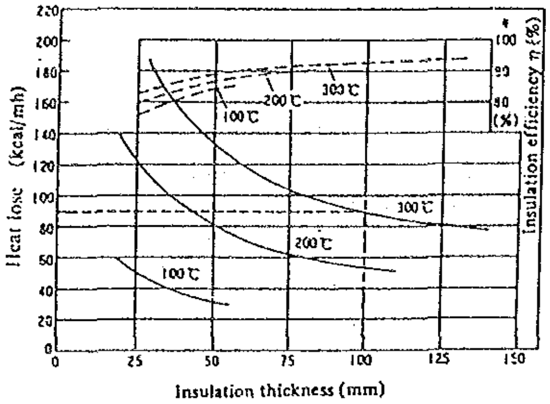


Figure 10.9 3" Piping

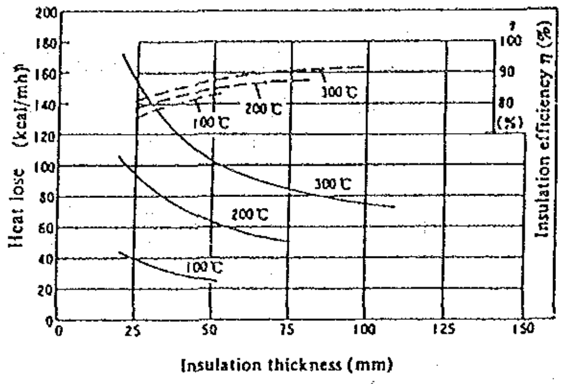


Figure 10.10 2" Piping

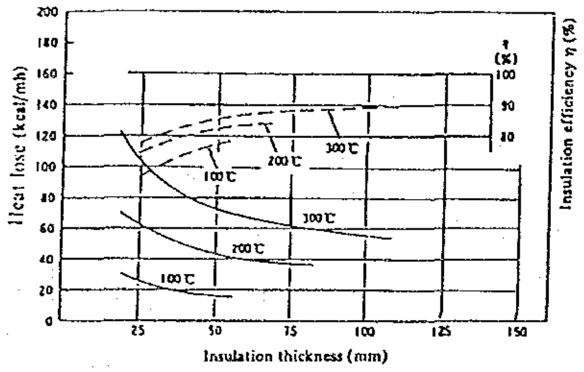


Figure 10.11 1" Piping

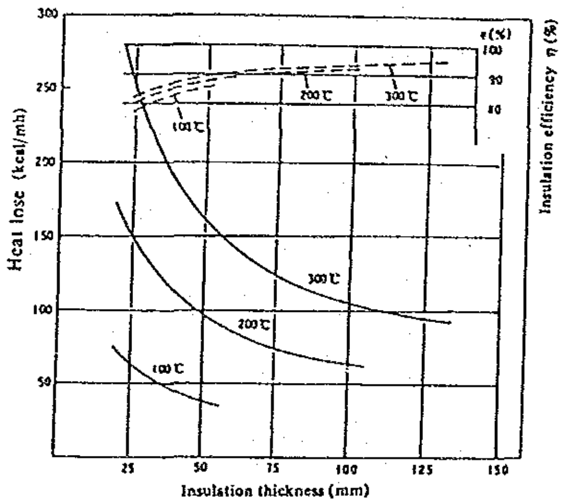


Figure 10.12 4" Piping

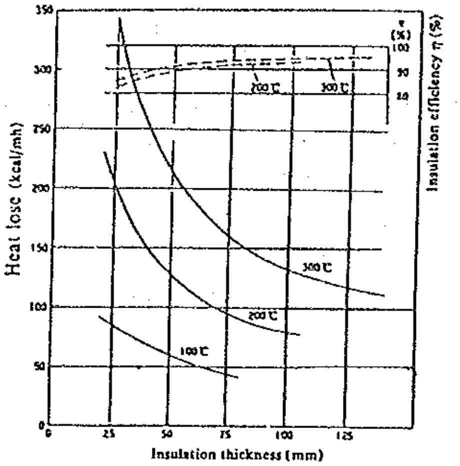


Figure 10.13 6" Piping

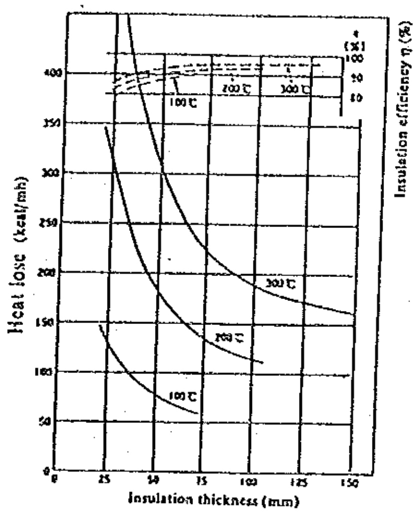


Figure 10.14 10" Piping

Heat insulation efficiency = $(Q_0-Q)/Q_0$
Q_0: Dissipated heat of bare pipe
Q: Dissipated heat after heat insulation

<Example of Figure 10.9>

When a heat insulation thickness of 100 mm is worked on 3" 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%).

10.4 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. In addition to prevention inflow of condensate occurring in the steam supply tube to the equipment, the occurrence of water hammer also must be prevented.

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 10.3.

Table 10.3 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 bucket type Inverted bucket type Free ball bucket 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.
Thermodynamic	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 opening 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 Figure 10.15.). 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 Figure 10.16.). This trap has a high reliability because there is little mechanical trouble. It has a continuous discharging characteristic of condensate.

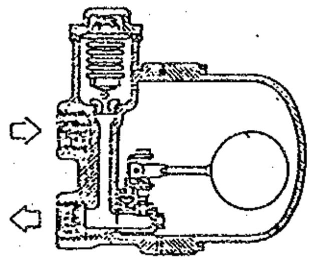


Figure 10.15 Float with lever type trap

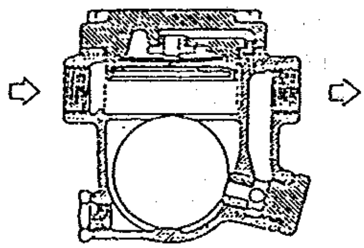


Figure 10.16 Free float type trap

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 Figure 10.17.).

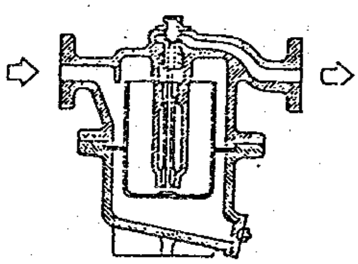


Figure 10.17 Open bucket type trap

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 Figure 10.18.). Deformation or abrasion of the lever might cause trouble.

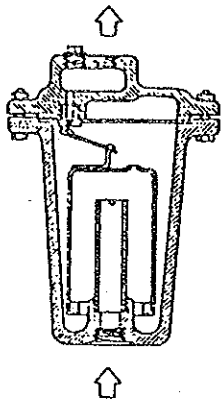


Figure 10.18 Inverted bucket type trap

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 (Figure 10.19.). 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.

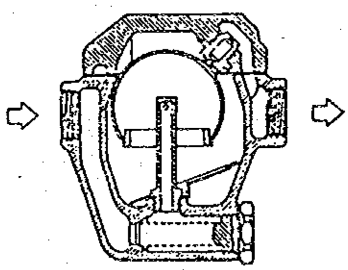


Figure 10.19 Free ball bucket type trap

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 Figure 10.20.).

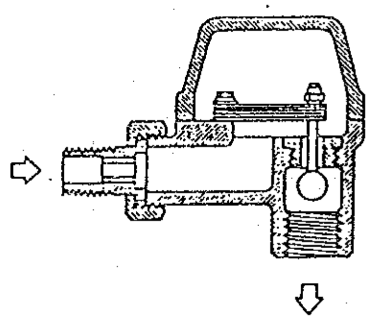


Figure 10.20 Bimetal type trap (Strip Type)

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 contractions of the enclosure due to the change of the liquid vapor pressure by temperature variation (See Figure 10.21.).

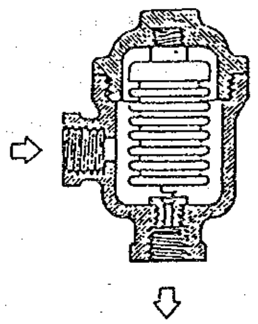


Figure 10.21 Bellows type trap

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.

When air or steam exists at the steam trap inlet, air locking or steam locking may occur easily and the condensate outflow may be impaired, so that care is required.

a. Impulse type trap

It is a trap utilized with fluid characteristics (when the condensate passes the orifice, some pressure drop is caused.) (Figure 10.22). 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 shuts and precision fitting part.

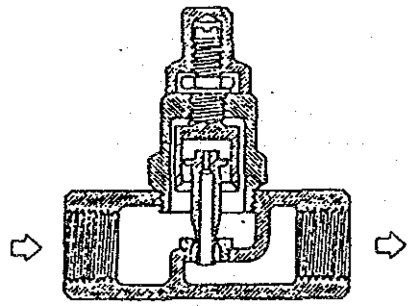


Figure 10.22 Impulse type trap

b. Disk 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 Figure 10.23.)

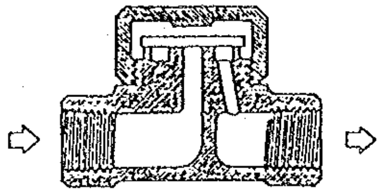


Figure 10.23 Disc type trap

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 condensate in case of rain and causes some heat loss.

(2) Steam trap selection

The following items must be investigated for the steam trap selection.

a. Condensate load of the steam use equipment and load characteristics

For decision of the steam trap size, the condensate quantity must be investigated and the steam trap tube diameter must be decided.

Simplified calculation of the condensate quantity is possible according to the following equation.

$$W_p = \frac{C \times G \times (T_2 - T_1)}{r}$$

with

Wp	: Condensate generation quantity	kg/h
C	: Specific heat of the heated fluid	kJ/(kg.°C)
G	: Weight of the heated fluid	kg/h
(T2 - T1)	: Temperature rise	°C
r	: Latent heat of the steam	kJ/kg

In addition, the amount carried in from the piping line, the radiation amount from the equipment, and condensate quantities generated otherwise are taken into consideration, and the generated condensate amount is made 1.5 to 2 times of the calculated value.

In case of continuous operation of the equipment, there are generally few load fluctuations. However, in the case of a batch process, start-up is executed several times per day, and with each start-up, large quantities of air and condensate must be discharged. In addition, from the point of view of productivity, the start-up time must be kept as short as possible, so that a trap with a sufficient discharge capacity must be selected. In the case of a bore of 1" and an operation pressure differential of 1.5 to 16 bar, the condensate discharge quantity is about 100 to 200 kg/h for a mechanical trap, 300 to 700 kg/h for a thermodynamic trap, and around 100 kg/h for a thermostatic trap.

b. Steam conditions (pressure, temperature, dryness)

For smooth condensate discharge, the following pressure differential is required over the steam trap.

- Mechanical or thermostatic trap: 0.1 bar (G) or more
- Thermodynamic trap: 0.3 bar (G) or more

On the other hand, blocking phenomena may occur with use at a pressure in excess of the max. use pressure.

c. Backpressure conditions

When condensate recovery is executed, the condensate is evaporated again, and a backpressure acts onto the trap.

$$\text{Permissible backpressure} = \frac{\text{Steam trap outlet pressure}}{\text{Steam trap inlet steam pressure}} \times 100\%$$

When the permissible backpressure is defined according to the above equation, the permissible backpressure differs according to the trap.

Mechanical trap: 90% or less
Thermostatic, thermodynamic trap: 30 to 50% or less

d. Maintenance conditions: Is there little trouble and is the life long? Are disassembly and inspection easy?

The following troubles can be considered for steam traps.

Blowing: This is caused by differential pressure failure or mechanical failure. Valve closing has become impossible for the trap. The trap continues to discharge a large quantity of steam together with the condensate. In this case, the production is not impaired, so that there is a tendency towards doing nothing, but the steam loss is large.

Blocking : The strainer is clogged by rust, scale, etc., the valve has become locked and can not open, and neither condensate nor air is discharged. As the trap has become cold, this can be confirmed easily.

When this condition occurs, a bypass valve must be opened in order to maintain the production, and a gigantic steam loss may be caused.

Steam leakage: This is caused by damage to valve, valve seat, or float. The trap operates, but in comparison to normal operation, the steam leakage is notably high.

As traps with a simpler construction have less trouble, simpler traps should be selected as far as possible.

e. Body material

Select a steam trap of a suitable material according to the used steam pressure.

- Up to 16 bar (G), 220°C: Cast iron (FC)
- Up to 20 bar (G), 350°C: Black heart malleable cast iron (FCMB)
- Up to 45 bar (G), 425°C: Cast steel (SCPH)

Table 10-4 shows the general caution items for steam trap selection.

Table 10-4 Steam trap selection

○ Appropriate　　△ Some problems　　× Problematic

	Control method		Processing method		Backpressure conditions	Air trouble	Pressure fluctuations	Others
	2-position control (ON/OFF)	Continuous control (P.PI, PID)	Continuous processing	Batch processing				
Downward bucket type	○ However, there is the problem of steam locking by reevaporation of drain in the trap at the time of control valve closing.	○ This is an intermittent discharge method, but as the inflowing drain is discharged quickly, there is little drain stoppage and the equipment efficiency is high. The permissible backpressure is high, and discharge is possible even at low pressure.	○ Structurally, the steam consumption amount is small, and the leakage steam amount also is small.	△ The drain discharge capacity is slightly low, so that the trap becomes large in order to maintain the equipment capacity. Large equipment expenses.	○ Permissible backpressure about 90%	○	△ The valve seat use pressure is divided, and when the use pressure range is exceeded, drain discharge becomes impossible.	• Large size → Large radiation • Strictly horizontal installation
Float type	× Float deformation damage from drain water hammer can occur at the time of control valve opening.	○ As this is a continuous discharge method, there is no drain stoppage and the equipment efficiency becomes high. The permissible backpressure is high.	○ As the discharge valve is below the water level, water sealing takes places, and the steam leakage amount principally is zero. However, the lever float type has loss from valve closing delay.	△ Same as above. There is the problem of air trouble at the time of start-up.	○ Same as above.	× However, there is no trouble when air blow equipment is installed.	△ Same as above.	Same as above.
Disk type	△ As the control valve opening/closing timing and the trap opening/closing timing are not the same, the control accuracy is bad.	× As this is an intermittent discharge method, drain stoppage increases, the equipment efficiency drops. The permissible backpressure is low, and blow-out occurs when the control valve is throttled.	× In many cases, steam leakage occurs at the time of steady operation (little drain generation).	△ The drain discharge capacity is high and the equipment start-up time becomes short, but steam entrainment occurs at the time of start-up, and in many cases, steam leakage occurs at the time of steady operation.	△ Permissible backpressure: 30 to 50% (Spouting occurs when the backpressure becomes high.)	×	○	• Small size and light weight • Vertical installation is possible.

