6.4 Factory Lighting

6.4.1 Purpose of Factory Lighting

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

(1) Improved operation efficiency

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

(2) Improved operation safety

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

(3) 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.

(4) Improved operator's morale

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

6.4.2 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 6.4 are recommended as illuminance standard values in Japan. For the aged, these standard values should be somewhat increased.

Table 6.4 Illumination Standard for Factory

Illumination [lx]	Place	Operation
3,000 2,000	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 ∘ assembly a, ∘ inspection a, ∘ test a, ∘ selection a, ∘ design, ∘ drawing.
1,500 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 ∘ assembly b, ∘ inspection b, ∘ test b, ∘ selection b.
750 500	Control room	Ordinary visual operation in general manufacturing processes, etc., such as ∘ assembly c, ∘ inspection c, ∘ test c, ∘ selection c, ∘ packing a, ∘ desk work in warehouses.
300 200	Electricity room and air conditioning machine room	Rough visual operation such as ∘ packing a, ∘ wrapping b, ∘ restricted operation
150 100	Entrance/exit, corridor, passage, warehouses involving operation, staircases, lavatories	Very rough visual operation such as ∘ wrapping c, ∘ packing b, c ∘ restricted operation
75 50	Indoor emergency staircases, warehouses, outdoor power equipment	Operation such as ∘ loading, unloading, load transfer, etc.
30 20 10	Outdoor (for passage and safety guard within compound)	

Remarks: 1. The work of the same kind is further subdivided into the following three categories depending on the objects to be looked at and the nature of the work:

(1) "a" in the table indicates the visual work for very fine, dark-colored, low-contrast, or particularly expensive objects, and the types of work which are related to sanitation, require high precision or take a long time.

(2) "b" in the table indicates work that falls in a category somewhere between (1) and (3).

(3) "c" in the table indicates the visual work for less fine (coarse), bright-colored, high-contrast, sturdy and less expensive objects.

2. The illuminance for dangerous work must be twice that for the ordinary type of work.

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

6.5 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 (lm)
U : Utilization factor (See Note 1)
M : Maintenance factor (See Note 2)

Note 1: Utilization factor is the ratio of luminous flux applied to the working plane against the full luminous flux from the lamp, and varies with luminous intensity 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 consumed 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 luminaires.
- Improve the utilization factor.
- Improve the maintenance factor.

6.6 Concrete Measure for Energy Conservation

6.6.1 Reduce the Lighting Time

Concrete measures are:

(1) Lights-out while unnecessary, including lunch breaks

(2) Individual lights-out near windows

(3) Provide an adequate number of switches for individual lights-out.

(4) Lights-out in quiet areas (without personnel)

(5) Adopt automatic switches or timer switches for outdoor lamps.

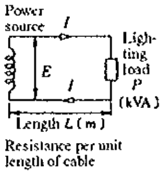
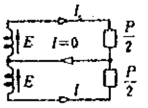
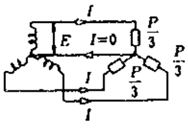
(6) Provide a device to detect a vehicle coming in or going out of the unmanned warehouse, etc. in order to allow a light to be automatically turned on or off.

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

6.6.2 Reduce the Distribution Line Loss

Since the distribution line loss greatly varies with the distribution system (See Table 6.5), 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 power factor, etc. must be studied.

Table 6.5 Comparison of Loss by Wiring System

Wiring system	Connection	Loss calculation	Loss ratio
Single-phase two-wire system		$P = EI \times 10^{-3}[kVA]$ $LossW = I^2 \times 2LR_1 = \left(\frac{P}{E} \times 10^3\right)^2 \times 2LR_1 = \frac{2P^2LR_1}{E^2} \times 10^6[W]$	100%
Single-phase three-wire system		$\frac{P}{2} = EI \times 10^{-3}[kVA]$ $W = 2I^2LR_1 = \left(\frac{P}{2E} \times 10^3\right)^2 \times 2LR_1 = \frac{P^2LR_1}{2E^2} \times 10^6[W]$	25%
Three-phase three-wire system		$\frac{P}{3} = E \times \frac{I}{\sqrt{3}} \times 10^{-3}[kVA]$ $W = 3I^2LR_1 = \left(\frac{P \times 10^3}{\sqrt{3}E}\right)^2 \times 3LR_1 = \frac{P^2LR_1}{E^2} \times 10^6[W]$	50%
Three-phase four-wire system		$\frac{P}{3} = EI \times 10^{-3}[kW]$ $W = 3I^2LR_1 = 3\left(\frac{P \times 10^3}{3E}\right)^2 \times LR_1 = \frac{P^2LR_1}{3E^2} \times 10^6[W]$	16.7%

NOTE: Each cable size is same.

