This example is shown in Fig. III-8-12.

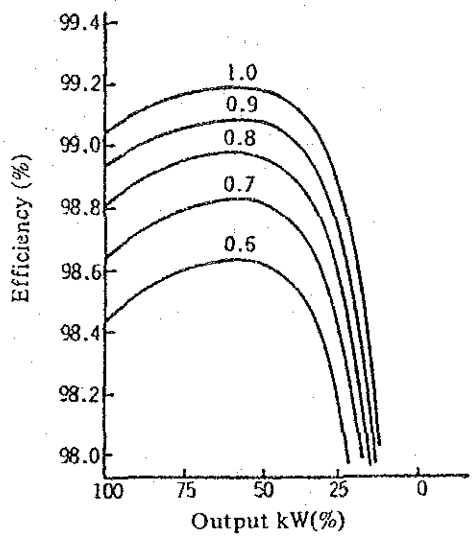
(2) All day efficiency of transformers

Although it is of course important to purchase and operate transformers considering the transformer maximum efficiency point, daily efficiency also must not be neglected because the transformer load varies every hour. Equation (3) is called "all day efficiency".

All day efficiency =

$$\frac{\text{Output energy per day (kWH)} \times 100\%}{\text{Output energy per day (kWh)} + \text{Loss energy per day (kWh)}} \quad \cdots\cdots (3)$$

If the daily pattern for load fluctuation is almost the same, it would be better to operate transformers so that the all day efficiency is better.



Note: Figure indicates power factor.

Fig. III–8–12 Relation between power factor and efficiency

(3) Energy conservation type transformers

Since conventional transformers use silicon steel plate for the core material and are of laminated core construction, the iron loss is 0.5 to 0.3%.

Recently, some transformers improved by using silicon steel belt (cold rolling plate) for the core material and by changing to wound core construction are manufactured. They are called conservation type transformers with the iron loss approximately 1/2 that of the conventional types. Anybody purchasing transformers had better keep above for future reference.

Table III-8-8 shows the comparison between conventional and energy conservation types.

8.2.2 Efficient operation of transformers

(1) Stopping of light-load transformers

Generally speaking, when there are two or more transformers and each of them has a low load factor, electric power can be saved by stopping low load factor transformers to integrate the load. However, in some cases, loss of transformers with increased load may exceed reduced loss of stopped transformers, causing an adverse effect. Therefore, it is always necessary to confirm by calculating, as shown in the following example.

(Example) When there are two 500 kVA transformers

In the case where each transformer has a load factor of 40% as shown in Fig. III-8-13, we will calculate the merit for when one transformer is stopped. We presume the transformer's characteristics to be of company A, specified in Table III-8-7.

Table III–8–8 Improvement example of transformer no-load loss (a certain manufacturer, 50 Hz)

Rated capacity (kVA)	Conventional type		Energy conservation type	
	Power loss (W)	Power loss / Rated capacity (%)	Power loss (W)	Power loss / Rated capacity (%)
500	2,200	0.44	1,100	0.22
300	1,500	0.50	700	0.23
200	1,200	0.60	600	0.30
150	500	0.33	420	0.28
100	400	0.40	350	0.35
75	350	0.47	300	0.40

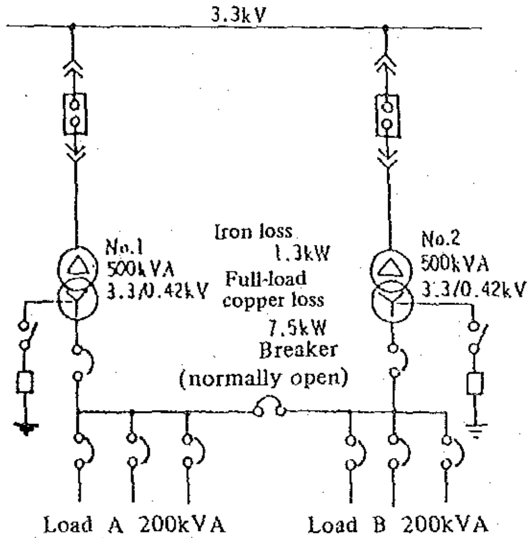


Fig. III–8-13

At present, for both transformer No.1 and transformer No.2,

Iron loss = 1.3 (kW)

$$\text{Copper loss} = \text{Full-load} \times \left(\frac{\text{Load factor}}{100}\right)^2 = 7.5 \times \left(\frac{40}{100}\right)^2 = 1.2\ (\text{kW})$$

Hence,

Total loss = 2 (1.3 + 1.2) = 5 (kW)

After stop of transformer No.1,

Iron loss of transformer No.2 = 1.3 (kW)

$$\text{Copper loss of transformer No. 2} = \text{Full-load} \times \left(\frac{\text{Load factor}}{100}\right)^2$$

$$= 7.5 \times \left(\frac{80}{100}\right)^2 = 4.8\ (\text{kW})$$

Total loss = 1.3 + 4.8 = 6.1 (kW)

Stopping one transformer increases the loss by 1.1 kW.

(2) Stopping of transformers at night and on holidays

In equipment and factories where operation is not performed at night and on holidays, the electric power can be saved by concentrating only loads for which electricity supply cannot be stopped even at night and on holidays, to certain transformers and stopping unnecessary transformers. However, when there is not much difference in electric power between the daytime and at night, there is no merit.

(3) Control of the number of transformers

When transformers with the same rating are operated in parallel, the total loss can be reduced by increasing or decreasing the number of transformers.

Overall loss when N units of transformers are operated in parallel is expressed by the following equation:

$$W_N = N\{W_i + (\frac{P_L}{N_Q})^2 W_c\}\ (kW)$$

Where W_N: Overall loss (kW)

W_i: Iron loss of one transformer (kW)

W_c: Copper loss of one transformer (kW)

P_L: Load capacity (kVA)

N: Number of transformers

Q: Capacity of one transformer (kVA)

Overall loss when (N-1) units of transformers are operated in parallel is expressed by the following equation:

$$W_{(N-1)} = (N-1)\{W_i + (\frac{P_L}{(N-1)Q})^2 W_c\}\ (kW)$$

Conditions at which parallel operation of (N-1) units of transformers has a smaller loss than N units is $W_N > W_{(N-1)}$. Therefore, P_L is expressed by the following equation:

$$P_L < \sqrt{\frac{N(N-1)}{\alpha}} \times Q\ (kVA)$$

Where,

$$\alpha = \frac{W_c}{W_i}$$

α: Loss ratio

For example, when three 500 kVA transformers whose α being 3 are operated

$$\sqrt{\frac{N(N-1)}{\alpha}} \times Q = \sqrt{\frac{3 \times 2}{3}} \times 500 = 707\ kVA$$

That is, when the load is 707 kVA or below, the energy can be saved by reducing one of the operated transformers to two units. Similar calculation with value of α varied is shown in Table III-8-9.

Table III–8–9 Number of operating transformers required to get minimum loss when transformers (same capacity and characteristics) are connected in parallel.

Threshold load (%) \ Number of transformers \ Loss ratio	α = 2		α = 3		α = 4		α = 5	
	2	3	2	3	2	3	2	3
Two and one unit	100	–	81	–	70	–	63	–
Three and two units	–	173	–	141	–	122	–	109

(Example) : When 3 transformers (same capacity) of loss ratio of 3 are operated in parallel, operation of 2 units is less in loss if total load is less than 141% of transformer capacity (1 unit) and operation of a single unit is less in loss if the total load is less than 81%.

8.2.3 Selection of transformer taps

Low-voltage transformers or main power lines have many loads and it is not easy to supply the voltage close to the rating of each load. However, it is important to optimize the transformer taps and endeavour to get as close as possible. Observing how motors are being operated in factories, full-load operations are few and 50% to 80% of the load is generally seen.

Relation between voltage fluctuation and load state of an induction motor is as shown in Table III-8-10 and Table III-8-11. When all loads for the transformer are motors, it is desirable to select the taps in the light of these.

Table III–8–10 Effect of voltage fluctuation on induction motor

	Voltage fluctuation	
	90% Voltage	110% Voltage
Starting torque, Maximum torque	–19%	+21%
Synchronous speed	Remain unchanged	Remain unchanged
% Slip	+23%	–17%
Full-load speed	–15%	+1%
Efficiency (Full-load)	–2%	Slightly increased
Power factor (Full-load)	+1%	–3%
Full-load current	+11%	–7%
Starting current	–10 ~ –12%	+10 ~ +12%
Full-load temperature rise	+6 ~ +7°C	–1 ~ –2°C
Magnetic noise	Slightly decreased	Slightly increased

Table III-8-11 Relation between voltage fluctuation and loading state of induction motor

		Voltage fluctuation	
		90% Voltage	110% Voltage
Efficiency	Full load	–2%	Slightly increased
	¾ Load	Remain unchanged	Remain unchanged
	½ Load	+1 ~ +2%	–1 ~ –2%
Power factor	Full load	+1%	–3%
	¾ Load	+2 ~ +3%	–4%
	½ Load	+4 ~ +5%	–5 ~ –6%

8.3 Motors

For motor energy conservation, the countermeasures are mainly classified into the following two cases:

(1) In the case of energy conservation by newly establishing or by greatly remodelling load and motor equipments.

(2) In the case of energy conservation by intensifying the management aspect of the existing equipment or by remodelling in a small scale.

Each of these will be discussed below:

8.3.1 In the case of newly establishing load and motor equipments

Although it applies not only to motor application equipment but also to general equipment, it can be stated that the amount of energy used may be determined to a certain degree at the equipment planning stage. If the equipment capacity is too big or unfit for the load equipment, the energy cannot be used in a rational manner. Matters which should be considered at the planning or introducing stage of newly-establishing equipment are described as follows:

(1) Basic expressions relating to motor-driven force applications

Basic expressions which must first be understood when condidering the motor energy conservation are shown in Table III-8-12. For reasons of space, the description is omitted, but see the technical books for reference.

(2) Load condition in the selection of motors

To select an optimum motor, it is necessary to know the load condition.

How a motor must be under various conditions of load, or what to be the allowable conditions are summarized in Fig. III-8-13. When the conditions shown here are clear, it is possible to select the motor and also to select the control equipment to follow it.

Although motor systems are classified into DC, induction and synchronous machines in Fig. III-8-13, induction and synchronous machines here are considered to be constant-speed drive systems for commercial power source. A thyristor motor applied to a synchronous machine and a frequency control method applied to an induction machine belong to the DC machines for system.

Main items for selection of motors are described following item (3):

Table III–8–12 Basic and practical expressions relating to motor application

Formulation / Item	Basic expression	Practical expression	Description of symbols
1 Power and torque	$P = \omega T$	$Rk[kW] = P \times 10^{-3}$ $N[rpm] = \frac{60}{2\pi}\omega$ $Tg[kg-m] = \frac{T}{g} = \frac{T}{9.81}$ $Pk[kW] = \frac{N[rpm]}{973} \times Tg[kg\text{-}m]$	P : Power (watt) Pk: Power (Kilo watt) T : Torque (N-m) Tg: Torque (Gravity unit Kg-m) W : Angular velocity (rad/sec) N : Rotating speed (rpm)
2 Moment of inertia and acceleration torque	$J\frac{d\omega}{dt} = T$	$GD^2 = 4J$ $Tg[kg\text{-}m] = \frac{1}{375} GD^2 \cdot \frac{dN}{dt}$	J : Moment of inertia (kg m^2) GD^2 : Flywheel effect
3 Acceleration time	$t = \int_0^{\omega_0} \frac{J}{Ta} d\omega [sec]$	$\overline{Ta} = \frac{\int_0^{\omega_0} Ta(\omega)}{\omega 0} d\omega$: $ta[sec] = \frac{1}{375} \frac{GD^2 N_0^2 [rpm]}{P[W]}$	t : Time required for acceleration (sec) ta : Time required for completion of acceleration (sec) Ta: Acceleration torque (Kg-m) $\overline{Ta}$: Mean acceleration torque (Kg-m)