(3) Steam trap installatin method

The installation place can be the lowest part of a riser, in front of a pressure-reducing valve or any other valve with automatic control, the drain separator, etc.

As the steam flow velocity in a steam transport pipe may be 20 to 30 m/s, a short pipe is connected to the lower part of the piping for removal so that the condensate can be separated easily. The basic rules for steam trap installation are that the condensate from the steam heating equipment shall flow smoothly by gravity flow to the trap, and that the condensate leaving the trap shall be sent by the steam pressure to the collection place. Figure 10.24 shows good and bad installation examples.

(4) Steam trap maintenance

A) Inspections

When steam traps are used for a long time, the internal mechanical parts like valve, valve seat, etc. become worn, the function is impaired, and they will not stand up to use. Also, the steam trap life becomes uncertain.

Accordingly, careful inspections must be executed at all times, and when trouble is detected, exchange or repair must be executed to maintain the equipment in good condition and to maintain highly efficient operation for the equipment using steam. Inspections are divided into periodic and daily inspections.

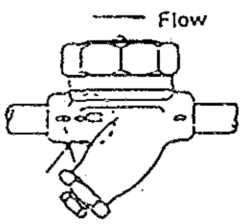
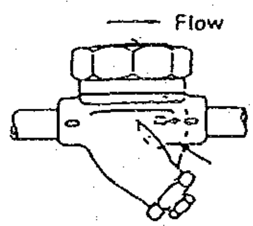
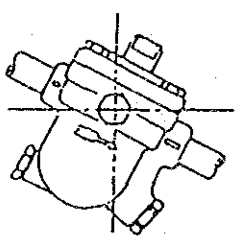
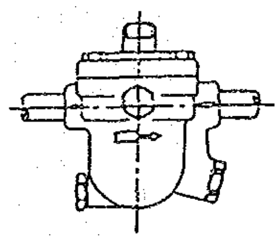
Wrong Installation	Description	Correct Installation
	Steam trap should be fitted in the direction of flow. All steam traps bear on the body stamp or mark showing flow direction.	
	Free float type steam trap should be fitted horizontally.	

Figure 10.24 Good example and worse example of Installation (1/4)

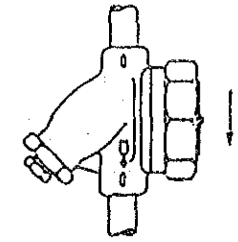
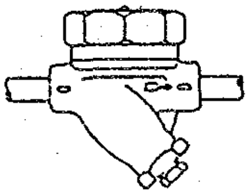
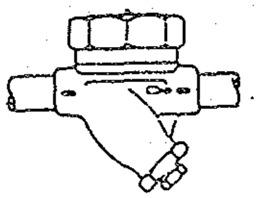
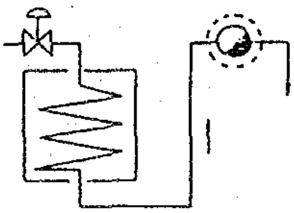
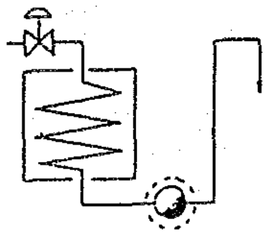
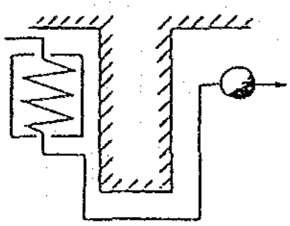
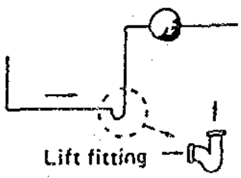
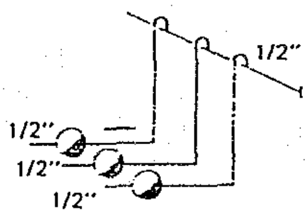
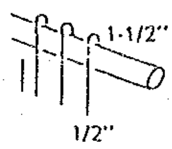
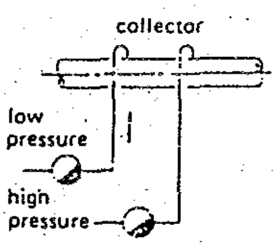
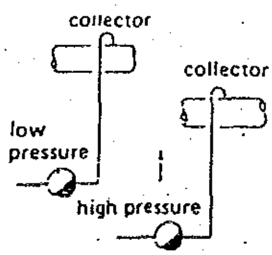
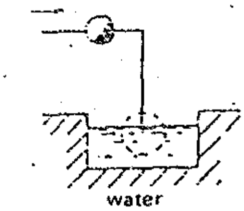
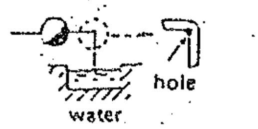
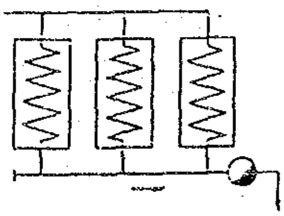
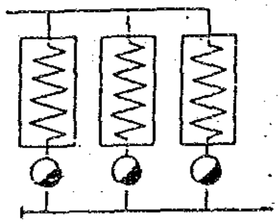
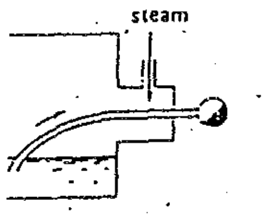
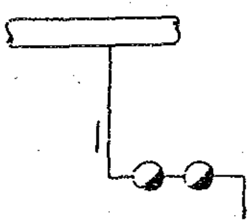
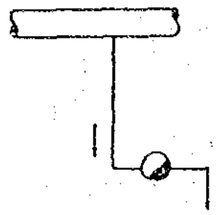
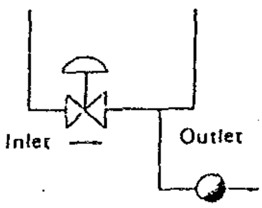
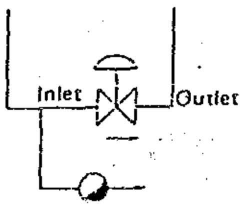
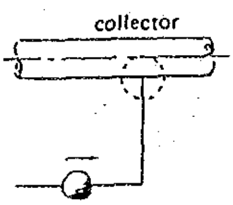
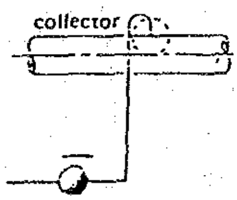
Wrong Installation	Description	Correct Installation
	Thermodynamic steam traps have no limitation as to position. It can be fitted vertically.	
	Never use an inlet pipe smaller than trap size. Steam locking and air binding are apt to occur when inlet pipe is too small.	
	Never install steam trap at a 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.	
	Condensate discharged through two traps which operate at different pressures should not be collected to a common collector.	

Figure 10.24 Good example and worse example of installation (2/4)

Wrong Installation	Description	Correct Installation
	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.	

Good example and worse example of Installation (3/4)

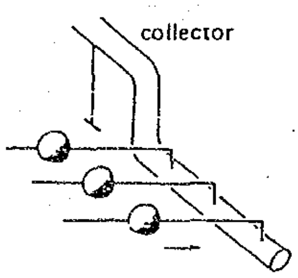
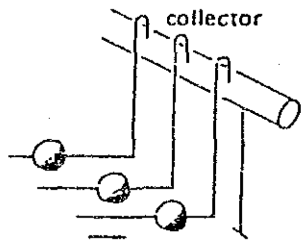
Wrong Installation	Description	Correct Installation
	Collector should not have a riser. The head of condensate in the collector exerts on the traps as a back pressure.	

Figure 10.24 Good example and worse example of installation (4/4)

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

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 not to 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.

10.5 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 Figure 10.25. If this heat contents of condensate is recovered 100% and utilized effectively, the fuel consumption can be saved by approximately 10 to 13%. This will result in large energy conservation.

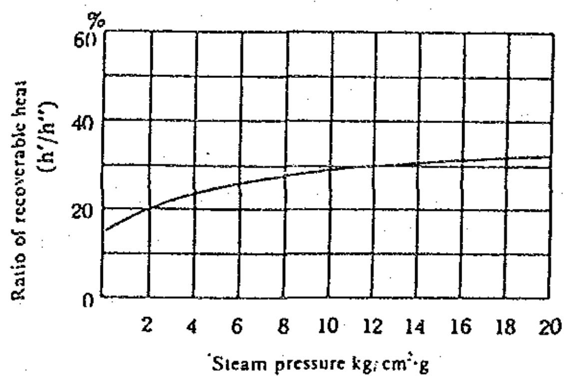


Figure 10.25 Ratio of recoverable heat (enthalpy of condensate/enthalpy of saturated steam)

(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 Figure 10.26.).

In this case, high-pressure condensate is discharged to the atmosphere, so that flash steam is generated, and care is required as this will escape into the atmosphere and cause a loss when it is not finely dispersed and absorbed in water.

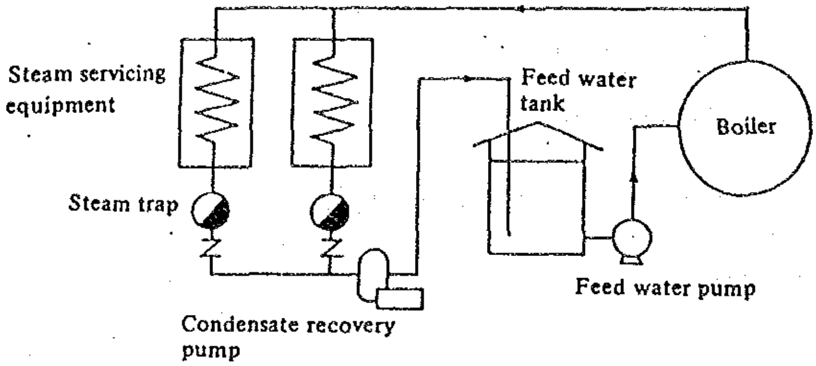


Figure 10.26 Direct utilization to feed water tank

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 (Figure 10.27).

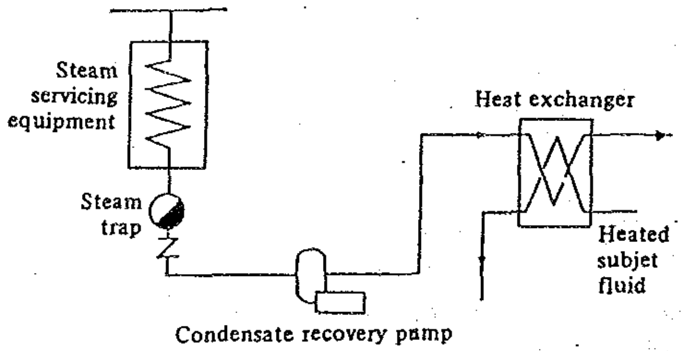


Figure 10.27 Indirect utilization through heat exchanger

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 Figure 10.28.).

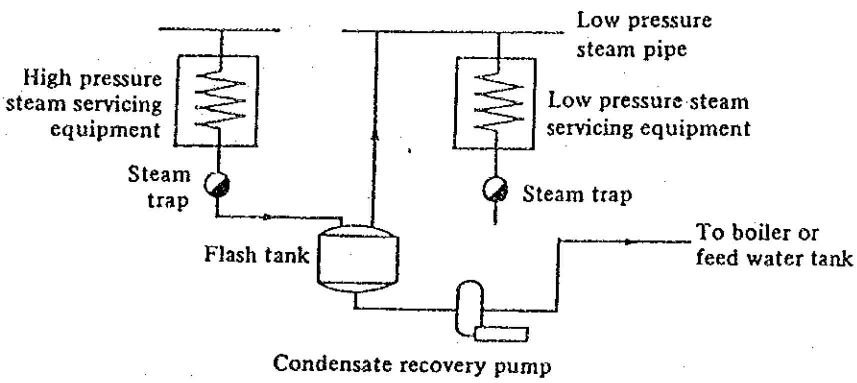


Figure 10.28 Flash steam utilization

(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 Figure 10.29).

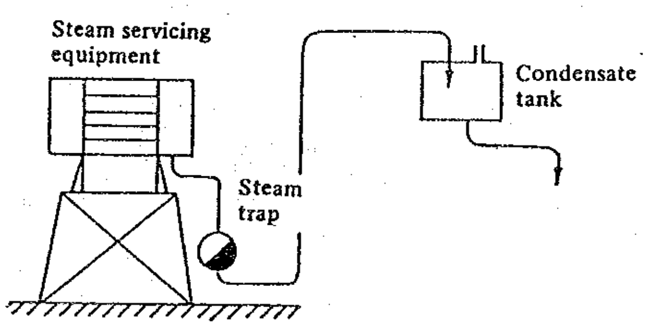


Figure 10.29 Recovery by steam trap only

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 Figure 10.30).

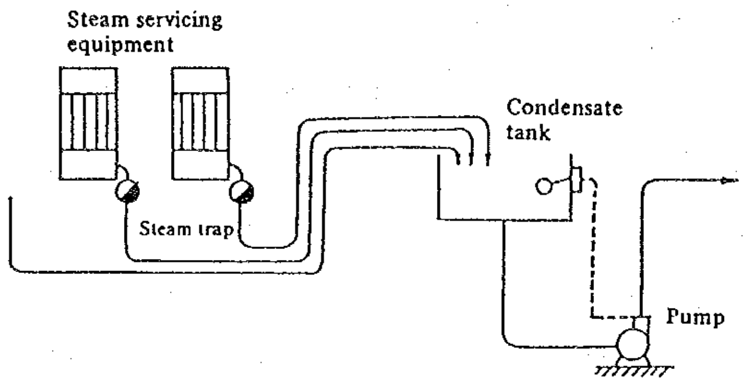


Figure 10.30 Recovery by centrifugal pump

In this case, care must be used for ensuring the water head of the pump, a level control of condensate tank, 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 centrifugal 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 (Figure 10.31).

