Text No.16

ENERGY CONSERVATION OF ELECTRICAL EQUIPMENT

電気機器の省エネルギー

June 3, 2003

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1.1 Thoughts on the energy conservation

1.1.1 Effective use of energy sources existing in the nature

The technological developments have enabled the use of solar thermal power generation, geothermal power generation, wind power generation, wave power generation, solar cells, solar thermal hot-water supply system, and the illumination system using daylight. It is considered that the active application of these clean energy sources constitutes energy conservation in the wide sense.

1.1.2 Technological developments of energy conservation equipments

Technological developments of equipments which conserve energy should be actively promoted. The energy conservation equipment must decrease energy consumption without losing its functions or performances. In order to develop these energy conservation equipments, it is necessary to conduct a detailed investigation of the functional requirement, performance, and energy consumption process and to investigate thoroughly the efficient design of the structural elements, the way to decrease energy loss, the combination to make the maximum efficiency system, and the maximum efficiency operations. Also detailed analyses, checks, and technical improvements should be made in these areas.

Concurrently with the technological developments for energy conservation of the equipment itself, it is necessary to actively promote the developments of the equipment which assists for operational control of energy and reduction of labor.

For instance, there are various measuring instruments which monitor the energy consuming systems, and automatic control equipment which control to maintain the maximum efficiency operation of the systems. Specifically, these include various types of automatic monitors, automatic controllers, automatic recorders, energy-load distributors, process controllers, demand monitors and controllers, optimal combustion controllers, and automatic power factor controllers.

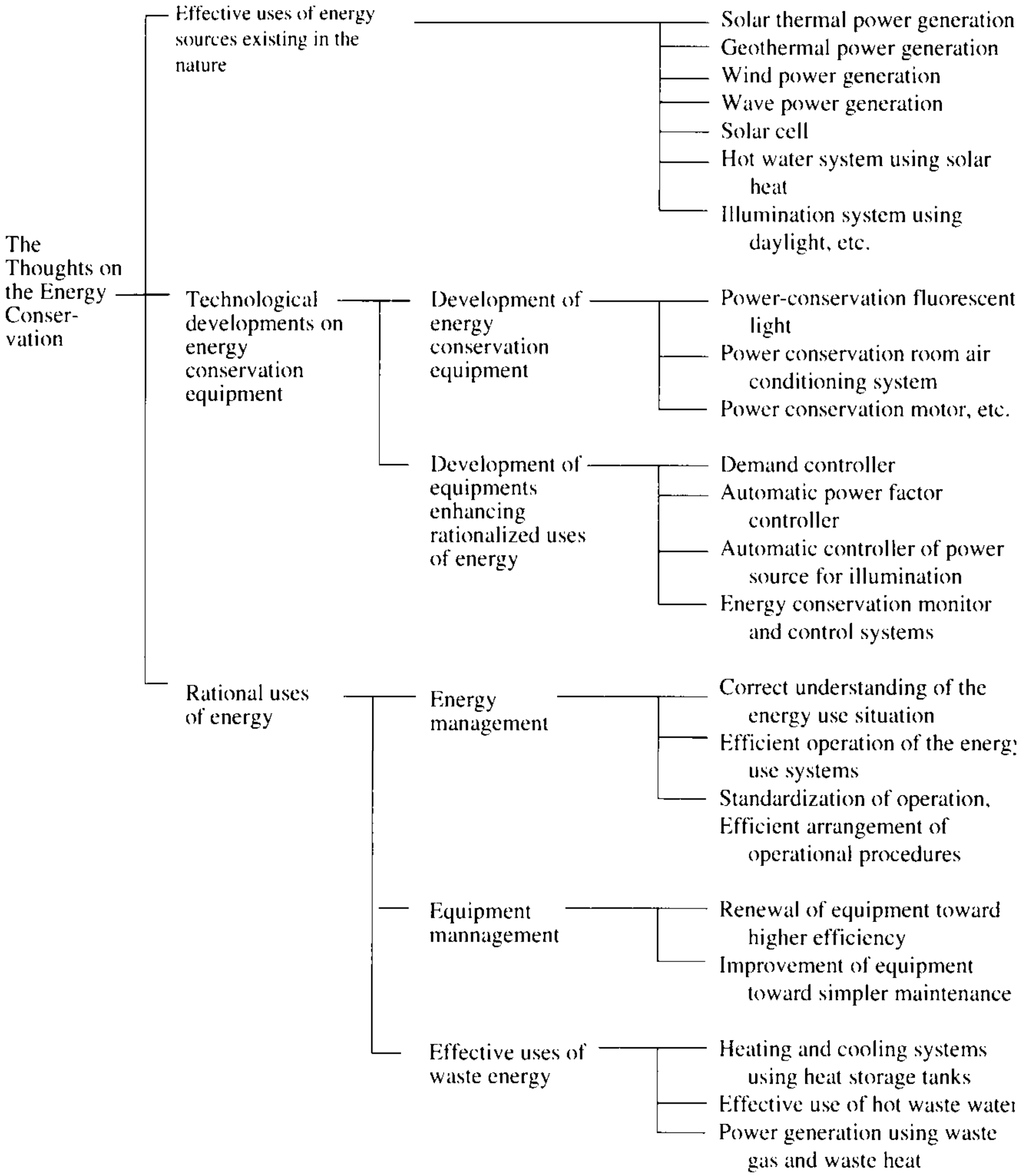


Figure 1 Thoughts on the energy conservation

1.1.3 Rational uses of energy

The rational use of energy is to construct the optimal system by the optimal equipment and to maintain and manage the system properly. So it is necessary to establish a management system for the rational use of energy. In other words,

- The level and quantity of energy is recorded, its detail is analyzed and studied, and the situation is grasped.
- Research is conducted with respect to the thermal efficiency, the power consumption rate, the load factor and the power factor, attempt to reduce the waste energy is made, and the energy consumption system is controlled at an optimal efficiency operation.
- Study is conducted to standardize labor and arrange processes efficiently, and the labor and energy loss is reduced.
- An attempt to cut down the loss is made through renewal of equipment, simplification of maintenance, and other improvements to the facilities.
- The effective use of wasted energy is studied.

Above mentioned is summarized by Figure 1.

1.2 Rationalization of electric power consumption

Electric energy has the following characteristics:

1) It is not a fuel in itself.
2) It is a multipurpose energy source (motive power, heating, lighting).
3) It can be generated from many sources: water, coal, natural gas, oil, atomic energy, waves, winds, solar energy, etc.
4) It is clean in use.
5) It cannot be stored. The quantity and timing of its use are determined by the consumer, not by the supplier.
6) Special measures are required in its use such as prevention of electric shock.

Since electric energy has many favorable characteristics in transportation, control, safety, stability and reliability, it is used for a wide range of purposes such as heating, motive power, lighting, communications and information processing.

The important steps for rationalization of the electric power consumption are first to pose problems regarding the current energy consumption situation, to obtain an accurate grasp on the current situation, to clarify the problems, and then based on the situation, to set targets, to make improvements, and to use those results for the feedback.

1.2.1 Grasp on the electric power consumption situation

Obtaining a grasp on the electric power consumption situation can be summarized as follows:

(1) Daily and monthly electric power consumption

(2) Daily and monthly load curve

(3) Maximum power, its time and its cause

(4) Daily and monthly power consumption by each process or use

(5) Electric power consumption rate (EPCR) by each product or process

$$EPCR = \frac{\text{Electric energy}}{\text{Production amount}}$$

(6) Voltage and power factor

It is important to understand power consumption in relation to the production, the operating state of the production facilities, and product items. Similarly, the calculation of EPCR is important in setting the targets for rationalization of the power consumption. It is necessary to select most suitable calculation method for each plant and process.

1.2.2 Improvement of electric power consumption rate

For improvement of EPCR, it is important to catch its change, classify it into each production process and each raw material and associate EPCR with changes in the processing method and for technical improvement. It is also essential to determine the target value for EPCR in each production process and set to work a problem which can be improved easily.

Important items to improve EPCR are 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 EPCR 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 endeavor 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 endeavor to prevent troubles by good maintenance. Special attention should be paid to troubles with the electric equipment since they are liable to cause the interruption of operation, the equipment damage and accident resulting in injury or death.

(4) Process management

Rationalize the operation processes and improve the layout.

(5) Quality control

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

(6) Participation by all employees

Enhance employees' consciousness for improved productivity and cost, and positively promote a work improvement proposal system and QC circle activities.

1.2.3 Improvement of power factor

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

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

Where P : Electric power (W)

E : Voltage (V)

I : Current (A)

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

θ : Phase difference between voltage and current

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

Then, the current increase in inverse proportion to the power factor. Condensers are generally provided to improve the power factor. Its energy conservation effect is obtained by reducing the surplus current and resistance loss of the distribution line or the transformer.

Effect obtained by improvement of the power factor is 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) by a condenser for improvement of power factor in Figure 2 is determined by the following equations:

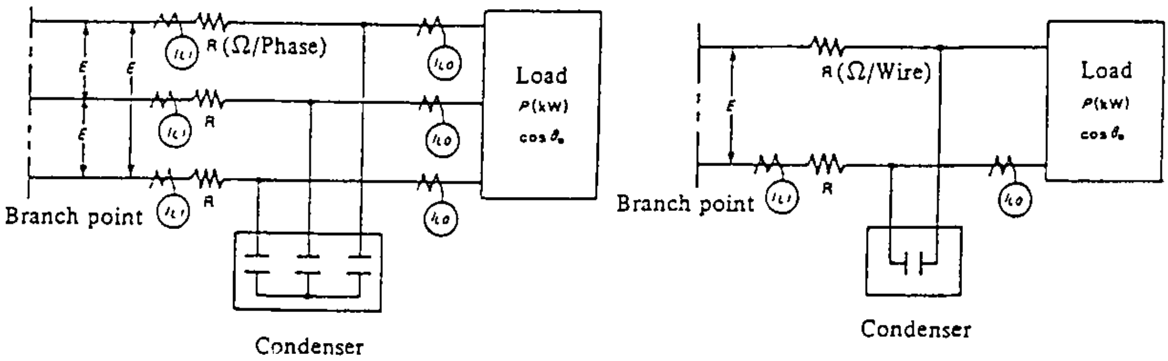
a) Equation for three-phase circuit

$$P_L = 3 \times (I_{L0}^2 - I_{L1}^2) \times R \times 10^{-3} \quad \text{(kW)} \quad \cdots\cdots (4)$$

Where

Before improvement

$$I_{L0}^2 = \left(\frac{P}{\sqrt{3} \times E \times \cos\theta_0}\right)^2 = \frac{P^2}{3E^2} \cdot \frac{1}{\cos^2\theta_0}$$



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

Figure 2 Reduction effect of distribution line loss

After improvement

$$I_{L1}^2 = \left(\frac{P}{\sqrt{3} \times E \times \cos\theta_1}\right)^2 = \frac{P^2}{3E^2} \bullet \frac{1}{\cos^2\theta_1}$$

$$I_{L0}^2 - I_{L1}^2 = \frac{P^2}{3E^2}\left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right)$$

Hence,

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

In equation (5), substituting

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

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

Where,

$$\frac{P^2}{E^2} = 3 \cos^2\theta_0 \bullet I_{L0}^2$$

Hence,

$$P_L = 3 \times (I_{L0} \times \cos\theta_0)^2 \times k_1 \times R \times 10^{-3} \quad \text{(kW)} \quad \text{.......... (7)}$$

b) Equation for single phase circuit

$$P_L = 2 \times (I_{L0}^2 - I_{L1}^2) \times R \times 10^{-3} \quad \text{(kW)} \quad \text{.......... (8)}$$

Where

Before improvement

$$I_{L0}^2 = \left(\frac{P}{E\cos^2\theta_0}\right)^2$$

After improvement

$$I_{L1}^2 = \left(\frac{P}{E\cos\theta_1}\right)^2$$

$$I_{L0}^2 - I_{L1}^2 = \frac{P^2}{E^2}\left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right)$$

Hence

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

$$= 2 \times \frac{P^2}{E^2} \times k_1 \times 10^{-3} \text{ (kW)} \qquad (10)$$

$$= 2 \times (I_{L0} \times \cos\theta_0)^2 \times k_1 \times R \times 10^{-3} \text{ (kW)} \qquad (11)$$

P (kW) : Load power
I_{L0} (A) : Present load current
I_{L1} (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

One calculation example of reduced loss in three-phase distribution line by the equation (7), as is shown in Table 1.

Table 1 Calculation example of reduction effect of loss in three-phase distribution line due to power factor improvement

Resistance value of distribution line and cable R: (Size of cross section)	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	m		A	A	A	kW	kW
0.20 (100 m² or equivalent)	500	0.60	131	87.3	82.7	2.87	3.10
		0.70	131	102	96.5	2.04	2.30
0.13 (150 m² or equivalent)	500	0.60	219	146	138	5.18	5.61
		0.70	219	170	161	3.68	4.26
0.10 (200 m² or equivalent)	500	0.60	262	175	165	5.74	6.21
		0.70	262	104	193	4.08	4.72
0.08 (250 m² or equivalent)	500	0.60	306	204	193	6.25	6.76
		0.70	306	238	225	4.44	5.14
0.06 (325 m² 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

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) by a phase-condenser on the secondary side of the transformer as shown in Figure 3 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.

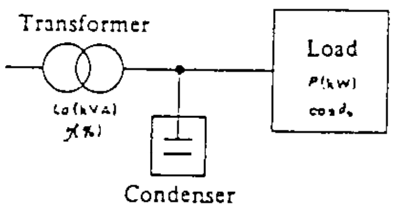
$$Pt = \left(\frac{100}{\eta} - 1\right) \times \frac{4}{5} \times \left(\frac{P}{L_0}\right)^2 \times \left(\frac{1}{\cos^2\theta_0} - \frac{1}{\cos^2\theta_1}\right) \times L_0\,(kW) \quad \ldots\ldots\ldots\ldots(12)$$

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

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

where,

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



Transformer rated capacity	: L_0 (kVA)
Transformer efficiency	: η (%)
Load power	: P (kW)
Present power factor	: $\cos\theta_0$
Power factor after improvement	: $\cos\theta_1$

Figure 3 Reduction effect of trnsformer loss

Table 2 Calculation example of reduction effect of transformer loss

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

Note: 1. P : Load power (kW)

L_0 : Transformer rated capacity (kVA)

2. Loss reduction (P_t) is determined from equation (14)

One calculation example of reduced transformer loss by the equation (14) is shown in Table 2.

(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, the following various problems caused by the increase of the voltage drop, can be reduced by improvement of the power factor.

a. Life of fluorescent and mercury lamps, etc. becomes short and the brightness lowers.
b. In electric heaters, 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, so motor 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 condensers 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 condensers themselves. Therefore, unnecessary condensers must be switched off by means of an automatic control system, etc. as described later.

b) Equation

Voltage drop reduction value (namely, voltage rise value) ΔV due to condensers can be generally determined by the following equation:

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

Where R.C. : Short-circuit capacity of condenser-connecting bus (kVA)
Q_c : Capacity of condenser (kVA)

c) Example of calculation

Bus voltage rise value ΔV is caluculated as follows, when 500 kVA condenser is connected to a bus with short-circuit capacity of 125 MVA.

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

(4) Margin capacity for distribution equipment

Load in distribution line decreases by the line current reduction due to the improved power factor. Namely, the equipment will have a margin in capacity.

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

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

Load increase 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 ($\cos\theta_1$). 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 condenser, to the existing load capacity P_0 (kW) that is, (k_3) is determined as follows.

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

Then

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

Hence

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

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

[Example]

When a 100kW 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.

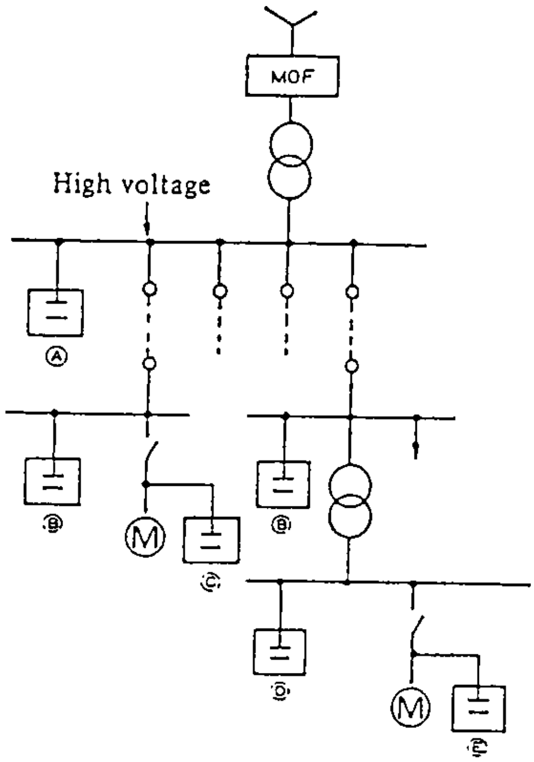
(5) Reduced electric charge

In most case, there is bonus and/or penalty system for power factor in electric charge. Accordingly, improving the power factor reduces the electric charge.

(6) Selection of condenser connection

a) Connection and effect

There are many points to be considered when connecting a condenser as shown in Figure 4.



(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 4 Connection points of condenser

a. Receiving power factor improvement effects
It has almost nothing to do with the connecting point of condenser.

b. Required condenser capacity
Generally, since more condensers are dispersed, the smaller their utilization factor (operating time) will be, the total capacity of required condensers will be the larger. In Figure 4, when all condensers are installed at (A), a required condenser capacity may be calculated for mean power of all loads, while when dispersed to (B) ~ (E), a condenser capacity to meet load for a restricted area must be calculated.

c. Reduction effect of power loss
It is needless to say that the closer a condenser is installed to the end of the distribution line, the greater the effect will be and, the longer the line length is the greater the effect will be.

d. Increased equipment margin capacity
Increased equipment margin capacity due to condenser occurs in the distribution line, cable and transformer inserted in a series between the condenser connection

and the receiving end. Therefore, the closer the condenser is connected to the end, the greater the effect will be.

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

b) Determination of condenser connection
To obtain the maximum energy conservation effect, condensers 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 Figure 4 (C), (E)).
b. Collectively install at the point of concentrated small loads.
(See Figure 4 (B), (D)).
c. For improving receiving power factor connect to the receiving high voltage bus (Figure 4,(A)).
The above methods should be determined according to each user's conditions on a basis of this information.

(7) Automatic switching control of condensers
Operating unnecessary surplus condensers increases the distribution line and transformer losses and causes the problem due to rises in the bus voltage, thus decreases the energy conservation effect. Therefore, a switching control should be required. Especially since condensers installed at the end of the load 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 Figure 5.

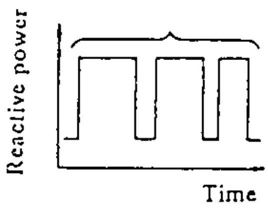
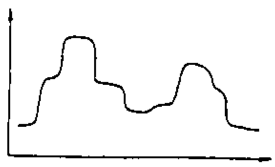
Load fluctuation pattern	(Same every day) 	(Changes every day) 
Applied control system	Reactive power control Current control Program control	Reactive power control

Figure 5 Condenser control system

1.2.4 Improvement of load factor

Load factor is defined as shown in equation (17).

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

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) About electric charge, 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 of one day power consumption in relation to time is drawn, and using this daily-load curve, the load shift should be determined.

(2) Extend the operating hours of machines

The extension of the facility operating hours should be attempted through mechanization and automatization, for using these facilities evenly throughout the day.

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

The peak should 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) Conduct 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) Improve the transport and preparation works

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

(6) Introduce the load control

One method is to limit the maximum power and to conduct load control by using demand controller, load controller, etc.

2. Energy Conservation in the Electrical Equipment

The electric power is a clean energy which is easy to use and is indispensable for the advancement of industry and the improvement of livelihood. It is predicted that in the future, the electric power will lead in the increase as a demand for energy. Hence, the energy conservation in the electrical equipment is the mission of the electrical equipment makers and users, and from the standpoint of the users, it is necessary to engage in the energy conservation on electrical equipment, within the context of the minimization of production costs.

As the fundamental factors determining energy conservation in the production processes are the method of production, the layout, and the control of production, it is necessary to study these to formulate the energy conservation design. These relationships are shown in Figure 6.

The electrical equipment is one of the important element of the production processes. As shown in Figure 7, these electrical equipments generally have a high efficiency, with the exception of illumination, and it is difficult to achieve significant energy conservation of the production processes, by these measures on electrical equipments themselves. It is required to take the step of seeing the entire view of process and then proceed on to the parts within this whole.