Table III-8-13 Conditions for motor selection

<table>
<tr><th colspan="2" rowspan="2">Conditions of load</th><th colspan="3">Motor system</th></tr>
<tr><th>DC machine</th><th>Induction machine</th><th>Synchronous machine</th></tr>
<tr><td rowspan="3">Starting conditions</td><td>Necessary frequency for starting</td><td></td><td colspan="2">Study heat capacity of motor</td></tr>
<tr><td>Necessary starting torque
• Moment of inertia of load
• Possibility of no-load starting</td><td>Application of series motor</td><td colspan="2">Application of wound-rotor type IM
Study starting current and time according to the above items</td></tr>
<tr><td>Necessity of smooth starting</td><td>Acceleration restriction</td><td>Reactor starting, soft starter, etc.</td><td>Low frequency starting, etc.</td></tr>
<tr><td rowspan="3">Stop conditions</td><td>Necessity and its degree of emergency stop (quick stop)</td><td>Regeneration system, dynamic braking, etc.</td><td>Reversing-phase braking</td><td>Brake, etc.</td></tr>
<tr><td>Necessity of precise stop position</td><td>Position control</td><td colspan="2">Difficulty</td></tr>
<tr><td>Necessity of holding the stop position</td><td colspan="3">Presence of brake</td></tr>
<tr><td rowspan="3">Operating conditions</td><td>Necessity and its conditions of reverse rotation</td><td>Field switching
Armature switching</td><td colspan="2">Main circuit switching</td></tr>
<tr><td>Rating of load (Continuous, time)</td><td colspan="3">Possibility of reducing frame No. for hourly rating</td></tr>
<tr><td>Special function</td><td>Restriction is comparatively small.</td><td colspan="2">Restriction is large.</td></tr>
<tr><td rowspan="3">Speed control</td><td>Constant speed or variable speed?</td><td>For variable speed</td><td colspan="2">For constant speed
Variable speed in conjunction with control equipment</td></tr>
<tr><td>Speed control range</td><td>Scope of application is large.</td><td colspan="2">Study combination with control equipment.</td></tr>
<tr><td>Necessity of speed control</td><td>Suitable</td><td>Change by amount of slip</td><td>Synchronize with the power source frequency.</td></tr>
<tr><td rowspan="5">Ambient conditions, etc.</td><td>Temperature and humidity conditions</td><td colspan="3">Study motor construction.</td></tr>
<tr><td>Necessity of explosion-proof construction</td><td>Possible, but difficult</td><td colspan="2">Possible</td></tr>
<tr><td>Whether good atmosphere or not</td><td>Problem on brush commutator</td><td>Squirrel cage type is for improper circumstance.</td><td>Brushless exciting is possible.</td></tr>
<tr><td>Problem on personnel for maintenance</td><td>Maintenance is important.</td><td colspan="2">In the case of brushless, easy maintenance.</td></tr>
<tr><td>Power source condition</td><td>Problem on higher harmonics and power factor</td><td>Starting current large,
Delay power factor</td><td>Leading power factor is possible.</td></tr>
</table>

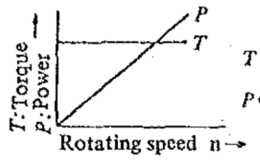
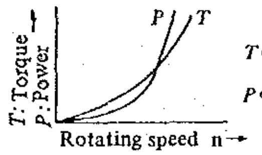
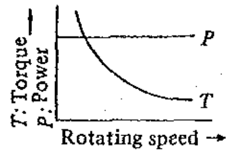
(3) Torque characteristics of load

Motors usually start in a load-coupled state from zero speed, accelerate to a specified speed and enter into a constant speed operation. Since the load has inherent torque characteristics, motors must generate a torque greater than that required by the load over all speed ranges.

Generally, when load and motors are more alike in torque characteristics, motors can be more economically designed.

As examples of typical torque-speed characteristics, there are three types. The first is constant-torque type in which the torque is constant in spite of the speed, the second is torque increasing type in which the torque is in proportion to the speed, its square or cube, and the third is constant-output type in which the necessary torque is in inverse proportion to the speed and torque multiplied by speed is constant. These relations are summarized in Table III-8-14.

Table III–8–14 Class of load and torque speed characteristic

Load characteristic			Typical load
Constant torque load		T = Constant $P \propto n$	Gravity load, Friction load [Example] Crane, Winding machine, Conveyor, Paper machine, Mixer
Increasing torque load		$T \propto n^2$ $P \propto n^3$	Fluid load [Example] Blower, Pump
Constant output load		$T \propto \frac{1}{n}$ P = Constant	Special load [Example] Winder, Constant cutting machine, Log barker

It is generally important in constant-speed motors such as three phase induction and synchronous motors whether starting torque and maximum torque are greater than the torque required by the load. It is also important in synchronous motors whether pull-in torque is greater than the torque required by the load.

(4) GD^2 of the load

The amount of the load GD^2 (Flywheel effect) is related to length of the starting time and the amount of the heating value during starting, so it is an important factor in the selection of motors.

Assuming the load torque as T_L (kg·m), the motor torque as T_M (kg·m) and the sum of the flywheel effect for the load and motor as GD^2 (kg·m²),

$$T_M = \frac{GD^2}{375} \cdot \frac{dN}{dt} + T_L \quad \cdots\cdots (1)$$

Accordingly, the starting time is

$$t = \int_0^{No} \frac{GD^2 \cdot dN}{375(T_M - T_L)} \text{(second)} \quad \cdots\cdots (2)$$

Where N_o: Rated speed

The needed time for starting is in direct proportion to GD^2. Since motors are unusually warmed when t is long, the allowable GD^2 of the load is determined for any motors. When GD^2 is great, on the contrary, it is necessary to select large motors fitting for it.

When GD^2 of motors: $G_1 D_1^2$, GD^2 of machines: $G_2 D_2^2$ and reduction ratio : $n_1 / n_2 = n$ as shown in Fig. III-8-14, GD^2 converted to the motor side is:

$$GD^2 = G_1 D_1^2 + \frac{1}{n^2} G_2 D_2^2 \quad \text{......} \quad (3)$$

This result is important because a reducer is, in most cases, used for industrial load.

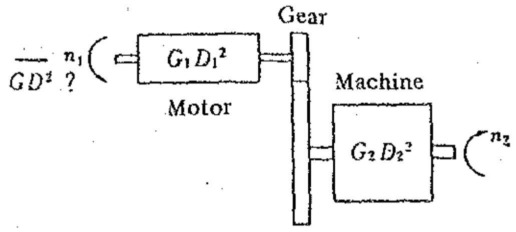


Fig. III–8–14 Conversion of flywheel effect

(5) Time characteristics of the load

Motors are used in various methods of use such as continuous, short-time and intermittent use, etc. and such hour application duty is called "Duty". When electrical machinery and apparatus are used under specified conditions for use, they are designed so that the allowable maximum temperature is not exceeded, and these conditions are called "Rating of machinery and apparatus".

For the ratings, there are rated output, rated rotating speed, rated voltage, rated current, rated frequency, etc., and for the duty, there are various classes such as continuous rating, short-time rating, periodic rating, etc.

A) Continuous rating

For 24 hour continuous operation, we select, of course, motor with a continuous rating. Generally, when continuously used for more than two or three hours, motors with continuous rating are mostly used because they are nearly the same in price. The motor, while continuously used, is heated from the inside due to copper and iron losses, etc., and at the same time cooled by radiant heat from the surface and operated at a balanced value between these two.

Assuming the heating value every second: Q, Difference between the motor and ambient temperature (temperature rise value): θ, Heating capacity of motor : C, Heat dissipation coefficient: A,

$$C \frac{d\theta}{dt} + A\theta = Q \quad \text{......} \quad (3)$$

Assuming $\theta = 0$ at $t = 0$,

$$\theta = \frac{Q}{A}(1 - \epsilon^{-\frac{t}{T}}) \quad \text{......} \quad (4)$$

Where, $T = \frac{C}{A}$

T in the above equation is called "Thermal time constant". If $t = \infty$ in equation (4), $\theta = Q/A$ and the final temperature rise is determined.

This is graphed in Fig. III-8-15. Also, the thermal time constant normally will be as shown in Table III-8-15. Next, when the motor is separated from the power source and stopped, substituting $Q = 0$ in equation (3) and $\theta = \theta_0$ at $t = 0$,

$$\theta = \theta_0 \epsilon^{-\frac{t}{T'}}$$

Where, $T' = \dfrac{C}{A'}$

T': Thermal time constant during cooling

A': Heat radiant coefficient during cooling

θ_0: Temperature when cooling starts. .

In separately-ventilated motors, the thermal time constant when stopped is the same as when operating because the amount of cooling air does not change even while stopped, but in self-ventilated motors it will be about three times that during operation.

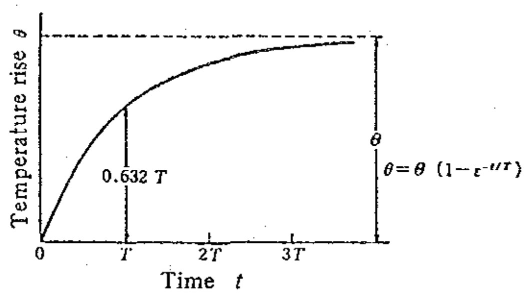


Fig. III–8–15 Temperature rise curve of motor

Table III–8–15 Example of thermal time constant

Type	Thermal time constant (minute)
Open type	20 ~ 40
Totally enclosed fan cooling type	50 ~ 150
Totally enclosed self cooling type	90 ~ 180

B) Short-time rating

There are 5, 10, 15, 30, 60, 120 minutes, etc. as a standard time in the short-time rating, among which the nearest one to the actual load condition should be selected.

C) Periodic rating

Periodic load means that load and rest period are periodically repeated, which is represented by a crane. For motors with crane, rated motors with % ED display are used (See Table III-8-17).

40% ED indicates a condition for use in which the motor is used at a rated capacity for four minutes in ten minutes.

D) Calculation of output by the root mean square method

Rated output of a motor is selected from the timely characteristics of the load, but when the load varies irregularly, it is rather difficult to determine the motor output.

However, when the load varies continuously and periodically, the root mean square method is often used as a simple output calculation method.

When the terminal voltage is constant in induction and DC shunt motors, the output is approximately in proportion to the load current. There are copper and iron losses as an exothermic source for motors and the copper loss is far greater than the iron loss. Also, since the copper loss is in proportion to the square of the load current, the loss in motor is almost in proportion to the square of the output.

Assuming the load current as I (t), and the output at this point as P(t),

$$\{I(t)\}^2R = k\{P(t)\}^2$$

Assuming that it takes time of $t_1, t_2, \ldots\ldots t_n$ for load of $P_1, P_2, \ldots\ldots P_n$ during one period T, the equivalent load as Pa

$$k\{P_1^2 t_1 + P_2^2 t_2 + \ldots + P_n{}^2 t_n\} = kP_a{}^2 \cdot T$$

Where, $T = t_1 + t_2 + \ldots + t_n$

$$\text{Hence, } P_a = \sqrt{\frac{P_1^2t_1 + P_2^2t_2 + \cdots\cdots + P_n{}^2t_n}{T}} \quad \ldots\ldots (6)$$

This P_a is an equivalent continuous load which gives out the same loss of load P which fluctuates periodically. In the case of an intermittent load, it is necessary to determine the equivalent load, taking into consideration generated heat and cooling during starting and stopping, since starting occurs very frequently.

For example, the equivalent load when a motor with a continuous rating is used for intermittent load as shown in Fig. III-8-16 is determined in the following way:

$$P_a = \sqrt{\frac{P_1^2t_1 + P_2^2t_2 + P_3t_3}{t_1\alpha_1 + A_2\alpha_2 + t_3\alpha_3 + t_4\alpha_4}} \quad \ldots\ldots (7)$$

However, α is heat extraction coefficient and its value is as shown in Table III-8-16.

Also,

$$T = t_1\alpha_1 + t_2\alpha_2 + t_3\alpha_3 + t_4\alpha_4$$

T shown in the above equation is an equivalent period, taking the heat extraction coefficient into consideration.

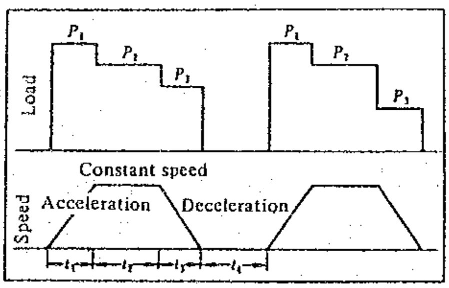


Fig. III–8–16 Example of periodic load

Table III-8-16 Example of cooling coefficient values

Type of motor	During stop	During acceleration	During operation	During deceleration
Open type AC motor	0.2	0.5	1	0.5
Enclosed type AC motor	0.3	0.6	1	0.6
Totally enclosed fan cooling type AC motor	0.5	0.75	1	0.75
Separately-cooling AC motor	1	1	1	1

E) Determination of motor capacity

When the rated output of motors are to be decided, it is oftenly determined by the maximum load. However, it should be determined by calculating the equivalent load as described in the preceding item.

For example, in continuous operation as shown in Fig. III-8-17,

$P_1 = 100$ kW $t_1 = 10$ minutes

$P_2 = 5$kW $t_2 = 15$ minutes

$P_3 = 80$ kW $t_3 = 10$ minutes

$P_4 = 50$ kW $t_4 = 20$ minutes

From equation (6), the required motor output P is

$$P = \sqrt{\frac{100^2 \times 10 + 50^2 \times 15 + 80^2 \times 10 + 50^2 \times 20}{10 + 15 + 10 + 20}} = 67.6 \text{ kW} \doteqdot 70 \text{ kW}$$

Accordingly, 75 kW should be selected for the motor. In this case, at the maximum load, 100/75 = 1.33 Namely, it will be 133% overload, but there will be no problem because the maximum torque of the motor is more than 200%. If the motor is selected at the maximum output of 100 kW, it will be a significant adverse factor for energy conservation.