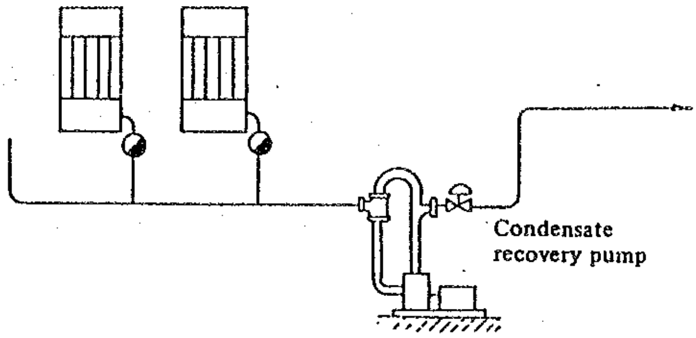


Figure 10.31 Recovery by condensate recovery pump

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

(4) Caution items for condensate recovery

A) Steam trap backpressure limit

When a backpressure acts onto the steam trap and when the conditions change, select a mechanical trap with little trouble. The backpressure of the recovery piping should be 40 to 45% of the min. pressure of the used steam or less.

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) Appropriate selection off the condensate recovery pipe

In case of piping systems with different backpressure, separate condensate recovery pipes must be installed for each pressure system.

In case of occurrence of flash steam, two-phase flow occurs, so that the pipe diameter must be set so that the flow velocity is within max. 15 m/s, and excessive pressure loss and water hammer must be prevented.

The pipe diameter for the recovery piping can be obtained from the following equation.

$$d^2 = \frac{3.53 \times W \times ve}{V}$$

with

d : Piping inside diameter, cm

W : Condensate quantity, kg/h

V : Flow velocity in the pipe, m/s

Open recovery : 10 to 15 m/s,

closed recovery: 5 to 10 m/s

ve : Equivalent specific volume

$$ve = v' (1 - f) + v''f$$

v' : Specific volume of saturated water at the pressure inside the recovery pipe, m^3/kg

v" : Specific volume of saturated steam at the pressure inside the recovery pipe, m^3/kg

f : Reevaporation ratio

$$f = \frac{h_1 - h_2}{r}$$

h_1 : Condensate enthalpy at the trap inlet side, kJ/kg

h_2 : Condensate enthalpy at the pressure inside the recovery pipe, kJ/kg

r : Evaporation latent heat at the pressure inside the recovery pipe, kJ/kg

When the recovery pipe is long, the pressure loss becomes large, so that the pressure inside the recovery pipe must be decided under consideration of the pressure loss, especially in case of self-pressure recovery.

Example for calculation of the pipe diameter:

$W = 300$ kg/h

$V = 10$ m/s

$h_1 = 670.4$ kJ/kg (6 bar)

$h_2 = 467.1$ kJ/kg (1.5 bar)

$r = 2{,}226.2$ kJ/kg (1.5 bar)

$v' = 0.00105$ m³/kg

$v'' = 1.159$ m³/kg

$$f = \frac{670.4 - 467.1}{2{,}226.2} = 0.0091$$

$ve = 0.00105 \times (1 - 0.0091) + (1.159 \times 0.091) = 0.1065$ m³/kg

$d = (3.53 \times 300 \times 0.1065/10)^{1/2} = 3.4$ cm

Accordingly, a 1-1/2" pipe is used.

D) Insulation

Thermal insulation shall be executed for the recovery piping. The piping shall be routed so that it will not get wet easily.

E) Flash loss prevention

Discharge of the flash steam generated when the condensate is depressurized to atmospheric pressure shall be prevented. When the condensate is led into liquid in the recovery tank, cooling shall be executed so that the temperature in the recovery tank does not exceed 90°C, and water shall be replenished.

As vibrations or noise may be caused when the temperature in the tank exceeds 80°C, a large number of small holes shall be provided and the condensate shall be dispersed widely.

The method with direct recovery of the condensate into the boiler, without depressurization, is most effective to prevent this loss.

F) Sight glass installation

A sight glass shall be installed in the recovery piping for monitoring of trap steam leakage.

G) 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 (2) C), 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. 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.

Figure 10.32 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 bar(G) is used by 2,500 kg/h and condensate is discharged into a flash tank of 0.5 bar(G) of internal pressure, the quantity of flash steam is generated with 12.3% (wt.) by Table 10.5 and a steam quantity of 307.5 kg/h is obtained.

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.

Figure 10.33 shows a chart to decide the inside diameter of the flash tank.

Obtain the inside diameter of the tank through the example shown in Figure 10.32.

Obtain the intersection of the steam pressure of 8 bar(G) in the high pressure side and the internal pressure of 0.5 bar(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 0.55 m. 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.

Table 10.5 Flash steam generating rate (wt.%)

Pressure in high pressure side (bar(G))	Low pressure side (bar(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

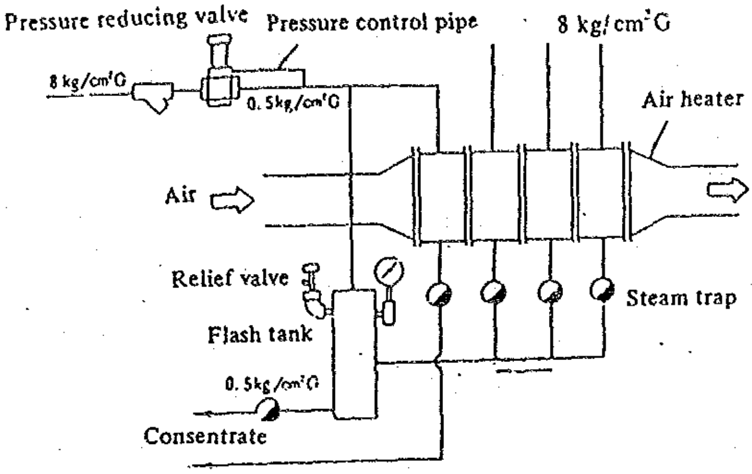


Figure 10.32 Example of flash steam use in air heater

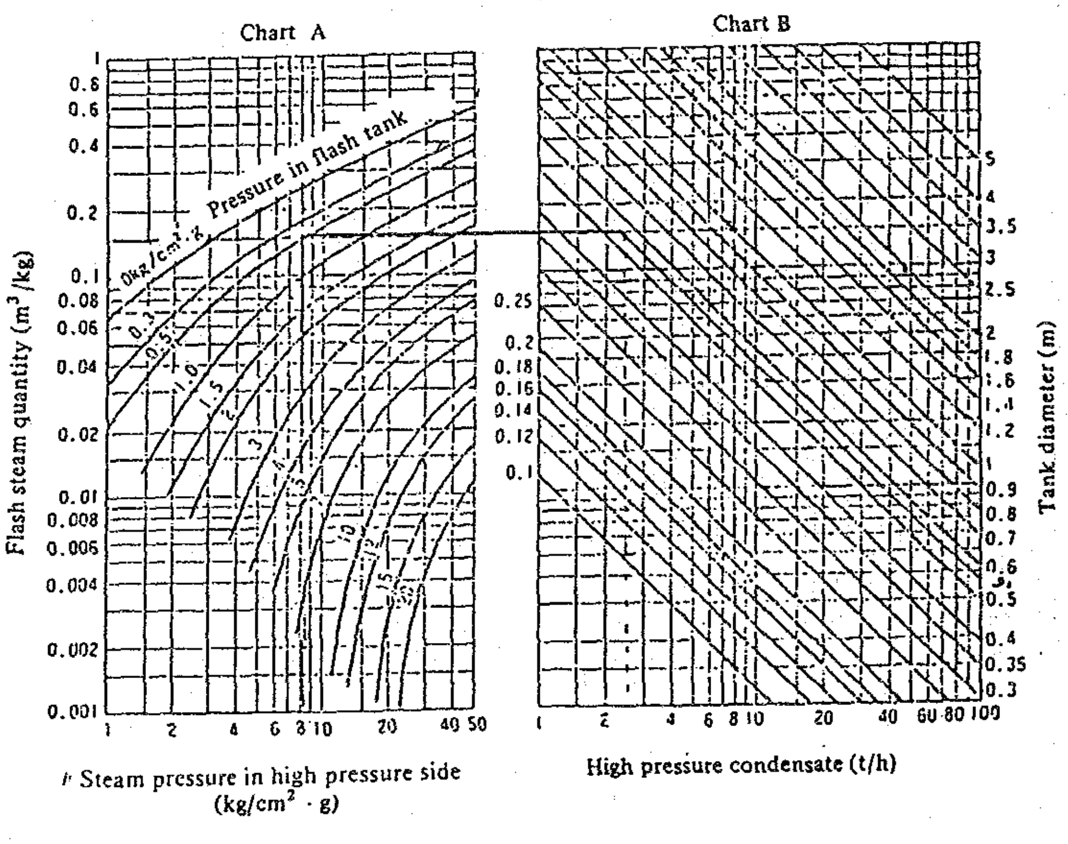


Figure 10.33 Chart of flash tank diameter

(6) Utilization of thermocompressors

The structure of thermocompressors is composed of three basic parts, body, a steam nozzle and diffuser as shown in Figure 10.34. 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.

Figure 10.35 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.

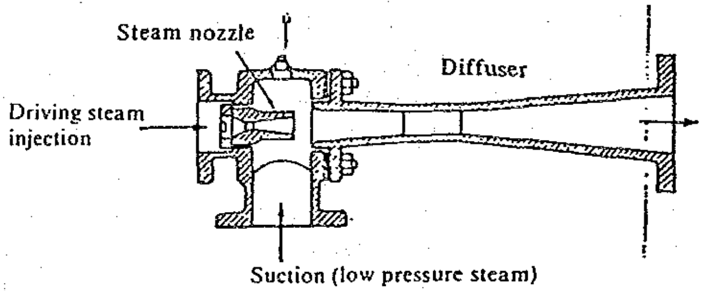


Figure 10.34 Thermocompressor

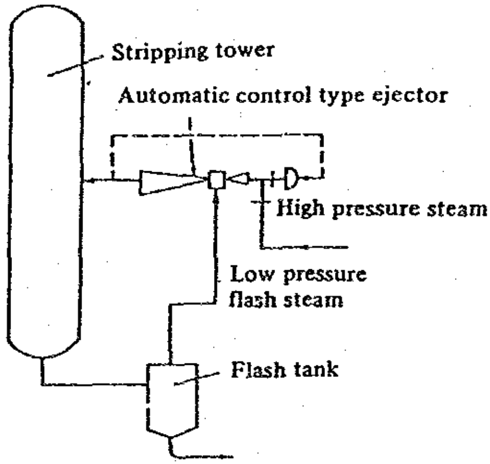


Figure 10.35 Example of thermocompressor use for stripping tower

10.6 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 than 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 10.6.

Table 10.6 Relation between the air mixing ratio and steam temperature

Steam Pressure bar / 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 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 Figure 10.36 and Figure 10.37).

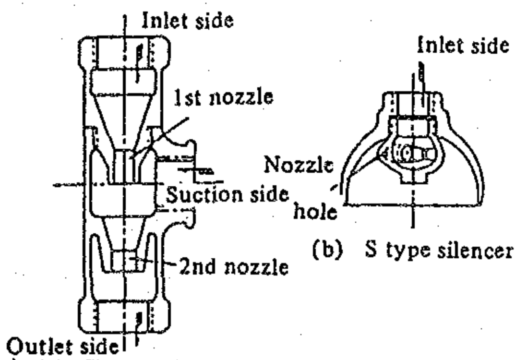


Figure 10.36 Silencer

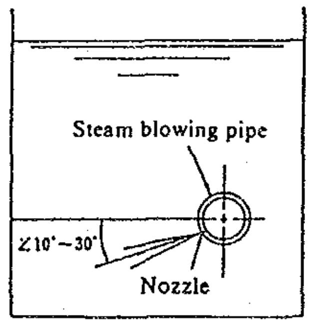


Figure 13.37 Steam blowing angle from nozzle

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

a. Reduce the velocity of steam bubbles blown 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 Figure 10.37).

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 Figure 10.38. 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.

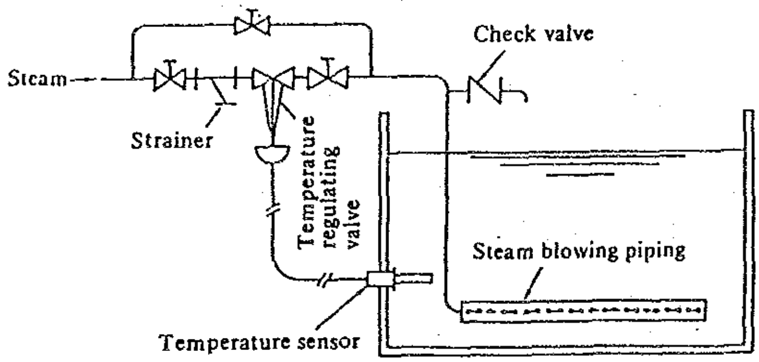


Figure 10.38 Steam direct blow-in heater

11. Electric Power Conservation

11. ELECTRIC POWER CONSERVATION

11.1 Electric Power Management

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

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

(1) Improvement of the electric power consumption rate

(2) Improvement of the power factor

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

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

(2) Electric power management

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

(3) Equipment management

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

(4) Process control

Rationalize the operation processes and improve the layout.

(5) Quality control

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

(6) Participation by all employees

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

11.1.2 Improvement of the Power Factor

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

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

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

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

ϕ: Phase difference between voltage and current

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

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

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

(1) Reduction effect of Distribution Line Loss

Since power loss in the distribution line is given by (Line current)^2 × (Line resistance), reduced distribution line loss (P_L) to be obtained by providing with a phase-advancing capacitor to improve the power factor in Fig. 11.1 is determined by the following equations:

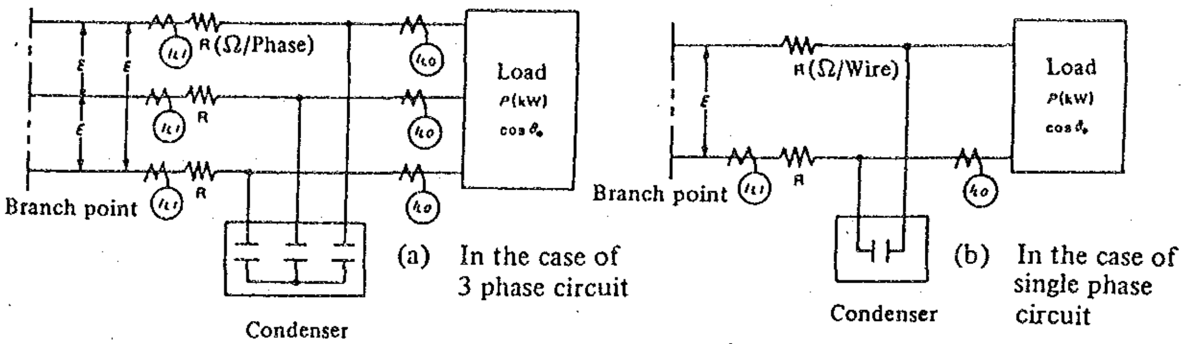


Figure 11.1 Reduction effect of distribution loss

A) Equation for three phase circuit

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

Where

Before improvement

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

After improvement

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

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

Hence,

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

In equation (5), substituting

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

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

Where,

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

Hence,

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

B) Equation for single phase circuit

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

Where

Before improvement

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

After improvement

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

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

Hence,

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

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

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

Where

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

C) Calculation example

Reduced loss in the model system of three phase distribution line is calculated by using the preceding equation (7), as is shown in Table 11.1.