6.6.3 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 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.

6.6.4 Use High-efficient Luminaires

Luminaires here mean stabilizers, lamps and light reflectors.

Table 6.6 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 luminaires to study the economical efficiency.

The recent advance of the electronic technology has allowed a wider use of high-efficiency luminaires with their luminoues efficiency enhanced and flicker reduced by using an inverter as a stabilizer and lighting fluorescent lamps at a high frequency of 10 to 50 [kHz]. Features of these luminaires include easy dimming, smaller-size and lighter-weight stabilizers, reduction of heat loss and so forth.

Table 6.6 Example of Stabilizer Characteristic (for 400 W Mercury Lamp)

	Non-dimming type			Dimming type			
	Low power factor type	High power factor type	Constant power type	Constant power type		General type	
Input voltage (V)	200	200	200	200		200	
Voltage tap (V)	200, 220	200, 220	200	200		200,	220
Input current (A)				Normal	Dimmed	Normal	Dimmed
When staring	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	

6.6.5 Improving Utilization Factor

The utilization factor means the ratio of the luminous flux entering the work area to the total luminous flux going out of the lamp. It varies depending on the installation location of a luminar, the room condition, etc. Table 6.7 shows an example of the utilization factor. Room index RI in this table is calculated in the following equation:

Table 6.7 Example of Utilization Factors

Reflectance																		
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	.33	.51	.48	.47	.39	.38	.37	.34	.33	.33
1.00	.63	.57	.55	.47	.45	.44	.41	.40	.35	.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	.66	.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	.82	.75	.72	.78	.72	.70
5.00	1.09	.88	.82	.96	.84	.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

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

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 will be higher with the higher reflectivity of the inner wall and floor and the higher room index.

6.6.6 Improving Maintenance Factor

The maintenance factor means the estimated rate of the initial luminos flux lowering due to dirt on the luminaires with laspe of the working time.

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

Figure 6.2 and Figure 6.3 show the lowering tendency of the luminous flux of lamp itself and the lowered luminous flux when dirt accumulates on luminaires respectively.

Figure 6.2 Lumen Maintenance Characteristic of Various Light Sources

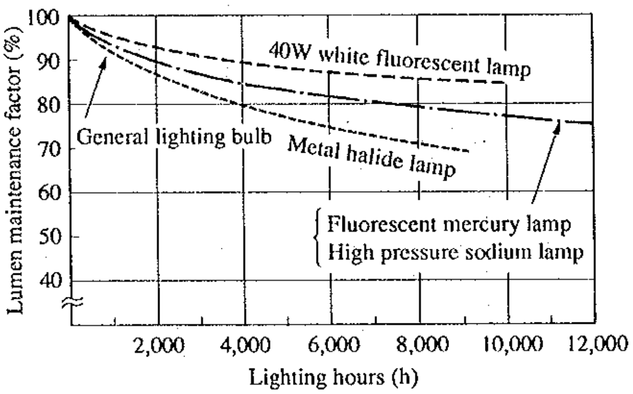
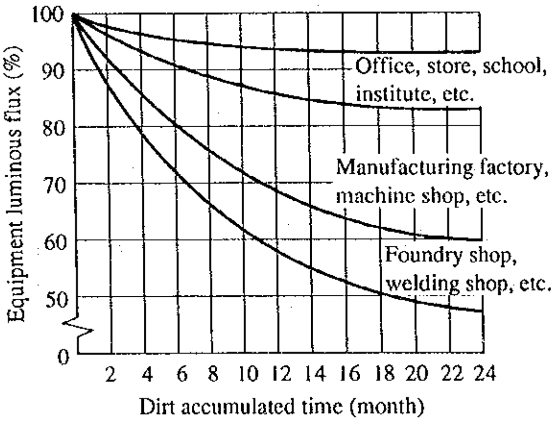


Figure 6.3 Lowered Lumen When Dirt Accumulated on Lamp and Lighting Equipment



6.6.7 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.