When in a motor for crane periodically used as shown in Fig. III-8-18

$P_1 = 50$ kW 1.5 minutes

$P_2 = 30$ kW 1.5 minutes

$t_1 = 1.5 + 1.5 = 3$ minutes $t_2 = 7$ minutes,

the root mean square load in operation is

$$P = \sqrt{\frac{50^2 \times 1.5 + 30^2 \times 1.5}{3}} = 39.3 \text{ kW} \doteqdot 40 \text{ kW}$$

Accordingly, a motor corresponding to 40% ED 45 kW may be selected from Table III-8-17.

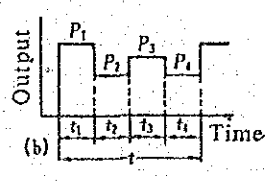


Fig. III-8-17

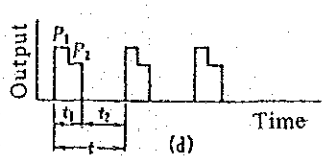


Fig. III-8-18

Table III–8–17 Frame number application table

Frame number \ Output (Load time factor)	15%ED kW	25%ED kW	40%ED kW	60%ED kW	100%ED kW	Number of pole
132 M	3	2.5	2.2	1.8	1.5	6
	5	4	3.7	3	2.8	6
160 M	7.5	6.3	5.5	4.5	4	6
	10	8.5	7.5	6.3	5.5	6
160 L	15	13	11	9	7.5	6
180 L	20	17	15	13	11	6
200 L	30	25	22	18.5	15	6
225 M	40	33	30	25	22	6
250 M	50	40	37	30	25	6
	63	50	45	37	33	6
280 M	75	63	55	45	37	8
315 M	100	85	75	63	50	8
	125	100	90	75	63	8
355 L	150	125	110	90	75	10
	185	150	132	110	90	10
400 L	220	185	160	132	110	10
	280	220	220	160	132	10

(6) Class, efficiency and power factor of motors

Let us compare the typical DC, induction and synchronous motors with induction motors mostly used in respect to efficiency and power factors.

A) DC and induction machines

Fig. III-8-19 shows the comparison in efficiency betwen DC and induction motors. As can be seen from the figure, the efficiency of the DC motor is 5 to 8% lower than the induction motor for small capacity machines 100 kW or less and 2 to 3% lower for 300 to 1000 kW. This DC motor, being of the separately-ventilated type, must be essentially evaluated including loss of the blower for cooling. Since, however, this value is omitted, the efficiency actually tends to lower further.

The DC motor is capable of operating in accordance with the load characteristic and also in easily controlling the speed or torque because it can be easily provided with various characteristics by means of excitation systems. On the other hand, the DC motor has the following defects; the efficiency is lower than AC motors such as induction and synchronous motors, etc.; it has difficulties in maintenance and in environment-proof because of a current collecting mechanism ; further, as shown in Fig. III-8-21, the output limit is two digits or more, lower than AC machines and not fit for large capacity with very high speed.

B) Synchronous and induction motors

Fig. III-8-22 shows the comparison in efficiency between synchronous and induction motors.

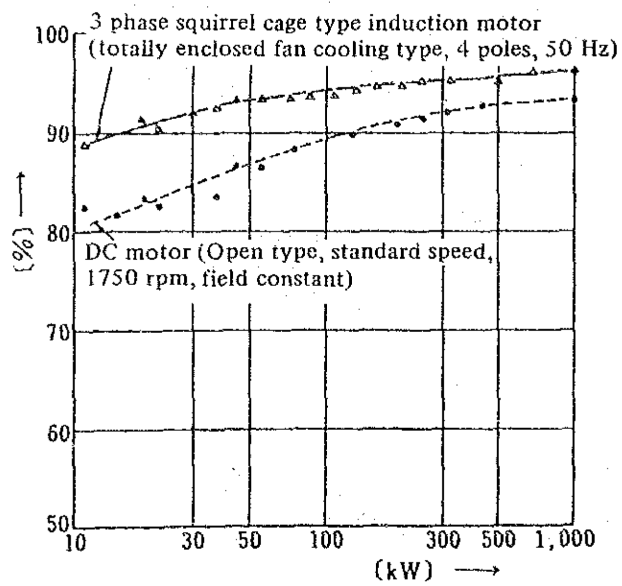


Fig. III–8–19
Comparative example of efficiency for induction and DC motors

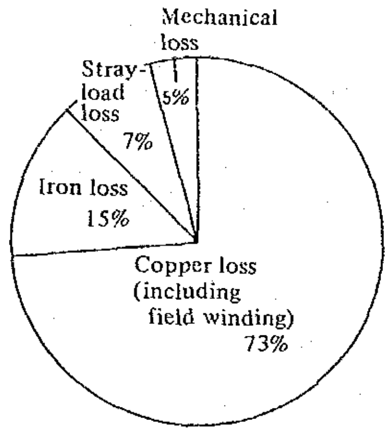


Fig. III–8–20
Analysis example of DC motor loss

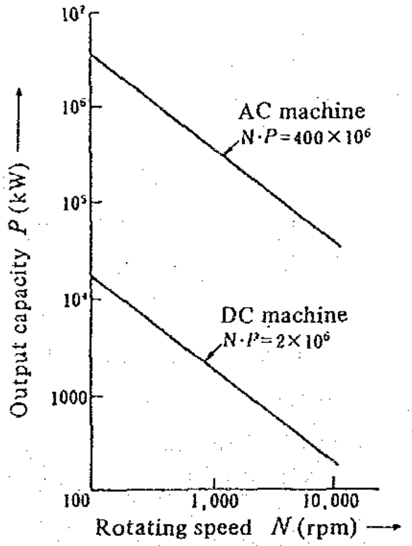


Fig. III–8–21
Marginal output of motor

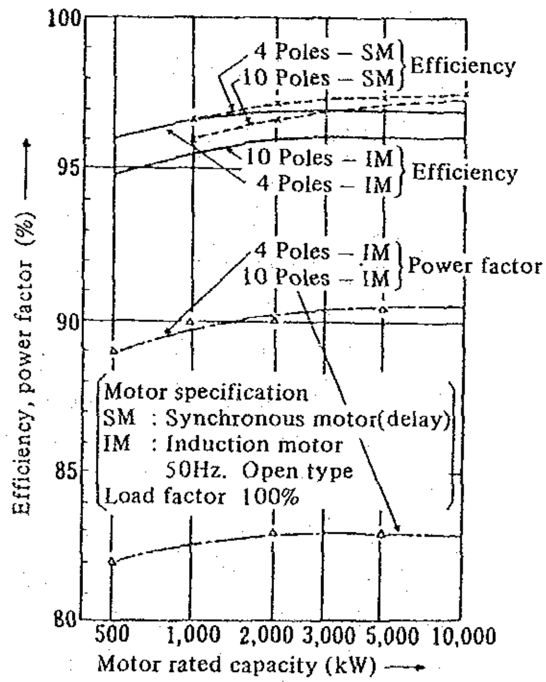


Fig. III–8–22
Comparative example of efficiency and power factor between synchronous and induction motors

The efficiency of synchronous motors is generally higher than that of induction motors and the tendency is remarkable in low-speed motors with larger numbers of poles. For example, in the case of 10 MW class, the efficiency of 4 pole synchronous motors is about 0.5% higher than induction motors, while 10 pole synchronous motors have an efficiency of about 1 to 1.5% higher.

Also, the greatest special feature of the synchronous motors is to freely select the power factor, enabling power factor 1.0 or advancing power factor and, at this point, they are quite different from the induction motors. Moreover, it is possible to control the system at a constant power factor by means of the field control, or to restrain voltage fluctuation of the system by performing constant control of the terminal voltage. Since the power factor considerably lowers with low-speed large capacity induction motors as can be seen from the figure, they are disadvantageous as compared to the synchronous motors in this respect also. Since, however, the synchronous motors including excitation power source equipment for the field system are expensive, generally selection should be studied, with the following points:

a. For 10 MW or more, study adoption of synchronous motors in respect to efficiency.

b. For low-speed motors with larger numbers of poles even 10 MW or less, study adoption of synchronous motors.

c. When power factor and voltage of the system must be controlled, study adoption of synchronous motors. However, the motor is limited to sufficient enough large capacity to supply the system reactive power (Var).

d. Generally, for 5 MW or less, induction motors are superior in simple starting and power source composition.

C) Induction motor and its number of poles

Fig. III-8-23 shows the relationship between number of poles and efficiency, power factor of a totally enclosed fan cooled type three phase squirrel cage induction motor with the output capacity as a parameter. In the figure, the efficiency does not vary much with the number of poles, because it is designed so that the efficiency does not vary much with the number of poles for each output capacity.

However, the power factor remarkably lowers with increased numbers of poles because the exciting current is in proportion to the number of poles. This tendency is remarkable with the smaller capacity motors with higher exciting current component as compared to load current components. Number of poles of a motor is selected according to rotating speed of the opposite machine. Generally, for motors with the same output, the larger the number of poles is, the larger the volume and weight become.

Fig. III-8-24 shows one example of the relationship between the number of poles and the weight ratio of a motor when the weight of a four-pole motor is regarded as 1. Since the weight is intimately related to the amount of materials used and material manufacturing expenses, it may represent a tendency of cost. Accordingly, since the larger numbers of poles generally raise the cost, it is better not to make the number of poles unnecessarily larger, otherwise, the initial investment will be larger and uneconomical.

Motors are rarely directly coupled to the opposite load machine and usually, a reducer lies between them. When a four-pole motor is selected with reference to the reducer, there will be no problem in respect of cost and power factor. But when a motor with larger numbers of poles is selected, it should be determined by taking into consideration the equilibrium between the efficiency merits of the drive system including the reducer and the increased investment amount for the motor.

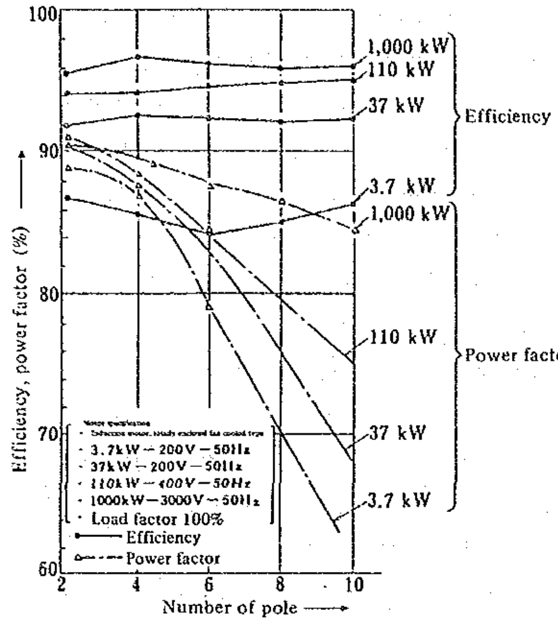


Fig. III–8–23 Relation between number of pole, efficiency and power factor of induction motors

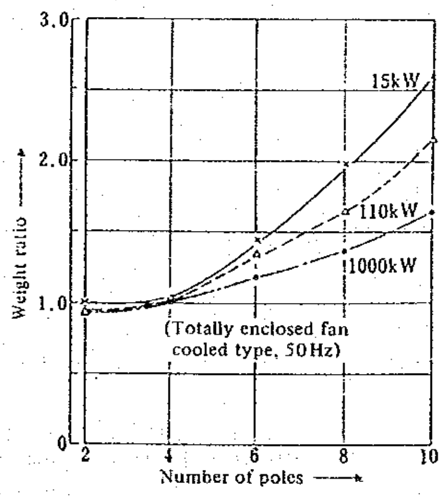


Fig. III–8–24

Relation between number of poles and weight of induction motor

(7) Selection of motor voltage

Determination of the distribution voltage is an important factor for energy conservation because the motor voltage is deeply related to efficiency and cost. It is not desirable to select an especially high rated voltage for a small capacity motor, or to select on the contrary, a low voltage for a large capacity motor.

Fig. III-8-25 shows the range of motor capacity for each voltage taking into consideration the technical problems and economical efficiency. The range shown with a white frame in this figure is a comparatively economical range containing few problems in manufacturing technique, and the shaded portion is the range which it is possible to manufacture technically if the economical efficiency is ignored to a certain degree.