Table 11.1 Calculation example of reduction effect of loss in 3 phase distribution line due to power factor improvement

Resistance value of distribution line and cable R: (Size of electric wire)	Length of wiring ℓ	Present power factor ($\cos\theta_0$)	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)	500 m	0.60	131A	87.3A	82.7A	2.87 kW	3.10 kW
		0.70	131	102	96.5	2.04	2.30
0.13 (150sq) or equivalent	500	0.60	219	146	138	5.18	5.61
		0.70	219	170	161	3.68	4.26
0.10 (200sq) or equivalent	500	0.60	262	175	165	5.74	6.21
		0.70	262	104	193	4.08	4.72
0.08 (250sq) or equivalent	500	0.60	306	204	193	6.25	6.76
		0.70	306	238	225	4.44	5.14
0.06 (325sq) or equivalent	500	0.60	350	233	221	6.12	6.62
		0.70	350	272	258	4.35	5.04

(2) Reduction effect of transformer loss

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

A) Equation

Reduced transformer loss (P_t) when the power factor is improved by a phase-advancing capacitor on the secondary side of the transformer as shown in Fig. 11.2 is determined by the following equations:

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

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

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

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

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

Where,

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

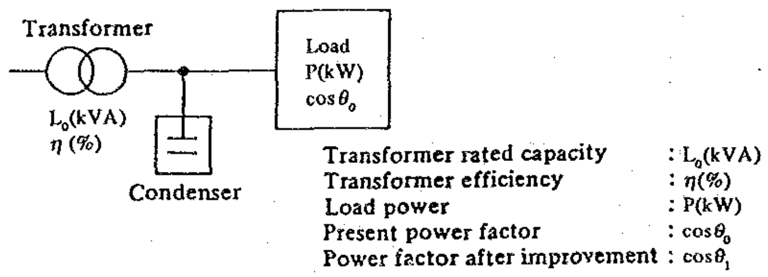


Figure 11.2 Reduction effect of transformer loss

The calculation example of reduced transformer loss using preceding equation (14) is shown in Table 11.2.

Table 11.2 Calculation example of reduction effect of transformer loss

Transformer specification		L_0=300kVA η=98%			L_0=500kVA η=98.5%			L_0=1,000kVA η=99%		
P/L_0		0.5	0.6	0.7	0.5	0.6	0.7	0.5	0.6	0.7
	$\cos\theta_0 \rightarrow \cos\theta_1$ 0.60 → 0.90	kW 1.89	kW 2.72	kW 3.70	kW 2.35	kW 3.39	kW 4.61	kW 3.12	kW 4.49	kW 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 (P_l) is determined from equation (14).

(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, 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:

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

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

Qc : Capacity of capacitor (kVA)

C) Example of calculation

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

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

(4) Increased surplus capacity for distribution equipment

Load on transformer and distribution equipment in distribution line 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) (k_3) is determined.

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

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

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

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

Example:

When a 100 kW load at a power factor of 70% is improved to 95% of the power factor, k_3=0.36. That is, a load of 100 kW × 0.36 = 36 kW (power factor 95%) can be increased with the present equipment as it is.

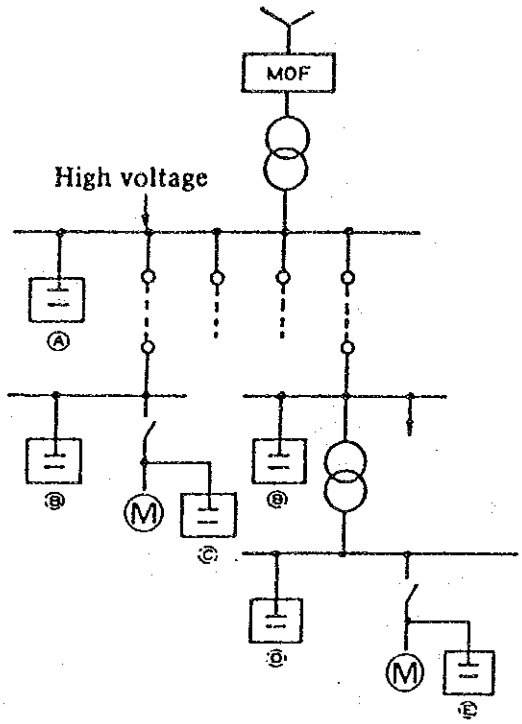
(5) Reduced electric charge

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. 11.3.



(A) Incoming high voltage bus
(B) Sub s/s high voltage bus
(C) High voltage load direct
(D) Low voltage bus lump
(E) Low voltage load direct

Figure 11.3 Connection points of capacitor

a. Receiving power factor improvement

The improvement 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 utilization factor (operating time) will be, the total capacity of required capacitors will be the larger. In Fig. 11.3, when capacitors are centralized to (A), a required capacitor capacity may be calculated for mean power of all loads, while when dispersed to (B) to (E), a capacitor capacity to meet load for a restricted area must be calculated.

c. Reduction 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 reduction will be and the longer the line length is, the greater the reduction will be.

d. Increased equipment margin capacity

Increased equipment margin capacity due to installation of a 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 margin capacity is increased, for example, it is no worth if there is no space to expand or no planning to increase load in the future.

e. Reduction of voltage drop

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

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. 11.3, (C), (E)).

b. Collectively install at point of concentrated small loads.

(See Fig. 11.3, (B), (D)).

c. Connect the capacitor for improving receiving power factor to the receiving high voltage bus (Fig. 11.3, (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 switching 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. 11.4.

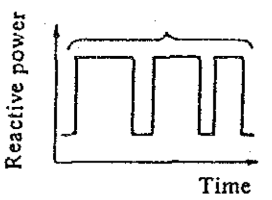
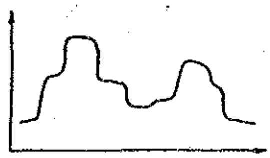
Load fluctuation pattern	(Same every day) 	(Changes every day) 
Applied control system	Reactive power control Current control Program control	Reactive power control

Figure 11.4 Capacitor control system

11.1.3 Improved Load Factor

Since 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.

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

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 demand charge by lowering the maximum power.

The method for improving the load factor is shown as follows.

(1) Draw and study the daily-load curve

A graph representing the change of power consumption in relation to time is drawn, and using this daily-load curve, the load shift which would average out the load through-out the day as possible should be determined.

(2) Extend the operating hours

The extension of the facility operating hours is attempted through its mechanization and automatization, for using the facility evenly throughout the day.

(3) Shift load to the light-load time such as late night

The peaks will be reduced through such measures as the operation of the air conditioning and heating systems late at night by using the heat accumulation, using the electric power equipment for only late at night, and the shift of operations of the large-capacity equipments and test equipments to the light-load hours or practicing time-differential operations.

(4) Promote an appropriate maintenance of the installations

It is necessary to promote appropriate preventive maintenances and productive maintenances in order to limit malfunctions to a minimum and to equalize the load.

(5) Improvement of the transport and preparation works

It is necessary to attempt the reduction of idle hours and empty operation, to improve transport, preparations, and layout so that work progresses smoothly, and to conduct appropriate operational control.

(6) Introduction of the load control

Installing demand controller, Load controller, etc would be one method to limit the maximum power and to control load.

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.

11.1.4 Higher Harmonics Generation and its Control Methods

(1) Causes of higher harmonics

a. With the advance of power electronics, thyristors etc. are used widely from OA equipment to industrial machines. Thyristor control is easy and the response is fast, but by cutting the waveform as the firing angle is changed, waveform distortion is caused and higher harmonics are caused.

b. During the initial melting phase of an arc furnace for steel making, voltage flicker is caused each time when the electrodes are short-circuited by scrap iron, the voltage waveform gets out of shape, and higher harmonics are caused.

c. On equipment like reactors and rotating equipment with magnetic circuits waveform gets out of shape because of core hysteresis phenomena and this is promoted by magnetic saturation, and higher harmonics are caused.

(2) Influence of higher harmonics

a. Higher harmonics become the cause for capacitor overheating and burning because of an increase of the effective current value.

b. The electromagnetic force of higher harmonics causes abnormal noise for series reactors of capacitors etc.

c. For induction motors, vibration torque is caused by the higher harmonics current, and this becomes the cause for vibrations and abnormal noise.

d. Higher harmonics electromagnetic noise increases, and flicker is caused for fluorescent lamps with light controllers.

e. Waveform distortion causes shift of synchronization with the commercial power frequency, and this becomes the cause for the following malfunction because of control circuit phase deviation.

- Computer stop
- NC equipment stop
- Stop of rotating equipment like rolling mills etc.

(3) Countermeasures for suppression of higher harmonics

The following countermeasures are taken to keep the higher harmonics below the permissible distortion rate for computers.

a. Active filters

In case of rectangular wave current, the difference between the rectangular wave current, synthesized from the fundamental wave and the various higher harmonics, and the fundamental sinusoidal wave current becomes the higher harmonics current. By instantaneous supply of the current with the opposite polarity of this higher harmonics current from the outside active filter, the higher harmonics component is eliminated.

b. AC filter

R, C, L series single shunt filters are used for the sources of fifth to thirteenth higher harmonics. Further, L, R parallel circuits in series with C are used as shunt filters for still higher harmonics.

c. Change to multiphase power transducers

For example, when the number of phases is increased from 3 to 12 phases, the ripple decreases and the higher harmonics are suppressed.

11.2 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

11.2.1 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)

$\cos\phi$: 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 11.3. However, it may exceed 10 in the energy conservation type transformers as described later.

Table 11.3 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 loss (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. 11.5.

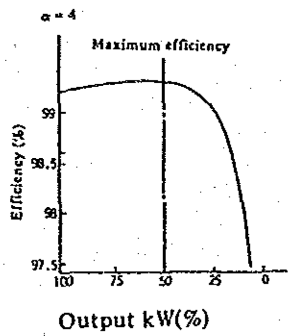
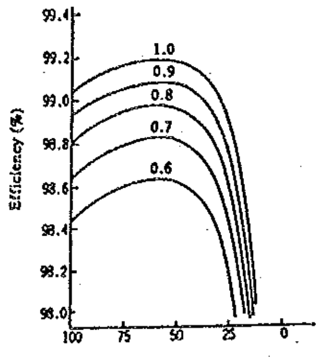


Figure 11.5 Transformer efficiency (Example)

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

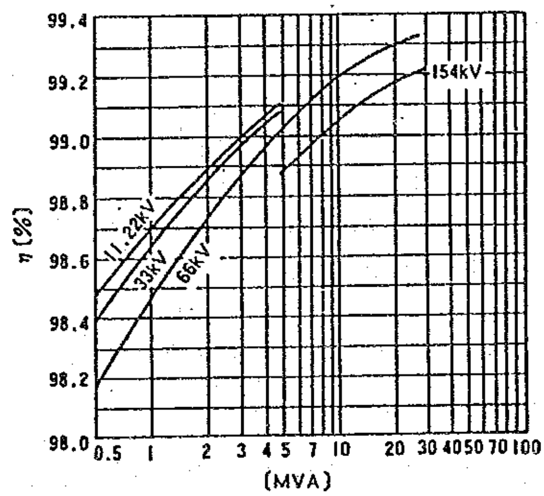
This example is shown in Fig. 11.6.



Note: Figure indicates power factor.

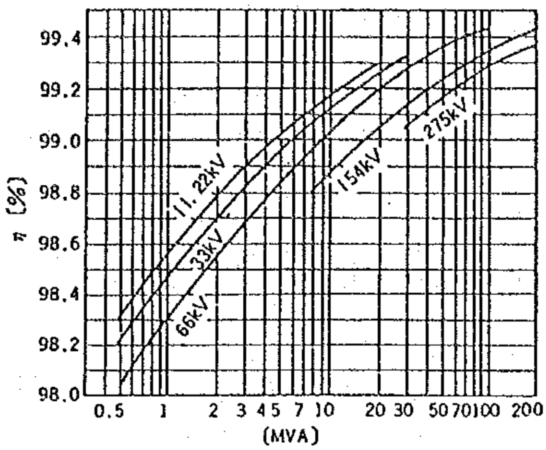
Figure 11.6 Relation between power factor and efficiency

The difference of efficiency due to the transformer capacity is shown in Fig. 11.7.



Example of efficiency of 50 Hz single oil immersed transformer

Figure 11.7 Example of efficiency of 50 Hz transformer (1/2)



Example of efficiency of 50 Hz 3 phase oil immersed transformer

Figure 11.7 Example of efficiency of 50 Hz transformer (2/2)

(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".

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

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.

(3) Energy conservation type transformers

Some transformers that use the laser treated plate of silicon steel belt for the core material and employ wound core construction are manufactured. They are called conservation type transformers with the iron loss approximately 40% of the conventional types. Anybody purchasing transformers had better keep above for future reference.

11.2.2 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. 11.8, 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 11.3.

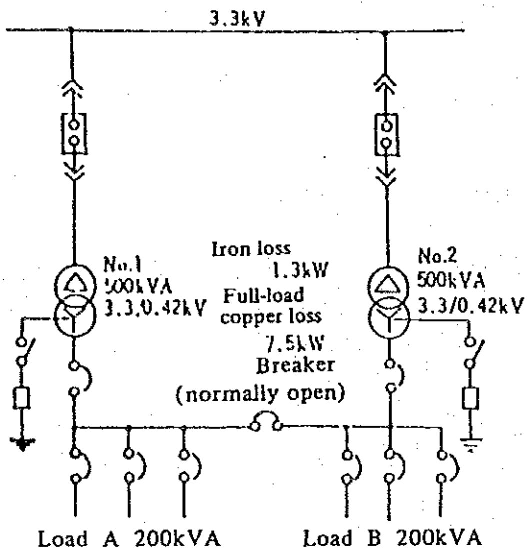


Figure 11.8 Method to use two 50 kVA transformer

At present, for both transformer No. 1 and transformer No. 2, Iron loss = 1.3 (kW)

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

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)

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

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

Total loss = 1.3 + 4.8 = 6.1 (kW)
Stopping one transformer increases the loss by 1.1 kW.

(2) 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:

$$W_N = N\left\{W_i + \left(\frac{P_L}{N \cdot Q}\right)^2 W_c\right\} \quad (\text{kW})$$

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:

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

In case of $W_n > W_{N-1}$, $(N-1)$ units operation is better for loss decreasing, so we get

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

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.