7. ENERGY CONSERVATION IN AIR COMPRESSORS

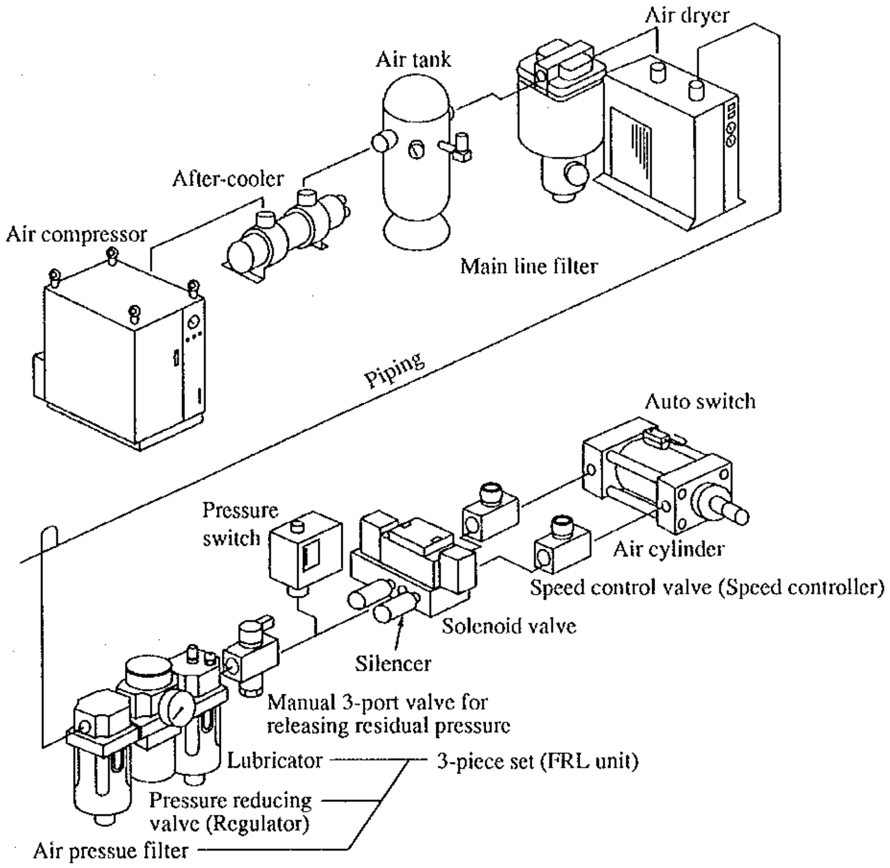
7. AIR COMPRESSOR

7.1 Pneumatic System

7.1.1 Configuration of Pneumatic System

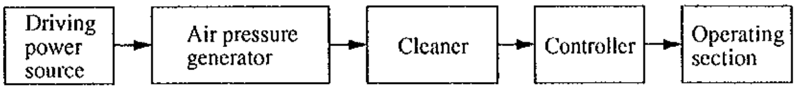
The pneumatic system is a power transmission system that sends the compressed air from a compressor to the actuator through pipes by controlling and adjusting with various control valves. The output is thus supplied as mechanical power suitable for load side requirements. Figure 7.1 shows a typical configuration of the pneumatic system.

Figure 7.1 Configuration Example of Pneumatic System



These components can be functionally categorized as shown in Figure 7.2.

Figure 7.2 Air Pressure System Flow



(1) Driving power source

Electricity or fuel is converted into mechanical power by a motor or engine.

(2) Air pressure generating unit

Compressed air is generated, and supplied to the pneumatic line in a stable manner.

- Air compressor: Atmospheric air is compressed to generate compressed air.
- After-cooler : Hot air (by adiabatic compression) delivered by the compressor is cooled and moisture is separated.
- Air tank : The compressed air is stored. Air pressure variation due to the pulsation from the compressor and the fluctuations in the volume of air consumption in the downstream pneumatic line is absorbed and removed.