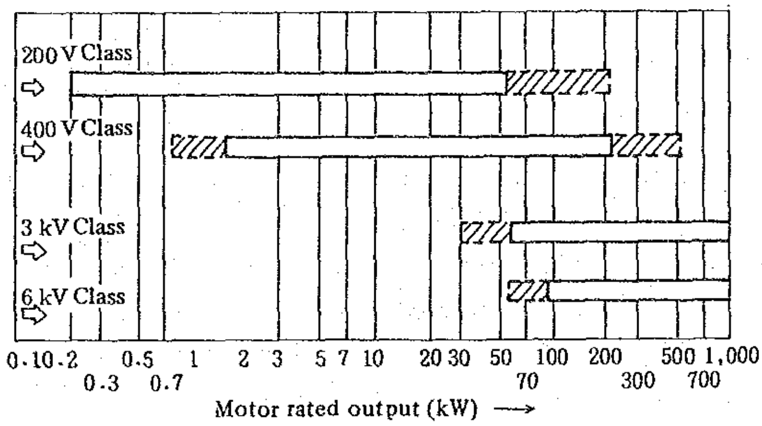


Fig. III–8–25 Optimum output range of motor each voltage

(8) Adoption of high-efficiency motors

In recent years, high-efficiency motors with iron and copper losses reduced by 20 to 30% have been sold on the market.

They have been developed by improving the low-voltage squirrel cage type induction motors through adoption of high-class steel plate and optimization of design with leaving the frame number and external dimensions as the present standard. Although the initial investment will be somewhat higher, they will deserve studying for adoption for long-time operating motors. Fig. III-8-26 and Fig. III-8-27 show comparison in efficiency between high-efficiency motors and standard type motors which are being manufactured at present. It should be noted in Fig. III-8-27 that the high-efficiency motors are remarkable in the improvement of efficiency at light-load.

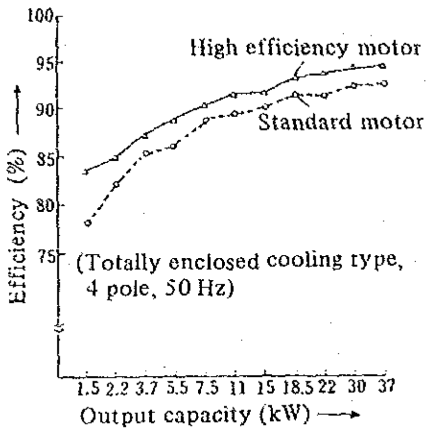


Fig. III–8–26
Efficiency comparison of 3 phase squirrel cage type induction motor

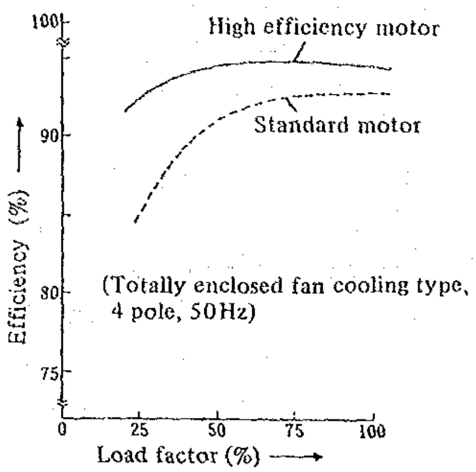


Fig. III–8–27
Efficiency comparison of 3 phase squirrel cage type induction motor

8.3.2 Energy conservation by remodelling the existing equipment in a small scale

(1) Induction motors and voltage control

Although induction motors are generally used because they are low-cost and simple to handle, it should be noted that supply voltage has the greatest impact on these motors. Fig. III-8-28 shows one example of loss of a three phase induction motor with a comparatively small capacity. As can be seen from this figure, a greater part of the loss is copper and iron losses which account for 86%. Accordingly, the impact of supply voltage fluctuation on the induction motor will be clarified by investigating these two.

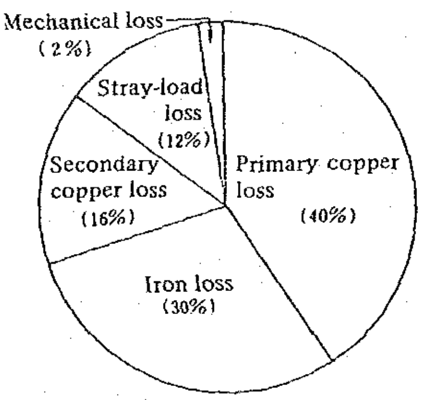


Fig. III–8–28
Loss analysis example of standard 3 phase induction motor

The copper loss is a resistance loss which occurs by current flowing through the induction motor stator winding (primary winding) and rotor (secondary winding) and it is in proportion to the square of the load current. Therefore, it is a loss component much dependent on the load factor.

$$W_c = 3\,(\gamma_1 + \gamma_2')I_2'^2\ (W) \quad \cdots\cdots (8)$$

Where W_c: Copper loss

γ_1: Resistance of primary winding each phase (Ω)

γ_2: Resistance of secondary winding each phase (primary side converted value) (Ω)

I'_2: Load current (A)

Secondary current, when the motor runs at a rated speed close to the synchronous speed, is as follow from the basic formula of the induction motor,

$$I'_2 \doteqdot \frac{\omega_0 T}{3V_1} (A) \quad \cdots\cdots (9)$$

Where ω_0: Synchronous angular velocity

V_1: Supply voltage

T: Load torque

From equation (8) and equation (9), the relation between the supply voltage and copper loss is

$$W_c \doteqdot (\gamma_1 + \gamma_2') \frac{\omega_0{}^2 T^2}{3V_1{}^2} (W) \quad \cdots\cdots (10)$$

That is, when the load torque does not change before and after the supply voltage fluctuation, the copper loss will be in inverse proportion to the square of the voltage.

On the other hand, iron loss W_i occurs when the magnetic flux in the iron core changes by means of the revolving magnetic field and consists of eddy current loss W_e and hysteresis loss W_h. The eddy current loss is in proportion to the square of the thickness of the iron plate of the core d and the square of the magnetic flux density B, while the hysteresis loss is said to be in proportion to the frequency f and the magnetic flux density to the 1.6th power according to Steinmetz's research. Since, however, silicon copper plate has recently been used for iron plate, considerably high magnetic flux density can be obtained. Therefore, the hysteresis loss is also considered to be practically in proportion to the square of the magnetic flux density.

Since B · f are in proportion to the voltage, the iron loss W_i is:

$$W_i = W_e + W_h = k_1(d/B)^2 + k_2 f B^2 = V_1^2 \left(k_1' + \frac{k_2'}{f}\right) (W) \quad \cdots\cdots (11)$$

Where k_1, k'_1: Constant representing the eddy current loss

k_2, k'_2: Constant representing the hysteresis loss

Since a greater part of the motor loss is iron and copper loss, supposing that total loss is a sum of the iron loss W_i and copper loss W_c, the total loss W comes to the following equation from equation (10) and equation (11).

$$W = \left(k_1' + \frac{k_2'}{f}\right) V_1^2 + (\gamma_1 + \gamma_2') \frac{\omega_0^2 T^2}{3V_1^2} (W) \quad \cdots\cdots (12)$$

Supply voltage V at which the total loss W is minimized is determined by using a condition of $dW/dV = 0$ in equation (12) into the following equation:

$$V = \sqrt[4]{\frac{(\gamma_1 + \gamma_2')\omega_0^2}{3\left(k_1' + \frac{k_2'}{f}\right)}} \cdot \sqrt{T}\ (V) \quad \cdots\cdots (13)$$

Since the supply voltage at which the loss is minimized is in proportion to $\sqrt{T}$ from the above equation, it lowers as the load factor lowers.

Fig. III-8-29 shows a conceptual diagram of the characteristics of copper and iron losses against the supply voltage. The torque may be regarded as the load factor because it is balanced with load torque Tl. Accordingly, copper loss curve W_c rises with the load factor and the iron loss value has nothing to do with the load factor. Since the minimal loss point is the point of intersection of iron loss curve W_i and copper loss curve W_c, it will swift to the right when the load factor is high, and it will swift to the left when the load factor is low.

Fig. III-8-30 shows one example of the efficiency curve when the supply voltage is actually changed with a motor. As shown in the figure, the efficiency during voltage fluctuation exhibits varied tendencies according to the load factor. When the load factor is high, the highest efficiency is shown at the rated voltage, while, when the load factor is low, the efficiency lowers as the voltage increases.

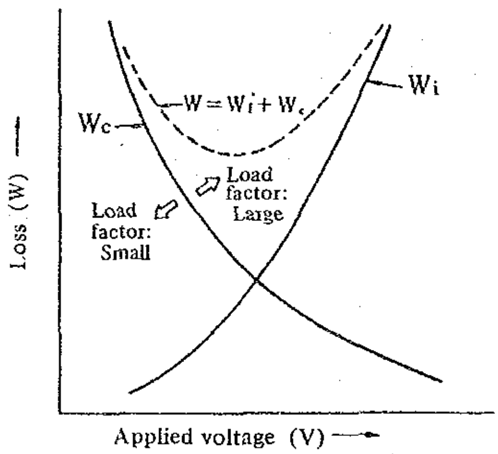


Fig. III–8–29 Tendency of loss against applied voltage

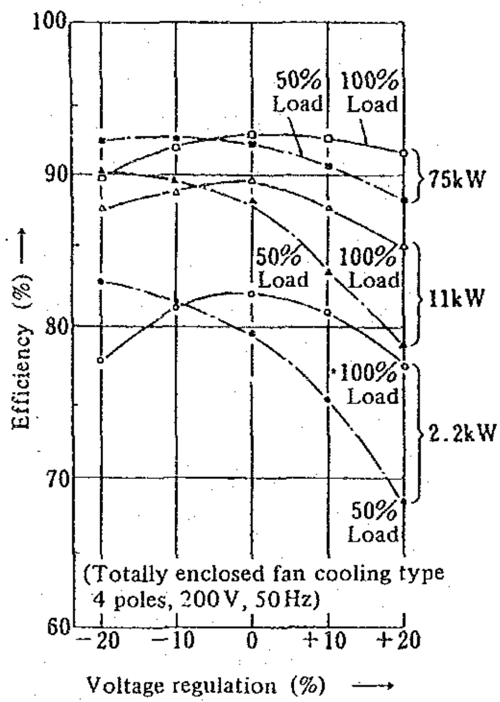


Fig. III–8–30
Example of efficiency during voltage fluctuation of induction motor

Fig. III-8-31 shows the change in the power factor of induction motors when the supply voltage fluctuates. The power factor increases as the voltage drops, because the exciting current of induction motors is in proportion to the supply voltage. What has been described until now is summarized in Table III-8-18. Efficiency and power factor during supply voltage fluctuation have been described in the foregoing. When the above are actually applied to motors in operation within the field, the following items should be studied together:

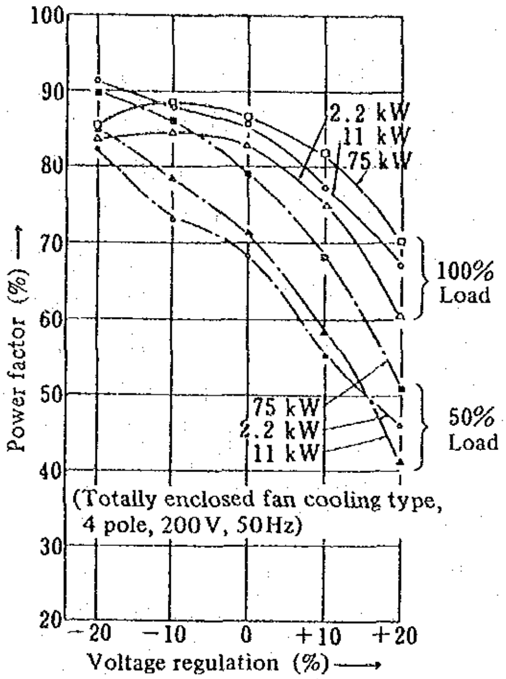


Fig. III–8–31
Example of power factor during voltage fluctuation of induction motor

Table III–8–18 Effect of voltage fluctuation on induction machine

	Voltage fluctuation		
	90% Voltage	Proportional relation	110% Voltage
Starting torque Stalling torque	−19%	V^2	+21%
Synchronous speed	Remain unchanged	Constant	Remain unchanged
% slip	+23%	$1/V^2$	−17%
Full-load speed	−1.5%	–	+1%
Efficiency — Full load	−2%	–	Slightly increased
Efficiency — ¾ Load	Actually no change	–	Actually no change
Efficiency — ½ Load	+1 ~ 2%	–	−1 ~ 2%
Power factor — Full load	+1%	–	−3%
Power factor — ¾ Load	+2 ~ 3%	–	−4%
Power factor — ½ Load	+4 ~ 5%	–	−5 ~ 6%
Full-load current	11%	–	−7%
Starting current	−10 ~ 12%	V	+10 ~ 12%
Full-load temperature rise	+6 ~ 7°C	–	−1 ~ 2°C
Magnetic noise	Slightly decrease	–	Slightly increase

a. Study when the supply voltage is lowered

When wanted to operate with the supply voltage lowered below the rated voltage, it is necessary to check accelerating torque during starting and the value of the peak load because the starting torque and maximum torque decrease at a rate of the square of the voltage as shown in Table III-8-18.