(3) 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.

11.2.3 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 11.4 and Table 11.5. When all loads for the transformer are motors, it is desirable to select the taps in the light of these.

Table 11.4 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 11.5 Relation between voltage fluctuation and loading state of induction motor

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

11.3 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 it in a small scale.

Each of these will be discussed below:

11.3.1 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 considering the motor energy conservation are shown in Table 11.6. For reasons of space, the description is omitted, but see the technical books for reference.

Table 11.6 Basic and practical expressions relating to motor application

Formulation item	Basic expression	Practical expression	Description of symbols
1 Power and torque	$P = \omega T$	$\begin{cases} Pk[kW] = P \times 10^{-3} \\ N[rpm] = \frac{60}{2\pi}\omega \\ Tg[kg-m] = \frac{T}{g} = \frac{T}{9.81} \end{cases}$ $Pk[kW] = \frac{N[rpm]}{973} \times Tg[kg-m]$	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 accelera-tion torque	$J\frac{d\omega}{dt} = T$	$GD^2 = 4J$ $Tg[kg-m] = \frac{1}{375} GD^2 \cdot \frac{dN}{dt}$	J : Moment of inertia (kg m²) GD²: Flywheel effect
3 Acceleration time	$t = \int_0^{\omega_0} \frac{J}{Ta} d\omega[sec]$	$\overline{Ta} = \frac{\int_0^{\omega_0} Ta(\omega)}{\omega_0} d\omega$: $ta[sec] = \frac{1}{365} \frac{GD^2 N_0^2[rpm]}{P[W]}$	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)

(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 Table 11.7. When the conditions shown here are clear, it is possible to select the motor and also to select the control equipment to follow it.

Table 11.7 Conditions for motor selection

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

Although motor systems are classified into DC, induction and synchronous machines in Table 11.7, 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 in the following item (3):

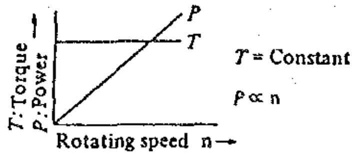
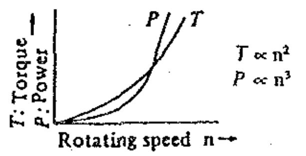
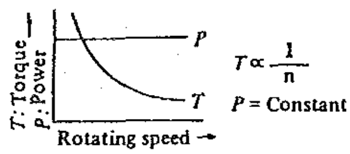
(3) *Torque characteristics of load*

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 or its square, 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 11.8.

Table 11.8 Class of load and torque speed characteristic

Load characteristic		Typical load
Constant torque load		Gravity load, Friction load [Example] Crane, Winding machine, Conveyor, Paper machine, Mixer
Increasing torque load		Fluid load [Example] Blower, Pump
Constant output load		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 (k•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

$$t = \int_0^{N_0} \frac{GD^2 \cdot dN}{375(T_M - T_L)} \text{ second} \quad \cdots\cdots (2)$$

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: $G_1D_1^2$, GD^2 of machines: $G_2D_2^2$ and reduction ratio: $n_1/n_2 = n$ as shown in Fig. 11.9, GD^2 converted to the motor side is:

$$GD^2 = G_1D_1^2 + \frac{1}{n^2} G_2D_2^2 \quad \cdots\cdots (3)$$

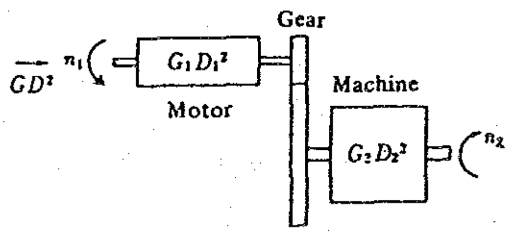


Figure 11.9 Conversion of flywheel effect

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

(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,

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

Assuming = 0 at t=0,

$$\theta=\frac{Q}{A}(1-\varepsilon^{-\frac{t}{T}}) \quad \cdots\cdots (4)$$

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. 11.10. Also, the thermal time constant normally will be as shown in Table 11.9. 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,

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

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

T′: Thermal time constant during cooling
A′: Heat radiant coefficient during cooling
θ_0: Temperature when cooling starts.

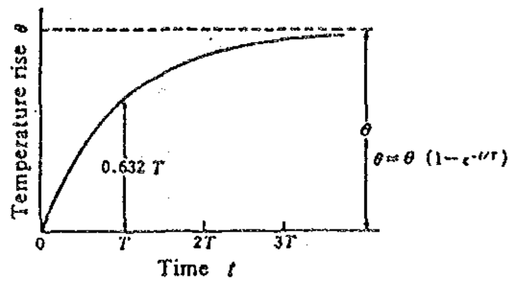


Figure 11.10 Temperature rise curve of motor

Table 11.9 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

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.

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 expression are used (See Table 11.10).

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

Table 11.10 Frame number application table

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

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, ... t_n for load of P_1, P_2, ... P_n during one period T, the equivalent load as Pa

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

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

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

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. 11.11 is determined in the following way:

$$P_a=\sqrt{\frac{P_1^2t_1+P_2^2t_2+P_3^2t_3}{t_1\alpha_1+t_2\alpha_2+t_3\alpha_3+t_4\alpha_4}} \quad \cdots\cdots (7)$$

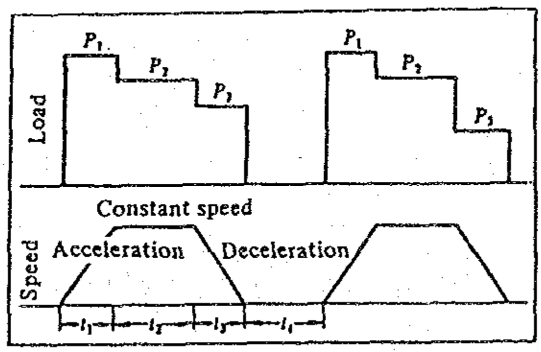


Figure 11.11 Example of periodic load

Table 11.11 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

However, α is heat extraction coefficient and its value is as shown in Table 11.11.

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.

E) Determination of motor capacity

When the rated output of motors is 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. 11.12,

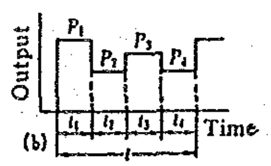


Figure 11.12 Example of load curve (1)

P_1 = 100 kW, t_1 = 10 minutes
P_2 = 50 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

$$P=\sqrt{\frac{100^2\times10+50^2\times15+80^2\times10+50^2\times20}{10+15+10+20}}=67.6\text{kW}\fallingdotseq 70\text{ kW}$$

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 a motor for crane is periodically used as shown in Fig. 11.13.

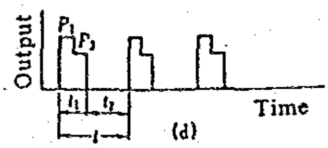


Figure 11.13 Example of load curve (2)

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

$$P=\sqrt{\frac{50^2\times1.5+30^2\times1.5}{3}}=41.2\text{ kW}$$

Accordingly, a motor corresponding to 40% ED 45 kW may be selected from Table 11.10.

(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. 11.14 shows the comparison in efficiency between 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 100 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.

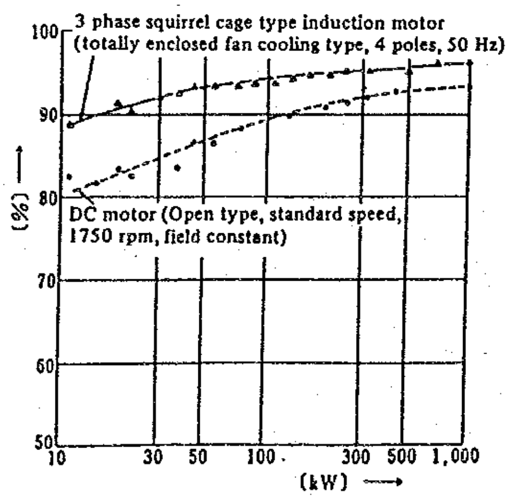


Figure 11.14 Comparative example of efficiency for induction and DC motor

B) Synchronous and induction motors

Fig. 11.15 shows the comparison in efficiency between synchronous and induction motors.

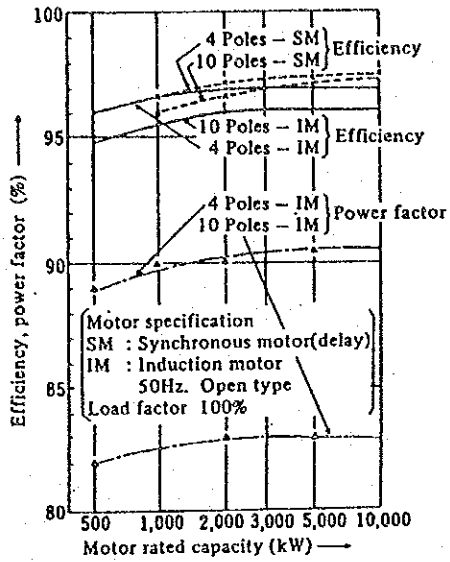


Figure 11.15 Comparative example of efficiency and power factor between synchronous and induction motors

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 power factor or terminal voltage. Since the power factor considerably lower 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.

e. It should be noted that since salient-pole synchronous motors are, in general, not provided with so large torque as induction motors, it is not easy for them to start up with large inertia moment load or large torque load.

C) Induction motor and its number of poles

Fig. 11.16 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.

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.

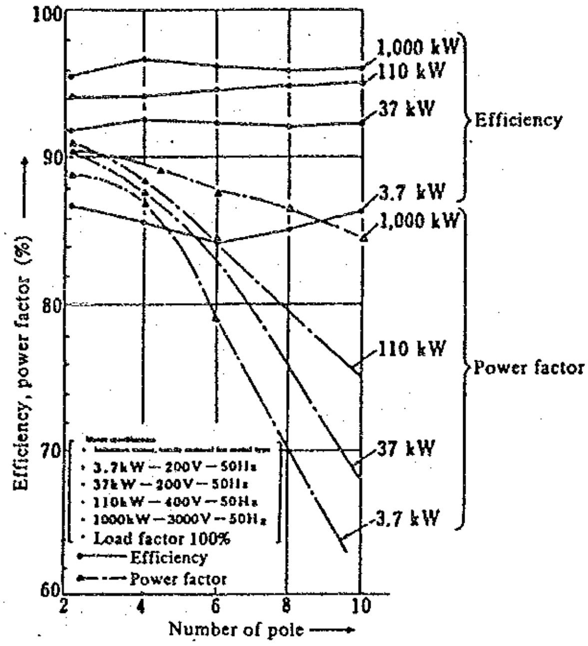


Fig. 11.16 Relation between number of pole, efficiency and power factor of induction motors

(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. 11.17 shows the optimum 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.

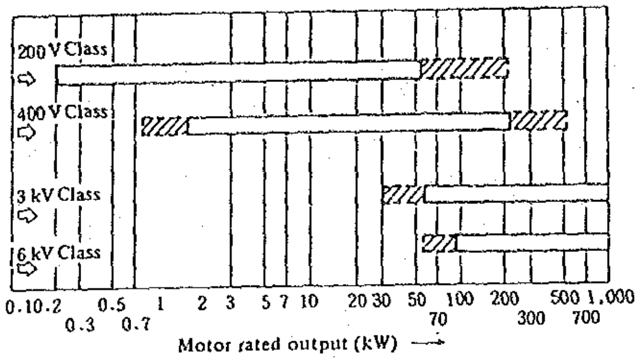


Figure 11.17 Optimum output range of motor

(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. 11.18 and Fig. 11.19 show comparison in efficiency between high-efficiency motors and standard type motors which are being manufactured at present. It should be noted in Fig. 11.19 that the high-efficiency motors are remarkable in the improvement of efficiency at light load.

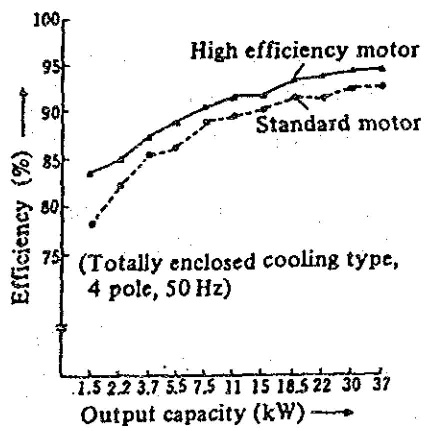


Figure 11.18 Efficiency comparison of 3 phase squirrel cage type induction motor

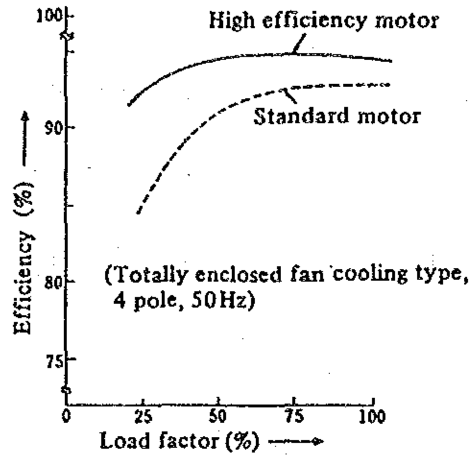


Figure 11.19 Efficiency comparison of 3 phase squirrel cage type induction motor

11.3.2 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. 11.20 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 investing these two.

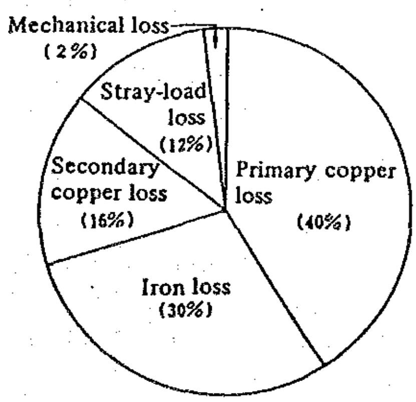


Figure 11.20 Loss analysis example of standard 3 phase induction motor

The copper loss is a resistance loss which occurs by current flowing through the induction motor startor 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.

$$W_c = 3(r_1 + r_2')I'^2_2 (W) \quad \cdots\cdots (8)$$

Where

W_c : Copper loss

r_1 : Resistance of primary winding each phase (Ω)

r_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.