(3) Air cleaning unit

The quality of the compressed air is controlled depending on the equipment that will use it and the purpose of use.

- Drain separator and discharger: Attached to the after-cooler outlet or tank bottom, these units discharge the separated moisture or oil.
- Filter : Removes pipe rust, solid foreign substances, moisture, and oil contained in the compressed air. The air cleanness by filtering is generally increased as the air goes from upstream to downstream to meet the requirement of equipment.
- Mist separator : Captures fine oil particles contained in the compressed air.
- Dryer (dehumidifier) : Removes humidity from the compressed air to increase the dryness.

(4) Control unit

The pressure, flow rate, and flow direction of the compressed air is adjusted to drive the controller and the actuator.

- Pressure reducing valve: A low pressure corresponding to the purpose of use is set and compressed air at a stable pressure and volume is supplied according to flow rate changes in the downstream.

- Lubricator : This device is used to feed lubricant into the compressed air to lubricate valves in the downstream and the actuator's sliding part. A lubricator is not required in a lubrication-free system.

- Direction control valve : This valve switches the flow direction of compressed air to drive the actuator.

- Speed control valve : This valve is attached to the piping between the direction control valve and actuator. It is used to adjust the flow rate of the compressed air by means of a throttle valve mechanism to control the actuator's operating speed.

(5) Operating unit

This is an actuator that converts the energy of the compressed air into mechanical energy of a displacement or speed to perform work. The actuator is available in various types and sizes according to the application (e.g. pneumatic cylinder, rotary actuator, etc.).

7.1.2 Features of a Pneumatic System

A pneumatic system is characterized by its use of a working fluid that can be compressed.

(1) Since the air tank can store compressed air, high-speed operation or a high output in a short period can be achieved depending on the load's property. In addition, the system has the features including easy maintenance of the output, operation available in case of an emergency such as power failure, suppression of surge and so on. On the other hand, there are some problems in positioning and response by the control of compressed fluid.

(2) Piping and unit arrangements are easy, and noise/oil leakage due to exhaust and leaks to the outside can be prevented easily if required. Such features allow the pneumatic system to be used in a wide range of fields.

(3) Safety against overload, speed control, and sequence control can be achieved by using relatively simple control valves.

(4) Transmission characteristics of the control signal are slightly inferior to those of electric and hydraulic systems. The pneumatic system, however, can be highly adaptable to an environment having problems in temperature, pulsation, and inflammability.

(5) By routing the piping line from one air source, the air pressure can be supplied over a wide area. Therefore, the power sources can be concentrated into one point.

(6) Pneumatic tools are smaller in size than electric tools and therefore are widely used as manual tools in machine assembly lines. Nowadays, however, the use of electric tools is increasing as well since they provide better efficiency in energy conservation.

7.1.3 Key Points of Energy Conservation in the Pneumatic System

Energy conservation for the pneumatic system should be based on the following three fundamental points:

(1) Improving the efficiency of conversion from electrical power (engine power) into pneumatic power in the air pressure generating unit

(2) Reducing the energy loss in the air pressure transmission line

(3) Improving the efficiency of conversion from pneumatic power into mechanical power in the actuator

7.2 Properties of Compressed Air

7.2.1 Terms

(1) Standard atmospheric air

The atmospheric air at the temperature, pressure, and density represented by the function of height from the sea level is referred to as standard atmospheric air.

(2) Standard air

Wet air at the temperature of 20 °C, absolute pressure of 101.3 kPa, and relative humidity of 65 % is referred to as standard air.

(3) Standard state

The state of air at the temperature of 20 °C, absolute pressure of 101.3 kPa, and relative humidity of 65 % is referred to as the standard state. In the pneumatic system, the volume of compressed air is expressed by the volume corrected from the actual state to the standard state.

(4) Reference state

The state of dry gas at the temperature of 0 °C and absolute pressure of 101.3 kPa is referred to as the reference state.

(5) Ratio of specific heat

If the constant-pressure specific heat is C_p and the constant-volume specific heat is C_v, the ratio of specific heat (k) is expressed by the following formula:

$$k = C_p/C_v$$

For air, a value of $k = 1.4$ is used.