Since the load current increases in inverse proportion to the voltage even if the total loss decreases, the motor copper loss increases, thus increasing the winding temperature and the line loss of distribution line, etc. Care should be taken. Therefore, the lower limit of the supply voltage should be determined within a range not to exceed the motor rated current.

b. Study when the supply voltage is raised

When operated with the supply voltage raised above the rated voltage, saturation of the magnetic flux increases the exciting current remarkably, causing lowered power factor, unusual magnetic noise and an unusually heated iron core due to increased iron loss, etc. Also, since the motor output torque increases at a rate of the square of the voltage, it is necessary to check whether the machine is ruined by excessive torque.

c. Study of entire equipment

Many motors are usually connected to the same distribution system and operated, but the individual motors are rarely operated under the same load conditions. Some of them are operated at close to the rated load and the rest may be operated at a load 50% or below. Since it is not possible to determine the supply voltage uniformly under such a condition, it is necessary to study the entire equipment.

(1) When motors operated at light-load hold an overwhelming majority, lower the distribution voltage and replace a few heavy-loaded motors with one rank higher capacity. In this case, if there are any unused motors available, study whether they are utilized or whether they are exchanged between respective equipment.

(2) When motors operated at heavy-load hold an overwhelming majority, maintain the distribution voltage at the motor rated voltage value and lower the output capacity of a few light-loaded motors by one rank. Also in this case, study utilization of any unused motors and exchange between respective equipments.

(3) When large-capacity motors are operated at heavy load and other small-capacity motors at light load, separate the distribution system for only large-capacity motors from others and lower the supply voltage for the light-loaded motor group.

Besides the above, various combinations are considered and, as such, study on a case-by-case basis. In any case, when replacement and installation of new motors are involved, it should be determined by taking into consideration the equilibrium between the investment amount and conservation energy charge due to improvement of the efficiency.

Another problem with voltage control is the unbalanced voltage. When unbalanced voltage is applied to a three phase AC motor, unbalanced current of zero-phase-sequence, positive-phase-sequence and negative-phase-sequence component current flows. Of these, the zero-phase-sequence component current, its resultant magnetomotive force being zero, induces no voltage in the secondary winding and, as such, no torque is generated. However, the magnetic field due to the negative-phase-sequence component rotates at synchronous speed in the opposite direction to the magnetic field due to the positive-phase-sequence component current, thus inducing a voltage having a frequency of ω_0 (2-S) in the secondary winding—then current flows and torque is generated. This torque is called "Negative-phase-sequence component torque".

This negative-phase-sequence component torque increases the copper loss remarkably, because the torque is going to rotate the motor in the reverse direction. As a result, the motor efficiency lowers.

Therefore, it is necessary to minimize the unbalance factor of supply voltage as much as possible and it should be controlled within 1 to 2%. When a single phase load is applied to a three phase AC power source, the current during each phase becomes unbalanced and voltage drops as each phase differs, causing unbalanced voltage. Therefore, it is important to electrically arrange a single phase load properly so that each phase is balanced.

(2) Prevention of idle running and reduced starting loss

Since a motor is sure to be connected to the opposite machine, electric power consumed at no-load running will be about two to three times that of the motor itself. Accordingly, it is important for electric power conservation to stop the motor when unnecessary. Also, in this case, it is desirable to stop the motor cooling fan and field system for the DC motor. At this time, the precautions are as follows:

a. Deterioration and output drop of motors due to multi-frequency starting should be restricted within a range so that they can be used as usual. In the case of large-capacity motors 100 kW or more and motors with high GD^2 as a load such as blower, etc., it is recommended to consult with the motor manufacturer.

b. Electric energy during starting should not exceed the electric energy during idle running.

Generally, to re-start a motor, care should be taken, because certain starting methods cause a considerable amount of loss. Starting loss of induction motors and its countermeasures are descibed as follows:

(1) Starting loss of three phase induction motors

Internal loss W_l of a motor when accelerated from a state of slip S_1 to a state of S_2 is generally expressed by the following equation:

$$W_l = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_0^2 (S_1^2 - S_2^2)(1 + \frac{\gamma_1}{\gamma_2'}) \frac{T_m}{T_m - T_e} \quad \cdots\cdots (14)$$

The loss from state of stop to synchronous speed is calculated as

$S_1 = 1$, $S_2 = 0$,

$$W_l = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_0^2 (1 + \frac{\gamma_1}{\gamma_2'}) \frac{T_m}{T_m - T_l} \quad \cdots\cdots (15)$$

Where γ_1: Primary resistance of induction motor (Ω)

γ_2': Secondary resistance of induction motor (Primary side converted value) (Ω)

T_m: Accelerating torque of induction motor (Mean value) (N-m)

T_l: Mean torque of load in acceleration (N-m)

ω_0: Synchronous angular velocity

(2) Reducing method of starting loss

Equation (15) shows that the following will reduce the starting loss.

- Start with a higher motor generated torque.
- From the standpoint of operation efficiency, it is desirable to start with the motor torque as high as possible. Starting with reduced voltage or with reduced current to restrain the starting current lowers the motor torque thus increasing the loss. Therefore, it is desirable to directly start as far as the power source circumstances permit.
- Increase the secondary resistance when starting. When a wound-rotor type induction motor is used, inserting a high external resistance when starting will not only greatly reduce the entire motor loss including the external resistance, but also restrain rotor heat and starting current.
- Change the synchronous angular velocity ω_0.

Changing the synchronous angular velocity of induction motor together with a rise in the motor speed greatly reduces the loss during starting.

To change this ω_0, there are two methods; one is to switch the synchronous angular velocity to step-wise using a pole change motor, and the other is to continuously change the power source frequency together with the speed.

Taking the case of two-step pole change induction motors, we will explain. First, starting with the low-speed side winding, accelerate to the synchronous angular velocity ω_{OL} of the low-speed winding (Number of poles : P_L), and switching to the high-speed winding side, accelerate to the synchronous angular speed ω_{OH} of the high-speed winding (Number of poles: P_H). Total loss of the motor during this period W_{2l} will be determined as follows. For simplification, it is assumed in equation (14) that $\gamma_1 = 0^{\Omega}$, $T_l = 0$.

$$W_{2l} = \frac{1}{2}\cdot\frac{GD^2}{4}\omega_{OL}^2 (1^2 - 0^2) + \frac{1}{2}\cdot\frac{GD^2}{4}\omega_{OH}^2 \{(\frac{\omega_{OH} - \omega_{OL}}{\omega_{OH}})^2 - 0^2\} \text{ (J)} \quad \ldots\ldots (16)$$

Assuming pole ratio $n = \frac{P_L}{P_H} = \frac{\omega_{OH}}{\omega_{OL}}$

$$W_{2l} = \frac{1}{2}\cdot\frac{GD^2}{4}\cdot\omega_{OH}^2 (1 + \frac{2}{n^2} - \frac{2}{n}) \text{ (J)} \quad \ldots\ldots (17)$$

Assuming the reduction factor for the loss when started with only the high-speed winding from the beginning as K_a, K_a is expressed by the following equation:

$$K_a = \frac{\text{Loss during starting with pole change}}{\text{Loss during starting with only high-speed winding}} = 1 + \frac{2}{n^2} - \frac{2}{n} \quad \ldots\ldots (18)$$

The pole ratio at which the loss is minimized in the above equation is determined by a condition of $dk_a/dn = 0$ and the loss will be 1/2 when n = 2. Fig. III-8-32 shows the relation between K_a and n. Moreover, increasing numbers of poles changing steps will reduce the loss further.

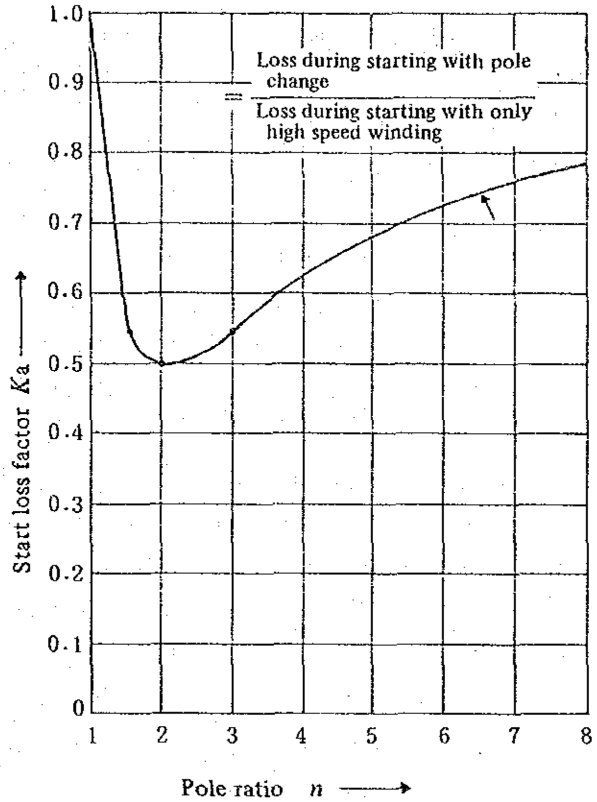


Fig. III–8–32 **Loss during starting with pole change**

(3) Control of induction motor rotating speed

Control of induction motor rotating speed is widely used for energy conservation of pump, fan, blower and motor for crane. Induction motor rotating speed is generally expressed by the following equation:

$$N = \frac{120f}{P}(1 - S) \quad \text{(19)}$$

As can be seen from the above equation, the induction motor rotating speed is controlled by any changing of the number of poles P, changing slip S or changing power source frequency f. Rotating speed control systems classified by these control factors are as below:

- Control of induction motor rotating speed
  - Change of number of poles
    - Pole change system
  - Control of slip
    - Secondary resistance control system
    - Primary voltage control system
    - Kuramer system
    - Static Scherbius system
  - Primary frequency control
    - Opened-control type frequency conversion system
    - Closed-control type frequency conversion system

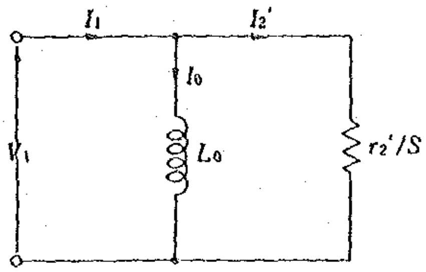
Of these, the primary frequency control system (VVVF) can be materialized from the standpoint of remodelling the existing equipment and as such it will be described.

The primary frequency control system controls the primary voltage and frequency of the motor at the same time, by means of a frequency converter, to change the synchronous speed. This control system is mainly divided into opened-control and closed-control types. Of these, the opened-control type is open-loop control in which the converter frequency is determined based on frequency instructions from a setting apparatus irrespective of changes in state such as the motor rotating speed, torque, etc. On the other hand, the closed-control type is closed-loop control in which the converter frequency is controlled according to changes in state of the motor. The opened-control type has V/f constant control in which the ratio of the motor primary voltage V to frequency f (V/f) is constant. The closed-control type has slip frequency control and vector control.

For a charateristic equation during primary frequency control of induction motor, approximations and simple equivalent circuits can be obtained if attention is given to the following points.

Exciting circuit is represented by exciting inductance L_0. Since operated at close to the synchronous speed with this system, the characteristic equation is approximated by a condition of $S \fallingdotseq 0$.

The simple equivalent circuit prepared under this condition is shown in Fig. III-8-33.



Equivalent circuit during operation near synchronous speed.

Fig. III–8–33 Simple equivalent circuit of induction motor at slip ≒ 0

Therefore, approximation of the characteristic equation can be expressed by the following equations:

$$I_1 = I_0 + I_2' \,[A] \quad \cdots\cdots (20)$$

$$I_0 = \frac{V_1}{\omega_0 L} \,[A] \quad \cdots\cdots (21)$$

$$I_2' = \frac{SV_1}{\gamma_2'} = \frac{S\omega_0}{\gamma_2'}\frac{V_1}{\omega_0} \,[A] \quad \cdots\cdots (22)$$

$$T = \frac{3SV_1^2}{\omega_0 \gamma_2'} = 3\frac{S\omega_0}{\gamma_2'}\left(\frac{V_1}{\omega_0}\right)^2 \,[N \cdot m/rad] \quad \cdots\cdots (23)$$

On the other hand, assuming the voltage factor as K_v, the magnetic flux ϕ is

$$\phi = \frac{V_1}{K_v \omega_0} = K_1 I_0 \,[W_b] \quad \cdots\cdots (24)$$

Where, $K_1 = \frac{L_0}{K_v}$

When control (V/f constant control) is performed so that the ratio of voltage V_1 to frequency ω_0 in the above characteristic equation is constant, the motor torque, current I_0, I_2 and magnetic flux become constant at constant slip frequency $S\omega_0$. Fig. III-8-34 shows torque-speed characteristic curve at this point and the maximum torque Tmax becomes constant against speed ω_0.