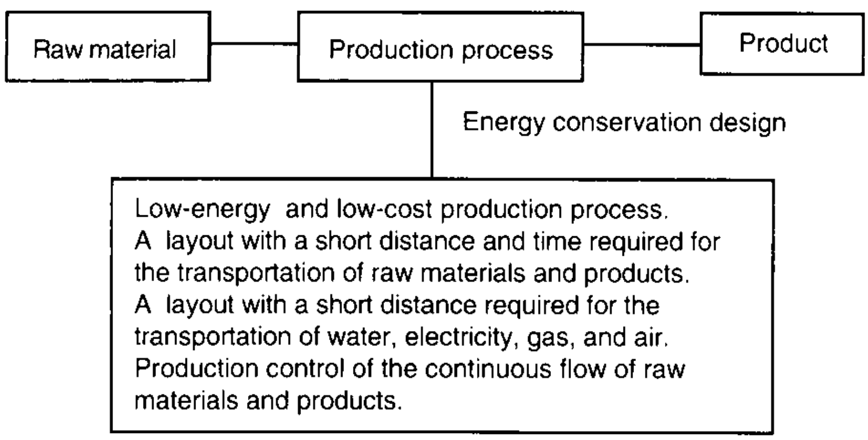


Figure 6 Energy conservation design for the production process

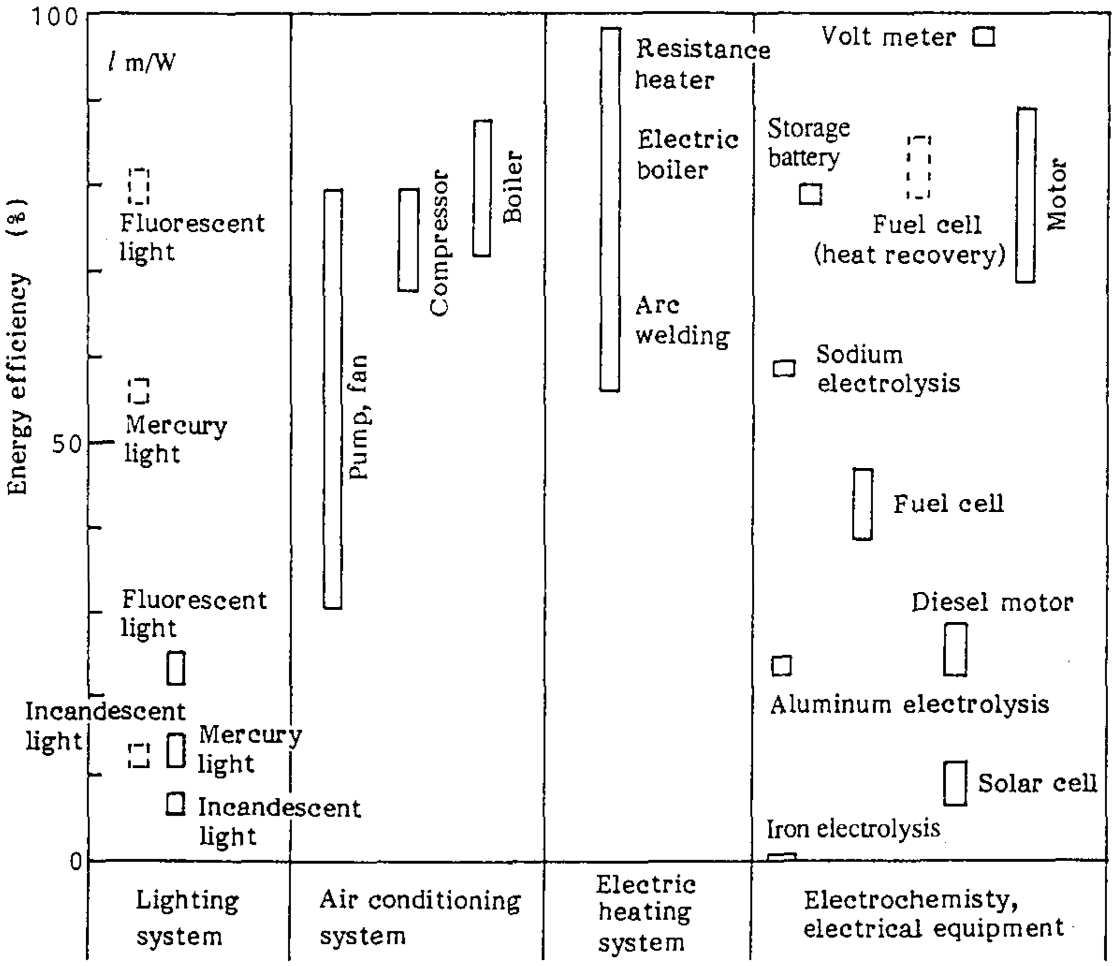


Figure 7 Energy conversion efficiencies of the electrical equipments

2.1 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 (1.4 for 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.

$$L = \frac{(a+1)K}{K-1} \cdot \frac{P_s Q_s}{60} \cdot \left[\left(\frac{P_d}{P_s} \right)^{\frac{K-1}{K(a+1)}} - 1 \right] \cdot \frac{\phi}{\eta_c \eta_t}$$

where,

P_s : KPa

P_d : KPa

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 high efficiency.

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

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

2.1.1 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° to 25°C reduces power 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.

2.1.2 Discharge pressure and amount of air

In equation (1), lowering discharge pressure of the compressor reduces the axial power greatly. Table 3 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 3 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/cm^2G)	7
Discharge amount	(m^3/min)	40
Capacity adjustment	(%)	0, 50, 100 3 stage
Motor		3.3 kV 220 kW

Figure 8 shows an example of characteristics of 37 kW air compressor.

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

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

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

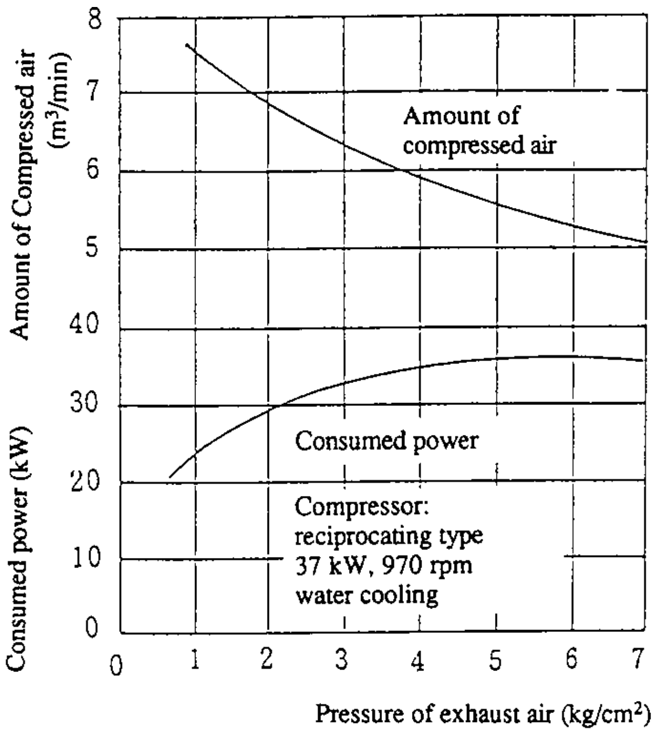


Figure 8 Characteristics of 37 kW air compressor

2.1.3 Selection of kinds of compressors and operation systems

From the standpoints of efficiency it is important to take next items into consideration when selecting the kinds of compressors:

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

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

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

Therefore, in a factory where light load 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 4 shows classification of air compressors by pressure range.

Table 4 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	3	Air capacity 2~60 m^3/min.
		2 stage	8.5	
	Screw compressor	1 stage	7	
		2 stage	7~8.5	

2.1.4 Air leakage from clearance, hole, etc.

(1) Air leakage

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

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

Where γ : Specific weight of air (kg/m^3)

S : Effective cross section (m^2)

P_1, P_2 : Absolute pressure inside and outside vessel (P_a abs)

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

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

Where C : Discharge coefficient

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 reducing the service pressure surely reduces the leakage. Figure 9 shows the blow-off air amount from a small diameter orifice. Figure 9 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 0.97 to 0.65 as discharge value because values in Figure 9 are based when discharge coefficient c = 1 (See Figure 10.)

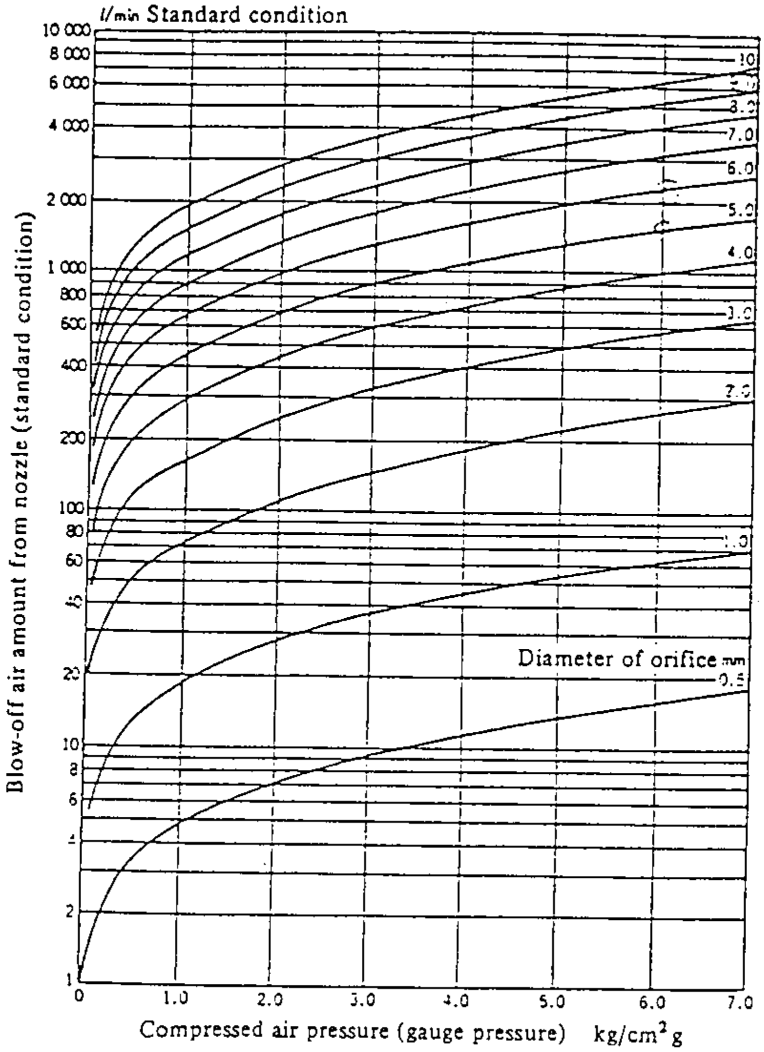


Figure 9 Compressed air pressure and blow-off air amount from nozzle

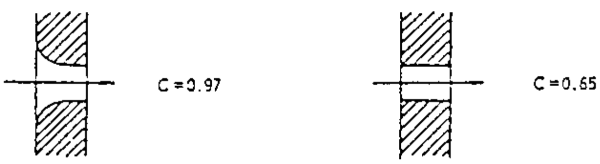


Figure 10 Shape of orifice and value of discharge coefficient

(2) Measurement of air leakage

It is possible to measure air leakage by following method: first, operate a compressor with the end closed and the pressure gradually rises as shown by ① in Figure 11. Stop the compressor at the specified pressure and let stand as-is, then the pressure will lower with 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.

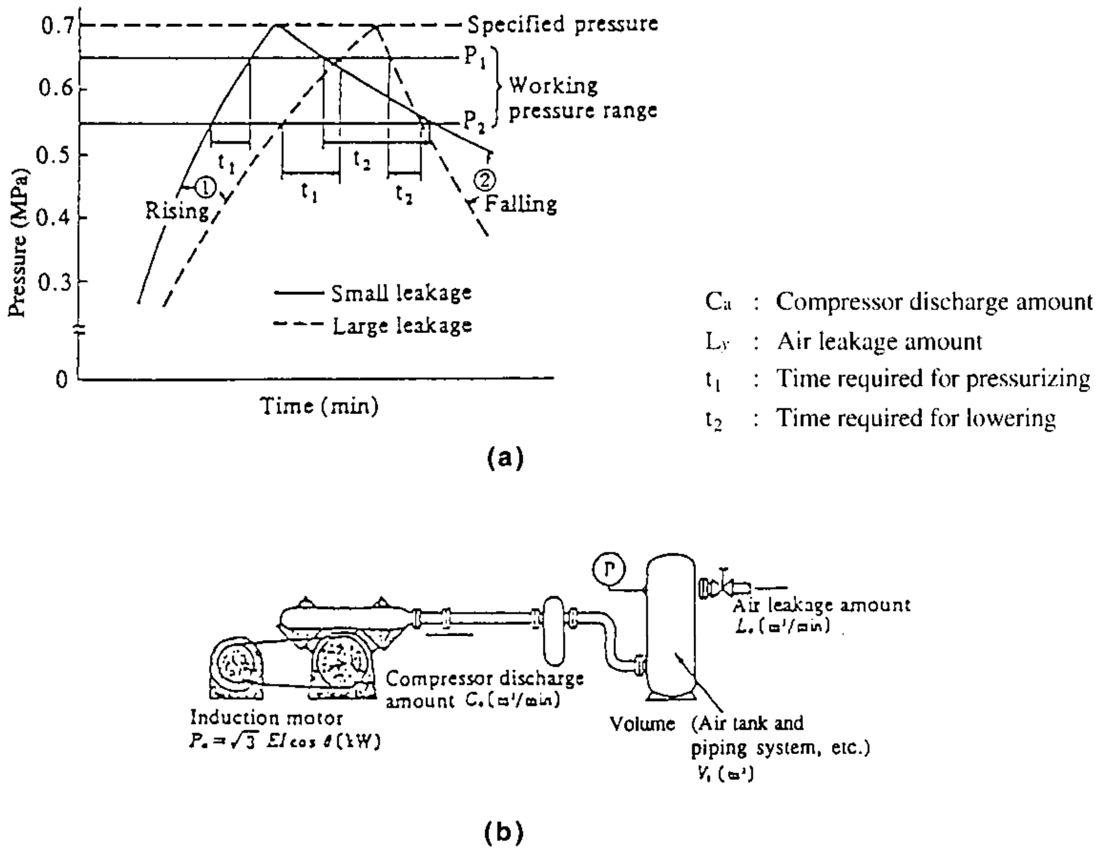


Figure 11 Pressure-time curve

Assuming that pressure range (P_1 to P_2) is treated as a pressure to be practically used (0.05~0.1MPa) 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 from compressor equipment (compressor proper, intercooler, air tank, etc.), piping system, pneumatic machine, control circuit, etc. is checked by leakage sound and the sprinkled soapy water.

2.1.5 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 noise?
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 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, always discharge drain at least once a day (preferably in the morning when operation is started).

[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?

2.2 Blowers (fan and blower)

2.2.1 Characteristics of blowers

Although blowers and compressors have the same principles, below 10 KPa, 10 KPa to below 100 KPa (1 kg/cm^2) and 100 KPa, 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 5 and Figure 12 show characteristics of blowers and the characteristic curves respectively.

Table 5 Characteristic comparison of blowers

System / Item	Axial flow system	Turbo system	Multivane system	Radial system
Range of use	Air capacity 1~10,000 m^3/min Static pressure ~ 3 KPa	Air capacity 1~10,000 m^3/min Static pressure 1 ~ 100 KPa	Air capacity 1~10,000 m^3/min Static pressure 0.5 ~ 10 KPa	Air capacity 1~10,000 m^3/min Static pressure 2 ~ 20 KPa
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 mils, 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

(1) Turbo types

The turbo types have two systems: centrifugal system, and axial-flow system. In the former, centrifugal force is caused by 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 axis 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 into 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.

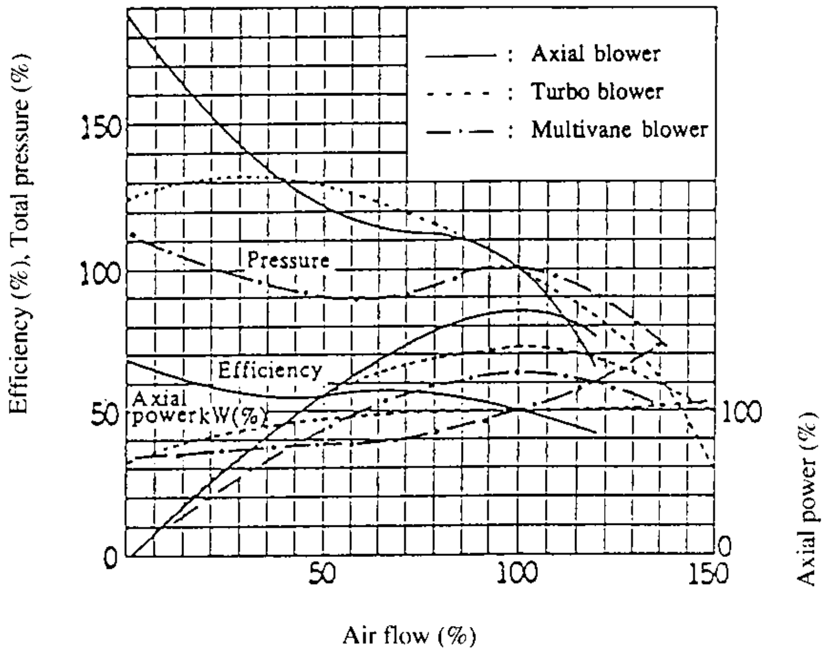


Figure 12 Characteristic curve for various blowers

2.2.2 Required power of blowers

(1) Air power (L_T)

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

$$L_T = \frac{K}{K-1} \cdot \frac{P_{t1} \cdot Q}{60} \left\{ \left(\frac{P_{t2}}{P_{t1}} \right)^{\frac{K-1}{K}} - 1 \right\} \text{ [kW]} \quad \text{.......} (1)$$

Where P_{t1} : Absolute pressure on suction side (KPa abs)

P_{t2} : Absolute pressure on discharge side (KPa abs)

Q : Air flow (m^3 /min)

K : Specific heat ratio (1.4 for air)

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

$$L_T = \frac{QP_T}{60} \text{ [kW]} \quad \text{.......} (2)$$

Where P_T : Total pressure of blower (KPa)

(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 Figure 12, but is generally displayed by that at rated air flow. Its approximate figures are shown in Table 5.

(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 the motor after careful 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 6 and Table 7.

Table 6 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 7 Values of ø

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

2.2.3 Energy conservation for blowers

Factors for blower electric power conservation are shown in Figure 13. Namely, the fundamental conception of the electric power conservation is:

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

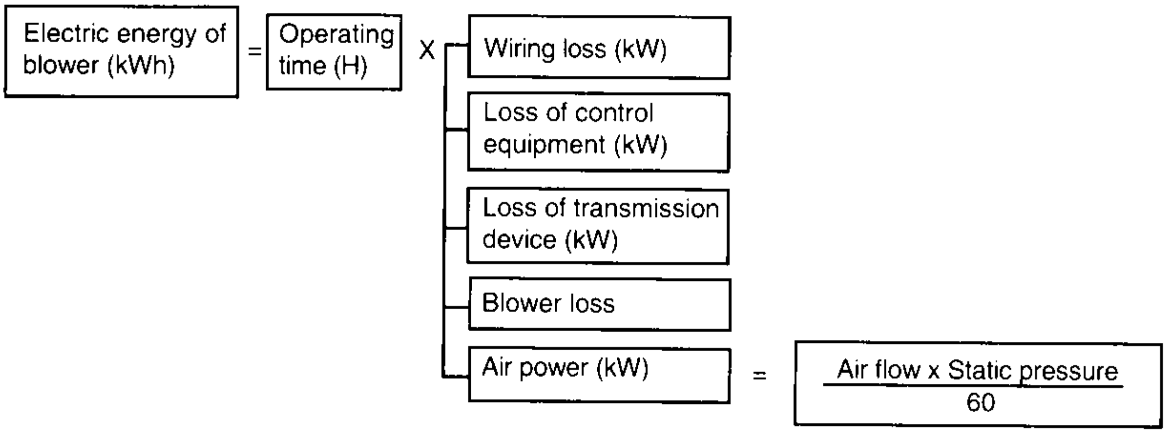


Figure 13 Factors for blower electric power conservation

(1) Reduce the operating time.

Too early start of blowers before the factory operation, or very late stop of blowers after factory operation is often seen in factories. Also, blowers in operation, in spite of stop of factory operation by some troubles, are often seen in general factories. Such useless operation of blowers is a significant adverse factor for energy conservation.

The most direct method to eliminate the 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 start-up times as the conditions is indicated to the manufacturer to order the equipment fit for the condition ordered. However, when the existing blower being almost continuously operated is going to be changed to ON-OFF operation, 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

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

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

c) Life of starting equipment

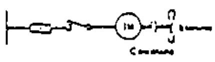
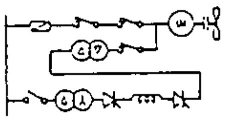
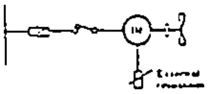
Reactors for start-up and starting compensator are generally of a short-time rating and when they are changed to very frequent use, the temperature of winding in these equipments will increase, possibly resulting in insulation deterioration and a burning accident. There, for very frequent use, it is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

d) Others

Precautions should be taken for generated heat for power source cable and life of switches, etc.

Table 8 and Table 9 show comparison of various starting systems when an induction motor is used for a blower, and general life of switches respectively.

Table 8 Comparison of various starting systems

Starting system	Composition diagram	Starting current	Starting torque	Voltage when starting	Electromagnetic force	Armature heating capacity	Problems when starting at multi-frequency
Direct starting		100 (6 to 7 times full-load current)	100 (About 150% on rated torque)	100	100 (In proportion to square of current)	$100 \times \frac{GD2 \cdot N_0^2}{730}$ (J)	Power voltage drop, motor life, breaker life
Reactor starting		50, 65, 80	25, 42, 64	50, 65, 80 (Standard tap)	25, 42, 64	100	Reactor heating capacity, motor life, breaker life
Closed circuit transition auto-trans-former starting		25, 42, 64	25, 42, 64	50, 65, 80 (Standard tap)	25, 42, 64	100	Starting compensator heating capacity, motor life, breaker life
VVVF Starting		17 or less (Any value below rated current)	70 or less (Any value below rated torque)	0~100 (In proportion to speed)	2~3 (Large when there is inrush current)	Hardly any	Transient torque (when switched from VVVF to main power source), inrush current (when switched from VVVF to main power source), effects from higher harmonics (motor temperature rise, occurrence of shaft voltage, resonance of pulsating torque and shaft torsion, surging voltage when commutating
Second-ary side resistor starting (limited to would-rotor type)		18~40 (Op-tional)	80~200 (Op-tional)	100	3~16	Hardly any (Consumed by external resistance)	External resistance heating capacity, breaker life, slip ring heating capacity, mechanical life of brush lifting mechanism, life of motor for brush lifting

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

Table 9 Life of switch (when not repaired)

	Mechanical life	Electrical life (rated current opening and closing)
Oil breaker	10,000 times	2,000~5,000 times
Vacuum breaker	10,000 times } Possible also for 50,000 times	10,000 times
Gas (SF_6) breaker	10,000 times } Possible also for 50,000 times	10,000 times
High voltage electro-magnetic contactor	5 million times (Class 1)	500 thousand times (Class 1)

(2) Adopt high-efficiency equipment

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, it 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.

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

a. What is the proper air flow?

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

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

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

a) Stationary types

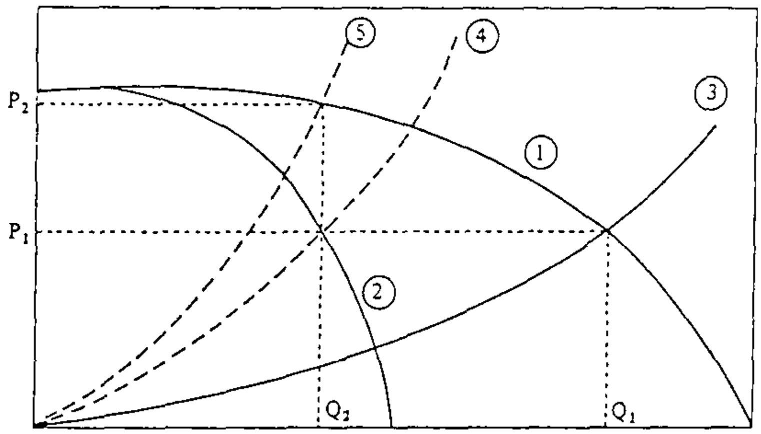
Table 10 shows a table for stationary types.

Table 10 Method to reduce blowing capacity (stationary system)

Main classification	Sub-classification
Reduction in blower ability	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 Figure 14, 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 14 Performance curve during parallel operation

b. Replacement of impellers

When the blower output becomes too high and the damper opening 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 as a result 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.