(6) Adiabatic change

When the ratio of specific heat is k, the state change resulting in $[P \cdot V^k = \text{constant}]$ is called the adiabatic change.

(7) Polytropic change

The state change resulting in $[P \cdot V^n = \text{constant}]$ is called the polytropic change.

(8) Polytropic index

Index "n" in the polytropic change is called the polytropic index.

(9) Isothermal change

The state change resulting in [P·V = constant] is called the isothermal change.

(10) Dew point

Temperature at which the steam content is saturated when gas containing steam is cooled at a constant pressure

7.2.2 Moisture Content in Air

Moisture existing in the gaseous state in air is called vapor. Air containing vapor is called wet air. On the other hand, air that does not contain moisture at all is called dry air. If moisture in air is condensed into water drops, adverse effects may be produced; i.e. the piping and components may generate rust, components may malfunction, or a spray painted surface may become uneven. Component malfunction may result in air leaks, thereby increasing the consumption of compressed air and causing energy loss. Therefore, moisture removal is a significant issue in maintenance of the pneumatic system.

7.3 Flow of Compressed Air

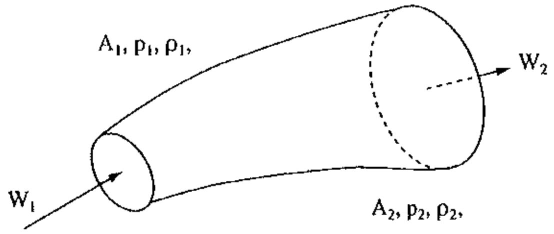
7.3.1 Formula of Continuation

Assuming that a given cross sectional area of the flow route is A, the compressed air speed is w, and the density is ρ, the mass flow rate q of compressed air in constant flow is represented as shown below according to the law of conservation of mass.

$$q = \rho_1 A_1 w_1 = \rho_2 A_2 w_2$$

Subscripts 1 and 2 represent two cross sections of the flow route in the figure.

Figure 7.3 Flow Route



7.3.2 Energy Formula for Compressible Fluid

If the speed is w, the pressure is P, the density is ρ, and the specific heat ratio is k, the following formula is established for compressed air in the constant flow. This formula is called the Bernoulli's equation.

$$\frac{w^2}{2} + \frac{k}{k-1} \cdot \frac{P}{\rho} = \text{Constant}$$

The first term is called specific speed energy and the second term is called the specific pressure energy. This formula indicates that along the flow route shown in Figure 7.3, the total energy per unit mass is constant.

7.3.3 Flow Passing Through Orifice

Assuming that compressed air flows through an orifice with a small cross sectional area provided in the route as shown in Figure 7.4, the mass flow rate is 0 when the pressure ratio between the downstream and upstream (P2/P1) is 1, and the mass flow rate increases from 0 as the pressure ratio is reduced as shown in Figure 7.5. When the critical pressure ratio becomes P2/P1 = 0.528, the flow speed reaches sonic speed. The mass flow rate remains constant until the pressure ratio becomes 0. The flow where the mass flow rate is saturated is called the choke flow or block flow. The flow that does not reach sonic speed at which the critical pressure ratio is at least 0.528 is called subsonic flow.

Figure 7.4 Orifice

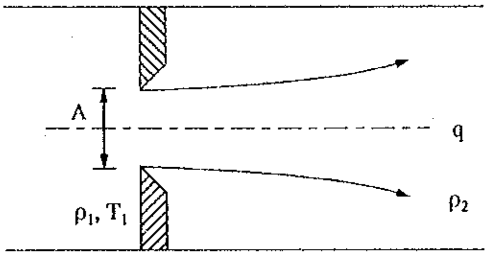
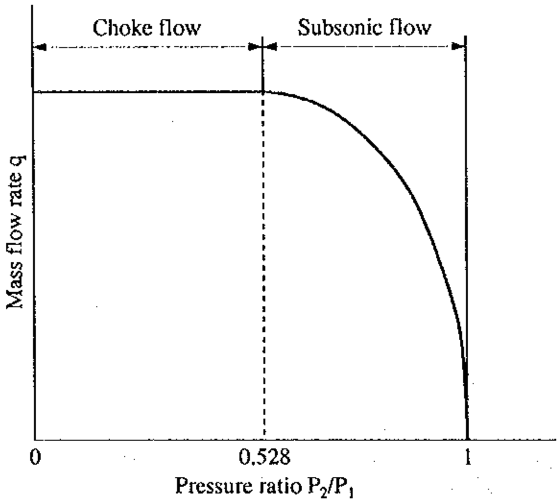