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

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

$$W_C \fallingdotseq (r_1 + r_2') \frac{\omega_0^2 T^2}{3V_1^2} (W) \quad \cdots\cdots (10)$$

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 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 steel 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 fB are in proportion to the voltage, the iron loss W_i is:

$$W_i = W_e + W_h = k_1(dfB)^2 + k_2 fB^2 = V_1^2(k_1' + \frac{k_2'}{f}) \text{ (W)} \quad \cdots\cdots (11)$$

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_e, the total loss W comes to the following equation from equation (10) and equation (11).

$$W = (k_1' + \frac{k_2'}{f})V_1^2 + (r_1 + r_2')\frac{\omega_0^2 T^2}{3V_1^2} \text{ (W)} \quad \cdots\cdots (12)$$

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

$$V = \sqrt[4]{\frac{(r_1 + r_2')\omega_0^2}{3(k_1' + \frac{k_2'}{f})}} \cdot \sqrt{T} \text{ (V)} \quad \cdots\cdots (13)$$

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. 11.21 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.

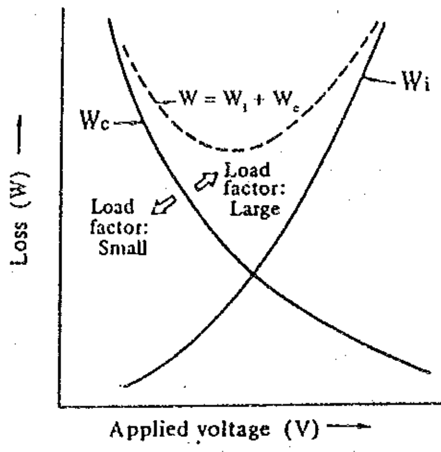


Figure 11.21 Tendency of loss against applied voltage

Fig. 11.22 shows one example of the efficiency curve when the survey 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.

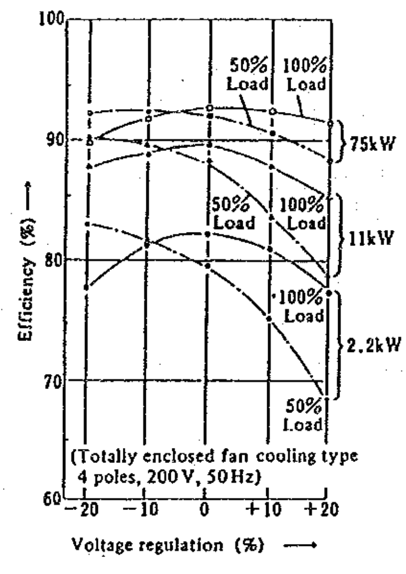


Figure 11.22 Example of efficiency during voltage fluctuation of induction motor

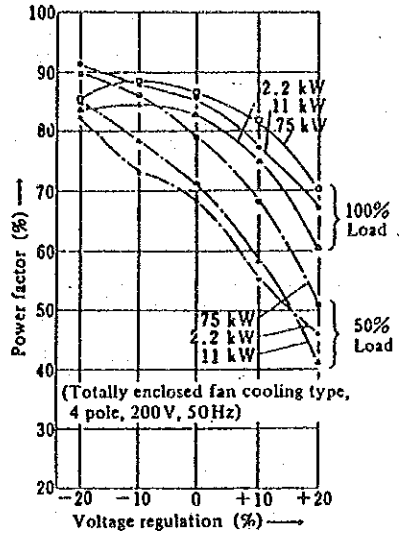


Figure 11.23 Example of power factor during voltage fluctuation of induction motor

Fig. 11.23 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 11.12. 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.

Table 11.12 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 3/4 load 1/2 load	–2% Actually no change +1 ~ 2%	— — —	Slightly increased Actually no change –1 ~ 2%
Power factor	Full load 3/4 Load 1/2 Load	+1% +2 ~ 3% +4 ~ 5%	— — —	–3% –4% –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 decreased	—	Slightly increased

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 11.12.

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 described 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:

$$W_l = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_0^2 (S_1^2 - S_2^2)(1 + \frac{r_1}{r_2'}) \frac{T_m}{T_m - T_l} \quad \cdots\cdots (14)$$

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

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

$$W_l = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_0^2 (1 + \frac{r_1}{r_2'}) \frac{T_m}{T_m - T_l} \quad \cdots\cdots (15)$$

Where

r_1 : Primary resistance of induction motor (Ω)

r'_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 ω_0 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_{0L} 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_{0H} of the high-speed winding (Number of poles: P_H). Total loss of the motor during this period $W_{2\ell}$ will be determined as follows. For simplification, it is assumed in equation (14) that $r_1 = 0$, $T_l = 0$.

$$W_{21} = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_{OL}^2 (1^2 - 0^2) + \frac{1}{2} \cdot \frac{GD^2}{4} \omega_{OH}^2 \left\{ \left(\frac{\omega_{OH} - \omega_{OL}}{\omega_{OH}}\right)^2 - 0^2 \right\} \quad (J) \cdots (16)$$

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

$$W_{21} = \frac{1}{2} \cdot \frac{GD^2}{4} \cdot \omega_{OH}^2 \left(1 + \frac{2}{n^2} - \frac{2}{n}\right) \quad (J) \cdots\cdots (17)$$

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

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

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. Moreover, increasing numbers of poles changing steps will reduce the loss further.

The following measures are effective in preventing idle running.

- Installation of an idle running alarm device
- Automatization of the process and equipment
- Reduction of the waiting time for handling the treated matter by improving the equipment layout and jigs and tools

(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:

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

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
    - Kraemer 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.

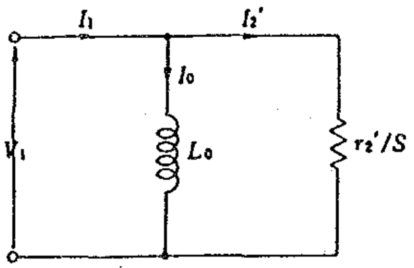
The primary frequency control system controls the primary voltage and frequency of the motor at the same time, by means of a frequency converter, to change the synchronous speed. This control system is mainly divided into opened-control and closed-control types. Of these, the opened-control type is open-loop 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 of (V/f) is constant. The closed-control type has slip frequency control and vector control.

For a characteristic 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. 11.24.

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



Equivalent circuit during operation near synchronous speed.

Figure 11.24 Simple equivalent circuit of induction motor at slip = 0

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

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

$$I_2' = \frac{SV_1}{r_2'} = \frac{S\omega_0}{r_2'}\,\frac{V_1}{\omega_0}[A] \quad \cdots\cdots (22)$$

$$T = \frac{3SV_1^2}{\omega_0 r_2'} = 3\frac{S\omega_0}{r_2'}\left(\frac{V_1}{\omega_0}\right)^2 \ [N \cdot m / rad] \quad \cdots\cdots (23)$$

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

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

Where

$$K_1 = \frac{L}{K_v}$$

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 ϕ become constant at constant slip frequency $S\omega_0$. Fig. 11.25 shows torque-speed characteristic curve at this point and the maximum torque Tmax becomes constant against speed ω_0.

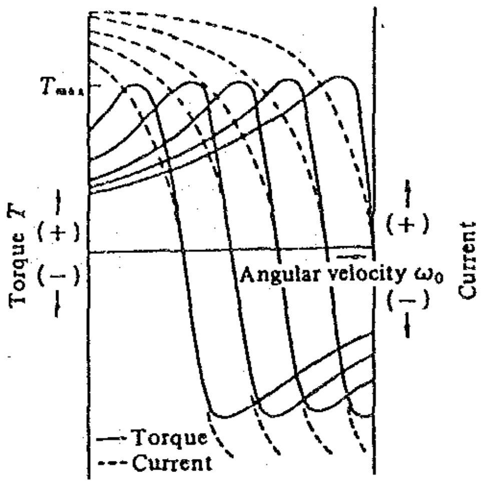


Figure 11.25 Torque-speed characteristics of V/f constant control

Inverters are usually used for the VVVF system. Characteristics of rotation control by an inverter are shown below.

① Can easily control a squirrel-cage induction motor without any additions except VVVF.
② Can apply stepless rotation control effectively in a wide range.
③ Power factor is high. Power capacity can be small for starting up.
④ Can reverse rotation direction electroniclly.
⑤ Can start and stop high-frequently.
⑥ Can apply breaking control electrically.
⑦ Suitable for rotation control of a motor placed in a severe environment.
⑧ Can control rotation of multiple motors at a time.
⑨ Can easily obtain constant torque characteristics and constant output characteristics.

As problems raised from introduction of an inverter, the following can be named: troubles by harmonic waves, troubles by speed control of general purpose motors, and troubles by operation switching between direct and inverter operations. Table 11.13 shows troubles and measures accompanied with the introduction of an inverter.

Table 11.13 Troubles and measures accompanied with introduction of inverter

No.	Trouble	Measures
I	Trouble by harmonic waves	
1	• Metalic sound is generated from motor.	• Insert an AC reactor between inverter and motor.
2 3	• Condensive capacitor or fluorescent lamp is heated. • Input transformer generates heat or causes vibration.	• Insert an AC reactor to the receiving side.
4 5	• AM broadcast on radio cannot be heard due to noise. • Electronic devices such as measuring instruments cause error.	• Install a noise filter. • Place an inverter in an iron case and earth the case. • Earth the motor frames. • Place input/output cables in an iron pipe and earth the pipe.
6	• Earth leakage breaker operates erroneously.	• Shorten connecting wire between inverter and motor. • Use breaker dedicated to inverters.
II	Troubles by speed control of general purpose motors	
7	• Resonance occurs between motor and the other machine.As a result vibration and noise are generated.	• Use tire-type coupling between motor and the other machine.
8	• Self-cooling efficiency of motor lowers. Temperature rises.	• Fit a forced cooling fan.
III	Troubles by operation switch between direct and inverter operations	
9	• Life of relay shortens due to frequent switching.	• Review control method.
10	• The device stops due to instantaneous power cut when switching.	• Checks sequence control circuit.
11	• Adjust time of motor after switching is too long.	• Increase the capacity of inverter.

(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.

11.4 Compressors

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

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

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

L : Required power (unit kW)
P_s : 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

Values η_c and η_t shall be given by the manufacturer.

Accordingly, to reduce 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.

11.4.1 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.

11.4.2 Discharge Pressure and Amount Used

In equation (1), lowering discharge pressure of the compressor reduces the axial power greatly. Table 11.14 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 11.14 Actual measurement example of compressor performance

(1) Discharge pressure and motor input (kW)

Load (%) \ Pressure (kg/cm^2G)	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/cm²G)	7
Discharge amount (m³/min)	40
Capacity adjustment (%)	0, 50, 100 3 stage
Motor	3.3 kV 220 kW

Fig. 11.26 shows an example of characteristics of 37 kW air compressor.

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.

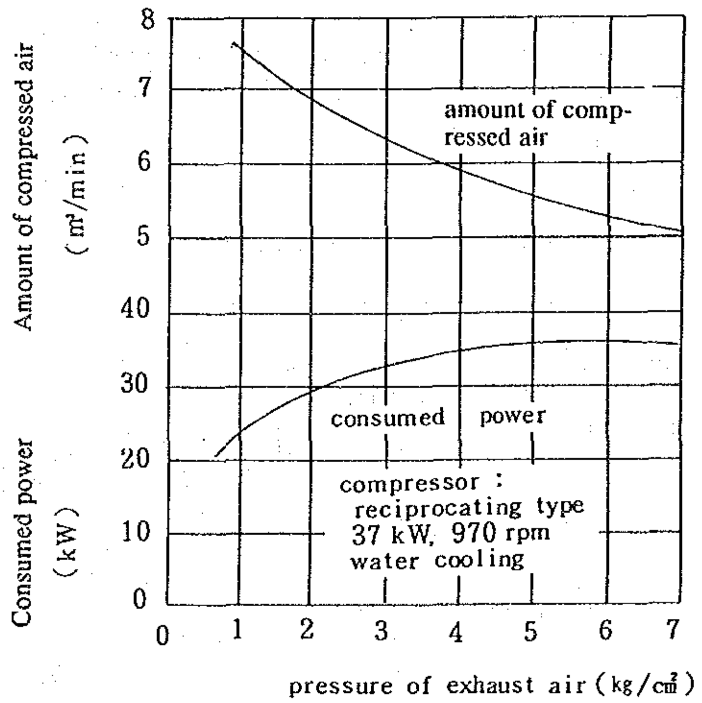


Figure 11.26 Characteristics of 37 kW Air Compressor

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.

11.4.3 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 11.15 shows classification of air compressors by pressure range.

Table 11.15 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, petrochemical 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	1 Stage 2 Stage	3 8.5	Air capacity 2~60 m^3/min.
	Screw compressor	1 Stage 2 Stage	7 7~8.5	

11.4.4 Air Leakage from Clearance, Hole, etc.

(1) Air leakage

Flow rate Q when air flows out from a vessel with a pressure of P_1 inside into a space at pressure of P_2 is given from Bernoulli's equation

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

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,

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

Where

C: Discharge coefficient

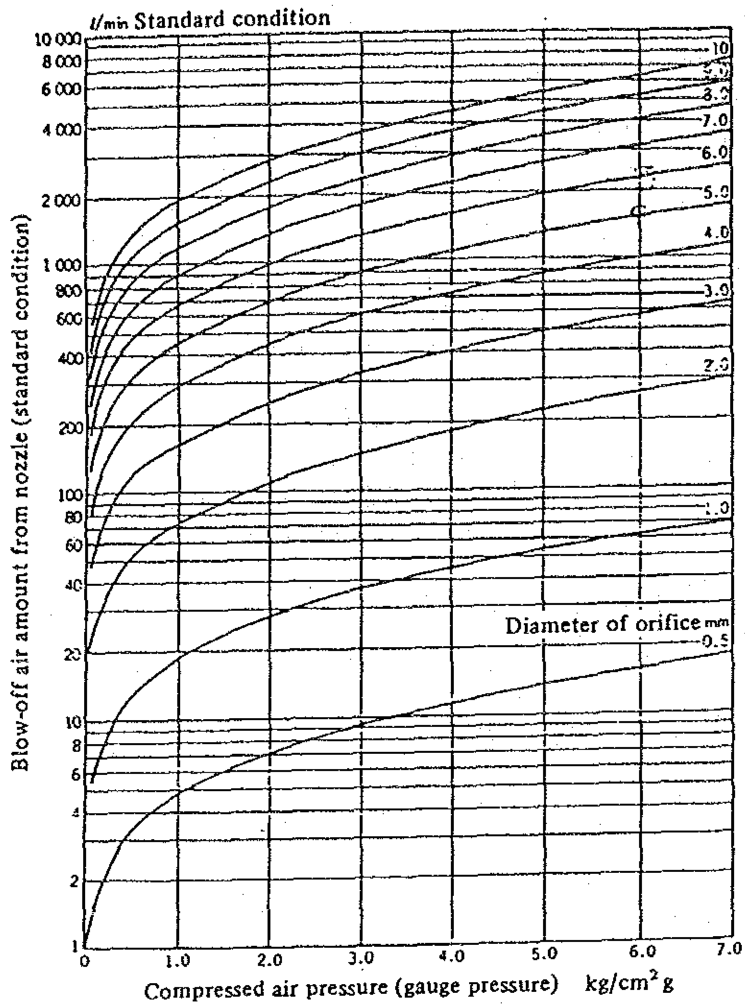


Figure 11.27 Compressed air pressure and blow-off air amount from nozzle

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. 11.27 shows the blow-off air amount from a small diameter orifice. Fig. 11.27 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 multiplied by 0.97 to 0.65 because values in Fig. 11.27 are based when discharge coefficient c=1.