$Q \propto D$

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

$L \propto D^3$

Accordingly, diminishing the diameter of the impeller as required will bring very great energy conservation. In this case, it is of course necessary after diminishing to adjust the balance. In the case of multi-stage blower, 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 discharge side, the opening changes the resistance curve and, when installed on the suction side, the opening changes the static pressure curve. The vane means a movable blade which is installed at the suction of the blower. Adjusting the vane changes the pressure-air flow curve.

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

Assuming the rotating speed of blower as N,

$Q \propto N$

$P \propto N^2$ .... (6)

$L \propto N^3$

From this 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 motor 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 12, of which we describe the eddy current joint control and Scherbius control.

Table 11 Damper, vane opening adjustment

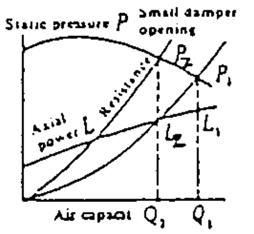
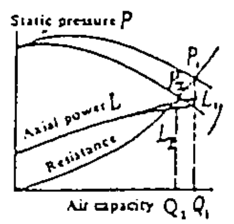
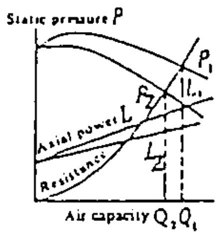
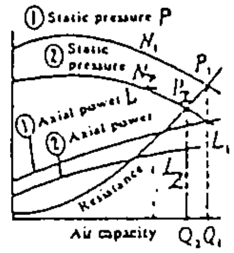
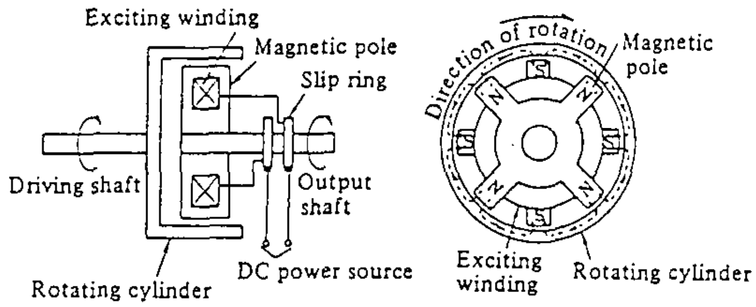
Method	Discharge damper opening adjustment	Suction damper opening adjustment (suction side piping)	Suction vane control	Changing the rotating speed
Principle	Change blower resistance curve by intentionally increasing resistance of the piping system.	Since damper resistance is provided on suction side, 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.

Table 12 Method to control air flow (variable system)

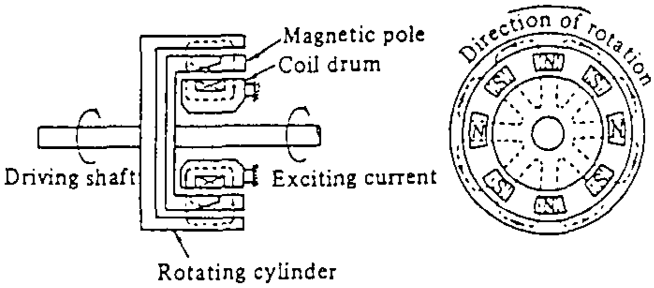
Discharge damper control (Variable)	Intake damper control (Variable)
Intake vane control (Variable)	Change in number of poles
Eddy current coupling control	Secondary resistance control
VVVF control	Scherbius control
	Others

a. Eddy current joint control

This eddy current joint control is a method to change the rotating speed in the following method: while a prime mover (motor) is running at a specified rotating speed, an eddy current joint is direct-coupled to the prime mover output shaft and the slip of the rotating speeds of the input and output shafts is altered to change the rotating speed. Figure 15 shows a principle diagram of the eddy current joint. The salient magnetic pole equipped with the exciting winding inside is direct-coupled to the output shaft, outside of which the rotating cylinder is provided across a small clearance. This rotating cylinder is direct-coupled to the driving shaft of the prime mover and while the cylinder is rotating at a specified rotating speed, the magnetic flux generated by the exciting winding is cut and, as such, eddy current flows in the cylinder. Electromagnetic force working between this eddy current and magnetic flux generates transfer torque and the magnetic pole direct-coupled to the load rotates in the same direction as the rotating cylinder.
The exciting current is supplied through the slip ring because the magnetic pole is a rotor. However, the slip ring can be eliminated by equipping the stator side with the exciting winding and providing the salient magnetic pole across the small clearance as shown in (b).



(a) With slip ring



(b) Slip ring-less

Figure 15 Principle of eddy current joint

Since the amount of the generated torque varies with the amount of the exiting current and the relative speed of magnetic pole to rotating cylinder, changing the exciting current changes the output torque or the speed optionally. The outside rotor has high-slip characteristics as shown in Figure 16.

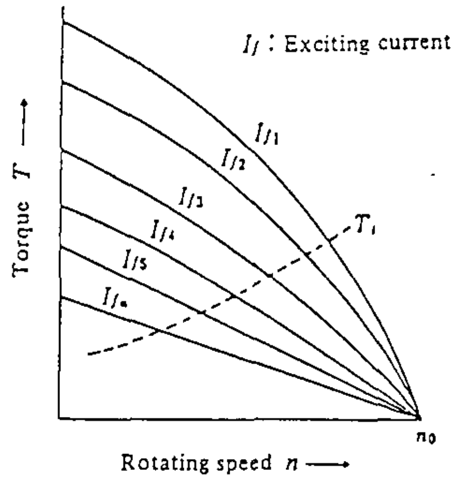


Figure 16 Torque characteristic of eddy current joint

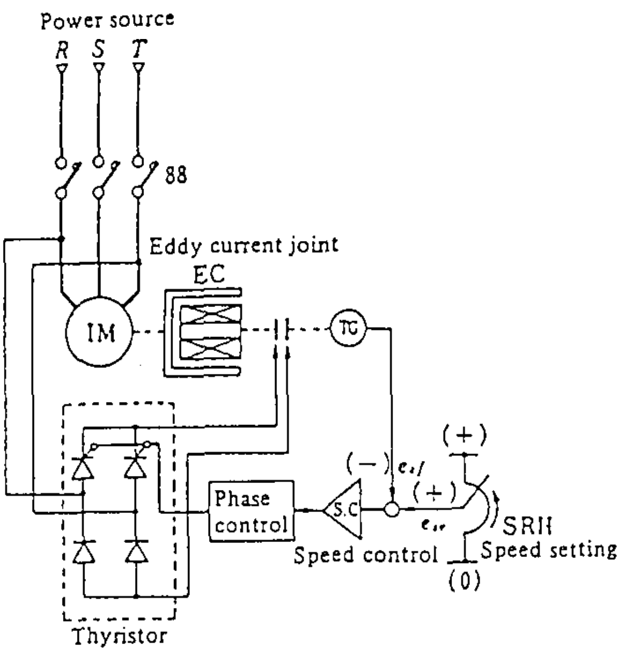


Figure 17 Distribution diagram of rotating speed control by means of eddy current joint

Figure 17 shows a distribution diagram of rotating speed control when an induction motor is used for the prime mover. For this control, first turn on switch 88 and operate the induction motor before operating the load. If the desired speed is set with the automatic control operated by means of the presetter SRH, the speed standard signal e_{ST} and speed feedback signal e_{sf} are compared and the difference ($e_{ST} - e_{sf}$) is amplified by the speed control circuit and the control angle α of thyristor conversion is controlled through the phase control circuit. The rotating speed can be controlled by controlling the exciting current of the eddy current joint. For the eddy current joint, assuming the slip between the input and output shaft as S, and efficiency of the prime mover as η_m, the system efficiency η_s will be quite the same as the secondary rheostatic control of the induction motor, and the efficiency in the low-speed area remarkably lowers.

$$\eta_s = (1 - S)\,\eta_m \times 100\ (\%) \quad \cdots\cdots (7)$$

Since the slip power generates heat as eddy current loss within the rotating cylinder, the water cooled type is generally adopted for of more than 55 kW.

b. Scherbius control

Assuming the induced electromotive force on the secondary as E_2, the secondary winding resistance per phase as γ_2 and reactance when slip s = 1 as x_2, the secondary current of the wound-rotor type induction motor I_2 (A) is

$$I_2 = \sqrt{x \frac{sE_2}{\gamma_2^2 + (sx_2)^2}} \quad \cdots\cdots (8)$$

When electromotive force E_c with the same phase and same frequency is supplied to the secondary winding from the outside,

$$I_2 = \sqrt{\frac{sE_2 + E_c}{\gamma_2^2 + (sx_2)^2}} \quad \cdots\cdots (9)$$

Here, E_2 is constant and when the load is constant, I_2 is constant. Accordingly, changing E_c changes the slip s. This is the principle of Scherbius control. Figure 18 shows a principle diagram. In the diagram, electric power corresponding to the secondary copper loss is taken out through the slip ring and returned to the power source by means of a DC-AC converter through a transformer. Adjusting the return power changes the speed.

The secondary rheostatic control system is of control with low efficiency because electric power corresponding to the secondary copper loss is consumed at the external resistance. This Scherbius control system recovers that electric power and, therefore, becomes a variable control system with very high efficiency. Figure 19 shows motor input (%) of various variable air flow control methods specified in Table 12.

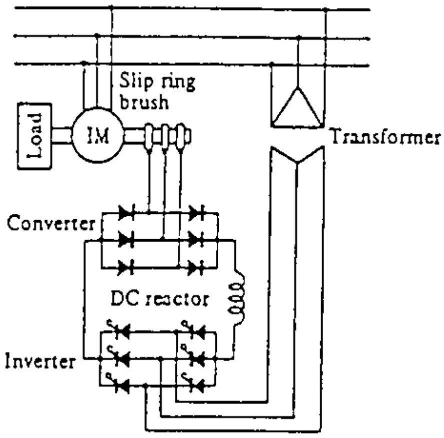


Figure 18 Principle of Scheribius control

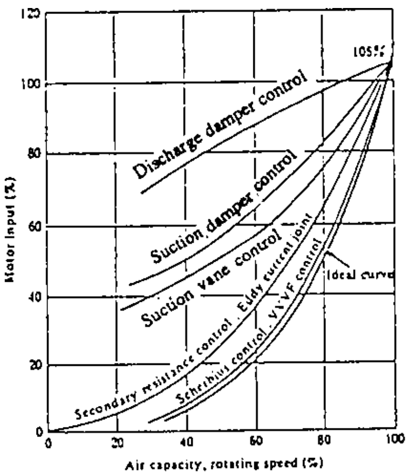


Figure 19 Comparison of blower motor's input

2.3 Pump

As electric power consumed by pumps for various facilities is huge, improvement of their efficiency is one of the most important concerns for saving electric power. 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 in the flow rate in prospect of future increase of supply or drainage quantity, and 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.

2.3.1 Type and construction of pumps

Pumps are classified into turbo pumps, positive displacement pumps and other pumps, as shown in Table 13. 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 13 General classification of pumps

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

However, turbo pumps are used by 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 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 N_S of pump is 1,200 ~ 2,000.

Shape of these pumps are shown in Figure 20.

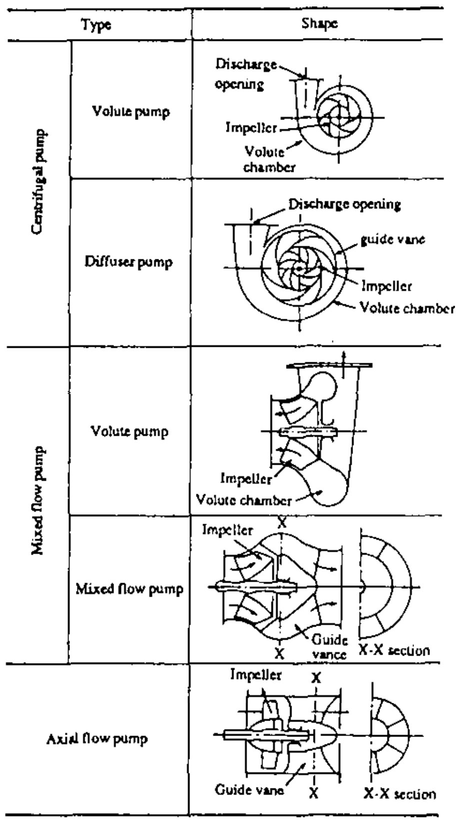


Figure 20 Pump shapes

2.3.2 Pump facilities by usage

(1) Pump facilities for water supply and sewerage

Many of these pumps are run continuously for 24 hours by expert who control the number of operating pumps and/or speed change automatically according to the quantity variation of water supply. At most pumps such considerations and measures have been taken on saving electric power from before.

(2) Pump facilities for rain drainage and other emergency purposes

Pumps for emergency purposes are facilities for preserving the living environment of local inhabitants and provide relatively large drive power in cases of emergency. However, their operating hours per year are negligible and moreover they are to be used for only heavy rainfall and floods, these pumps are excluded from the scope of electric power saving.

(3) Pump facilities for agricultural use

Pump facilities for agricultural use include various different pump plants from big plants, to very small terminal plants. While the large-scale pump plants are thoroughly studied for electric power saving and efficient operation from the design stage, many of the small-scale pump plants are not met by each thorough study. And, as water level and other operational conditions vary largely in the latter case, there seems to be a considerable number of pump plants which have leeway for electric power saving if their operational state is confirmed with more care.

(4) Pump facilities for industrry

Pump facilities in the equipment industry should correspond with the production capacity of each factory. Actually, however, there are many cases in which pump facilities are run inefficiently, such as flow control by valves, due to the factory operation rate being below 100%, or in which too much leeway is considered in the plan of pump facilities. Therefore, it is expected that a considerable electric power saving measure is possible when their actual operational state is checked and suitable measures are taken.

2.3.3 Characteristic curves and operating points of pumps

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 guide line 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:

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

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 21 shows the relationship of N_S and impeller shape.

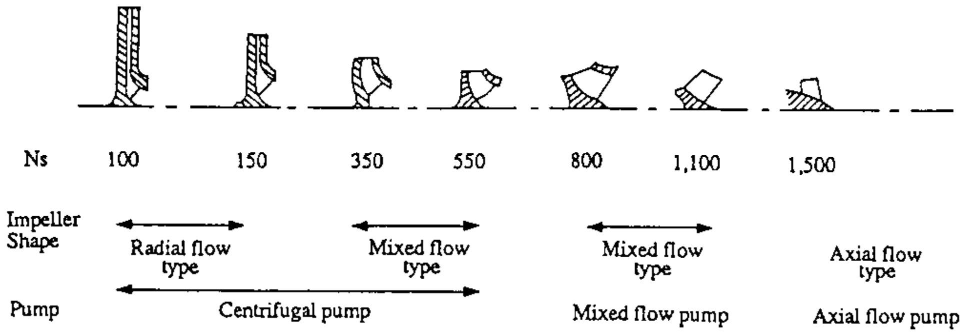


Figure 21 N_S and impeller shape

(1) Characteristics at fixed rotational speed

For operation at fixed rotating speed, performance characteristic curves of various pumps are shown in Figure 22 ~ Figure 24. For each case, flow rate, head, efficiency and axial power at the max. efficiency point (specified point) are set as 100.

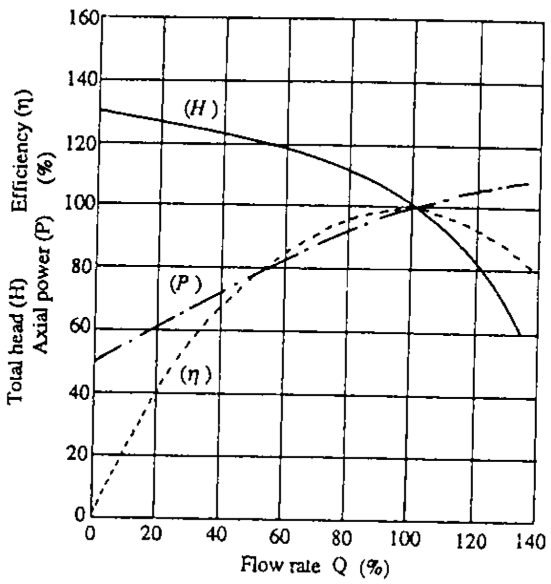


Figure 22 Characteristics of volute pump

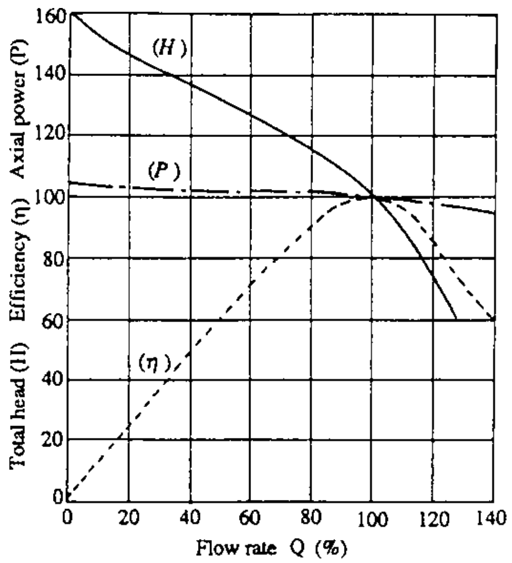


Figure 23 Characteristics of mixed flow pump

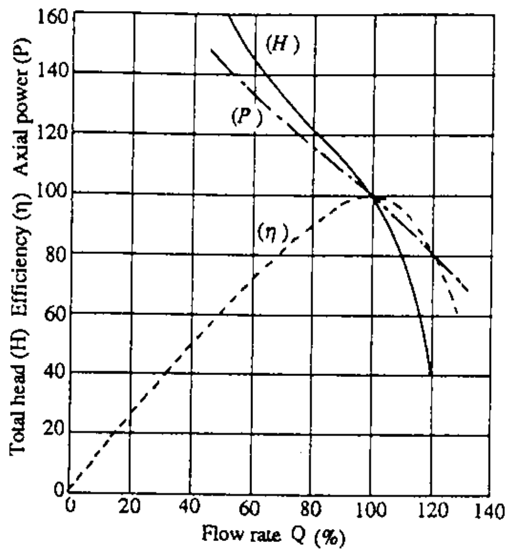


Figure 24 Characteristic of axial flow pump

(2) Characteristics when rotating speed is varied

When rotating speed of a pump is varied, the performance characteristic curves will also differ. However, since the impeller is the same, the aforementioned characteristic of the impellers with the same N_S rests satisfied, and yet the following relations are established among the performance characteristics curves at each rotating speed on mutually corresponding points:

$N \propto Q$

$N^2 \propto H$

$N^3 \propto P$

$\eta = \text{const}$

(3) 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 the state 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 25.

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 25 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.

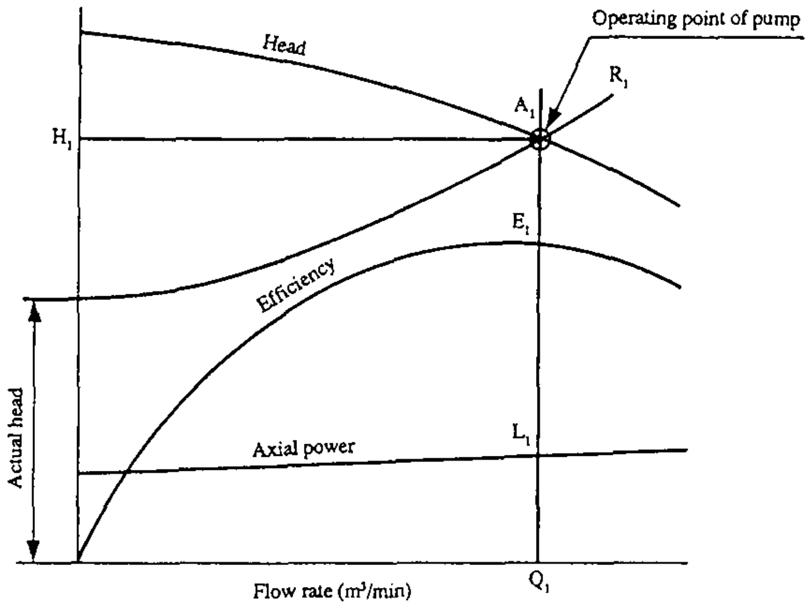


Figure 25 Performance curve of pump

2.3.4 Necessary power and pump drive motor

(1) Necessary power

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

$P = 0.163 \cdot \gamma \cdot Q \cdot H$ [kW] .... (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:

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

η : Efficiency of the pump (%)

α : Tolerance

The approximate values of η and α are shown in Figure 26 and Table 14.

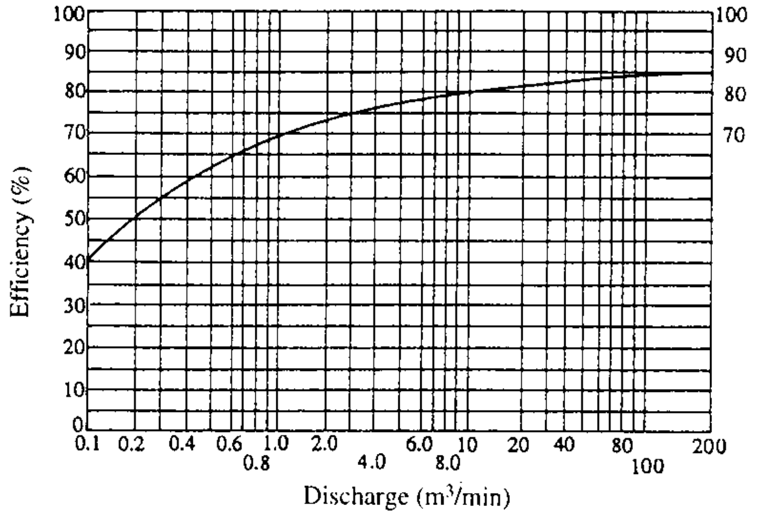


Figure 26 Standard efficiency of general purpose pumps

Table 14 Tolerance of pumps

Pump type		Tolerance α (%)	
		Fluctuation of head is relatively small.	Fluctuation of head is relatively large.
Volute pump	High head	15	20
	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 said 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 start-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 start 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 pumps with 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% of that at the rated speed 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 27.

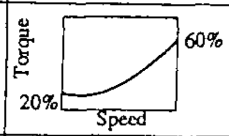
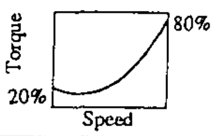
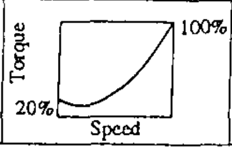
Pump type		Start torque characteristics	GD^2
Centrifugal pump	Ns ≦ 300		Small
	300 < Ns ≦ 450		Small
Mixed flow pump Axial flow pump			Small

Figure 27 Start characteristics of pumps

Each pump drive motor should be selected by considering the given start conditions. Generally, squirrel cage motors are often used. 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.