Figure 7.5 Rate of the Flow Passing through the Orifice



The flow of compressed air passing through an orifice is divided into two zones as shown above.

7.3.4 Practical Calculation Formula for Flow rate

An example of the practical calculation formula used for calculating the flow rate of compressed air passing through the valve and piping in the pneumatic system is given below.

(1) When the flow is in the subsonic flow zone

$$Q = 235 \times S \times \sqrt{(P_1 - P_2)(P_2 + 0.1013)} \times \sqrt{\frac{293}{273 + t}}$$

(2) When the flow is in the choke flow

$$Q = 117 \times S \times (P_1 + 0.1013) \times \sqrt{\frac{293}{273 + t}}$$

where Q: Flow rate of compressed air (L/min) (Standard air)
S : Effective cross-sectional area (mm^2)
P_1: Upstream side pressure (MPa [gauge])
P_2: Downstream side pressure (MPa [gauge])
t : Air temperature (°C)

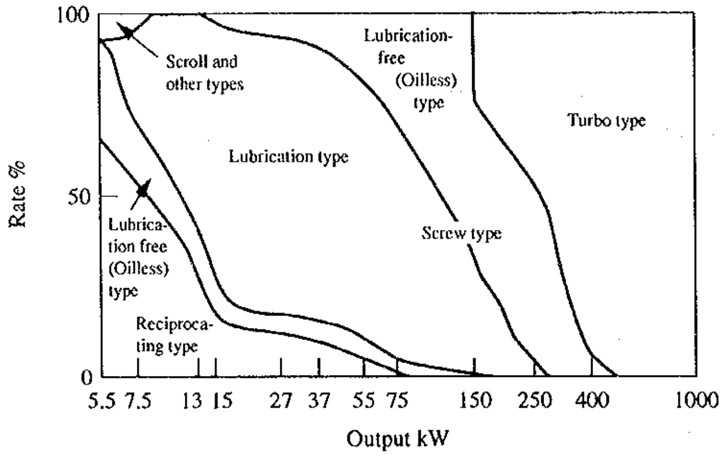
Various formulas are used for the compressed air flow rate depending on country and industry. ISO has established ISO6358 for standardization which is currently underway.

7.4 Air Compressor

7.4.1 Models and Characteristics

The types of air compressors that command a large share of the market in Japan are small size reciprocal type, medium size screw type and large size turbo type.

Figure 7.6 Market Shares of Air Compressors by Type



For example, Table 7.1 shows the relationship between the compressor output and discharge air volume of the screw type, although the relationship varies slightly depending on the model of compressor.

Table 7.1 Discharge Air Volume and Specific Power of Screw-type Air Compressors

Compressor output kW	1.5	2.2	3.7	5.5	7.5	11	15	22	37	55	75	110	150	220
Discharge air volume m^3/min	0.2	0.3	0.5	0.75	1.0	1.5	2.2	3.3	5.8	8.5	12.0	17.5	27.5	40.0
Specific power kW/m^3/min	7.5	7.3	7.4	7.3	7.5	7.3	6.8	6.7	6.4	6.5	6.3	6.3	5.5	5.5

The specific power ranges from 7.5 to 5.5 kW/m^3/min.