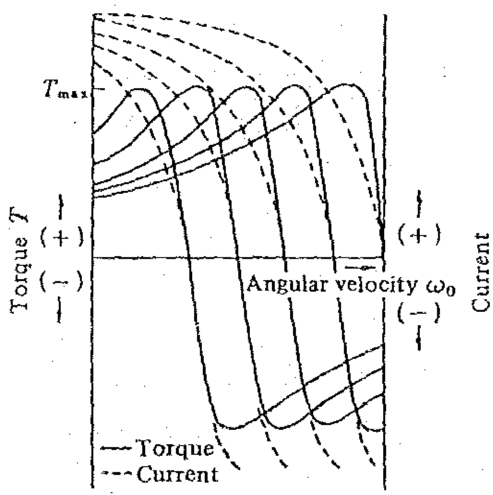


Fig. III–8–34 Torque-speed characteristic of E_2/ω_0 constant control

This VVVF system is mainly divided into two systems: voltage control system, and current control system. Both systems have respective special features and the block diagram is shown in Fig. III-8-35. See the technical books for a detailed comparison.

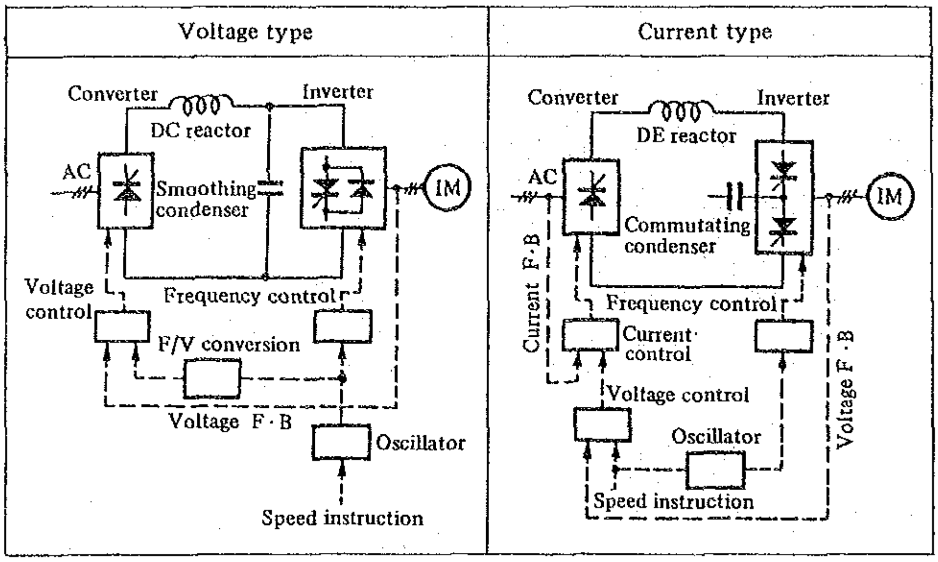


Fig. III–8–35 Comparative diagram of VVVF

When this VVVF system is used for motor for crane, this has basically the following merits as compared to the rheostatic control system of conventional wound-rotor type motors:

a. Energy conservation effect is great because there will be no heat loss of secondary resistance.
b. Maintenance is easier because there will be no slip ring and brush.
c. Adding a speed control device enables high precision control.
d. It is very convenient to operate, especially for inching operation at low speed, etc.

(4) Other countermeasures

Diagnose the present equipment capacity. When the equipment capacity is too large as compared to the production scale, it is important for energy conservation to reduce the rotating machine and equipment output. For example, with motors being used as-is, the power to drive the load can be reduced by changing the power transmission mechanism (diameter of a pulley, or reduction ratio of gear etc.). Also, when there are stand-by motors, the energy can be saved by replacing them with smaller motors or lower rotating speed motors.

8.4 Compressors

Energy conservation countermeasures for pneumatic systems are mainly divided into those for air compressor, piping and air-operated apparatus.

Power used for compressors is generally given by the following equation:

$$L = \frac{(a+1)K}{K-1} \cdot \frac{P_s Q_s}{6120} \cdot \left[\left(\frac{P_d}{P_s}\right)^{\frac{K-1}{K(a+1)}} - 1\right] \cdot \frac{\phi}{\eta_c \eta_t} \qquad (1)$$

L_1, P_s, P_d, Q_s, a, K, η_c, η_t and ϕ in the above equation shall represent the following values respectively:

L: Required power (unit kW)

P_3: Absolute pressure of intake air (unit; kg per square m)

P_d: Absolute pressure of discharge air (unit; kg per square m)

Q_s: Amount of air per unit time converted to a state of intake (unit; cubic m per minute)

a: Number of intercoolers

K: Adiabatic coefficient of air

η_c: Overall adiabatic efficiency of compressor

η_t: Transfer efficiency

ϕ: Allowance rate

Values η_c and η_t shall be given by the manufacturer. Also, value ϕ shall be values on the following table:

Reciprocating compressor	Lubricated screw compressor	Nonlubricated screw compressor	Turbo compressor
1.10	1.10	1.15	1.20

Accordingly, to reduce service power for compressors,

(1) Lower temperature of intake air. Also, improve the cooling effect in the intercooler.

(2) Lower the discharge pressure. Also, reduce the amount of air used.

(3) Select compressors and systems with good efficiency.

(4) Prevent air leakage from the compressor proper and piping, etc.

(5) Intensify management for the entire system for compressed air.

The above items are important. Respective items will be described below.

8.4.1 Intake air and intercooler

When intake temperature rises, air density generally becomes smaller and the actual volume of air sucked with the same power reduces. Since this relation is in inverse proportion to the absolute temperature of intake air, for example, changing intake side temperature from 35° C to 25° C reduces power cost by 3.3%

Therefore, the air intake opening should be located at a cool place where it is not exposed to the direct rays of the sun. Insufficient cooling in the intercooler brings air compression close to adiabatic compression and increases the compression power on the second stage and after. Since lowered efficiency of the intercooler is caused possibly by lowered heat transfer efficiency due to adherence of scale or slime, or insufficient amount of cooling water, it is necessary to clean the inter-cooler and work out other appropriate countermeasures.

8.4.2 Discharge pressure and amount used

In equation (1), lowering discharge pressure of the compressor reduces the axial power greatly. Table III-8-19 shows an experimental example of a compressor actually in use and the required power could be reduced by about 4% by lowering the service pressure 1 kg/cm.^{2}

Table III–8–19 Actual measurement example of compressor performance

(1) Discharge pressure and motor input (kW)

Pressure (kg/cm² G) / Load (%)	7	6	5	4	3
100	226	216	205	190	166
50	156	150	144	134	120

(2) Load (flow rate) and motor input

Load (%)	0	50	100
Discharge amount (m^3/min)	0	20	40
Input (kW)	44	132	220

(3) Compressor specification

Discharge pressure (kg/cm°C)	7
Discharge amount (m^3/min)	40
Capacity adjustment (%)	0, 50, 100 3 stage
Motor	3.3 kV 220 kW

Generally, when the same operation is performed, many machines and tools having the same capacity differ in the pressure of air required by them. Therefore, if possible, study thoroughly and standardize service pressure of machines and tools in the whole factory to the lower one, to reduce the required electric power.

When there is equipment requiring high compressed air such as pressing machines in the factory, it is economical to install a booster for exclusive use.

Also, since reduction in the amount of air used is almost in proportion to reduction in the power cost, it is better not to use compressed air for cooling, cleaning, etc., if possible, and it is also better to control the condition for use thoroughly by re-checking the nozzle diameter, etc.

8.4.3 Selection of kinds of machines and operation systems

The air compressors have the following tendencies from the standpoints of efficiency and it is important to take into consideration when selecting the kinds of machines:

(1) The larger the compressor capacity is, the higher the efficiency will be.

(2) The more the number of compression stages is, the higher the efficiency will be.

(3) When operated with the load factor nearer to 100%, the efficiency will be higher.

Therefore, in a factory where small-scale operation is performed during holidays, operating a large-capacity compressor causes a great power loss and, therefore, it is advisable to separately install a small-capacity compressor which is capable of operating at a load close to 100% on holidays.

Also, when two or more compressors are operated in parallel, it is important to control the number of the compressors in order to make the compressor load factor as high as possible. When the load fluctuates, operate the rotary type compressor at base load and operate the reciprocating type compressor to correspond to the fluctuating load. This serves for energy conservation in the respect of efficiency of both types. Table III-8-20 shows classification of air compressors by pressure range.

Table III–8–20 Classification of air compressor

Type	Class	Main pressure range (kg/cm^2)		Applications
Reciprocating compressor	General purpose compressor	7~8.5		2 stage compressor for 100 kW or more Standard type for 1,000 kW or less
	Intermediate pressure compressor	10~100		For petroleum refining, petro-chemical and general chemical industry processes
	High pressure compressor	150~1,000		For synthetic chemistry such as ammonia, methanol and hydrogenation. Mostly large scale such as several thousand kW.
	Superhigh pressure compressor	1,500~3,500		Mainly, ethylene compressor for synthesis of polyethylene and ethylene.
	Oilless compressor	7~8.5		Oxygen gas, air for food processing industry and instrumentation, etc.
Rotary compressor	Movable profile compressor Screw compressor	1 Stage 2 Stage 1 Stage 2 Stage	3 8.5 7 7~8.5	Air capacity 2~60 m^3/min.

8.4.4 Air leakage from clearance, hole, etc.

(1) Air leakage

Flow rate when air flows out from a vessel with a pressure of P inside into a space at pressure of P_2 is, from Bernoulli's equation

$$Q = S\sqrt{\frac{2g(P_1 - P_2)}{\gamma}}\ [m^3/s] \qquad \cdots\cdots (2)$$

Where g: Acceleration of gravity 9.8 (m/S^2)

γ: Specific weight of air (kg/m^3)

s: Effective cross section (m^2)

P_1, P_2: Absolute pressure inside and outside vessel (kg/m^2 abs)

Actually, compressibility and adiabatic expansion become problems and as a practical equation,

$$Q = C\epsilon S\sqrt{\frac{2g(P_1 - P_2)}{\gamma}}\,[m^3/S] \quad \cdots\cdots (3)$$

Where C : Discharge coefficient

ϵ: Correction factor due to expansion

Since the loss due to this air leakage is very great, it is necessary to check the piping, etc. for leakage and, if any, to repair and correct immediately. The leakage is in proportion to $\sqrt{P_1 - P_2}$ in equation (3) and, as such, reducing the service pressure surely reduces the leakage. Fig. III-8-36 shows the blow-off air amount from a small

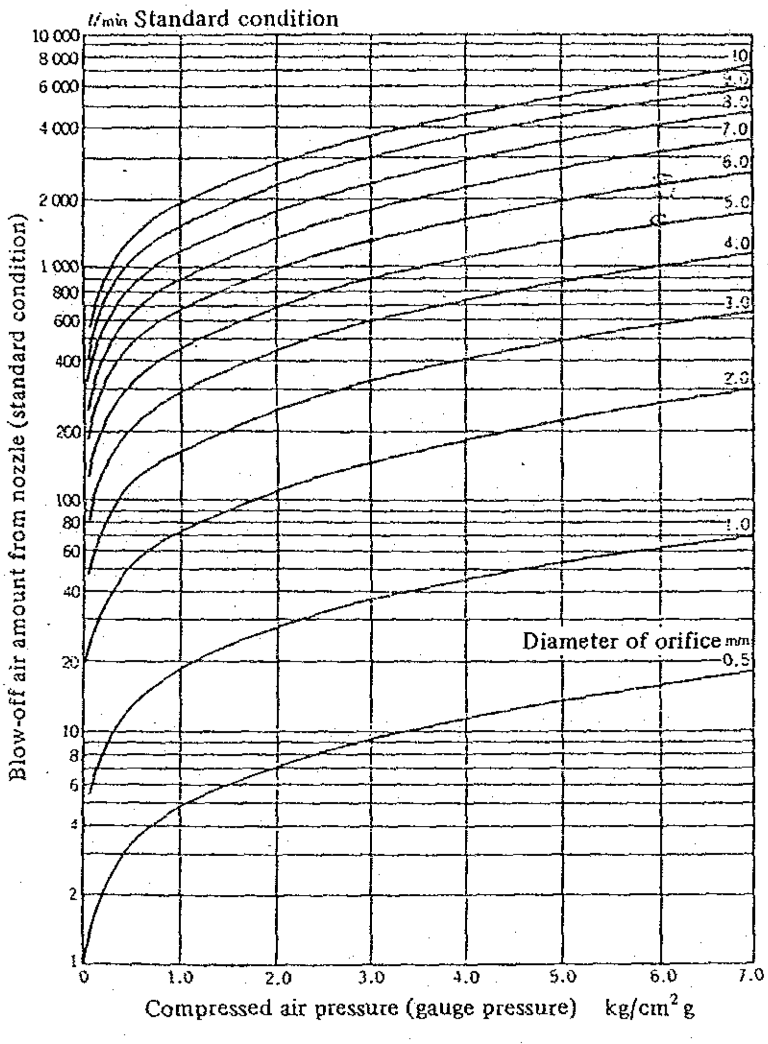


Fig. III–8–36 Compressed air pressure and blow-off air amount from nozzle

diameter orifice. Fig. III-8-36 is used to determine the blow-off air amount when there is a sufficient large capacity receiver tank and piping as compared with the size of the blow-off nozzle. It is assumed that pressure in the tank and piping remains unchanged during blow-off at normal temperatures. The blow-off air amount is converted to a standard condition (20° C, 1 atmospheric pressure).