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.

2.3.5 Resistance of feed pipe

Generally, resistance of feed pipes is calculated by Darcy a formula when the feed pipe is short, and by Hezen. William's formula when it is long.

(1) Darcy's formula

$$Hf = \lambda \bullet \frac{L}{D} \bullet \frac{v^2}{2g} \quad \cdots\cdots (4)$$

Hf : Resistance of feed pipe (m)

λ : Loss factor

L : Length of feed pipe (m)

D : Inside diameter of pipe (m)

v : Velocity in pipe (m/s)

g : Gravity acceleration 9.8 m/s^2

The value of λ is normally set as $\lambda = 0.02 + 1/2{,}000D$, which is multiplied by a modulus determined by the smoothness of the internal face of the feed pipe. For this calculation, the loss factor by Colebrook's experimental formula, as shown in Figure 28, will facilitate the procedure.

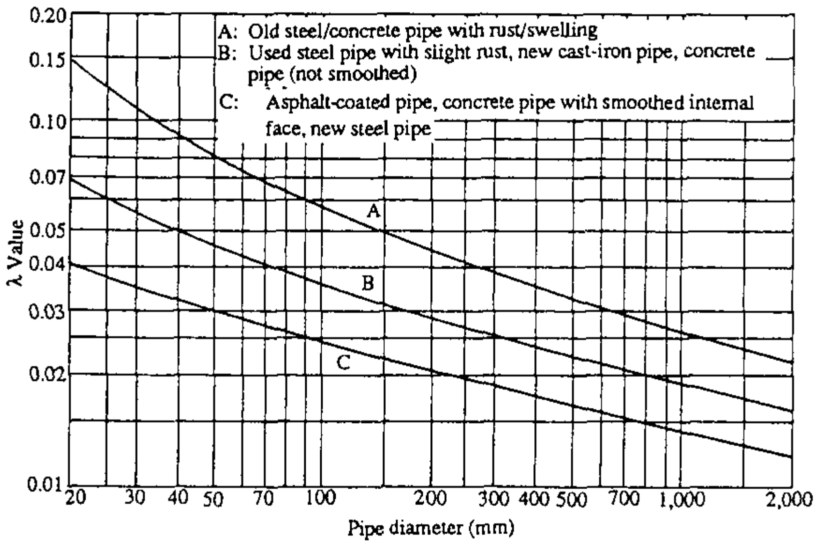


Figure 28 λ values by Colebrook

(2) Hezen William's formula

$$Hf = 10.666 \frac{Qs^{1.85}}{c^{1.85} \bullet D^{4.87}} \bullet L \qquad (5)$$

Hf : Resistance of feed pipe (m)

Qs : Flow rate (m^3/s)

c : Velocity modulus

L : Length of feed pipe (m)

D : Inside diameter of pipe (m)

The velocity modulus c is shown as Table 15. According to formula (5), it is understood that the resistance of feed pipe can be greatly reduced by using tar-epoxy coated steel pipes when the feed pipe is long, with the velocity modulus calculated as c = 100 for ordinary steel pipes and c = 130 for tar-epoxy steel pipe; $(100/130)^{1.85} = 0.62$.

Table 15 Values of velocity modulus c

Pipe type (state of internal face)	Velocity modulus c		
	Max.	Min.	Standard
Cast-iron pipe (not coated) (1)	150	80	100
Steel pipe (not coated) (1)	150	90	100
Coal-tar-coated pipe (cast-iron) (1)	145	80	100
Tar-epoxy-coated pipe (steel) (2)	–	–	130
Mortar lined pipe (steel cast-iron)	150	120	130
Centrifugal reinforced concrete pipe	140	120	130
Rolled reinforcement concrete pipe	140	120	130
Prestressed concrete pipe	140	120	130
Asbestos cement pipe	160	140	140
Hard vinyl chloride pipe (3)	160	140	150
Hard polyethylene pipe (3)	170	130	150
Reinforced plastic composite pipe (3)	160	–	150

(Notes) (1) Secular change is considered.

(2) The coating method shall be in accordance with JWWAK-115-1974, the coating thickness is preferably 0.5 mm and over. Provided, this shall not apply when field coating cannot be met by thorough execution control.

(3) To pipes 150 mm or less, c = 140 shall apply.

In the pump performance curve of Figure 29, the operating point of pump is A_1, where increase of resistance by secular change is considered in prospect. Actually, resistance of the feed pipe is small and the resistance curve is R_2 for a while after completion of the pump facility. When the pump is operated under this state, a point of intersection A_2 of the pump performance curve and resistance curve R_2 becomes the operating point of the pump, with the flow rate Q_2 and the pumping power L_2.

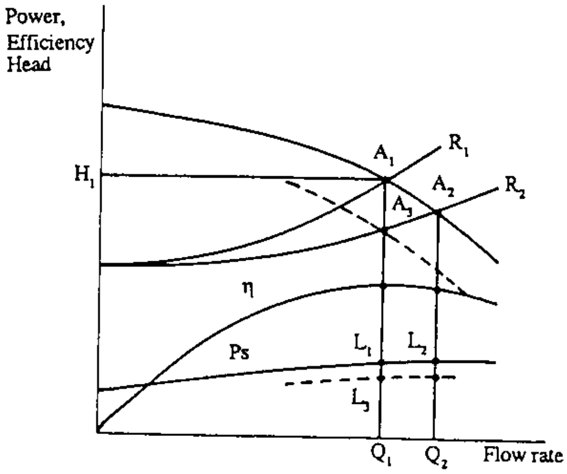


Figure 29 Pump performance and operating point

To control the flow rate at Q_1, it is necessary to add resistance by throttling the valve on the discharge side of the pump so the resistance curve R_2 reaches R_1. If the pump performance curve turns out to be a broken-line curve and the point of intersection with resistance curve R_2 is A_3, it is possible to supply water at the flow rate Q_1 without adding resistance by throttling the valve. So, the pumping power is reduced to L_3, consequently saving electric power by $(L_1 - L_3)$.

(3) Determining the resistance curve

When the pump performance curve, current operating point (flow rate Q_0, total head H_0) and actual head H_a of the pump in the facility are known, the current operating point is A and the required flow rate of the facility is Q_2 in Figure 30. An example on determining the resistance curve is shown below.

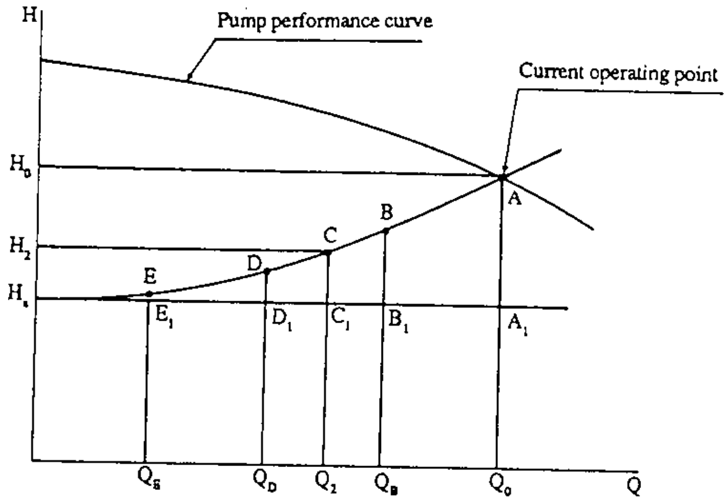


Figure 30 Determining the resistance curve

First draw vertical lines to points where the flow rate $Q_B = Q_0 \times 3/4$, $Q_D = Q_0 \times 1/2$, and $Q_E = Q_0 \times 1/4$, and draw a horizontal line from a point H_a of the actual pump head. Pressure loss of the facility is $H_0 - H_a$, and it is equal to a line AA_1 of Figure 30. And, pressure loss when the flow rate Q_B is applied is equal to a line BB_1. Generally if in the same facility, each respective pressure loss is proportionate to the square of the velocity by Darcy's formula, therefore:

$BB_1 = AA_1 \times (Q_B/Q_0)^2 = AA_1\ (3/4)^2$

$DD_1 = AA_1 \times (Q_D/Q_0)^2 = AA_1\ (2/4)^2$

$EE_1 = AA_1 \times (Q_E/Q_0)^2 = AA_1\ (1/4)^2$

By connecting points A, B, D, E and H_a, a resistance curve can be obtained. When a vertical line is drawn from a point Q_2 of a flow rate required for the facility, the point of intersection C with the resistance curve is the operating point corresponding to the flow rate Q_2.

Besides the above method, the operating point C can also be determined as follows:

$CC_1 = AA_1\ (Q_2/Q_0)^2$ .... (6)

Q_2 : Necessary flow rate (m^3/min)

Q_0 : Flow rate of current operating point (m^3/min)

The total head H_2 of point C can be determined as,

$H_2 = CC_1 + H_a$

[Example]

Let's suppose the actual head is 20 m, the flow rate is 4.0 m³/min and total head 25 m at the current operating point. When the necessary flow rate is 3.0 m³/min, the total head is determined as,

$AA_1 = 25 - 20 = 5$ m

$CC_1 = 5 \times \left(\frac{3}{4}\right)^2 = 2.8$ m

$H_2 = CC_1 + H_a = 2.8 + 20 = 22.8$ m

2.3.6 Pump performance when the outside diameter is worked upon

Volute pumps, like the frame number of motors, fabricate impellers according to the pump specification, within the ranges of a certain flow rate and head as a single barrel. Therefore, in cases where specifications are prepared in prospect of the future but have too much leeway performance for the time being as previously mentioned, a method to first fabricate the impeller according to a broken line is in Figure 31, and then make a new one when the flow rate later becomes insufficient due to increase of line resistance.

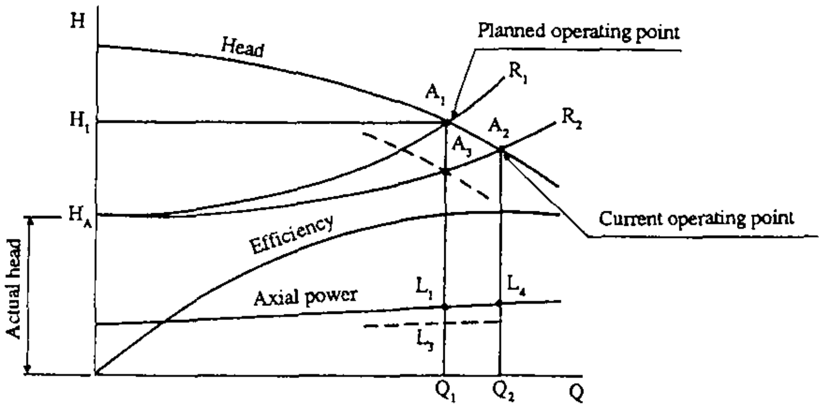


Figure 31 Pump performance and resistance curve

Also, when impeller is rebuilt by increasing the size of the feed pipe to shift the resistance curve from R_1 to R_2, with the same actual head, it allows the operating point of the pump to change from A_1 to A_3, thus saving electric power by $(L_1 - L_3)$.

Change of performance when the outside diameter D_1 of the impeller of an operating pump is worked to D_2 as shown in Figure 32 is illustrated in Figure 33. When the outside diameter of the impeller is worked from D_1 to D_2 in Figure 32, the flow rate, head and power are obtained by equational (7), (8) and (9), respectively.

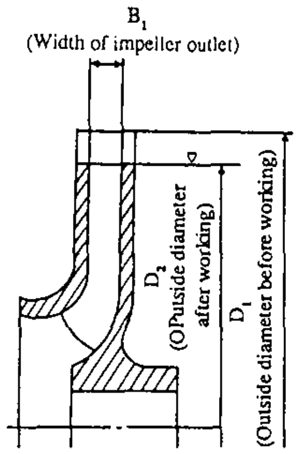


Figure 32 Working the impeller of its outside diameter

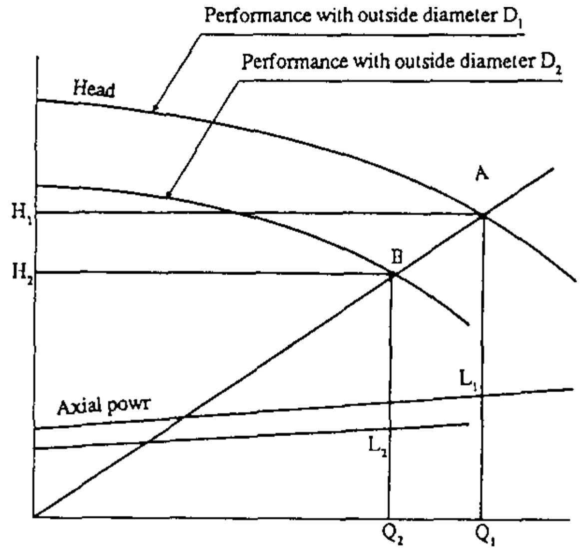


Figure 33 Change of performance by working on impeller diameter

$$\frac{Q_2}{Q_1} = \left(\frac{D_2}{D_1}\right)^2 \cdots\cdots (7)$$

$$\frac{H_2}{H_1} = \left(\frac{D_2}{D_1}\right)^2 \cdots\cdots (8)$$

$$\frac{L_2}{L_1} = \left(\frac{D_2}{D_1}\right)^4 \cdots\cdots (9)$$

Connect an optional point A, on the Q-H curve of outside diameter D_1, to the origin with a line, and obtain a point B from $H_2 = (D_2/D_1)^2 \times H_1$, or $Q_2 = (D_2/D_1)^2 \times Q_1$. Determine several points for the performance of outside diameter D_2 in the same manner, and prepare the Q-H curve of outside diameter D_2 by connecting these points. Likewise, calculate the power from $L_2 = (D_2/D_1)^4 \times L_1$, and obtain a point L_2 on the vertical line BQ_2. Determine several points in the same manner, and prepare the power curve by connecting these points.

• Points to be noted on working the outside diameter of the impeller

1) As the impeller is balanced during fabrication, it should be re-balanced after worked.
2) For cases when the work ratio of the outside diameter of the impeller, $\{(D_1 - D_2)/D_1\} \times 100\%$, exceeds 20%, the expressions (7), (8) and (9) will sometimes not apply, not enabling pumping.
3) Note that working on the outside diameter is not necessarily available depending on the materials of the impeller, such as pressed stainless steel.

2.3.7 Rotating speed control of pump

Rotating speed control may be adopted for purposes as process control, flow rate control of pumps, or energy saving. As methods of rotating speed control for pump drive motors, there are various methods as described in 2.5.4, (3). To perform rotating speed control, relations of the equations (10), (11) and (12) are established by supposing the rotating speed of the pump to be N_0 and N_1, the flow rate Q_0 and Q_1, the pump head H_0 and H_1, and the axial force L_0 and L_1:

$$\frac{Q_1}{Q_0} = \frac{N_1}{N_0} \qquad \cdots(10)$$

$$\frac{H_1}{H_0} = \left(\frac{N_1}{N_0}\right)^2 \qquad \cdots(11)$$

$$\frac{L_1}{L_0} = \left(\frac{N_1}{N_0}\right)^3 \qquad \cdots(12)$$

Figure 34 shows changes in characteristics of the pump when the rotating speed is changed, where the flow rate, head and axial power are changed in a manner so that the expressions (10), (11) and (12) show their relations to the rotating speed. When the resistance curve of the feed pipe is R_3 in Figure 34, and when the rotating speed of the pump is changed from N_0 to N_1 and N_2, the operating point of the pump is changed from A_3 to B_3 and C_3, and the flow rate from Q_3 to Q_2 and Q_1.

If the rotating speed of the pump is left as N_1 when the necessary flow rate is Q_1, the resistance curve must be changed from R_3 to R_1 by throttling the valve, when the operating point of the pump is A_1 and the axial power is L_1'. When the rotating speed is changed to N_2, it will change the operating point to C_3 and axial power to L_1 while leaving the resistance curve as R_3. Therefore, a considerable amount of electric power can be saved.

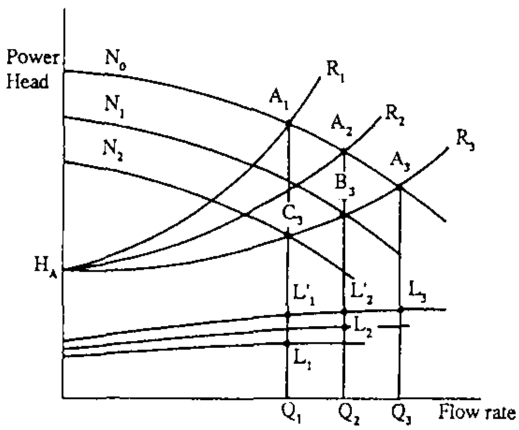


Figure 34 Changes of characteristics by change of rotational speed

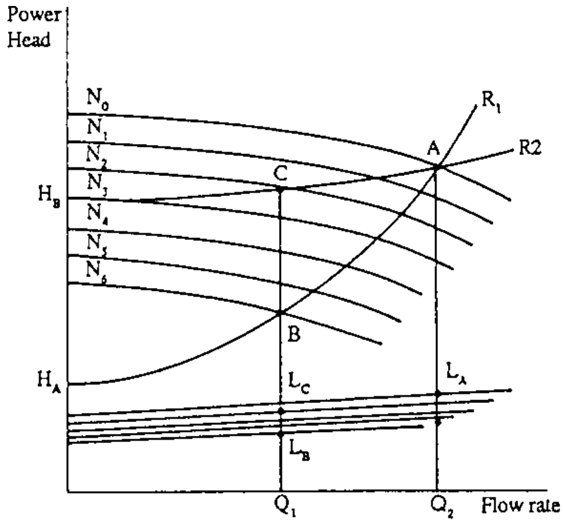


Figure 35 Difference of axial power by actual head power

Provided, however, it should be noted that, as the above description applies only when the actual head is small and the line resistance is large like H_A of Figure 35, rotating speed would not result in a significant saving of electric power if made when the line resistance is small and the actual head is H_B.

- Method to determine rotating speed to change flow rate from Q_0 to Q_2

Suppose that the pump is operating on the operating point A of Figure 36. The resistance curve can be determined from the actual head H_a and the total head H_0. (See 2.3.5. (3); Determining the resistance curve.) On the resistance curve, the total head is H_2 and operating point C when the discharge is Q_2.

A curve CB is a quadratic curve passing the origin, obtained as follows:

Supposing the quadratic curve to be,

$$H = a \times Q^2$$

the modules a is obtained from the point C,

$$a = H_2 / Q_2^2$$

When factors of Figure 36 are substituted,

$$a = 22.5 / (1.5)^2 = 10$$

Therefore, curve CB is expressed as,

$$H = 10 \times Q^2$$

The point of intersection of this curve with the pump performance curve at the rotating speed would be point B. From the figure, the discharge Q_1 = 1.7m^3/min, total head H_1 = 28.2 m, and axial power L_1 = 10.8 kW.

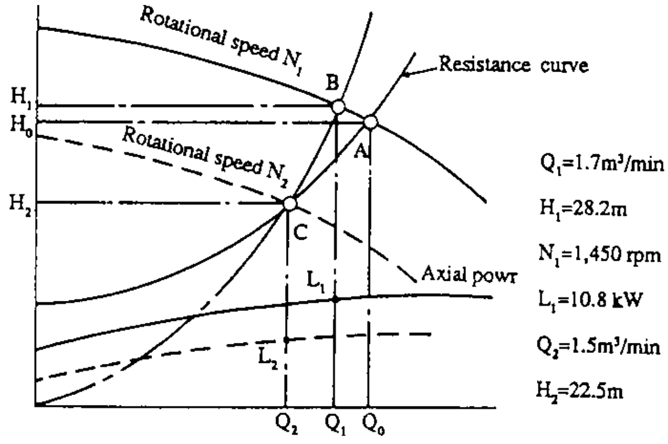


Figure 36 Change of pump performance by rotational

To determine a rotating speed of the pump for reaching the operating point C required by the facility, it is calculated by formula (11), as,

$$N_2 = \frac{N_1}{(H_1/H_2)^{1/2}} = \frac{1,450}{(28.2/22.5)^{1/2}} = 1,295 \text{ rpm}$$

Here, the axial power is obtained from formula (12), as

$$L_2 = L_1 \times \left(\frac{N_2}{N_1}\right)^3 = 10.8 \times \left(\frac{1,295}{1,450}\right)^3 = 7.7 \text{ kW}$$

As the axial power is 11.0 kW at point A of Figure 36, it is reduced to 7.7 kW by changing the rotating speed.

2.3.8 Pump unit control

Even if flow control is performed by operating the valve of a large-capacity pump when the required volume of water varies seasonally or by time, or by rotating speed control, the max. efficiency point of the pump is in a zone with large flow rate, and the efficiency is low in zones with small flow rates. In such a case as shown in Figure 37, the number of pumps may be made multiple to perform parallel operation for cases requiring a large volume of water and use only one pump in cases requiring a small volume of water, so that operation can always be performed in zones with high pump efficiency, resulting in saving of electric power. However, it is necessary to make sure of the operating point in order to avoid overload of motor.

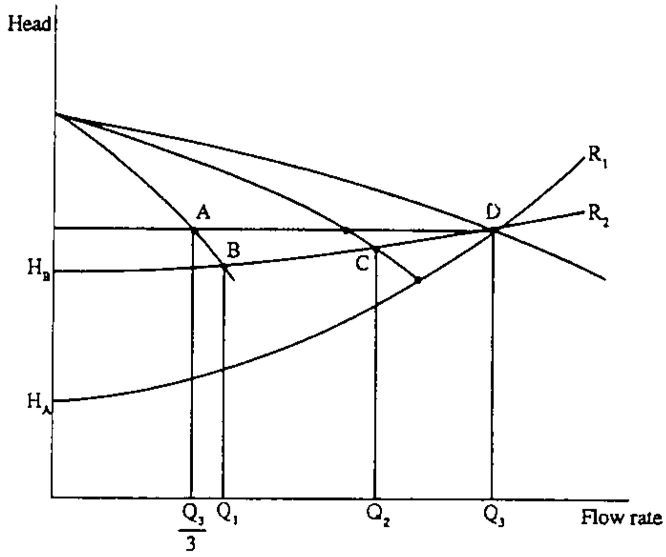


Figure 37 Parallel operation characteristics of pump

If the actual head is H_B and the resistance curve of the feed pipe is R_2, the flow rate is Q_3 when 3 pumps are in operation. Therefore, if only one pump is used, the pump must be operated at the flow rate $Q_3/3$. However, since the flow rate is smaller and resistance of the feed pipe smaller when only one pump is used, the operating point of the pump is B, consequently resulting in a flow rate Q_1 larger than $Q_3/3$. Therefore, study should be made so the motor is free of overloading even when the pump is operated at the flow rate Q_1.