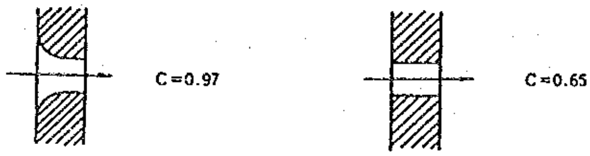
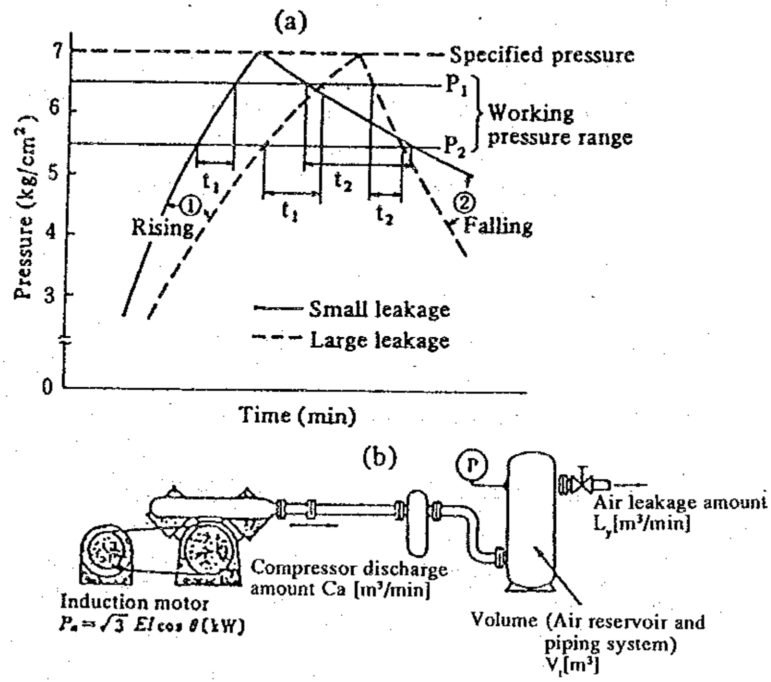


Figure 11.28 Shape of orifice and value of discharge coefficient

(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. 11.29(a). Stop the compressor at the specified pressure and let stand as-is, then the pressure will lower 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.



C_a: Compressor discharge amount
L_y: Air leakage amount
t_1 : Time required for pressurizing
t_2 : Time required for lowering

Figure 11.29 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,

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

Air leakage factor L_p (%) is

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

Air leakage is measured by measuring compressor equipment (compressor proper, intercooler, air tank, etc.), piping system, pneumatic machine, control circuit, etc. in the group unit using the sound and the daubed soapy water.

11.4.5 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 pressure of the line required?
: 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 at 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?

11.5 Blowers (Fan and Blower)

11.5.1 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 11.16 and Fig. 11.30 show characteristics of blowers and the characteristic curves respectively.

Table 11.16 Characteristic comparison of blowers

Item \ System	Axial flow system	Turbo system	Multivane system	Radial system
Range of use	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2	Air capacity 1 - 10,000 m^3/min Static pressure 1 mmAq - 1 kg/cm^2
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

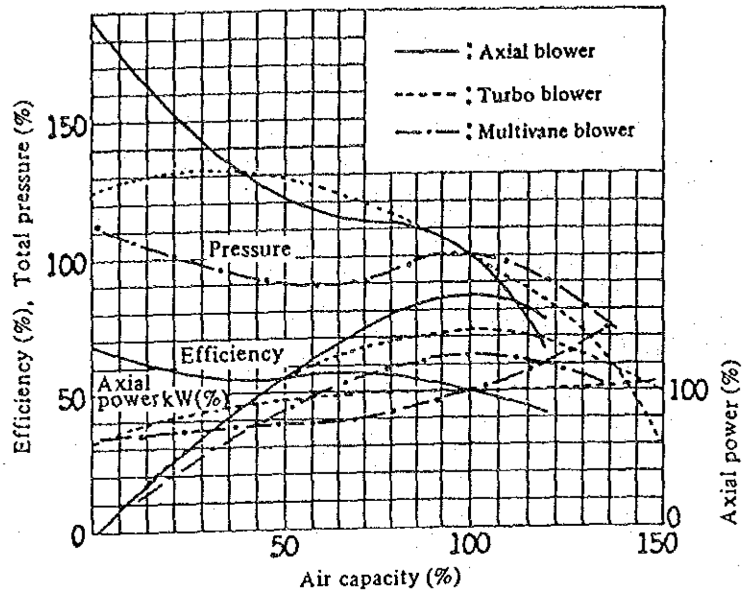


Figure 11.30 Characteristic curve for various blowers

(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.

11.5.2 Required Power of Blowers

(1) Air power (L_T)

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

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

Where

P_{t1} : Absolute pressure on suction side (kg/m² abs)
P_{t2} : Absolute pressure on discharge side (kg/m² abs)
Q : Air flow (m³/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. 11.30, but is generally displayed by that during rated air flow. Its approximate figures are shown in Table 11.16.

(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 11.17 and Table 11.18.

Table 11.17 Value of η_t

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 11-18 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

11.5.3 Electric Power Conservation for Blowers

Factors for blower electric power conservation are shown in Fig. 11.31. 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:

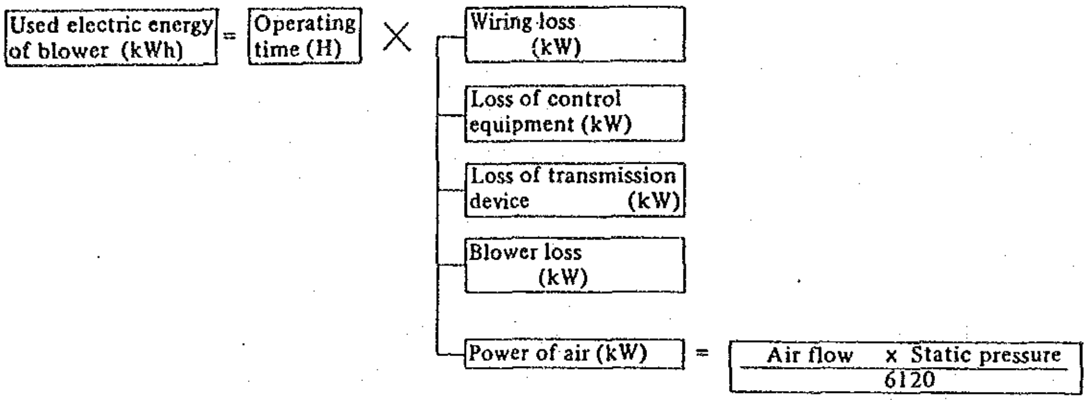


Fig. 11.31 Factors for blower electric power conservation

(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. 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 blower is 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 conditions is indicated to the manufacture 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 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 occur.

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 countermeasures such as reactor starting or adoption of VVVF will be required.

C) Life of starting equipment

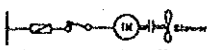
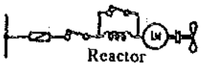
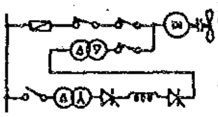
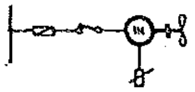
Reactors for start-up and starting compensator are generally of a short-time rating and when they are changed to very frequent use, the temperature of winding in these equipment will increase, possibly resulting in insulation deterioration and a burning accident. Therefore, for very frequent use, it 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 11.19 and Table 11.20 show comparison of various starting systems when an induction motor is used for a blower, and general life of switches respectively.

Table 11.19 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	 Coupling	100 (6 to 7 times full-load current)	100 (About 150% on rated torque)	100	100 (In proportion to square of current)	$100\left(\frac{GD^2 \cdot N_0^2}{730}[J]\right)$	Power voltage drop, Motor life, Breaker life
Reactor starting	 Reactor	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	 Autotransformer	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 (limited to wound-rotor type)	 External resistance	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 mechanisms, 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 11.20 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 (SF6) breaker	10,000 times (Possible also for 50,000 times)	10,000 times
High voltage electromagnetic contactor	5 million times (Class 1)	500 thousand times (Class 1)

(2) Adopt high-efficiency equipment

Remarkable points 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 according to 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 at reduced air flow, the blower is operated at full capacity because the proper air flow is not decided. Also, when a blower for cooling has no problems, even if the 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; fixed type, and variable type of rotation numbers.

A) Fixed types

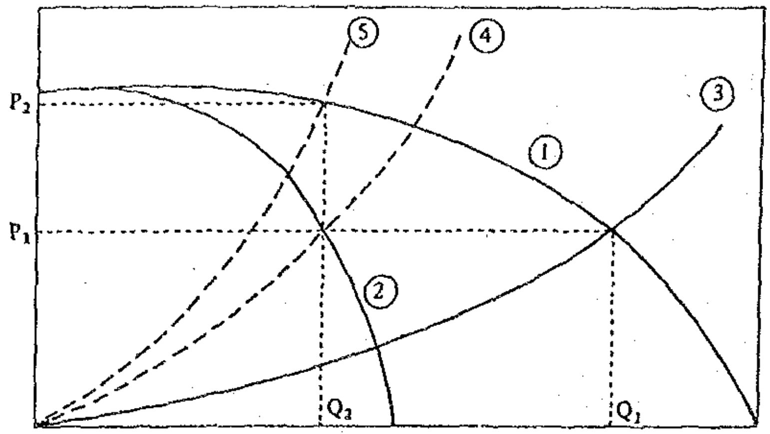
Table 11.21 shows method for fixed types.

Table 11.21 Method to reduce blow air capacity (fixed type)

Main classification	Sub-classification
Reduction in blower 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 rotating speed	Replace motor. Replace 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. 11.32, 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 $P_2 \times Q_2 - P_1 \times Q_2 = Q_2 \times (P_2 - P_1)$ 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)

Figure 11.32 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, the air flow as Q, the pressure as P and the axial power as L, the following relations generally exist.

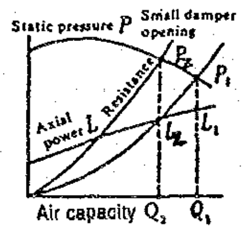
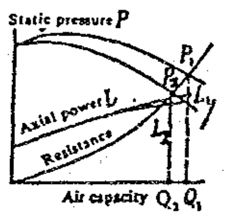
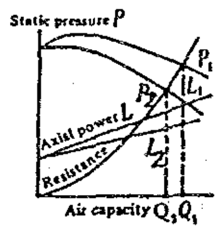
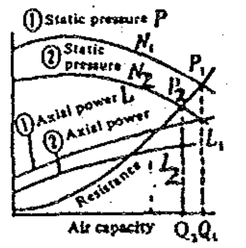
$$Q \propto D^2$$
$$P \propto D^2 \qquad (5)$$
$$L \propto D^4$$

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 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 11.22, in which the rotating speed control method is specified for comparison.

Table 11.22 Damper, vane opening adjustment

Method	Discharge damper opening adjustment	Intake damper opening adjustment (discharge side piping)	Intake vane control	Changing the rotating speed
Principle	Change blower resistance curve by intentionally increasing resistance of the piping system.	Since damper resistance is provided on intake side, it serves as a negative pressure and pressure curve slightly changes. Axial power curve also changes slightly.	Reduce the impeller work done by intentionally changing gas flowing angle against blower impellers, thus changing the pressure and power curves at the same time.	Air capacity is in proportion to the rotating speed, the pressure to square of the rotating speed, and the axial power to cube of the rotating speed.
Diagram of principle	 When damper is closed, resistance increases and operating point changes from (P_1, L_1, Q_1) to (P_2, L_2, Q_2). Note: Operating point is a point of intersection of pressure and resistance curves.	 When damper is closed, pressure curve falls and operating point changes from (P_1, L_1, Q_1) to (P_2, L_2, Q_2).	 Reducing vane lowers pressure and axial power curves. Operating point changes from (P_1, L_1, Q_1) to (P_2, L_2, Q_2). Reduction in axial power is far larger than damper opening adjustment.	 Changing the rotating speed from N_1 to N_2 shifts the pressure and axial power curves from (1) to (2), and the operating point from (P_1, L_1, Q_1) to (P_2, L_2, Q_2).
Special features	1) Surging area is wide and effective air capacity control cannot be performed. 2) Axial power does not lower much even in low air capacity area.	1) Surging area is narrower than for discharge damper. 2) Axial power lowers almost in proportion to air capacity.	1) Same as at left. 2) Axial power lowers almost in proportion to air capacity and tends to lower much more than the intake damper.	Axial power lowers most and this is the best method for electric power conservation.

d. Change in rotating speed (change of motor or diameter of pulley)

Assuming the rotating speed of blower as N,

$$Q \propto N$$
$$P \propto N^2 \qquad (6)$$
$$L \propto N^3$$

Since there is the above relation, when it is possible to replace with a motor with lower rotating speed, energy can be greatly saved. However, in this case, once it is changed, it cannot be easily returned to the original position unlike the damper adjustment. Therefore, carefully investigate the resistance curve of load, etc. and be careful so that the air flow is not insufficient after replacement. Also, in the case of belt-drive, it is an effective method to lower the rotating speed by changing the diameter of the pulley.

B) Variable types

In variable control systems of air flow, there are various systems as shown in Table 11.23.

Table 11.23 Method to control air flow (variable type)

Discharge damper control (Variable)	Intake damper control (Variable)
Intake vane control (Variable)	Change in number of poles
Eddy current coupling control	Secondary resistance control
VVVF control	Scherbius control
	Others

Fig. 11.33 shows motor input (%) of various variable air flow control methods specified in Table 11.23.