Air compressors are classified according to the pressure range as shown in Table 7.2

Table 7.2 Classification of Air Compressors

Type	Class	Main pressure range (MPa)	Applications
Reciprocating compressor	General purpose compressor	0.7 ~ 0.85	2 stage compressor for 100 kW or more
	Intermediate pressure compressor	1 ~ 10	Standard type for 1,000 kW or less
	High pressure compressor	15 ~ 100	For petroleum refining, petrochemical and general chemical industry processes
	Superhigh pressure compressor	150 ~ 350	For synthetic chemistry such as ammonia, methanol and hydrogenation. Mostly large scale such as several thousand kW.
	Oilless compressor	0.7 ~ 0.85	Mainly, ethylene compressor for synthesis of polyethylene and ethylene.
Rotary compressor	Variable profile compressor	1 Stage 2 Stage	Oxygen gas, air for food processing industry and instrumentation, etc.
	Screw compressor	1 Stage 2 Stage	Air capacity 2~60 m³/min.
	Turbo compressor		Air capacity 500 m³/min

(1) Power required for compressors

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

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

L : Required power (unit; kW)
P_s : Absolute pressure of intake air ($kg/m^2 \cdot abs$)
P_d : Absolute pressure of discharge air ($kg/m^2 \cdot abs$)
Q_s : Amount of air per unit time converted to a state of intake (m^3/min)
a : Number of intercoolers
K : Adiabatic coefficient of air
η_c : Overall adiabatic efficiency of compressor
η_t : Transfer efficiency

Values η_c and η_t shall be given by the manufacturer.

The power, provided when $\eta_c\ \eta_t = 1$, is called the theoretical power. Table 7.3 lists the theoretical power for one-stage compression and two-stage compression.

Table 7.3 Theoretical Power of Air Compressor (kW)

Compression pressure	One-stage compression	Two-stage compresssion
0.1	1.261	
0.2	2.129	
0.3	2.811	
0.4	3.380	2.999
0.5	3.874	3.390
0.6	4.312	3.725
0.7	4.707	4.023
0.8	5.069	4.290
0.9	5.404	4.534
1.0	5.715	4.757
1.2		5.163
1.4		5.506
1.6		5.818
1.8		6.100
2.0		6.357

Accordingly, to reduce power for compressors, the following items are important.

(a) Select compressors and systems with good efficiency.
(b) Lower temperature of intake air. Also, improve the cooling effect in the intercooler.
(c) Lower the discharge pressure. Also, reduce the amount of air used.
(d) Prevent air leakage from the compressor proper and piping, etc.
(e) Intensify management for the entire system for compressed air.

(2) Lubrication type and lubrication-free(oil-less) type

The reciprocal and screw compressors are available as both lubrication type and lubrication-free type (oil-less), while the turbo compressors are available as the lubrication-free type only. In the lubrication type, since air is cooled in the compression process and air leakage to the intake side is sealed, the specific power is smaller than that in the lubrication-free type and it costs less. Therefore, the lubrication type has the largest market share among small and medium size compressors. In the reciprocating type, the oxidized lubricant oil mist and carbonized carbon are mixed in the discharge air, and in the screw type, oil mist is mixed in the discharge air. Therefore, the lubrication-free type is used if clean compressed air is required or when the drain must not contain oil. The lubrication-free type is used in most cases when 150 kW or higher large screw compressors are needed. Use of the lubrication-free type is gradually increasing for small and medium size requirements.