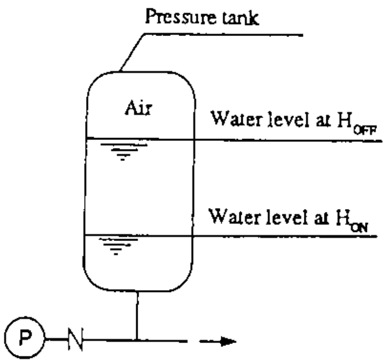
Also, for pumps with small actual head, like those with the actual head H_A and the resistance curve of the feed pipe R_1, the flow rate of a pump, when only one pumps is to be operated, will exceed the max. flow rate of the pump, requiring an additional resistance by throttling the discharge valve.

2.3.9 Water supply facility using pressure tank

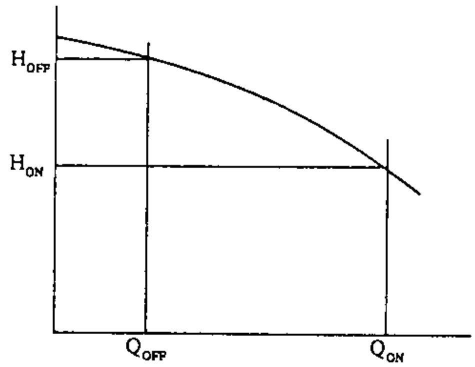
In order to apply pressure to the feed pipe even when water is not used, and make ready to use water as in the case of city water, pump operation is required for supplying even small quantities of water, resulting in an operation with very inefficient flow rates.

It such a case, considerable saving of electric power is possible by providing a pressure tank on the discharge side of the pump. There the pump may run when pressure in the tank drops below the set starting pressure, and stop when its pressure reaches over the set terminal pressure. And yet, as the difference between the tank levels at set starting pressure and at stoppage pressure can be effectively used as the volume of water by suitably selecting the size of the pressure tank, it is possible to stop the pump even when there is any leakage from the feed pipe or when small volume of water is used occasionally.

Figure 38 illustrates an effective volume of water in the case a pressure tank is installed. (a) is a conceptional view of the pressure tank, and (b) is the flow rate-head curve of the pump. When the volume of used water drops during a pump operation, head of the pump rises according to the drop of discharge.



(a)



(b)

Figure 38 Illustration of the effective volume of water of pressure tank

When the pressure in the tank reaches H_{OFF}, this pressure is detected by a pressure switch attached to the pressure tank to stop the pump. When water is used, water is pushed out by compressed air of the pressure tank, and thereby the tank water level drops and air expands in the pressure tank to drop the pressure. When the water level drops further and pressure in the pressure tank drops to H_{ON}, this pressure is detected by the pressure switch to start the pump again, and the pump supplies water. Generally, the volume of air V_{ON} when the water level of the pressure tank is at its lowest is set as 70% of the total volume V of the pressure tank. And, since the product of the volume of air in the pressure tank and the absolute pressure at that time is constant, the following formula is established.

$V_{ON} = 0.7\ V$ ....(13)

$V_{ON} \times (10 + H_{ON}) = V_{OFF} \times (10 + H_{OFF})$ ....(14)

$V_A = V_{ON} - V_{OFF}$ ....(15)

V : Total volume of pressure tank (m^3)

V_{ON} : Volume of air at tank pressure H_{ON} (m^3)

V_{OFF} : Volume of air at tank pressure H_{OFF} (m^3)

V_A : Effective volume of pressure tank (m^3)

H_{OFF} : Tank pressure at pump stop (m)

H_{ON} : Tank pressure at pump start (m)

Q_{OFF} : Flow rate at pump head H_{OFF} (m^3/min)

Q_{ON} : Flow rate at pump head H_{ON} (m^3/min)

From the equations (13), (14) and (15), total volume of the pressure tank is calculated as the following formula (16).

$$V = \frac{(10 + H_{OFF})}{0.7(H_{OFF} - H_{ON})} \times V_A \quad \text{.......(16)}$$

2.3.10 Electric power saving measures of pump

Since both gas and liquid are fluid and the basic theories are the same, the method which was discussed about the blower thus applies similarly. However, an exception is that the valve control is performed only on the discharge side and not on the suction side. Valve control on the discharge side is the worst method for power saving purpose.

The electric power saving flow of pumps is shown in Figure 39.

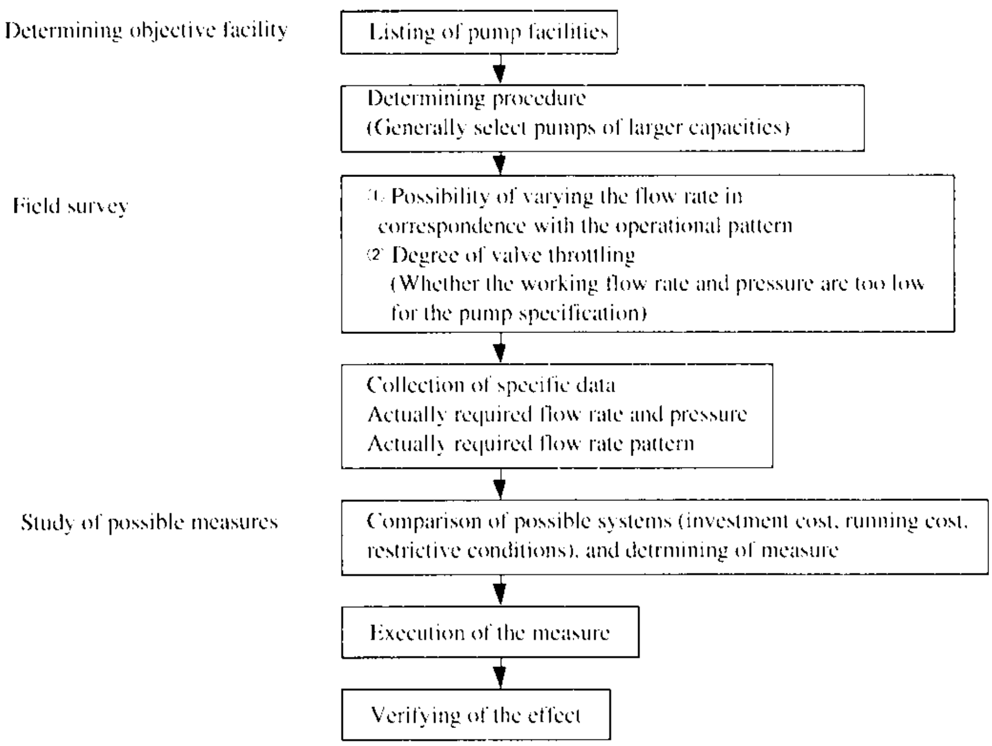


Figure 39 Electric power saving flow of pumps

The 3 factors of electric power saving of pumps are (1) reduction of required flow rate, (2) reduction of pipe resistance, and (3) efficient flow rate control.

(1) Reduction of required flow rate

The first to be done is to reduce the required flow rate. Pumps should be those that meet the required flow rate, however actually in most cases the pump performance is larger than the actually required head and flow rate, because of the following reasons:

i) In many cases pumps having considerable excess capacity in their total head are installed in prospect of an increase of secular loss of piping.

ii) May facilities are installed with excess capacity of flow rate in prospect of a future increase of supply and drainage quantities.

iii) Because of the current JIS test standard which states that the actual flow rate-head curve should not be below the prescribed head by means of the flow rate as decided by pump specifications, most pumps have capacities above the flow rate and head as set by the specifications.

(2) Reduction of pipe resistance

Although pipe resistance is mostly fixed during construction and rebuilding of existing facilities is difficult, factors which form the resistance may be described as follows:

i) Friction loss of direct pipe

According to Darcy's formula (formula (4)), friction loss of a direct pipe is proportionate to (resistance modulus of pipe) × (velocity)^2 × (pipe length)/(pipe diameter).

ii) Loss at piping elements

Suction port, bends, acute expanded portions, acute contracted portions, orifices, diverting points, confluent points, effluent outlet, etc.

iii) Loss at valves

In short, piping should be arranged closest to the direct pipe with large diameter and short length, excluding unnecessary accessories from the piping in order to reduce the resistance.

(3) Efficient flow rate control

When the required flow rate is reduceable, methods of saving electric power of pumps are discussed as follows:

i) Intermittent operation

When water use is clearly distinct between periods of need and no need, pumps may be stopped during unnecessary periods.

That is, pumps may be run by intermittent operation. It is a simple method, but turning on and off within in short cycles too frequently should be refrained to avoid water-hammer effects.

ii) Pump unit control

A method varying the number of pumps according to the fluctuation of flow rate aims at reducing the axial power of pumps so they can be operated with relatively favorable efficiency meeting the fluctuation range of flow rate.

The control system is simple and risks can be avoided by increasing the number of pumps, but discharge changes by stages. Therefore, when the resistance curve is steep, there exist many problems such as discharge does not increase so much even when there are more pumps, and so on.

iii) Rotating speed control

In spite of large initial investment cost, this method offers several such advantages as great reduction in electric power costs and smooth pump operation even at low flow rate. This method is effective for pumps with large capacities, and for cases with large head fluctuation ranges.

iv) Replacing pumps

As a method for replacing pumps with those meeting the required flow rate when the discharge load is stable but the flow rate has dropped lower than before, or when the flow rate fluctuates seasonally, this is simple but has some problems such that flow control is not available, and replacement takes much time.

Additionally, sometimes only motors are replaced for the purpose of reducing the flow rate by changing the revolution.

v) Replacing the impeller

It is applicable for volute pumps operated under fixed discharge load, and afford efficient changes of pump performance. However, disassembling and assembling of pumps are necessary.

2.4 Transformers

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

(1) Transformer efficiency

(2) Operation with an efficient number of transformers.

(3) Selection of transformer taps

2.4.1 Selection of Transformers

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

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

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 is ignored. Also, the ratio of copper loss W_c to iron loss W_i at rated load is called "Loss ratio α".

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

The loss ratio is generally 2 to 5 as shown in Table 16. However, it may exceed 10 in the energy conservation type transformers as described later.
From equation (1), the transformer efficiency is maximum when $n = \sqrt{W_i/W_c}$, namely, at the output when the iron loss is equal to the copper loss. One example of efficiency change to output is illustrated in Figure 40.
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 Figure 41.

Table 16 Efficiency of three-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 α	Efficiency (%)	Iron loss (kW)	Copper loss (kW)	Loss ratio α
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	95.52	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

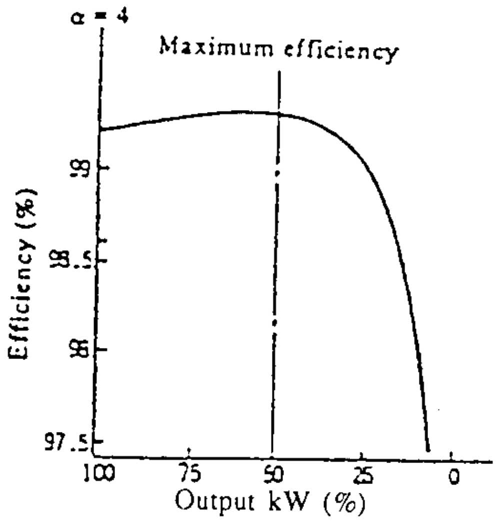
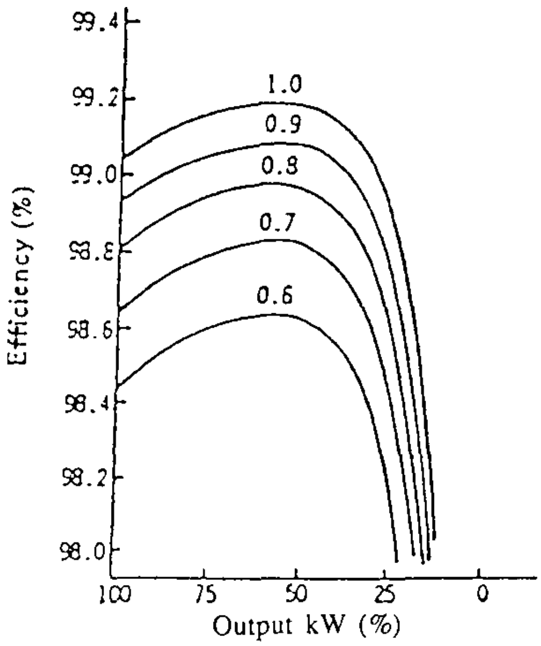


Figure 40 Transformer efficiency (Example)



Note: Figure indicates power factor.

Figure 41 Relation between power factor and efficiency

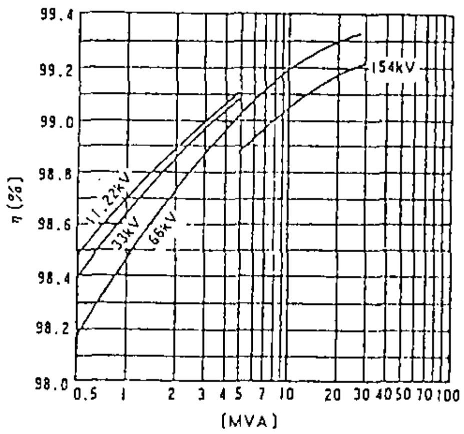


Figure 42 (a) Example of efficiency of 50 Hz transformer (single phase)

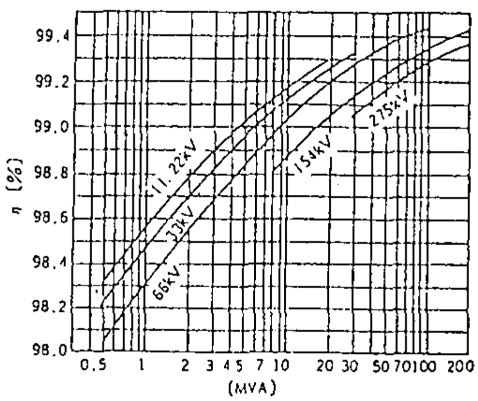


Figure 42 (b) Example of efficiency of 50 Hz transformer (3-phase)

The difference of efficiency due to the transformer capacity is shown in Figure 42.

(2) All day efficiency of transformers

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

All day efficiency

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

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

(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.

2.4.2 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 operating transformers may exceed reduced loss of stopped transformers, causing adverse effect. Therefore, it is always necessary to confirm by calculating, as shown in the following example.

[Example] Case of two 500 kVA transformers

In the case where each transformer has a load factor of 40% as shown in Figure 43, we calculate the merit for when one transformer is stopped. We presume the transformer's characteristics to be of company A, specified in Table 16.

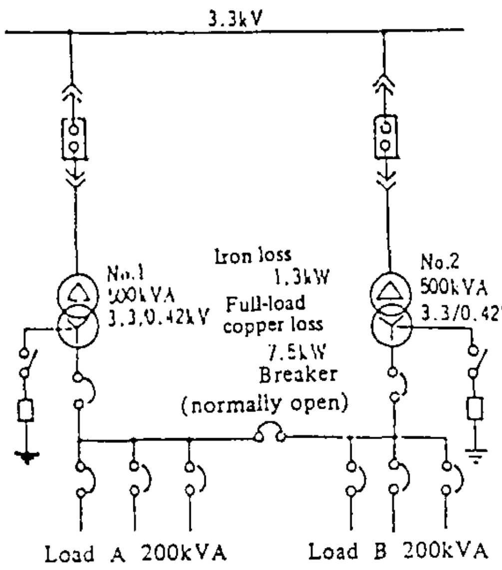


Figure 43 Method to use two 50 kVA transformers

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

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

Hence,

Total loss = $2 \times (1.3 + 1.2) = 5$ (kw)

After stop of transformer No.1,

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

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

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

$$W_N = N \left\{ W_i + \left(\frac{P_L}{N \bullet Q}\right)^2 \bullet W_c \right\} \quad \text{..........} (4)$$

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:

$$W_{N-1} = (N-1)\left\{(W_i + (\frac{P_L}{(N-1) \cdot Q})^2 \cdot W_c\right\}(kW) \quad \cdots\cdots (5)$$

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

$$P_L < \sqrt{\frac{N(N-1)}{\alpha}} \times Q\ (kVA) \quad \cdots\cdots (6)$$

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 loads for which electricity supply cannot be stopped even at night and on holidays, to certain transformers and stopping unnecessary transformers.

2.4.3 Selection of transformer taps

Low-voltage transformers or main power lines have mostly 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 endeavor to get as close as possible. Observing how motors are being operated in factories, full-load operations are few and operations of 50% to 80% of the load are generally seen.

Relation between voltage fluctuation and load state of an induction motor is as shown in Table 17 and Table 18. When all loads for the transformer are motors, it is desirable to select the taps in the light of these.

Table 17 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 18 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%

2.5 Motors

2.5.1 Motor equipments

There have been technological advancements in terms of automation and power conservation of the production facilities in recent years. These facilities have many motors which are the prime power behind these facilities, from the ratio of 1 motor per plant, then to 1 motor per machine, 1 motor per function, and to 1 motor per 1 motion.

Various types of motors are being developed and put to practical applications in accordance for various purposes.

In other words, with the increase in the number of motors as the prime driving force, there have also been a wider range of applications, extending into the areas of oil pressure types and pneumatic types because of the excellent controllability and maintenance. These motors are now serving as the leading equipment for the advancement of the production facilities. The percentage occupied by motors in the manufacturing plants are approximately 60% of total electric load, demonstrating the importance of its management and the need for its rational use.

Table 19 shows the characteristics of the motor equipments.

Table 19 Characteristics of electric motor equipments

Advantages	Defects
• Electric motor makes it easy to concentrate and distribute. • There are many types of electric motors; it is possible to select the type which is suited to a particular load. • Selection of the location for installation of the motor can be made optionally. • Selection of the operating method can be made optionally. • Easy and accurate control • Auto and remote controls are possible. • High efficiency, good reliability and safety. • Measurements and records can be taken easily, and observations and improvements can be made at ease. • Machines can be structured simply through multiple independent operations and speed control.	• The malfunctioning point cannot be discovered from outside, and it is necessary to detect this through electric measurements. • In case of short-circuit, there might be serious accidents affecting wide areas of the installations. • If the motor is used for locomotion, the wires and mobile power sources might hinder.

2.5.2 Method of energy conservation

(1) General condition for the selection of motors

The applications of motors are various, and there are motors of many types, formats, and capacities to meet specific purposes. In selecting the motor, it is necessary to carefully study these characteristics and pick the optimal motor for the specific mechanical load.

That is:

a. The motor is optimal for the starting characteristics and the operating characteristics of the load.

b. The protection and cooling method is suitable for environment of the site.

c. The motor is highly reliable and easy to maintain.

d. Standard motor is better for their compatibility and fast delivery.

e. Reasonable installation and operating costs, including the accessories.

(2) Selection of the motor capacity

The selection of the motor capacity is detailed later, so only the basic point for the selection is mentioned here.

The efficiency of the motor is best operating at 80% ~ 100% of the rated load capacity, and the efficiency drops and loss increases significantly at below 50%. In particular, there is a tendency to select larger motor by overestimating the safety factor against the load, so this should be avoided.

(3) 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.

Figure 44 shows desirable range of motor capacity for each voltage class. The range shown with a white frame 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.

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

a) Newly establishing or greatly remodelling load and motor equipments.

b) Remodelling the existing equipment in a small scale.

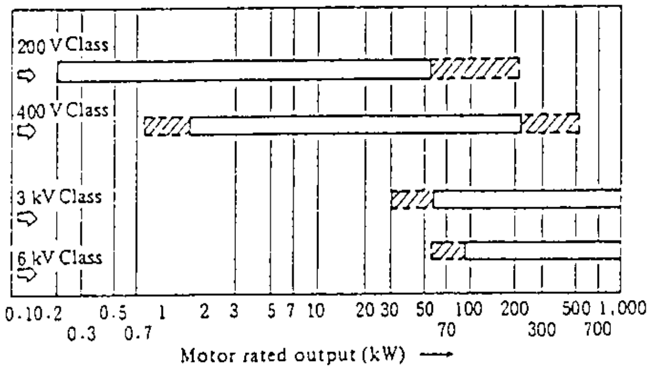


Figure 44 Optimum output range of motor

2.5.3 Energy conservation for newly establishing load and motor equipments

The energy consumption used in motor equipment may be determined to a certain degree at the planning stage. If the motor capacity is too big or unfit for the load equipment, the energy cannot be used rationaly. Matters which should be considered at the planning or introducing stage are described as follows:

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

Basic expressions for the motor energy conservation are shown in Table 20. For further description is refer to the other technical books.

Table 20 Basic and practical expressions relating to motor application

	Item	Basic expression	Practical expression	Description of sysmbols
1	Power and torque	$p = \omega T$	$Pk\,[kW] = p \times 10^{-3}$ $N\,[rpm] = \frac{60}{2\pi}\omega$ $T_g\,[kg\text{-}m] = \frac{T}{g} = \frac{T}{9.81}$ $P_k\,[kW] = \frac{N[rpm]}{973} \times T_g\,[kg\text{-}m]$	p: Power (watt) P_k: Power (kW) T: Torque (N-m) T_g: Torque (Gravity unit kgf-m) ω: Angular velocity (rad/sec) N: Rotating speed (rpm)
2	Moment of inertia and acceleration torque	$J\frac{d\omega}{dt} = T$	$GD^2 = 4J$ $Tg\,[kgf\text{-}m] = \frac{1}{375} GD^2 \cdot \frac{dN}{dt}$	J: Moment of inertia (kg m²) GD^2: Flywheel effect
3	Acceleration time	$1 = \int_0^{\omega_0} \frac{J}{Ta} d\omega\,[sec]$	$Ta = \frac{\int_0^{\omega_0} Ta(\omega) \cdot d\omega}{\omega_0}$ $ta\,[sec] = \frac{1}{365} \frac{GD^2 N_0^2\,[rpm]}{P\,[W]}$	t: Time required for acceleration (sec) ta: Time required for completion of acceleration (sec) Ta: Acceleration torque (N-m) Ta: Mean acceleration torque (N-m)

(2) Load condition in the selection of motors

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

How a motor must be selected under various conditions of load, or what to be the allowable conditions are summarized in Table 21 When the conditions shown here are clear, it is possible to select the motor and also to select the control equipment to follow it.

Although motor systems are classified into DC, induction and synchronous machines in Table 21, induction and synchronous machines here are considered to be constantspeed drive systems for commercial power source. A thyristor motor applied to a synchronous machine and a frequency control method applied to an induction machine are similar to DC machines as system.

Table 21 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	
	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.

Main items for selection of motors are described following:

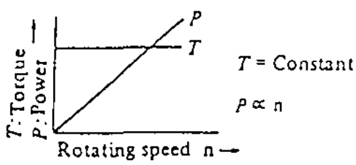
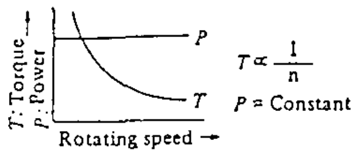
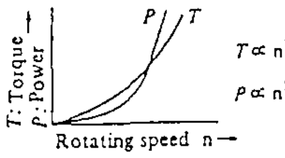
(3) Torque characteristics of load

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 motor are more alike in torque characteristics, motor can be more economically designed.