To apply practically, use selectively a value multiplid by 0.97 to 0.65 because values in Fig. III-8-36 are based when discharge coefficient c = 1 (Fig. III-8-37).

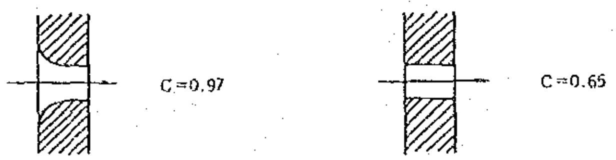
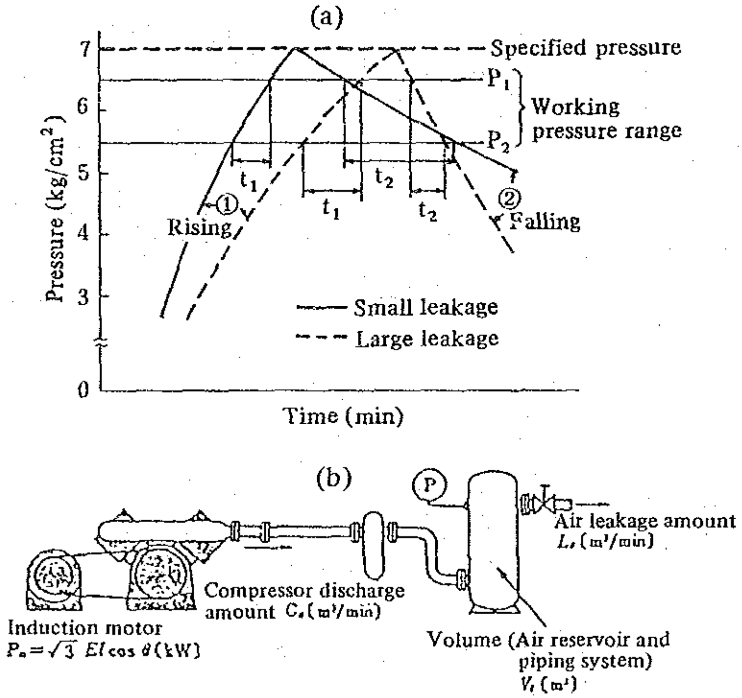


Fig. III–8–37 Shape of orifice and value of discharge coefficient

(2) Measurement of air leakage

It is possible to measure air leakage in the following way: first, operate a compressor with the end closed and the pressure gradually rises as shown by (1) in Fig. III-8-38(a). Stop the compressor at the specified pressure and let stand as-is, then the pressure will lower because of the air leakage as shown by (2). In the case of (a), it shows that the solid line has less leakage than the dotted line.



Ca : Compressor discharge amount

L_y : Air leakage amount

t_1 : Time required for pressurizing

t_2 : Time required for lowering

Fig. III–8–38 Pressure-time curve

Assuming that pressure range (P_1 to P_2) is treated as a pressure to be practically used, and t_1, t_2 are treated as shown in the figure, the following equation is formed.

Assuming volume of compressor equipment, piping system, etc. as V_t,

$V_t = t_1 (C_a - L_y) = L_y t_2 \ (m^3)$

When air leakage L_y is determined from the above equation,

$$L_y = \frac{C_a t_1}{t_1 + t_2} \ (m^3/min)$$

V_t: Volume of compressor equipment, piping system, etc. (m^3)

Air leakage factor L_p (%) is

$$L_p = \frac{L_y}{C_a} \times 100 = \frac{t_1}{t_1 + t_2} \times 100 \ (\%)$$

Next, amount of power loss P_1 is determined by the following equation:

$$P_1 = \frac{P_m Q_t L_p}{100} (kWh)$$

Where P_1: Amount of power loss of compressor for hours t_1 (kWh)

P_m: Mean motor input power of compressor for hours t_1 (kW)

Q_t: Compressor operating hours (h)

Air leakage can be more clearly measured by measuring compressor equipment (compressor proper, intercooler, air tank, etc.), piping system, pneumatic machine, control circuit, etc. in the group unit.

8.4.5 Management of compressed air equipment

Precautions for management of compressed air system are as follows:

(1) Management of compressor

To operate compressors in a stable condition at all times, items to be daily checked are:

a. Is cooling water for compressors, aftercoolers, etc. well supplied?

b. Is not generated heat of compressors unusually high?

c. Is the pressure switch for unloader normally operating? Also, is the set value for the pressure switch proper?

d. Does not the compressor give unusual noises?
Also, is the vibration within a normal range?

e. Is the amount of the lubricating oil normal?
Is normal lubricating oil used?

f. Is not the intake side filter clogged?

g. Does the safety valve normally operate?
Is the set value for the safety valve normal?

h. Is the indicated pressure on the pressure gauge normal?
Also, is not the pressure gauge out of order?

i. Is the air tank drain ejector operating normally?

j. Is the intercooler operating normally?

(2) Control of pressure

To control pressure, it is necessary to know the following points:

a. What is the minimum operating pressure of the line?
: the minimum pressure to get stable control.

b. What is the maximum pressure of the line?
: the maximum pressure to get stable control.

c. What is the proof pressure of the line?
: the pressure which the control equipment will be damaged.
Set the pressure switch, safety valve and relief valve after knowing the above matters. Items to check in this case are as follows.

a. Are the set values for the pressure switch, safety valve and relief valve in the air tank and piping proper?
Are they operating normally?

b. Is the check valve to prevent back flow of air operating normally?

c. Is the regulator operating normally?

d. Is the pressure gauge used in the line normal?
Is not the indication out of order?

(3) Control of drain

For the drain valve installed where drain collects, always discharge drain at least once a day (preferably in the morning when the equipment is operated).

Check Items:

a. Discharge drain by means of the drain valves installed in the air tank, piping down portion, end of the piping and air filter.

b. Is the automatic drain apparatus operating normally?

c. For the air filter and automatic drain apparatus, etc., clean the internal elements periodically.

(4) Control of pipe

Since air leakage causes energy loss and lowered pressure, take care to prevent leakage as much as possible.

Check Items:

a. Does not air leak due to looseness of joints?

b. Does not air leak due to breakage of pipe, hose or tubes?

c. Can the stop valve, etc. be securely closed?

8.5 Blowers (Fan and blower)

8.5.1 Characteristics of blowers

Although blowers and compressors have the same principles, below 1 mAq, 1 mAq to below 10 mAq (1 kg/cm^2) and 10 mAq, or the above in discharge pressure are usually called "Fan", "Blower" and "Compressor" respectively.

For classification, they are mainly divided into turbo types and displacement types according to the operating principle, and the turbo type is further classified into an axial-flow system and centrifugal system.

Table III-8-21, Table III-8-22 and Fig. III-8-39 show classifications of blowers, their characteristics and the characteristic curves respectively.

Table III-8-21 Classification of blowers

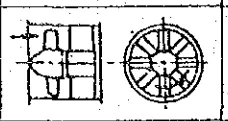
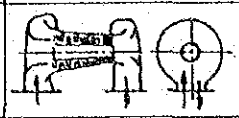
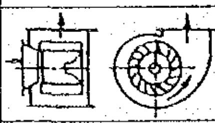
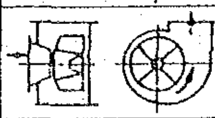
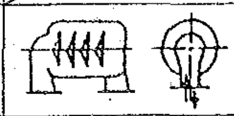
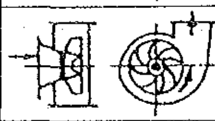
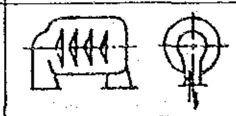
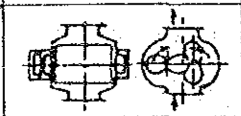
Name / Type			Blower: Fan	Blower: Blower
		Pressure	1,000 mmAq or below	1 to below 10 mAq
Turbo type	Axial flow type	Axial flow		
Turbo type	Centrifugal type	Multivane		
Turbo type	Centrifugal type	Radial		
Turbo type	Centrifugal type	Turbo		
Displacement	Rotary type	Roots		
Displacement	Rotary type	Movable vane		
Displacement	Rotary type	Screw		
Displacement	Reciprocating type	Reciprocating		

Table III-8-22 Characteristic comparison of blowers

Item \ System	Axial flow system	Turbo system	Multivane system	Radial system
Range of use	*Air capacity* 1~10,000 m³/min Static pressure 1 mmAq~1 kg/cm²	Air capacity 1~10,000 m³/min Static pressure 1 mmAq~1 kg/cm²	Air capacity 1~10,000 m³/min Static pressure 1 mmAq~1 kg/cm²	Air capacity 1~10,000 m³/min Static pressure 1 mmAq~1 kg/cm²
Efficiency (%)	80~92	70~85	50~60	60~70
Efficiency curve	When varied from the planned air capacity, rapidly decreases.	Shows no rapid decrease.	Comparatively smooth	Shows no rapid decrease.
Starting	Fully open damper.	Fully close damper.	Fully close damper.	Fully close damper.
Noise (dB)	39~55	32~44	22~41	28~42
Limit surging air capacity (%) (against air capacity at maximum efficiency point)	70~80	30~60	60~80	50~70
Applications example	For ventilation fan (buildings, architecture, tunnel), for boiler forced draft, for induced exhaust, for mine blower	For various blowers for steel mills, for dust collecting tunnel ventilation, for boiler forced draft, for induced exhaust, for cement kiln exhaust	For various blow and exhaust for steel mills, for boiler forced draft, for building and tunnel ventilation,	For various blow and dust collection for steel mills, for boiler induced draft, exhaust for gas re-circulation, for cement kiln exhaust

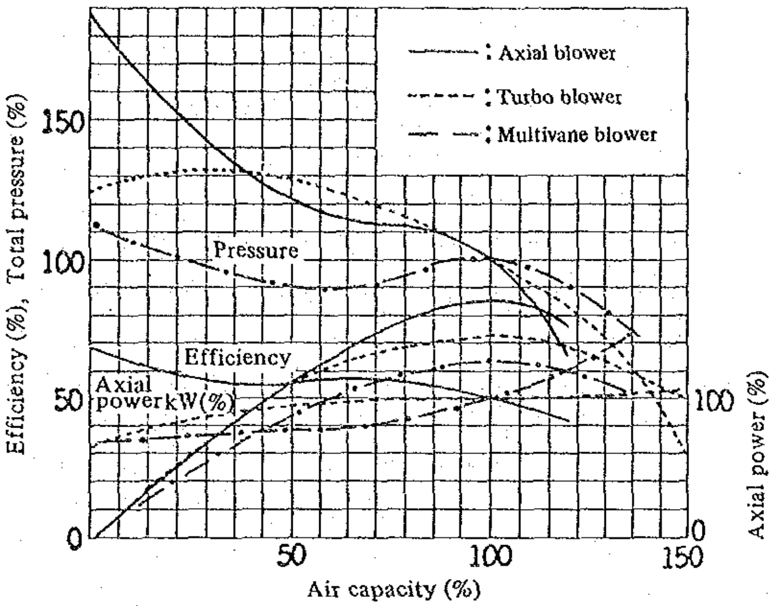


Fig. III–8–39 Characteristic curve for various blowers

(1) Turbo types

The turbo types have two systems: centrifugal system, and axial-flow system. In the former, centrifugal force is involved in rotation of impellers housed in the casing which provides the gas with speed energy, while in the latter, pressure and speed energy are provided while the gas is being flowed in the direction of rotation by rotating impeller blades with the blade section in the straight pipe. "Turbo type blowers" is a general term for these types.

(2) Displacement types

In the displacement types, the gas is sucked in a chamber with a specified volume, the inlet port is closed and the gas is pressed out to the discharge opening separately provided while the chamber is being pushed, lessened and compressed. This operation is repeated. The gas is pushed out by means of piston reciprocating operation or rotary operation of cocoon type (roots type) rotor.