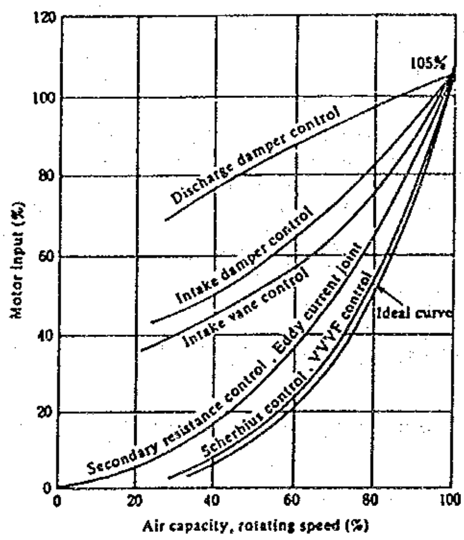


Figure 11.33 Comparison of blower motor's Input

11.6 Pump

As electric power consumed by pumps in various facilities is huge, improvement of their efficiency is one of the most important concerns for electric power conservation. So far the head of pumps was designed to allow considerable excess on account of the secular increase of line resistance of piping facilities. Also, many of these pumps have excess capacity in prospect of future increase of supply or drainage quantity, so the flow rate is adjusted by valves.

In these cases, while pump efficiency itself is high, efficiency of the pump facilities as a whole is low, resulting in wasteful consumption of electric power.

11.6.1 Type and Construction of Pumps

Pumps are classified into turbo pumps, positive displacement pumps and other pumps, as shown in Table 11.24. The turbo pump rotates the impeller in the casing to give fluid energy. Centrifugal pumps, mixed flow pumps and axial flow pumps belong to this category. As there is no seal between the impeller and casing in the pump body, the discharge varies largely by pressure.

Whereas the positive displacement pump is that which delivers fluid from the suction side to the discharge side by means of displacement or change of enclosed space which is generated between the casing and inscribed movable members. Reciprocating pumps and rotary pumps belong to this category. As there is a seal line provided between the casing and the movable members, keeping leakage at a minimum, discharge is hardly affected even when the discharge pressure is varied.

Other pumps include jet pumps and air lift pumps, both of which are used for pumping of water.

Table 11.24 General classification of pumps

Pumps	Turbo pumps	Centrifugal pumps
		Mixed flow pumps
		Axial flow pumps
	Positive displacement pumps	Reciprocating pumps
		Rotary pumps
	Other types	Jet pumps
		Air lift pumps

However, as pumps, turbo pumps are used for the most. So, the following descriptions mainly refer to turbo pumps:

(1) Centrifugal pump

In this type of pumps, flow discharged from the impeller is mainly within a plane perpendicular to the pump shaft, and there are volute pumps which give water a velocity energy by centrifugal force of the impeller, and convert it to a pressure energy in the volute chamber, and diffuser pumps which convert the velocity energy to a pressure energy by means of the guide vane type diffuser. The specific velocity of pump N_s is 100 - 700.

(2) Mixed flow pump

In this type of pumps, velocity energy and pressure energy is given to water by centrifugal force of the impeller and lift of the vane, and the water flows in from the axial direction to the impeller and discharged to a conical plane having the center line of the pump shaft as its axis. Generally, these pumps have a guide vane type diffuser on the discharge side of the impeller, but some pumps have a direct volute type casing. The specific velocity of pump N_s is 700 - 1,200.

(3) Axial flow pump

The propeller shaped impeller gives water a velocity energy and pressure energy by lift of the vane, and the water flows in from the axial direction to the impeller and discharged into a cylinder which is provided coaxially with the pump shaft. The specific velocity of pump N_s is 1,200 - 2,000.

Shapes of these pumps are shown in Figure 11.34.

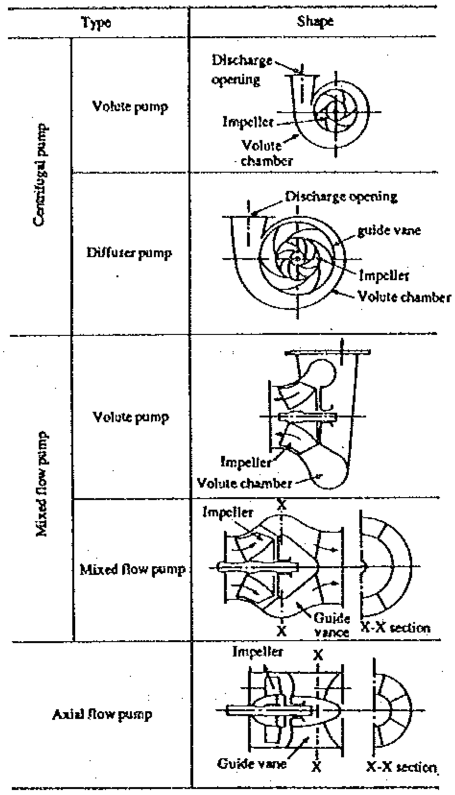


Figure 11.34 Pump shapes

11.6.2 Characteristic Curves and Operating Points of Pumps

(1) Specific velocity

Specification of a pump is decided basically by discharge Q (m^3/min), total head H(m) and rotating speed N (rpm). Q and H are decided by purpose and N by selection of suitable model. For pumps, generally the specific velocity is understood as a guideline for characteristic classification. The specific velocity N_s is a value set to be constant for impellers with similar shape, irrespective of the size and rotational speed of each pump, and is used as the model number of impellers.

Specific velocity N_s is determined by the following formula:

$$N_s = N \cdot Q^{\frac{1}{2}} / H^{\frac{3}{4}} \quad \cdots\cdots (1)$$

N: Revolution/min

Q: Discharge at max. efficiency point (m^3/min) (Provided, 1/2Q for double suction)

H: Total head at max. efficiency point (m)
(Provided, total head of each stage for multistage pumps)

As it is clear from formula (1), when N_s is small, this means a pump with small flow rate and high head, and when N_s is large, this means a pump with large flow rate and low head. Figure 11.35 shows the relationship of N_s and impeller shape.

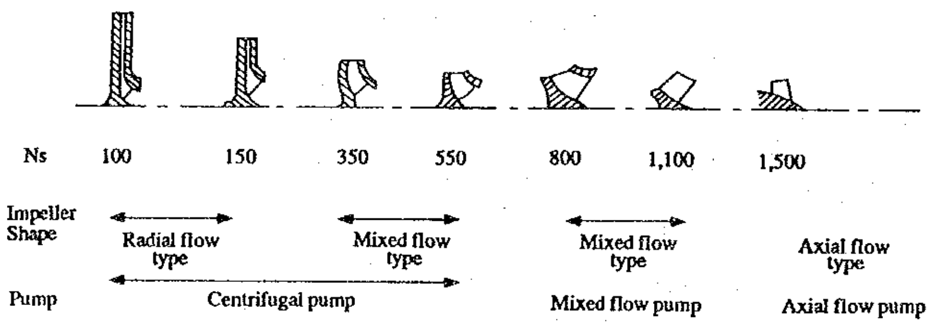


Figure 11.35 N_s and impeller shape

(2) Operating point of pump

Pumps are not always operated under constantly fixed conditions. However, in each operating state, stable operation is performed at that point of time. This indicates that the state of pipe connected before and after a pump, and of the whole pump system including the water level condition at the suction valve and discharge valve are in a balanced state. Factors that determine the operating point are pressure loss of the line itself, the throttling of valves in the line, and difference of water level between the suction valve and discharge valve, etc. which are not related to the pump characteristics.

Generally, performance of volute pumps is shown in Figure 11.36.

Each pump uses a feed pipe to supply water, and the resistance increases almost proportionately to the velocity squared inside the pipe. A resistance curve R_1 of Figure 11-36 is the addition of the line resistance of the feed pipe to the actual head of the pump and a pressure required at the end of the feed pipe, and the pump operates with the flow rate Q_1 and head H_1 at a point of intersection A_1 of this resistance curve R_1 and performance curve of the pump. In this case, the axial power of pump is a point of intersection L_1 of a vertical line drawn from the point A_1 with the power curve, and the pumping efficiency is a point of intersection E_1 of the same vertical line with the efficiency curve.

Admitting that the actual head and the pressure at the end of the feed pipe are necessary, electric power can be saved by minimizing the resistance of the feed pipe, since the total head H_1 of the pump can be reduced accordingly.

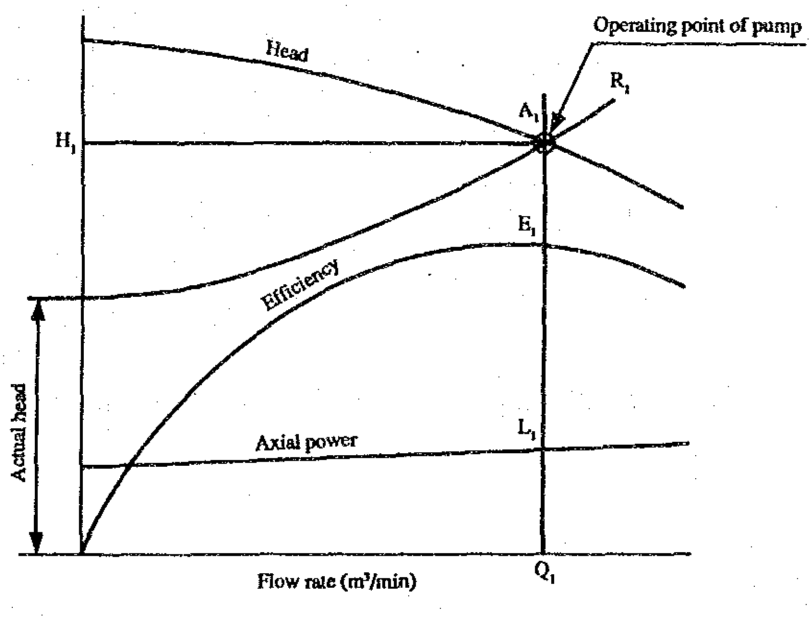


Figure 11.36 Performance curve of pump

11.6.3 Necessary Power and Pump Drive Motor

(1) Necessary power

The theoretical power of a pump is given by the following formula:

$$P = 0.163 \cdot \gamma \cdot Q \cdot H \text{ [kW]} \quad \cdots\cdots (2)$$

γ: Weight of fluid per capacity
Q: Discharge of the pump (m^3/min)
H: Total head of the pump (m)

An output (axial power) which is required of the motor is given by the following formula:

$$P = 0.163 \cdot \gamma \cdot Q \cdot H \frac{100}{\eta}(1+\alpha) \quad \cdots\cdots (3)$$

η: Efficiency of the pump (%)
α: Tolerance

The approximate values of η and α are shown in Figure 11.37 and Table 11.25.

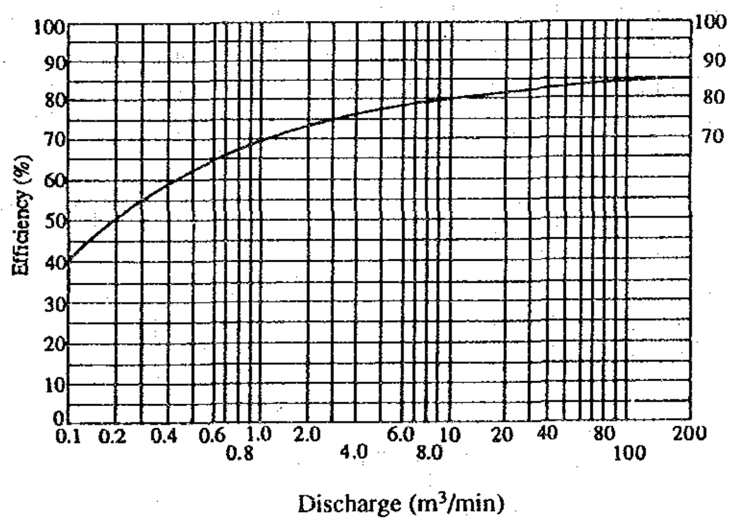


Figure 11.37 Standard efficiency of general purpose pumps

Table 11.25 Tolerance of pumps

Pump type	Tolerance (%)	
	Fluctuation of head is relatively small.	Fluctuation of head is relatively large.
Volute pump — High head	15	20
Volute pump — Medium, low head	10	15
Mixed flow pump	15	20
Axial flow pump	20	25

(2) Pump drive motor

In selecting the motor, it is necessary to grasp the torque characteristics of the pump at start and during acceleration, as well as the operation system. To start a pump from the stationary state, the motor should have a power exceeding the static friction torque of the bearing, but when the pump is rotating, a dynamic friction which is smaller than the static friction is generated, and a load torque is generated as the pump is accelerated.

Relationship of rotating speed and load torque of each pump is different depending on the pump type and opening state of the discharge valve. In particular, it should be noted that the starting-torque characteristic differs according to opening state of the discharge valve.

Axial power of the pump when the discharge valve is closed shows a minimum for models with 650 or less of N_s, and exceeds 100% of rated load torque and even reaches 200% for models with 650 and over of N_s. For the centrifugal pump of which N_s is 100 ~ 700, the starting torque is small when the valve is closed at start, and for the mixed flow pump of which N_s is 700 ~ 1,200, the starting torque is 150% ~ 200% when the discharge valve is closed.

Therefore, for the centrifugal pump, start from the state with the discharge valve closed, and for the mixed flow pump and axial flow pump which are not operable with the valve closed, special care is needed to start. To start axial flow pump small capacities, a method in which the discharge valve closes in the beginning and opens with the increase of rotating speed up to 100% torque at the rated speed is adopted.

For the case of large-capacity axial flow pumps, sometimes a movable vane is adopted (partly for adjustment of the flow rate) to allow start at 100% torque with the discharge valve closed. Therefore, the pump torque at the rated speed during start may be considered to be 40% ~ 80% for centrifugal pumps, and 100% for mixed flow pumps and axial flow pumps.

Additionally, vertical type pumps have large static friction due to the thrust bearing, with some reaching up to 40% torque.

The above may be summarized as shown in Figure 11.38.

Each pump drive motor should be selected by considering the given start conditions. Generally, squirrel cage motors are often used, and while inconveniences such as start delay do not occur in the case of direct-input start, start delay may occur due to torque drop during acceleration in the case of start under reduced voltage such as reactor start.

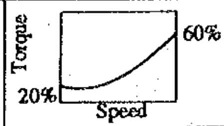
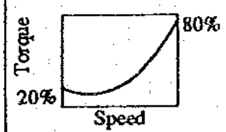
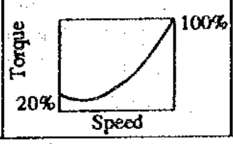
Pump type		Start torque characteristics	GD^2
Centrifugal pump	$Ns \leqq 300$		Small
Centrifugal pump	$300 < Ns \leqq 450$		Small
Mixed flow pump Axial flow pump			Small

Figure 11.38 Start characteristics of pumps

However, when wound-rotor induction motors are used, start jam does not occur. In the case of synchronous motors, sometimes almost 100% pull-in torque is required.