As examples of typical torque-speed characteristics, there are three types. The first is constant-torque type in which the torque is constant in spite of the speed, the second is torque increasing type in which the torque is in proportion to the speed, its square or cube, and the third is constant-output type in which the necessary torque is in inverse proportion to the speed and torque multiplied by speed is constant. These relations are summarized in Table 22

Table 22 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 load GD^2 (Flywheel effect) is related to the starting time and the heat generation during starting, so it is an important factor in the selection of motors.

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

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

Accordingly, the starting time is

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

Where N_0 : Rated speed

The needed time for starting is in proportion to GD^2, Motors are unusually warmed when t is long, so the allowable GD^2 of the load is determined for any motors. When GD^2 is great, 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 Figure 45, GD^2 converted to the motor side is:

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

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

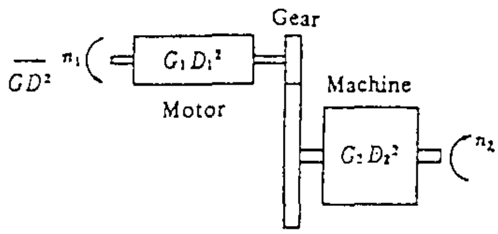


Figure 45 Conversion of flywheel effect

(5) Time characteristics of the load

Motors are used in various 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, 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 motor with a continuous rating. Generally, when continuously used for more than two or three hours, motors with a continues rating are mostly used, because they are the same in price. 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 generated heat every second: Q, Difference between the motor and ambient temperature (temperature rise value): θ, Heating capacity of motor: C, Heat dissipation coefficient: A,

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

Assuming θ = 0 at t = 0,

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

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

T is called "Thermal time constant". If t = ∞ in equation (4),θ = Q/A, that is the final temperature rise.

This is graphed in Figure 46. Also, the thermal time constant normally is as shown in Table 23.

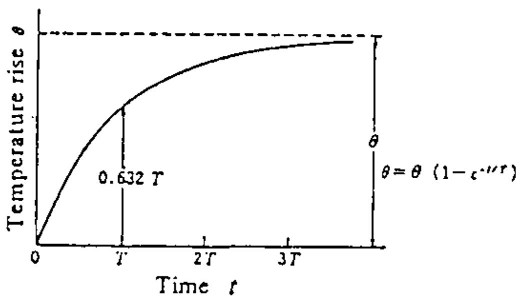


Figure 46 Temperature rise curve of motor

Table 23 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

Next, when the motor is switched off and stopped, substituting $Q = 0$ in equation (3) and $\theta = \theta_0$ at $t = 0$,

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

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

T' : Thermal time constant during cooling
A' : Heat dissipation coefficient during cooling
θ_0 : Temperature when cooling starts

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

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 24).

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

d) Calculation of output by the root mean square method

Rated output of a motor is selected from the time 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 a heat 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),

$$I(t)^2 = k\,P(t)^2$$

Table 24 Frame number application table

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

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

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

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

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

This P_a is an equivalent continuous load which gives out the same loss of load 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 Figure 47 is determined in the following way:

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

However, α is cooling coefficient and its value is as shown in Table 25.

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 cooling coefficient into consideration.

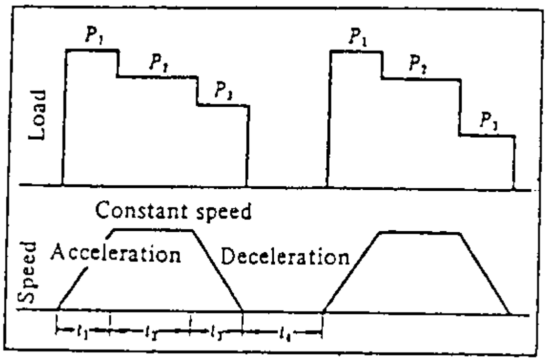


Figure 47 Example of periodic load

Table 25 Example of cooling coefficient values α

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

e) Determination of motor capacity

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

For example, in continuous operation as shown in Figure 48.

$P_1 = 100$ 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

$$P = \sqrt{\frac{100^2 \times 10 + 50^2 \times 15 + 80^2 \times 10 + 50^2 \times 20}{10 + 15 + 10 + 20}}$$

$= 67.6$ kW $= 70$ kW

Accordingly, 75 kW should be selected for the motor. In this case, at the maximum load, 100/75 = 1.33. Namely it is 133% overload, but there is 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 Figure 49.

$P_1 = 50$ kW 1.5 minutes

$P_2 = 30$ kW 1.5 minutes

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

the root mean square load in operation is

$$P = \sqrt{\frac{50^2 \times 1.5 + 30^2 \times 1.5}{3}} = 41.2 \text{ kW}$$

Accordingly, a motor corresponding to 40% ED 45 kW may be selected from Table 25.

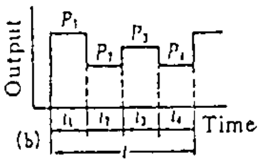


Figure 48

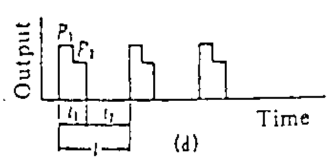


Figure 49

(6) Kind of motors and their efficiency and power factors.

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

a) DC and induction motors

Figure 50 shows the comparison in efficiency between DC and induction motors. 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. But this DC motor, being of the separately-ventilated type, must be essentially evaluated including loss of the blower for cooling. Since this value is omitted, the efficiency actually tends to lower further.

By various excitation systems the DC motor is capable of operating in accordance with the load characteristic and also in easily controlling the speed or torque. 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.

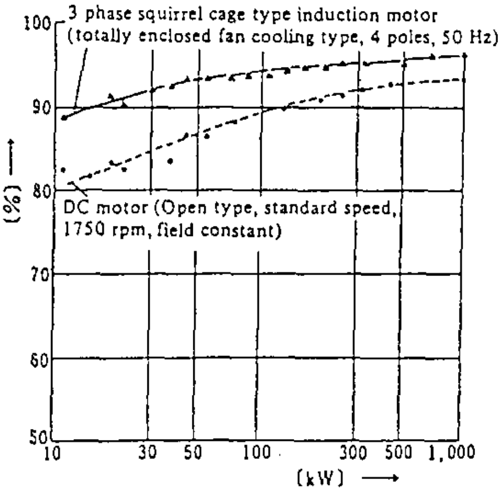


Figure 50 Comparative example of efficiency for induction and DC motor

b) Synchronous and induction motors

Figure 51 shows the comparison in efficiency between synchronous and induction motors.

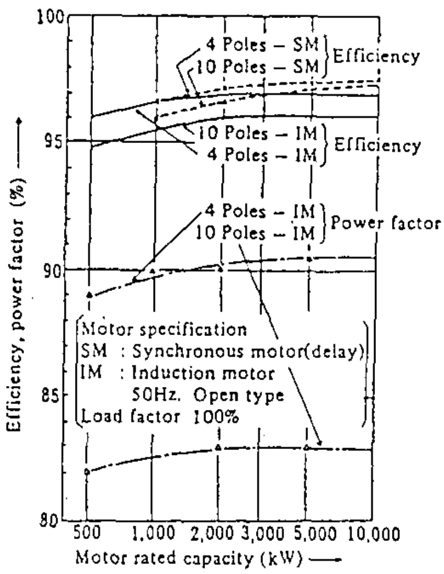


Figure 51 Comparative example of efficiency and power factor between synchronous and induction motors

The efficiency of synchronous motors is generally higher than that of induction motors and this 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 he 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, they are disadvantageous as compared to the synchronous motors in this respect also. Since, however, the synchronous motors including excitation equipment system are expensive, generally selection should be studied, with the following points:

a. For 10 MW or more, adoption of synchronous motors in respect to efficiency.
b. For low-speed motors with larger numbers of poles even 10 MW or less, adoption of synchronous motors.
c. When power factor and voltage of the system must be controlled, study adoption of synchronous motors. However, the motor is limited to sufficient enough large capacity to supply the system reactive power (Var).
d. Generally, for 5 MW or less, induction motors are superior in simple starting and power source composition.

c) Induction motor and its number of poles

Figure 52 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 load 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.

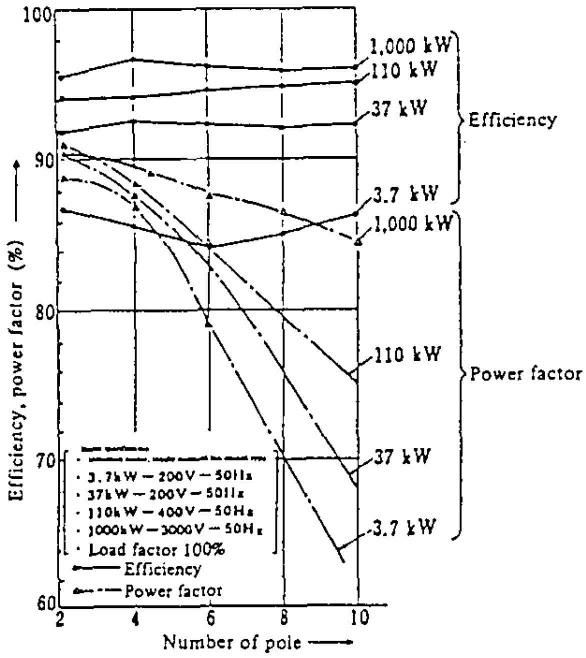


Figure 52 Relation between number of pole, efficiency and power factor of induction motors

Motors are rarely directly coupled to the load machine and usually, a variable speed gear lies between them. When a four-pole motor is selected with reference to the variable speed gear, there is 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 variable speed gear and the increased investment amount for the motor.

(7) 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 deserve studying for adoption for long-time operating motors. Figure 53 and Figure 54 show comparison in efficiency between high-efficiency motors and standard type motors at present. It should be noted in Figure 54 that the high-efficiency motors are remarkable in the improvement of efficiency at light-load.

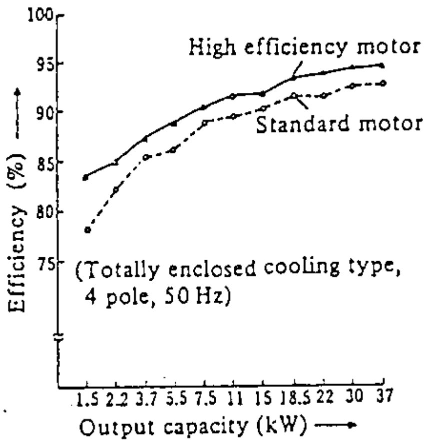


Figure 53 Efficiency comparison of three-phase squirrel cage type induction motor

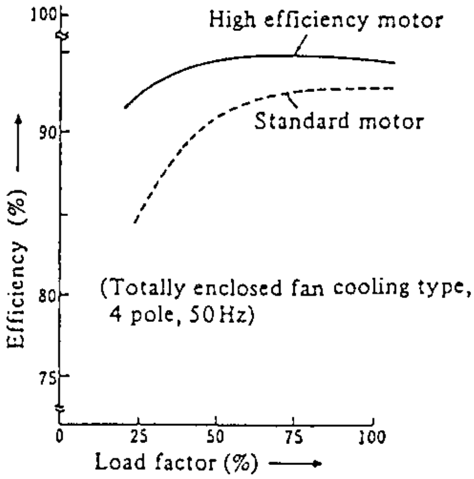


Figure 54 Efficiency comparison of three-phase squirrel cage type induction motor

2.5.4 Energy conservation for 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 effect on these motors. Figure 55 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 effect of supply voltage fluctuation on the induction motor is clarified about these two.

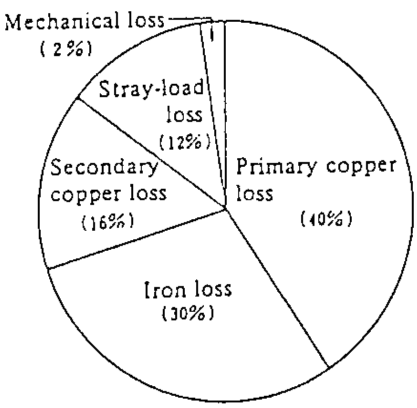


Figure 55 Loss analysis example of standard three-phase induction motor

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

$$Wc = 3\ (\gamma_1 + \gamma'_2) I'^2_2\ (W) \quad \text{.......... (8)}$$

Where Wc : Copper loss

γ_1 : Resistance of primary winding each phase (Ω)

γ'_2 : Resistance of secondary winding each phase (primary side converted value) (Ω)

I'_2 : Load current (A)

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

$$I'_2 = \frac{\omega_0 T}{3V_1}\ (A) \quad \text{.......... (9)}$$

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 given by equation (10).

$$W_c = (\gamma_1 + \gamma'_2) \frac{\omega_0^2 T^2}{3V_1^2}\ (W) \quad \text{.......... (10)}$$

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 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, the square of frequency 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 core plate, considerably high magnetic flux density can be obtained. Therefore, the hysteresis loss is also considered to be practically in proportion to the square of the magnetic flux density.

Since B $\cdot f$ are in proportion to the voltage, the iron loss W_i is:

$$W_i = W_e + W_h = k_1\ (df B)^2 + k_2 f B^2 = V_1^2 \left(k'_1 + \frac{k'_2}{f}\right)\ (W) \quad \text{.......... (11)}$$

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

k_2, k'_2: Constant representing the hysteresis loss

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

$$W = (k'_1 + \frac{k'_2}{f}) V_1^2 + (\gamma_1 + \gamma_2) \frac{\omega_0^2 T^2}{3V_1^2} (W) \quad \text{.....(12)}$$

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:

$$V = \sqrt[4]{\frac{(\gamma_1 + \gamma'_2)\omega_0^2}{3(k'_1 + \frac{k'_2}{f})}} \cdot \sqrt{T} (V) \quad \text{.....(13)}$$

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.

Figure 56 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 T_l. 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 shifts to the right when the load factor is high, and it shifts to the left when the load factor is low.

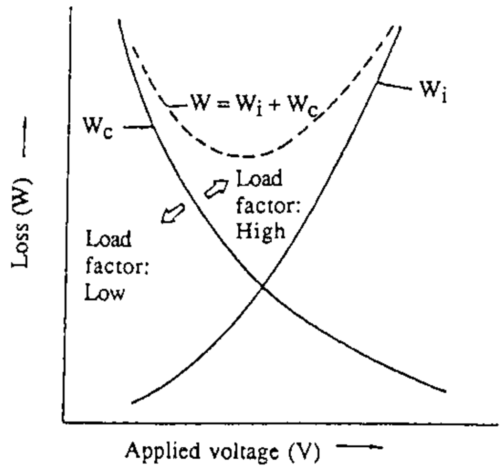


Figure 56 Tendency of loss against applied voltage

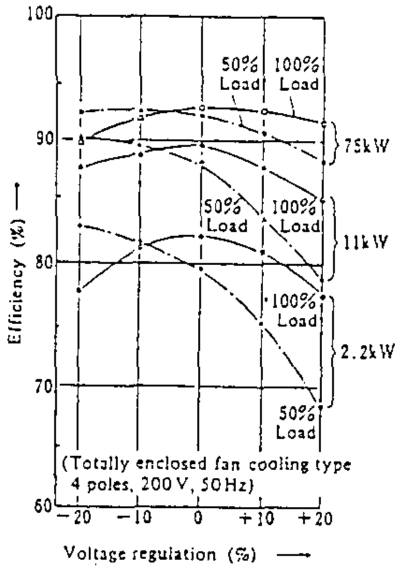


Figure 57 Example of efficiency during voltage fluctuation of induction motor

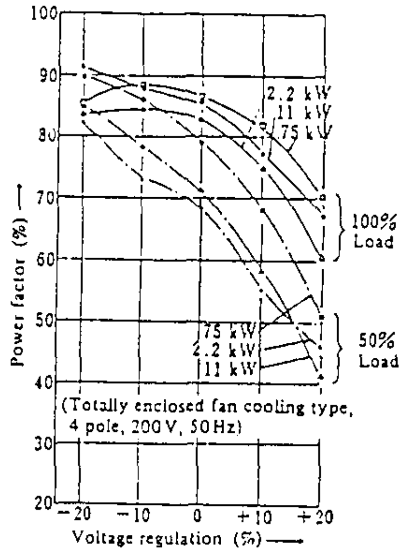


Figure 58 Example of power factor during voltage fluctuation of induction motor

Figure 57 shows one example of the efficiency curve when the supply voltage is actually changed with a motor. As shown in the figure, the efficiency during voltage fluctuation exhibits varied tendencies according to the load factor. When the load factor is high, the highest efficiency is shown at the rated voltage, while, when the load factor is low, the efficiency lowers as the voltage increases.

Figure 58 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 26. When the above are actually applied to motors in operation, the following items should be studied together.

a) Operation at lowered supply voltage

When wanted to operate with the supply voltage lowered below the rated voltage, it is necessary to check accelerating torque during starting and the torque 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 26.

Table 26 Effect of voltage fluctuation on induction machine

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

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. Therefore, the lower limit of the supply voltage should be determined within a range not to exceed the motor rated current.

b) Operation at raised supply voltage

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 destroyed 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.

a. 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.
b. When motors operated at heavy-load hold an overwhelming majority, maintain the distribution voltage at the motor rated voltage value and lower the 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.
c. 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 connected to the load machine, electric power consumed at no-load running is about two to three times that of the motor itself. At this time, the precautions are as follows:

a) Deterioration and output drop of motors due to multi-frequency starting should be restricted within an allowable range. 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.

Also, in this case, it is desirable to stop the motor cooling fan and field system for the DC motor.

When restarting 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:

a. 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 shown as follows.

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

The loss from state of stop to synchronous speed is calculated as $S_1 = 1$, $S_2 = 0$,

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

Where γ_1 : Primary resistance of induction motor (Ω)

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

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

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

ω_0 : Synchronous angular velocity

b. Reducing method of starting loss

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

- Start with a higher 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 would-rotor type induction motor is used, inserting a high external resistance not only greatly reduces the entire motor loss including the external resistance, but also restrains rotor heat and starting current.
- Change the synchronous angular velocity ω_0.

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

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

In the case of two-step pole change induction motors, 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_{OH} of the high-speed winding (Number of poles: P_H). Total loss of the motor during this period W_{2l} will be determined as follows. For simplification, it is assumed in equation (14) that $\gamma_l = 0$, $Tl = 0$.

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

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

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

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:

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

The pole ratio at which the loss is minimized in the above equation is determined by a condition of $dKa/dn = 0$ and the loss will be 1/2 when n = 2. Moreover, increasing numbers of poles changing steps reduces the loss further.

The following measures are effective in preventing idle running.

- Installation of an idle running alarm device
- Automization of the process and equipment

- Reduction of the waiting time 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:

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

From the equation, the rotating speed is controlled by changing 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:

Of these, the primary frequency control system (VVVF) can be practically adopted from the standpoint of remodelling the existing equipment.

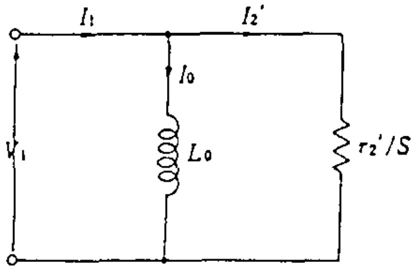
The primary frequency control system controls the primary voltage and frequency of the motor at the same time, by means of a frequency converter, to change the synchronous speed. This control system is mainly divided into opened-control and closed-control types. Of these, the opened-control type is open-loop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

- 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

motor,approximations and simple equivalent circuits can be obtained as follows. 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 = 0.

The simple equivalent circuit prepared under this condition is shown in Figure 59.



Equivalent circuit during operation near synchronous speed.

Figure 59 Simple equivalent circuit of induction motor at slip ≒ 0

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

$I_1 = I_0 + I_2'$ [A] ....(20)

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

$I'_2 = \frac{SV_1}{r_2'} = \frac{S\omega_0}{r_2'} \times \frac{V_1}{\omega_0}$ [A] ....(22)

$T = \frac{3SV_1^2}{\omega_0 r_2'} = 3\frac{S\omega_0}{r_2'}(\frac{V_1}{\omega_0})^2$ [N • m/rad] ....(23)

On the other hand, assuming the voltage factor as K_V, the magnetic flux ø is

$ø = \frac{V_1}{K_v \omega_0} = K_1 I_0$ [Wb] ....(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 become constant at constant slip frequency $S\omega_0$. Figure 60 shows torque-speed characteristic curve at this point and the maximum torque T_{max} becomes constant against speed ω_0.

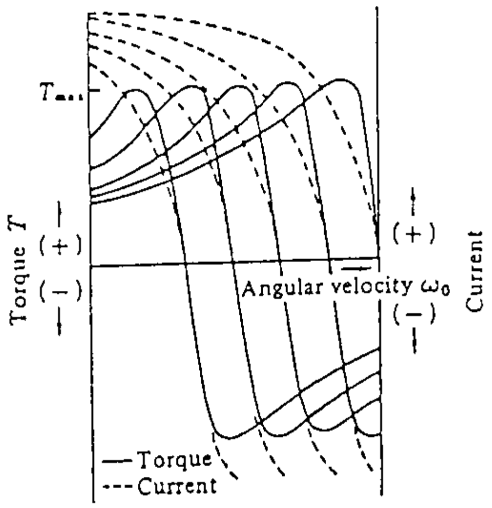


Figure 60 Torque-speed characteristic of V/f constant control

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

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

(4) Other countermeasures

When the equipment capacity is too large as compared to the production scale, it is important for energy conservation to reduce the rotating speed 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.

2.5.5 Heightening expectations for high-efficiency motors

(1) High-efficiency motor trends

Industry is currently expending considerable effort on cutting back the annually increasing energy consumption. Power load equipment are particularly anxious for energy-saving measures from the viewpoint of obtaining stable power supply and reducing expenses.

Approximately 70% of power volume at general production plants is used by motors for production power and power for air conditioning. For this reason energy-savings through high-efficiency motors have become the focus of attention from the perspectives of environmental preservation, stable power supply and reduced costs.

a) America's response to energy saving

At the end of the 1980s, American power companies which were purchasing power from Canadian power companies, introduced a rebate program in which users of high-efficiency motors were compensated the difference in price between standard motors and the high-efficiency motors as a measure to address insufficient power supplies.

This was possibly prompted by the heightening of public opinion in regard to the preservation of the global environment, and administrative guidance. The aim, however, stemmed from the judgment that rather than construct new power stations, (which were becoming more difficult to build) in response to increasing power demands, it was better to encourage power consumers to use high-efficiency motors to dampen the growth of the total volume of power demand. This is why power companies were made to introduce and disseminate the rebate program.