8.5.2 Required power of blowers

(1) Air power (L_T)

Air power means effective energy given to air by a blower in unit time.

$$L_T = \frac{K}{K-1} \cdot \frac{P_{t1} \cdot Q}{6{,}120} \{(\frac{P_{t2}}{P_{t1}})^{\frac{K-1}{K}} - 1\} \text{[kW]} \quad \cdots\cdots (1)$$

Where

P_{t1}: Absolute total pressure on suction side (kg/m^2 abs)

P_{t2}: Absolute total pressure on discharge side (kg/m^2 abs)

Q: Air flow (m^3/min)

K: Specific heat ratio (1.4 for air)

When the pressure ratio is 1.03 or below, it may be calculated by the following equation:

$$L_T = \frac{QP_T}{6{,}120} \text{[kW]} \quad \cdots\cdots (2)$$

Where P_T: Total pressure of blower (mmAq)

(2) Axial power (L)

Axial power is obtained by dividing the air power by the blower efficiency (η_F).

$$L = \frac{L_T}{\eta_F} \text{(kW)} \quad \cdots\cdots (3)$$

The efficiency varies with the air flow as shown in Fig. III-8-39, but is generally displayed by that during rated air flow. Its approximate figures are shown in Table III-8-22.

(3) Motor output

Induction motors with simple construction and low-cost are generally used for blowers. Squirrel cage type induction motors are used for comparatively small-capacity blowers. In this case, since the inertia (GD^2) of the blower impeller is great, it is necessary to select after due consideration. The motor output (L_M) is determined by the following equation:

$$L_M = L \times \phi \frac{1}{\eta_t} \text{(kW)} \quad \cdots\cdots (4)$$

Where ϕ: Allowance rate

η_t: Transfer efficiency

Values of ϕ and η_t are from Table III-8-23 and Table III-8-24.

Table III–8–23 Value of ηt

1 stage parallel shaft type gear reducer with transfer power of 55 KW or less	1 stage parallel shaft type gear reducer with transfer power of 55 KW or more	Constant speed type fluid coupling with transfer power of 100 KW or less	Constant speed type fluid coupling with transfer power of 100 KW or more
0.95	0.96	0.94	0.95

V-belt	Flat belt	Direct-coupled
0.95	0.90	1.00

Table III–8–24 Values of ϕ

Propeller fan	Disk fan	Multivane fan	Turbo fan	Plate fan	Profile type fan
1.30	1.50	1.30	1.15	1.25	1.15

8.5.3 Electric power conservation for blowers

Factors for blower electric power conservation are shown in Fig. III-8-40. Namely, the fundamental conception of the electric power conservation is:

- Reduce the operating time.
- Adopt high-efficient equipment.
- Reduce air power.

These will be described as follows:

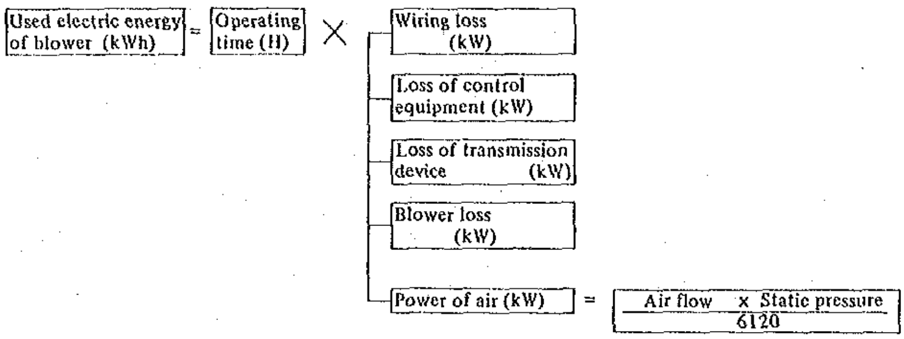


Fig. III–8–40 Factors for blower electric power conservation

(1) Reduce the operating time.

Too early start of blowers before the factory operation starts, or very late stop of blowers after close of the factory is often seen in factories which haven't much interest in energy conservation. Also, blowers in operation, although the entire factory is at a stop because of some troubles, are often seen in general factories. Since such useless operation of blowers is a significant adverse factor for energy conservation, it is necessary for the factory manager to give special attention.

The most direct method to eliminate this useless operation of blowers is many times ON-OFF operation of blowers. Countermeasures and precautions for prevention of general idle operation for motors were described in the section for Motors. However, blowers generally have great GD^2 and special precautions for ON-OFF operation are as follows:

A) Check the motor for mechanical and electric life.

When new equipment is established, the daily number of times for start-up as the condition is indicated to the manufacturer and the equipment fit for the condition is ordered. Therefore, there will be no problem. However, when the blower being almost continuously operated at present is going to be changed to operate to this system, it is necessary to carefully study problems concerning mechanical strength and heat, etc. of the motor caused by frequent start-up.

B) Voltage drop of power source

Since the blower has been started while other loads are at a stop, voltage drop due to the starting current has not become a problem. However, when ON and OFF is repeated while other loads are in operation, troubles by voltage drop of power source may be occured.

Electric machinery and apparatus are generally designed to perform their functions even at a voltage drop of about 10% and they are likely to cause trouble at a voltage drop of more than that. Therefore, in this case, appropriate counter-measures such as reactor starting or adoption of VVVF will be required.

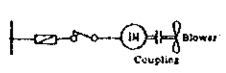
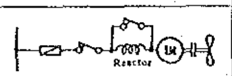
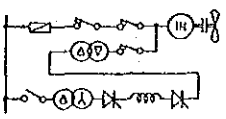
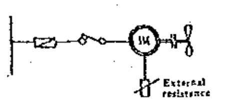
C) Life of starting equipment

Reactors for start-up and starting compensator are generally of a short-time rating and when they are changed to very frequent use, the temperature of winding in these equipment will increase, possibly resulting in insulation deterioration and a burning accident. Therefore, for very frequent use, it is necessary to carefully study the temperature rise beforehand.

D) Others

Precautions other than the foregoing are for generated heat for power source cable and life of switches, etc. Table III-8-25 and Table III-8-26 show comparison of various starting systems when an induction motor is used for a blower, and general life of switches respectively.

Table III–8–25 Comparison of various starting systems

Starting system	Composition diagram	Starting current	Starting torque	Voltage when starting	Electromagnetic force	Armature heating capacity	Problems when starting at multi-frequency
Direct starting		100 (6 to 7 times full-load current)	100 (About 150% on rated torque)	100	100 (In proportion to square of current)	$100\left(\frac{GD^2 \cdot N_e^2}{730}[J]\right)$	Power voltage drop, Motor life, Breaker life
Reactor starting		50, 65, 80	25, 42, 64	50, 65, 80 (Standard tap)	25, 42, 64	100	Reactor heating capacity, motor life, breaker life
Closed circuit transition autotransformer starting		25, 42, 64	25, 42, 64	50, 65, 80 (Standard tap)	25, 42, 64	100	Starting compensator heating capacity, motor life, breaker life
VVVF Starting		17 or less (Any value below rated current)	70 or less (Any value below rated torque)	0~100 (In proportion to speed)	2~3 (Large when there is inrush current)	Hardly any	Transient torque (when switched from VVVF to main power source), inrush current (when switched from VVVF to main power source), effects from higher harmonic (motor temperature rise, occurrence of shaft voltage, resonance of pulsating torque and shaft torsion, surging. voltage when commutating
Secondary side resistor starting (limitted to wound-rotor type)		18~40 (Optional)	80~200 (Optional)	100	3~16	Hardly any (Consumed by external resistance)	External resistance heating capacity, breaker life, slip ring heating capacity, mechanical life of brush lifting mechanism, life of motor for brush lifting

(Note) (1) Value at direct starting is regarded as 100%. (2) Starting torque is generated torque of motor and shall be (Starting torque + Stalling torque)/2.

Table III–8–26 Life of switch (When not repaired)

	Mechanical life	Electrical life (rated current opening and closing)
Oil breaker	10,000 times	2,000~5,000 times
Vacuum breaker	10,000 times } Possible also for 50,000 times	10,000 times
Gas (SF.) breaker	10,000 times	10,000 times
High voltage electro-magnetic contactor	5 million times (Class 1)	500 thousand times (Class 1)

(2) Adopt high-efficiency equipment.

In this case, the points to which attention should be given are:

a. Efficiency of blowers

b. Efficiency of power transmission equipment

c. Efficiency of motors.

Especially for blowers, it is necessary to select the optimum type after having a correct understanding of the fluctuation range for air flow, pressure and temperature. Recently, new products with higher efficiency by improving shape of blade, even of the same type, have been developed.

(3) Reduce air power.

As described in the section for compressors, lowering the air flow, pressure and intake temperature reduces the required power. In the case of a blower, it is generally used with an excessive air flow. For example, when dust collecting effect is sufficient even if the air flow of the dust collector is reduced, it is operated at full capacity because the proper air flow is not known. Also, when a blower for cooling has no problems, even if this air flow is reduced according to the season, it is operated at full capacity. These examples are often seen.

That is, to reduce the air flow, it is necessary to study the following:

a. What is the proper air flow?

b. To acquire this proper air flow, what is the most efficient method?

c. Does not air leak from piping and at the place for use?

There are two methods to reduce the air flow; stationary (fixed) type, and variable type.

A) Stationary types

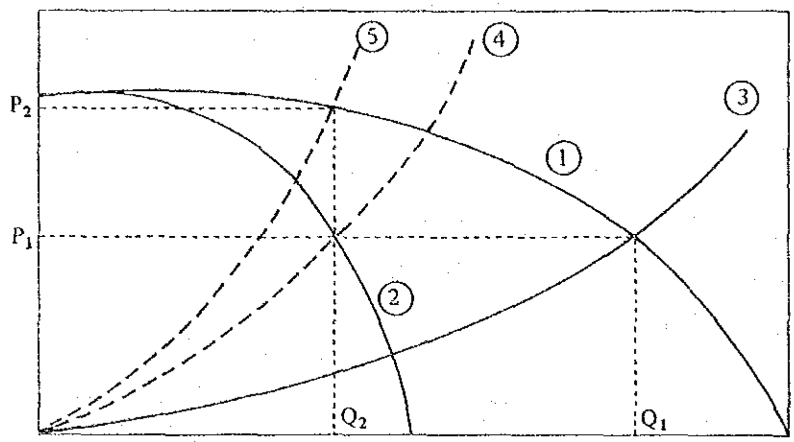
Table III-8-27 shows a table for stationary types. The main items of these will be described.

Table III–8–27 Method to reduce blower air capacity (Fixed system)

Main classification	Sub-classification
Reduction in blowing capacity	When blowers are operated, reduce the number. Replace blower. Blower impellers (replace or cut)
Damper, vane opening adjustment	Reducing damper opening Reducing vane opening
Change in rotaing speed	Replace motor. Repalce belt-driven pulley. Insert or replace reducer.

a. Reduction in units

In case two blowers with the same specifications are operated in parallel, when the required air flow is changed from Q_1 to 1/2 of Q_1 as shown in Fig. III-8-41, it is necessary to change the resistance curve of the piping system including damper from (3) to (5). The required power at this point is in proportion to $P_2 \times Q_2$. On the other hand, when the operated blowers are reduced to one unit and the resistance curve is changed to (4) the required power at this point is in proportion to $P_1 \times Q_2$. That is, the difference in blowing power between two units and one unit operation is in proportion to $P_2 \times Q_2 - P_1Q_2 = Q_2 \times (P_2 - P_1)$ and it gives a great energy conservation effect. Since, in fact, the difference in efficiency is added to this, this effect will be greater.



(1) Static pressure curve when two units are operating

(2) Static pressure curve when one unit is operating

(3) Resistance curve to obtain required air capacity, Q_1 (When two units are operating)

(4) Resistance curve to obtain required air capacity, Q_2 (When one unit is operating)

(5) Resistance curve to obtain required air capacity, Q_2 (When two units are operating)

Fig. III–8–41 Performance curve during parallel operation

b. Replacement of impellers

When the blower output becomes too high and the damper is exceedingly narrowed down after the amount of air used is reduced, or when the gas specific weight becomes higher, the wind pressure is too high and the motor is overloaded, it is desirable to replace the impellers.

Assuming the diameter of impeller as D_1, the air flow as Q_1, the pressure as P_1 and the axial power as L, the following relations generally exist.

$Q \propto D^2$

$P \propto D^2$ .... (5)

$L \propto D^4$

Accordingly, diminishing the diameter of the impeller as required will bring very great energy conservation. In this case, it is of course necessary after working to adjust the balance. If there is a large amount of working in the case of multi-stage block, the blade in the 1st stage or 2nd stage may be removed. Adjustment of blowing capacity by this method is limited to about 20%.

c. Damper, vane opening adjustment

The damper is installed vertically to the air duct shaft direction to change the opening as shown in Fig. III-8-42 and when installed on the outlet side, the opening changes the resistance curve and, when installed on the inlet side, the opening changes the static pressure curve. The vane means a movable blade which is installed at the inlet of the blower and provides the gas entering the blower impeller with swirl in the direction of rotation. Accordingly, adjusting the vane changes the wind pressure-air flow curve. Special features of this method are shown in Table III-8-28, in which the rotating speed control method is specified for comparison.