Following these developments, the legislating of the Energy Policy Act of 1992 was announced, after which it was implemented on October 24, 1997 after a five year period of grace.

The existing rebates were abolished with this legislation. Indeed, the legislation provided for penalties on the sale of motors, or products incorporating motors, which did not meet the efficiency standard values prescribed in the EP Act.

This also applied to motors which were imported from overseas. Canada also enacted a similar kind of legislation from January 1996.

b) Japanese regulations regarding high-efficiency motors

The Section for Energy-saving Measures in the Ministry of International Trade and Industry revised the enforcement regulations and proclamation of the Law Pertaining to Rationalization in the Use of Energy (the Energy Saving Law) in February 1997.

The revisions included the setting of objectives for "each plant and each business to reduce their energy consumption rate by an annual average of 1% or more by 2000," indicating that each plant was to proceed with independent energy saving.

Following the 1982 oil shock, the Japan Electric Machine Industry Association Technical Material, No. 137, "The Selection and Application of Motors for Energy Saving," was published. In this was an annexed table showing efficiency standard values for totally enclosed power-saving motors.

These are presently the efficiency standard values for high-efficiency motors in Japan.

Table 27 shows the efficiency standard values for totally enclosed power-saving motors table annexed in the Japan Electrical Manufacturers Association Technical Material, No. 137; Table 28 shows the efficiency standard values of the American Energy Policy Act. There is a significant disparity between the two in respect of efficiency calculation methods.

Responding to these needs of society on a broad scale with the Toshiba Gold Motor (Photo 1), a motor having higher efficiency and lower noise than conventional motors, and the EP Act Series, which complies with the Energy Policy Act of the United States, our company has speedily established line-ups in both Japan and the United States.

Here we present the characteristics of high-efficiency motors based on company examples, and advise on points to note when introducing them and their energy-saving effect.

Table 27 Efficiency standard values for enclosed power-saving motors

HP KW	Efficiency standard values for totally enclosed power-saving motors (%)					
	2P		4P		6P	
	50Hz	60Hz	50Hz	60Hz	50Hz	60Hz
0.2	73.8	75.3	72.6	75.4	-	-
0.4	78.0	79.4	77.5	80.0	74.6	78.0
0.75	81.8	82.4	81.4	83.2	80.0	82.0
1.5	84.4	84.8	84.4	85.8	83.5	85.0
2.2	86.5	86.3	86.6	87.6	85.8	86.8
3.7	88.0	87.8	88.4	89.2	87.4	88.0
5.5	89.3	89.0	89.8	90.3	88.8	89.3
7.5	90.4	90.0	90.8	91.0	89.8	90.3
11	91.2	90.8	91.6	91.8	90.8	91.2
15	91.8	91.5	92.2	92.2	91.6	91.8
18.5	92.4	92.0	92.6	92.6	92.2	92.4
22	92.9	92.3	93.0	92.8	92.7	92.8
30	93.3	92 .6	93.3	93.0	93.0	93.0
37	93.5	92.8	93.5	93.2	—	—

Note: Full load efficiency standard values are determined by the characteristics calculation method regulations according to the JIS C4207 (three phase induction motor characteristics calculation method) circle diagram method.

Table 28 Efficiency standard values of America's Energy Policy Act

HP	Open Motors			Enclosed Motors		
	2P	4P	6P	2P	4P	6P
1	—	82.5	80.0	75.5	82.5	80.0
1.5	82.5	84.0	84.0	82.5	84.0	85.5
2	84.0	84.0	85.5	84.0	84.0	86.5
3	84.0	86.5	86.5	85.5	87.5	87.5
5	85.5	87.5	87.5	87.5	87.5	87.5
7.5	87.5	88.5	88.5	88.5	89.5	89.5
10	88.5	89.5	90.2	89.5	89.5	89.5
15	89.5	91.0	90.2	90.2	91.0	90.2
20	90.2	91.0	91.0	90.2	91.0	90.2
25	91.0	91.7	91.7	91.0	92.4	91.7
30	91.0	92.4	92.4	91.0	92.4	91.7
40	91.7	93.0	93.0	91.7	93.0	93.0
50	92.4	93.0	93.0	92.4	93.0	93.0
60	93.0	93.6	93.6	93.0	93.6	93.6
75	93.0	94.1	93.6	93.0	94.1	93.6
100	93.0	94.1	94.1	93.6	94.5	94.1
125	93.6	94.5	94.1	94.5	94.5	94.1
150	93.6	95.0	94.5	94.5	95.0	95.0
200	94.5	95.0	94.5	95.0	95.0	95.0

Note: Efficiency tests performed with Method B of IEEE std. 112.

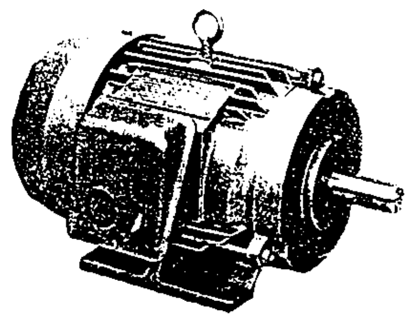


Photo 1 Gold motor

(2) Characteristics of high-efficiency motors

As Figure 61 shows, when the electrical energy which is supplied from a power source is converted to mechanical energy (power) in a motor, part of that energy is consumed as thermal energy inside the motor.

The energy which cannot be used as power by the motor output shaft is known as "loss."

The ratio between input and output is the motor "efficiency," and is represented as in Figure 62.

To boost efficiency it is obvious that this loss must be reduced as much as possible.

In other words, high-efficiency motors can produce the same output as a standard motor with comparatively less input, saving on power and costs.

The high-efficiency motors developed by our company against the aforementioned background have the following characteristics.

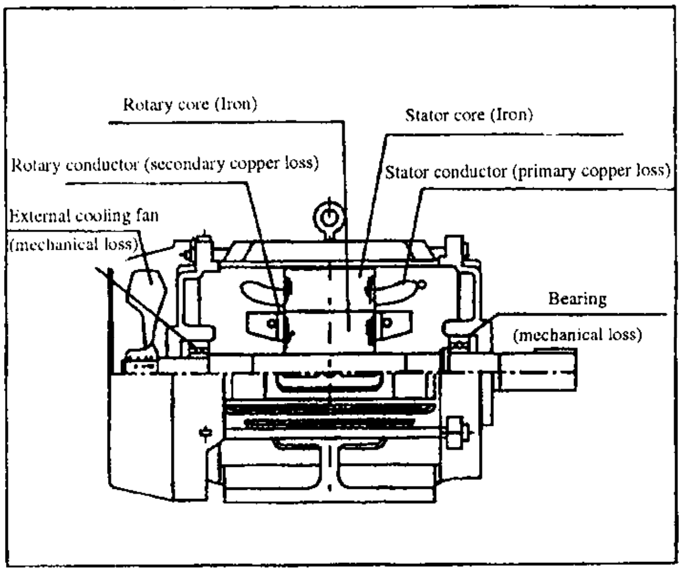


Figure 61 Structure and loss of squirrel-cage induction motor

$$\text{Efficiency} = \frac{\text{Output } (P_0)}{\text{Input } (P_1)} \times 100 = \frac{\text{Output } (P_0)}{\text{Output } (P_0) + \text{Loss } (W)} \times 100\ (\%)$$

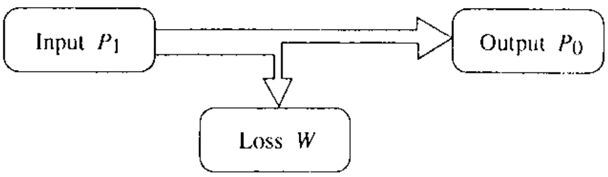


Figure 62 Relationship of input and output

a) High efficiency from low energy consumption
Energy consumption is cut through the use of design philosophies and manufacturing technology that aim to lower loss.

b) Economical operation
Because energy consumption is lower than that of general standard motors, short-term recovery of the initial capital investment for the introduction of high-efficiency motors can be achieved. After this, significant energy savings can be enjoyed (Figure 63).

c) Low noise
Noise reduction has been achieved through the use of high-efficiency, low-noise fan covers and plastic fans.

d) Same dimensions as standard motors
External dimensions are the same as for standard motors, making them easily interchangeable. Our company manufactures and sells motors in both Japan and the United States, using JIS standard dimensions in Japan and NEMA standard dimensions in the United States to manufacture motors which conform with the Energy Policy Act.

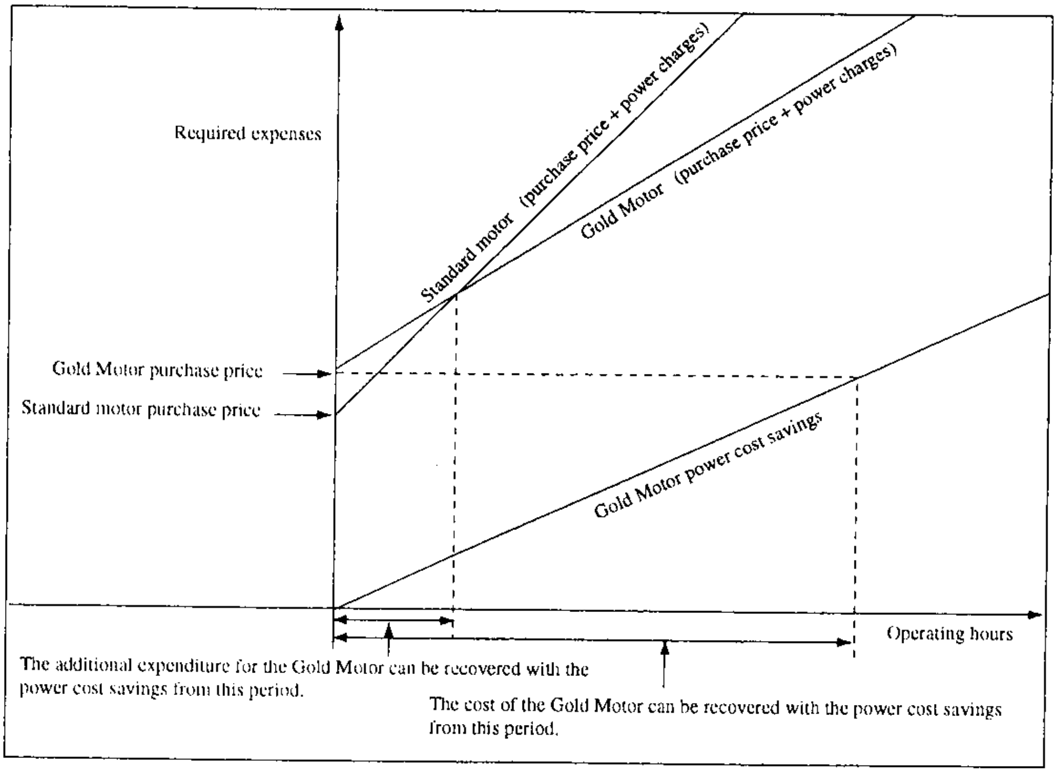


Figure 63 Economical operations

(3) Introduction of the high-efficiency motors

a) Points to note Upon introduction

The following are points which should be noted and considered when thinking of introducing high-efficiency motors.

a. Economy

The additional expenditure upon the purchase of high-efficiency motors can be recovered in a short period of time.

b. Fitting dimensions

These motors follow JIS standards as do standard motors.

c. Characteristics

High-efficiency motors differ slightly from standard motors in torque characteristics and current characteristics as they focus on reducing loss. Prior considerations will need to be made when replacing existing motors.

Apart from the use of high-efficiency motors, also important when considering energy-saving measures in facilities which use electric power are thorough checks on load characteristics and operating state of load machinery to select the appropriate motor for the application.

If, for example, a high-efficiency motor is used where electric power volume is low with load machinery that operates for short periods, the effect will be limited. In another example, the selection of special motors is necessary for repetitive operations such as the high-frequency loads of presses, hoists and cranes.

b) Energy-saving effects

a. Calculation of Power Cost Savings

Power cost savings (¥/year) that can be obtained through the use of high-efficiency motors can be calculated using the following formula.

$S = WXCXN$

Where:

W = input difference (kW) between standard motors and high-efficiency motors

$W = P_0 \times 100/Effs - P_0 \times 100/Effh$

P_0: Motor output (kW)

Effs: efficiency of standard motor (%)

Effh: efficiency of high-efficiency motor (%)

C: power charges (¥/kWh)

N: Operating hours (h/year)

b. Calculation of period for recovery of additional expenditure for the purchase of high-efficiency motors

The period for recovery of additional expenditure on high-efficiency motors, which is the point from which savings are made, can be calculated using the formula shown in Figure 64.

$$\left[\begin{array}{c}\text{Recovery period of additional expenditure on} \\ \text{purchase of high-efficiency motors (years)}\end{array}\right] = \frac{[\text{High-efficiency motor purchase price (¥)}] - [\text{Standard motor purchase price (¥)}]}{[\text{Annual power cost savings S (¥/year)}]}$$

Figure 64 Recovery period of additional expenditure on purchase of high-efficiency motors

c. Calculation examples

Power-saving effects will be as follows when a standard motor is replaced by a high-efficiency motor (4 pole 2.2 kW 1 set).

- Power-saving effect

Annual power cost savings = 6500 (¥/year)
(comparison by this company)
Recovery period for additional expenditure on motor purchase price = 0.7 year

- Calculation Conditions

Power source: 200 V – 50 Hz
Operation: 100% load factor, 4000 h/year
Power charges: ¥20/kWh

(4) Future trends

The dissemination rate of high-efficiency motors in Japan is a miniscule 0. 1 % (based on unit numbers), possibly because greater emphasis has been placed on the initial investment rather than the post-introduction power-saving effect.

When viewed from the stance of the preservation of the global environment, including the prevention of global warming and reducing the release of green-house gases into the atmosphere, however, suppressing power demand is an issue which cannot be avoided, and on which will likely accelerate the move towards high-efficiency motors in the future.

From this aspect, also, it is certainly desirable that high-efficiency motors be actively introduced and promoted.

References: The Selection and Application of Motors for Energy Saving, Japan Electrical Manufacturers Association Technical Material, No. 137.

2.6 Lighting

2.6.1 Factory lighting

(1) Purpose of factory lighting

Good lighting facilitates various visual operations and has the following effects:

a) Improved operation efficiency

Proper illuminance diminishes nerve strain, reduces defective products and improves the operation efficiency.

b) Improved operation safety

Since things can be clearly seen and the visual range is widened, operators are careful for their operation and any disasters due to mistakes, etc. can be prevented.

c) Thorough shop management

It becomes easier to point out any defects in the operation and shop, morale for proper arrangement and environmental hygiene is enhanced, and management for the operation and equipment, etc. can be thoroughly achieved.

d) Improved operator's morale

A shop with a well-ordered working environment including lighting enhances the operators' pride and responsibility, and excites their desire to work.

(2) Good factory lighting

Good factory lighting has the following factors:

- Proper illuminance and illuminating distribution
- Free from flickering and glare
- Color rendering properties of light source should not be exceedingly improper.
- Good economical efficiency

For proper illuminance, the necessary value is determined by content of the operation, size of the object and color, etc. Values specified in Table 29 are recommended as illuminance standard values in Japan. For the aged, these standard values should be somewhat increased.

Also, flickering and glare cause eye fatigue, hindering the operation and lowering the efficiency. Color rendering properties may also hinder some operations.

Table 29 Illumination standard

Illumination [lx]	Place	Operation
3,000 – 1,500 (3,000, 2,000, 1,500)	• Instrument panel and control panel in control room, etc.	Exceedingly fine visual operation in manufacture of precision machines and electronic parts, printing factory, etc., such as o assembly a, o inspection a, o test a, o selection a, o design, o drawing.
1,500 – 750 (1,000)	Design and drawing rooms	Fine visual operation in selection and inspection in textile mills, typesetting and proofreading in printing factory, analysis, etc. in chemical industry, such as o assembly b, o inspection b, o test b, o selection b.
750 – 300 (500)	Control room	Ordinary visual operation in general manufacturing processes, etc., such as o assembly c, o inspection c, o test c, o selection c, o packing a o desk work in warehouses.
300 – 150 (200)	Electricity room and air conditioning machine room	Rough visual operation such as o packing a, o wrapping b, o restricted operation
150 – 75 (100)	Entrance/exit, corridor, passage, warehouses involving operation, staircases, lavatories	Very rough visual operation such as o wrapping c, o packing b, o restricted operation
75 – 30 (50)	Indoor emergency staircases, warehouses, outdoor power equipment	Operation such as o loading, unloading, load transfer, etc.
30 – 20	Outdoor (for passage and safety guard within compound)	Operation such as o loading, unloading, load transfer, etc.
20 – 10	Outdoor (for passage and safety guard within compound)	—

(Remarks)

1. Similar operation are divided into the following three according to the object to view and nature of the operation:

(1) a in the above table indicates fine, dark colored, weak-contrasted, specially expensive, hygiene-related ones and when high precision is required or when long working hours are required, etc.

(2) b in the above table indicates an intermediate between (1) and (3).

(3) c in the above table indicates coarse, light-colored, strong-contrasted, robust, not so expensive ones.

2. For dangerous operation, double above shall be required.

3. For places for operation marked o, this illumination may be obtained by local lighting. It is desirable that illumination for general lighting in this case is more than 1/10 of illumination by local lighting.

2.6.2 Energy conservation for lighting

As an equation for general lighting in a factory and office, the following equation is well-known.

$$E = \frac{N \times F \times U \times M}{A} \text{ (lx)} \quad \cdots\cdots (1)$$

Where E : Illuminance (lx)

A : Area of room (m^2)

N : Number of lamps

F : Luminous flux emitted from one lamp (*l*m)

U : Utilization factor (See Note 1)

M : Maintenance factor (See Note 2)

Note 1: Utilization factor U is the ratio of luminous flux applied to the working plane against the full luminous flux from the lamp, and varies with light distribution of the luminaire, installed position, room condition, etc.

Note 2: Maintenance factor is the predicted lowering rate (figure) of initial illuminance with lapse of the working time. This varies with how well the equipment will be maintained, which is determined at the design stage.

Determining the energy required for lighting by transforming equation (1),

$$W \cdot H = \frac{N \times F}{\eta} \times t = \frac{A \times E \times t}{U \times M \times \eta} \text{ [Wh]} \quad \cdots\cdots (2)$$

Where W•H : Watt-Hour

η : Lamp efficiency

t : Lighting time (hour)

Since the actual electric power for lighting contains the distribution line loss for lighting added to this equation (2), the following can be considered for energy conservation for lighting:

- Reduce the lighting time
- Reduce the distribution line loss.
- Keep the illuminance proper.
- Use high-efficient luminaries.
- Improve the utilization factor.
- Improve the maintenance factor.

2.6.3 Concrete measure for energy cconservation

(1) Reduce the lighting time

Concrete measures are:

a. Lights-out while unnecessary, including noon recess

b. Individual lights-out near windows

c. Provide many switches for individual lights-out.

d. Lights-out in empty areas

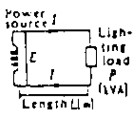
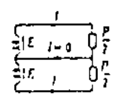
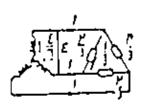
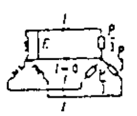
e. Adopt automatic switches or timer switches for outdoor lamps, etc.

In any case, these countermeasures much depend upon the employees' consciousness and therefore, it is necessary to endeavor to enhance it.

(2) Reduce the distribution line loss

Since the distribution line loss greatly varies with the distribution system (See Table 30), it is desirable to compare and study well for determination when establishing new equipment. Besides, to increase voltage level in the distribution line and to improve of power factor, etc. must be studies.

Table 30 Comparison of loss by wiring system

Wiring system	Connection	Loss calculation	Loss ratio
Single phase two wire system	 Resistance per unit length of cable R_1 (Ω/m)	$P = EI \times 10^{-3}$ [kVA] Loss $W = I^2 \times 2LR_1 = (\frac{P}{E} \times 10^3)^2 \times 2LR_1 = \frac{2P^2LR_1}{E^2} \times 10^6$ [W]	100%
Single phase three wire system		$\frac{P}{2} = EI \times 10^{-3}$ [kVA] $W = 2I^2LR_1 = (\frac{P}{2E} \times 10^3)^2 \times 2LR_1 = \frac{P^2LR_1}{2E^2} \times 10^6$ [W]	25%
Three phase three wire system		$\frac{P}{3} = EI \times \frac{1}{\sqrt{3}} \times 10^{-3}$ [kVA] $W = 3I^2LR_1 = 3(\frac{P \times 10^3}{\sqrt{3}E})^2 \times LR_1 = \frac{P^2LR_1}{E^2} \times 10^6$ [W]	50%
Three phase four wire system		$\frac{P}{3} = EI \times 10^{-3}$ [kVA] $W = 3I^2LR_1 = 3(\frac{P \times 10^3}{3E})^2 LR_1 = \frac{P^2LR_1}{3E^2} \times 10^6$ [W]	16.7%

Note: Each cable size is same.

(3) Keep the illuminance proper

Although it is of course important to secure illuminance required for the operation, it is important for energy conservation to reexamine the lighting level and provide with local lighting for passages, places where persons do not much enter and outdoor lighting, etc.

Also, when establishing a new factory, adoption of natural daylight should be positively considered.

(4) Use high-efficient luminaries

Luminaries here mean stabilizers, lamps and light reflectors. Table 31 shows one example of stabilizers' characteristics. To diminish the distribution line size, the current when starting should be smaller, and to reduce the distribution line loss, the power factor should be higher. However, the weight and cost increase in inverse proportion to these and, therefore, it is necessary for selection of kinds of luminaries to study the economical efficiency.

Table 31 Example of stabilizer characteristic (for 400W mercury lamp)

		Non-dimming type			Dimming type			
		Low power factor type	High power factor type	Constant power type	Constant power type		General type	
					Normal	Dimmed	Normal	Dimmed
Input voltage (V)		200	200	200	200		200	
Voltage tap (V)		200, 220	200, 220	200	200		200, 220	
Input current (A)	When starting	5.7	4.0	2.3	2.3	–	3.8	–
	When stabilized	3.3	2.3	2.3	2.3	1.3	2.4	1.3
Input power (W)		425	425	435	435	255	432	255
Power factor (%)		64	90	95	95	95	90	95
Weight (kg)		4.6	5.2	10.0	13.5		7.0	
Volume ratio (%)		100	160	270	340		220	
Price ratio (%)		100	150	240	310		260	

Table 32 and Table 33 show features and general applications of various lamps.

Table 32 Special features and applications of various lamps

Class of lamps	Special features	Scope of size (W)	Main performance of standard quality				Applications
			Efficiency (lm/w)	Color temperature (K)	Color rendering index (Ra)	Life	
Incandescent lamp	• Stable light color • Possible to light as-is. • Instantaneous lighting high luminance	Several W ~ Several kW	100W				Residence, store, office
			15	2,350	100	1,000	
Tungsten halogen lamp	Small-size, high efficiency and long life lamp	Several 10W~ Several kW	For general use 500W				For floodlamp, for automobiles, for projection, for photography, for copying machine, studio
			21	3,000	100	2,000	
Fluorescent lamp	• High efficiency and long life • A wide variety of light colors • Little glare	4~ 220W	White 40W				Residence, office, store
			82	4,500	69	10,000	
Mercury lamp	High efficiency, long life, high luminance lamp	40~ 2kW	400W				For floodlamp (baseball ground, golf course)
			51	5,800	23	12,000	
Fluorescent mercury lamp	Mercury lamp with luster improved	40~ 1kW	400W				Roads, factory, street lighting, arcade lighting
			60	4,100	44	12,000	
Chokeless mercury lamp	Mercury lamp requiring no stabilizer	160,250 500W	500W				For works, stores
			27	3,000	42	6,000	
Halide lamp	Higher efficiency and color rendering lamp than mercury lamp	250~ 1kW	400W				Gymnasium, factory, shopping street, open space, park
			80	4,500	65	9,000	
High color rendering halide lamp	High color rendering, high luminous lamp	250~ 400W	400W				Gymnasium, lobby, hall
			50	5,000	92	6,000	
Low pressure sodium lamp	Highest efficiency, yellow, luminous lamp	35~ 180W	180W				Tunnel, high-way, switch-yard
			175	1740	44	9,000	
High pressure sodium lamp	Highest efficiency, luminous lamp for general lighting	150~ 1,000W	360 W				Gymnasium, high-ceiling factory, warehouse, roads, open space
			120	2,100	29	12,000	
High efficient fluorescent lamp	• High efficiency and long life • A wide variety of light colors • Little glaze	32W 52W	100	5000	88	12,000	Residence, office, store

Note: Efficiency of fluorescent and mercury lamps is of 100 hrs value.

Table 33 Selection of lamps from standpoint of typical applications

Class of lamps		Incandescent lamp			Fluorescent lamp			Mercury lamp				Halide lamp		Sodium lamp		Xenon lamp
		General lamp	Reflector lamp	Halogen lamp	General fluorescent lamp	High color rendering properties	High output type	Transparent mercury lamp	Fluorescent mercury lamp	Reflector mercury lamp	Stabilizer built-in type	General type	High color rendering type	High pressure	Low pressure	
Residence		◎	○	△	◎	○	×	×	×	×	×	×	×	×	×	×
Office	General office	△	△	△	◎	△	○	×	×	×	×	△	△	×	×	×
	High-ceiling office, lobby	○	○	○	○	△	○	×	○	○	△	◎	○	×	×	△
	Single room, drawing room	○	○	△	◎	○	×	×	△	×	×	△	△	×	×	×
Store	General stores	◎	◎	○	◎	◎	○	×	○	△	△	△	△	×	×	×
	High-ceiling stores	○	○	○	○	○	◎	×	○	○	○	◎	○	△	×	△
	Exhibits, showcase	◎	◎	◎	◎	◎	○	×	△	△	○	○	○	×	×	△
Factory	Low-ceiling factory	△	△	○	◎	○	○	×	△	△	△	△	△	△	×	×
	High-ceiling factory	△	△	○	△	△	◎	×	◎	○	○	◎	○	○	×	△
	Warehouse	○	△	○	◎	△	○	△	◎	○	○	○	△	○	×	×
School	Class room	△	△	△	◎	○	△	×	△	×	×	△	△	×	×	×
Hospital	Operating room	○	○	△	◎	◎	△	×	×	×	×	×	×	×	×	×
Theater, hall	Spectator's seats	◎	◎	◎	◎	○	△	×	△	△	△	○	○	×	×	△
	Stage	◎	◎	◎	◎	○	○	×	△	△	△	△	△	×	×	△
Art museum, museum	General	◎	◎	○	○	◎	△	×	△	△	△	○	○	×	×	△
	Exhibits	◎	◎	○	○	◎	△	×	×	×	×	○	○	×	×	△
Roads	Automobiles exclusive roads	×	×	×	△	×	×	△	◎	×	×	△	×	○	○	△
	Automobiles exclusive tunnel	×	×	×	△	×	×	△	○	×	×	△	×	○	◎	×
	Streets	△	×	×	○	×	×	△	◎	△	△	△	△	○	△	×
	Shopping streets	○	×	○	○	△	◎	×	◎	△	△	◎	△	○	×	×
	Roads in resident area	○	×	×	○	×	×	△	◎	△	×	△	×	○	×	×
Parking zone	Indoor	△	△	△	◎	×	○	×	○	△	△	△	△	○	×	×
	Outdoor	△	△	△	○	×	×	△	◎	○	△	△	△	○	△	△
Open space, park, garden		○	△	△	○	△	×	△	◎	△	△	○	△	○	×	△
Floodlight lighting	Structure	○	○	○	×	×	×	△	◎	◎	○	○	○	○	△	○
	Advertisement, signboards	○	◎	◎	○	○	○	△	◎	◎	△	○	○	△	×	○
Sports	Indoor	○	○	◎	○	○	○	△	◎	○	△	◎	○	△	×	△
	Outdoor	○	○	○	×	×	×	△	◎	○	△	◎	○	◎	×	○

◎ most suitable　△ not recommendable

○ suitable　× not suitable

(5) Improving utilization factor

Table 34 shows an example of the utilization factor table. Room index RI in this table is calculated in the following equation:

$$RI = \frac{W \times L}{H(W + L)} \quad \cdots\cdots (3)$$

Where W : Width of room (m)

L : Depth of room (m)

H : Height of light source from the working plane (m)

The room index has a higher value when it is a square room. And the utilization factor is higher with the higher reflectivity of the inner wall and floor and the higher room index.

Table 34 Example of utilization factor

Ceiling*	80%									50%								
Wall*	60%			30%			10%			60%			30%			10%		
Floor surface*	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%
Room index	Utilization factor																	
0.60	.45	.42	.40	.31	.30	.30	.26	.25	.25	.41	.39	.38	.30	.29	.29	.25	.25	.25
0.80	.56	.51	.49	.41	.39	.38	.35	.34	.23	.51	.48	.47	.39	.38	.37	.34	.33	.33
1.00	.63	.57	.55	.47	.45	.44	.41	.40	.39	.57	.53	.52	.45	.44	.43	.40	.39	.38
1.25	.71	.63	.60	.55	.52	.50	.48	.46	.45	.64	.59	.57	.52	.50	.49	.46	.45	.44
1.50	.76	.68	.64	.61	.56	.54	.54	.51	.50	.68	.63	.61	.57	.54	.53	.52	.50	.49
2.00	.85	.75	.70	.71	.65	.62	.64	.59	.57	.76	.70	.67	.66	.62	.60	.60	.58	.56
2.50	.91	.79	.74	.78	.70	.66	.71	.65	.62	.80	.73	.70	.71	.67	.65	.66	.63	.61
3.00	.95	.82	.76	.83	.74	.70	.77	.69	.66	.84	.76	.73	.76	.70	.68	.71	.67	.65
4.00	1.01	.86	.80	.91	.79	.75	.85	.76	.71	.88	.80	.77	.28	.75	.72	.78	.72	.70
5.00	1.09	.88	.82	.96	3.8	.77	.91	.79	.78	.91	.82	.79	.88	.78	.78	.82	.76	.73
10.00	1.13	.93	.86	1.08	.90	.84	1.05	.89	.82	.97	.87	.83	.94	.85	.81	.92	.84	.80

Light output ratio: 83% Light source: FL 40 SW 3,400 lm Fluorescent lamp reflector used

*Figures show the reflectivity.

(6) Improving maintenance factor

To improve the maintenance factor, first adopt luminaries with less lowering of luminous flux with lapse of the working time and secondly periodically clean the luminaries and replace the lamps. However, with much expenditures in labor cost, it is unavoidable to replace the lamps and clean the luminaries when the lamps are burnt out. Therefore, the first countermeasure is to use luminaries with less lowering rate.

Figure 65 and Figure 66 show the lowering tendency of the luminous flux of lamp itself and the lowered luminous flux when dirt accumulates on luminaries respectively.

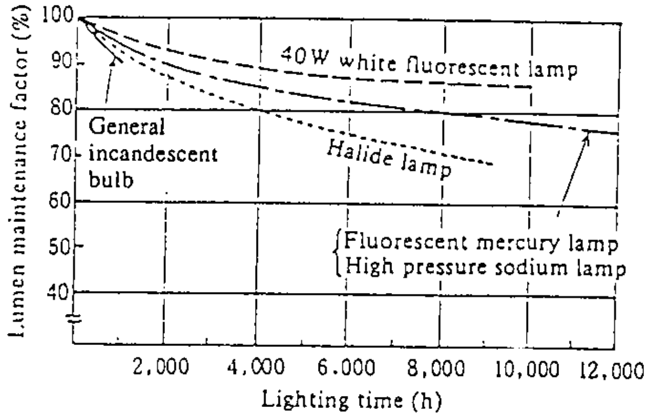


Figure 65 Lumen maintenance characteristic of various light source

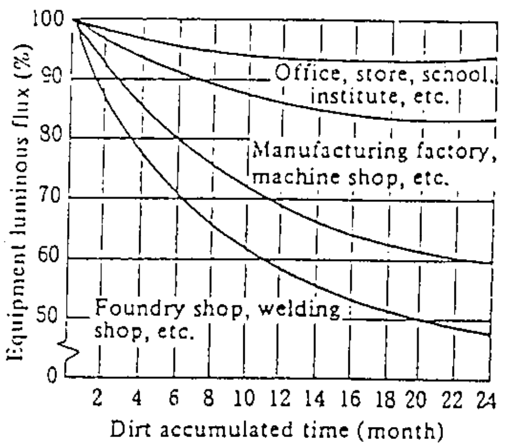


Figure 66 Lowered lumen when dirt accumulated on lamp and lighting equipment

(7) Others

Other precautions for lighting are not to fluctuate the supply voltage. Although motors, etc. are capable of operating smoothly even at ±10% fluctuation, lamps are manufactured to perform their best functions and ensure the longest lives at the rated voltage. Therefore, it is desirable to separate illuminating circuits from motor circuits and also to restrict the voltage fluctuation with ±5%.

Also for ambient temperatures, it is important not to deviate from the manufacturer's specified value.

2.7 Electric heating systems

The electric heating systems are those which convert electricity to thermal energy, such as the electric furnaces and drying furnaces. These electric heating systems have relatively large power consumptions, as well as lower efficiencies as compared to motors and transformers. In addition, the equipments with the same format might sometime have different efficiencies, depending on its heat retaining performance.

Other heat sources for these furnaces include coal, gas, petroleum, and stocks, and when compared to these energy sources, electricity is more costly. If it is simply the case of boiling water or heat-welding the metal, coal or fuel oil would sufficiently serve the purpose, but on the other hand, there are the environmental concerns, and one could not draw conclusions simply from economic aspect.

2.7.1 Types of electric heating systems

The electric heating systems are classified as shown in Table 34. Their common features are as stated below.

a. High temperature

It is possible to heat to the high temperature of 2,000°C or more by arc heating and by directly conducting current through a heating object.

b. High heating efficiency

The heating efficiency is high because an object generates heat and there is no exhaust gas loss. However, it is necessary to make a general judgement considering lower efficiency of power generation.

c. Quick heating

It is possible to change the electric power to heating by fossile fuel in an object and conduct quick heating by raising the electric power density.

d. Easy temperature control

As automatic control and remote control can be made easily, it is possible to control the temperature precisely.

e. Easy atmospheric control

Atmospheric control can be made easily because no combustion is involved.

Table 35 Type and main applications of electric heating systems

Heating method	System for converting electric energy to heat: Conversion system	Heating system	Main applications and examples of units
Utilization of Joule heat and arc heat	Resistance heating	Indirect resistance heating (50/60 Hz)	Various types of heat treatment furnaces using resistance heating means, sintering furnace, diffusion furnace, brazing furnace, salt bath furnace, and fluid bed heating
		Direct resistance heating (50/60 Hz) (DC)	Direct energizing heating of metal, graphitizing furnace, glass melting furnace, and ESR furnace
	Infrared ray heating	Proximate infrared ray heating (0.76 ~ 2.5 μm)	Baking of painted surface, drying, and molding and processing of plastics
		Remote infrared ray heating (2.5 ~ 25 μm)	Heating at 650 C or less, drying of painting, baking, resin hardening and processing, bread baking heating, plant rearing
	Arc heating	Arc heating (50/60 Hz)	Steel making, dissolution of fire resisting materials, and dissolution of vacuum arc
		Plasma arc heating (DC)	Dissolution of heat resisting steel, Ni alloy steel, high melting point metal and alloy, dissolution of high melting point compound, production of single crystal, and high temperature thermochemical processing of other materials
Utilization of electromagnetic induction	Skin effect heating	High frequency induction heating (50/60 Hz ~ 450 kHz)	Dissolution of metal and alloy, heating for thermal processing, heat treatment of metal, welding, and brazing
		Low frequency induction heating	Dissolution of cast steel and heating of large-sized steel
	Transverse flux heating		Heating of sheets such as non-ferrous metal and stainless steel
	Short-circuit heating	For metal dissolution	Groove-shaped blast furnace and temperature rise of molten bath
		For metal heating	Interference of metal parts
Utilization of high frequency electric field	Induction heating (3 ~ 40 MHz)		Drying of lumber, drying and heat treatment of food, leather, textile, chemicals and synthetic resin, bonding of lumber, and welding of synthetic resin
Heat developed by the impact of electronic and jon flow	Electron beam heating		Evaporation of metal, dissolution of high melting point metal, and fine processing of metal
	Ion and jon beam heating and processing		Ion carburizing, heat treatment such as nitriding, surface coat treatment, etching of semi-conductor, implantation, and other surface treatment
	Glow discharge heating		Surface heat treatment of metal and metal heating
Utilization of electro-magnetic wave	Laser heating and processing (1 ~11μm)		Drilling processing of process-resistant material, welding, heat treatment and cutting of metal material, welding and processing of electronic parts, etc.
	Microwave heating (915, 2,450 MHz)		Preparation (electronic oven), drying and thawing of food, heating and vulcanization of rubber, and sterilization of food and chemicals
Utilization of electric mechanical power	Heat pump system	For household use	Air conditioning, hot water supply, and building air conditioning
		For industrial use	Drying of food, lumber and leather, effective utilization of exhaust heat, and others

2.7.2 Energy conservation for heating systems

(1) Conversion of the heat source

When one considers the power generation in thermal power generation and atomic power generation, the energy efficiency is approximately 35%, including the electricity loss during transmission and distribution, so heating method is extremely inferior as compared to other sources of heat. If there are no reasons for using electric heat as given above, other sources of heat (e.g. petroleum, coal, gas, and steam) should be used.

Even when the electric heat should be used, if it is possible to convert the heating method (e.g. indirect heating → direct heating), then the thermal efficiency might be raised.

(2) Correction of the capacity of equipment

In the electric heating systems, a continuous operation with a constant load would be desirable. Intermittent operation would repeat heating and cooling, resulting in the waste of power, so that the difference in the heat efficiency between the continuous and intermittent operations becomes enormous. It will therefore be necessary to restudy the production processes and work procedures and to select the capacity of equipment which would result in a continuous operation.

In particular, the electric heating systems tend to deteriorate by adopting easily the larger equipment when the smaller one is sufficient, so the power consumption per process becomes large, and therefore it will be necessary to compute the power consumption and find a method which would enable operation at a minimum loss.

(3) Reinforced heat insulation

The electric heating systems generate various heat losses, as compared to the motors and transformers, so that the differences in heat efficiencies depends on the heat retaining property. Measuring the heat loss by the temperature sensors and heat flow meters attached to various parts of the equipment and strengthening the heat insulation in the parts of significant heat loss will be needed in order to raise the heat efficiency.

Case Study of ECCJ Factory
(Blower, Pump, Transformer, Lighting)

1. Blower for Dust Collector

Motor input at present

All units are operating according at 800 m^3/min and 300 m^3/min.

Real power of motor L_R at 800 m^3/min

$$L_R = \frac{800 \times 150}{0.7 \times 6120} = 28.0 \text{ (kW)} \quad \rightarrow \quad L_R = \frac{800 \times 150 \times 0.0098}{0.7 \times 60} = 28.0 \text{ (kW)}$$

The ratio of real power to motor = $\frac{28}{75}$ = 0.37

From Table 36

Motor efficiency

75 kW : 0.87 at 25% of load factor
0.92 at 50% of load factor
0.89 at 37% of load factor

Motor efficiency = 0.89

So motor input $L_I = 28.0 \times \frac{1}{0.89} = 31.5$ (kW)

2. Pump

Motor input at present

Motor input Li is obtained by equation (3) on page 45 divided by motor efficiency η_M.

1) At flow rate 4 m^3/min

η: 76% (from Figure 26)

η_M: 0.91 (from Table 36)

$$L_i = \frac{0.163 \cdot 1 \cdot 4 \cdot 20}{0.76} \times \frac{1}{0.91} = 18.85 \text{ (kW)}$$

2) At flow rate 2 m^3/min

η: 73% (from Figure 26)

η_M: 0.89 (from Table 36)

$$L_i = \frac{0.163 \cdot 1 \cdot 2 \cdot 20}{0.73} \times \frac{1}{0.89} = 10.39 \text{ (kW)}$$

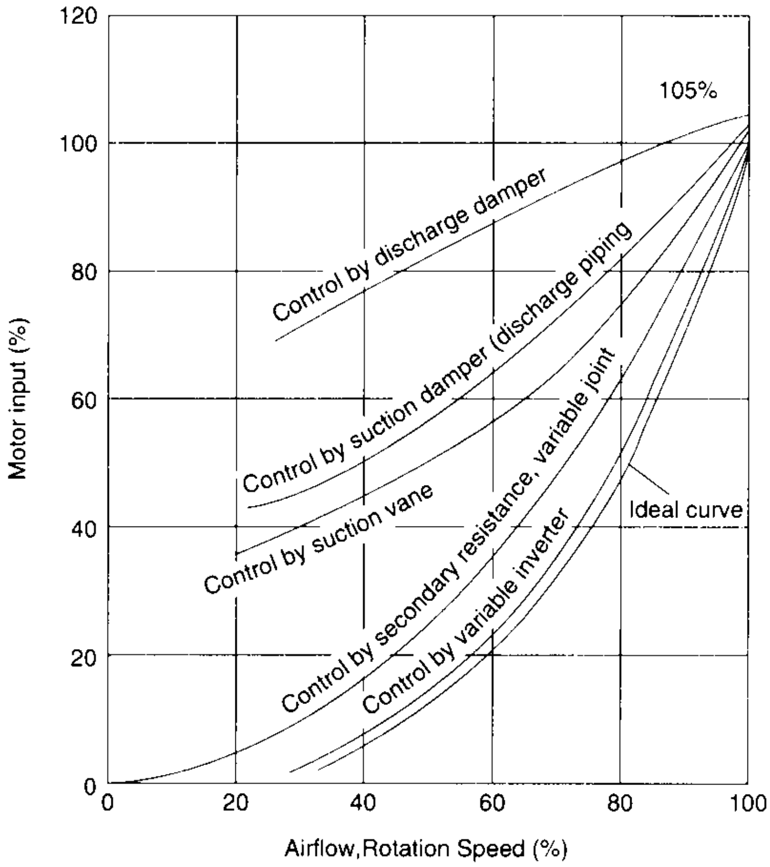


Figure 67 Power consumption curve of motor by airflow

Table 36 Efficiency of motor (%) (Standard type)

Motor rating kW	Load factor			
	25%	50%	75%	100%
3.7	71	84	84	86
11	80	88	89	89
22	81	89	91	91
37	83	90	91	91
55	85	91	92	92
75	87	92	93	93

Table 37 Efficiency of motor (%) (High efficiency motor)

Motor rating kW	Load factor			
	25%	50%	75%	100%
3.7	76	86	86	88
11	84	91	92	92
22	85	92	93	93
37	87	93	94	94
55	88	93	94	94
75	89	94	95	95

3. Transformer

Total transformer loss (Pt) = iron loss (Pi) + copper loss (Pc)

$$\text{Copper loss} = \text{copper loss (at full load)} \times \left(\frac{\text{Transformer load (kVA)}}{\text{Transformer capacity (kVA)}} \right)^2$$

kVA, kvar are obtained by next equations.

$$\text{kVA} = \frac{\text{kW}}{\text{p.f}} \times 100$$

$$\text{kvar} = \sqrt{(\text{kVA})^2 - (\text{kW})^2}$$

(1) Transformer loss at present

We can get next table from equations above.

1) kVA, kvar and losses of Transformer A

Hour	0–8	8–12	12–13	13–20	20–24
kW	200	600	200	600	200
p.f (%)	90	85	90	85	90
kVA	222.2	705.9	222.2	705.9	222.2
kvar	96.9	371.8	96.9	371.8	96.9
Pi	4.5	4.5	4.5	4.5	4.5
Pc	0.36	3.65	0.36	3.65	0.36
P_T	4.86	8.15	4.86	8.15	4.86

2) kVA, kvar and losses of Transformer B

Hour	0–8	8–12	12–13	13–20	20–24
kW	300	800	300	800	300
p.f (%)	90	85	90	85	90
kVA	333.3	941.2	333.3	941.2	333.3
kvar	145.3	495.8	145.3	495.8	145.3
Pi	2.5	2.5	2.5	2.5	2.5
Pc	1.39	11.07	1.39	11.07	1.39
P_T	3.89	13.57	3.89	13.57	3.89

3) kVA, kvar and losses of total Transformers (A + B)

Hour	0–8	8–12	12–13	13–20	20–24
kW	500	1,400	500	1,400	500
p.f (%)	90	85	90	85	90
kVA	555.6	1,647.1	555.6	1,647.1	555.6
kvar	242.2	867.6	242.2	867.6	242.2
P_T	8.75	21.72	8.75	21.72	8.75

Loss of total transformers in one day P_{D1} (kWh/d)

PD1 = 8.75 × 13 + 21.72 × 11 = 352.75 kWh/d

4. Lighting

Lighting load at present (equation on 2.6.3 (5))

$$\text{Room index} = \frac{50 \times 80}{7.7 \times (50 + 80)} = 4$$

From utilization factor table (Table 34) Utilization factor = 0.69

Illuminance of present E is obtained by equation on 2.6.2 (1).

$$E = \frac{150 \times 60 \times 400 \times 0.69 \times 0.8}{80 \times 50}$$

$$= 500 \text{ lx}$$

So E saticifies illumination standard (500 lx) at working area, but at utilities area E is extremely over than illumination standard (300 lx)

Power consumption $= 400 \times 150 \times 10^{-3}$ (kW)

$= 60.0$ kW