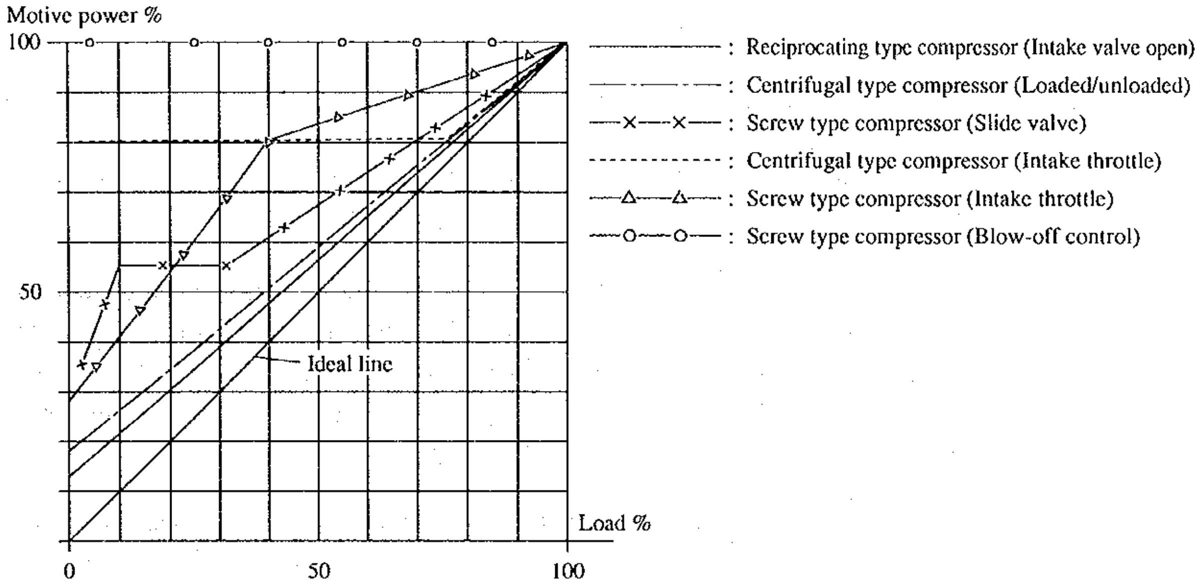
(3) Number of stages for compression

The multi-stage compression type reduces axial power by cooling the compressed air by intercooler during each stage of the compression stroke. If one-stage compression is changed into two-stage compression, power can be reduced by approximately 15 % when the discharge pressure is 0.7 MPa.

(4) Load characteristics

Figure 7.7 shows an example of the air compressor's load characteristics. If the load rate is smaller than 100 %, the power is small but the relationship is not directly proportional. A no-load axial power of not less than about 10 % exists even for the reciprocating type. Therefore, operation at a load rate close to 100 % is most efficient.

Figure 7.7 Load Characteristics of Air Compressors



(6) Number of runing compressors and installation method

Compressors may be installed collectively in a central power room or distributed and installed near the work sites. In any case, layout of the compressors should be determined based on the load variation of the entire factory, risk dispersion, and future plan.

For centralized installation, large models are selected in smaller numbers. Therefore, efficiency of the compressors at a 100 % load is improved, while on the other hand the maximum pressure required for equipment in the factory is supplied to all plants. Also, since the piping to the end use point of air is longer, the piping air feed pressure loss increases. Efficiency for minimum use on holidays and partial load efficiency should be also considered.

For distributed installation, one or a few small compressors are selected. Therefore, although the efficiency of the compressors at a 100 % load is poorer, the smaller piping pressure loss is a merit. To improve the efficiency for a partial load, use of capacity control should be examined. Also, a backup in the event of an accident needs to be considered.

7.4.2 Capacity Control

(1) Pressure switch-driven opening/closing type

This automatic start/stop control system automatically stops the compressor by means of a pressure switch if the air consumption volume decreases and the discharge pressure exceeds the set value. The system automatically starts the compressor again if the pressure drops below the specified value. This system is applied when air consumption is intermittent and pressure variation is large. Although electricity is not consumed while the motor is stopped, the use of this system is limited to small compressors due to the frequency of start/stop operation.

(2) Constant control of discharge pressure

This system maintains and controls the discharge pressure within a certain range. The control method varies depending on the type of the compressor.

For the reciprocating type, if the volume of air consumption decreases and the discharge line pressure exceeds the set value, the unloader piston valve opens the intake valve to continue operation without compressing air. This system is applicable in cases where the air consumption volume varies. Although there is a large fluctuation in pressure, a substantial energy conservation effect is achieved.

For the screw type with lubrication, if the air consumption volume decreases and the discharge pressure increases, the intake throttle valve is closed while the discharge pressure adjusting valve is opened to discharge compressed air and match the intake air volume with the air consumption volume. On the other hand, if air consumption increases and the discharge pressure drops, the pressure adjusting valve gradually closes to open the intake throttle valve and to restore the system to operate with the load. This system is applicable in cases where the load variation is small during continuous air consumption. While the fluctuation in the discharge pressure is small, the energy conservation effect is small as well.

Employing a slide valve that does not drop the intake pressure but shortens the effective part of the screw/rotor when the air consumption volume decreases will eliminate the rise of the pressure ratio, thus enhancing the energy conservation effect.

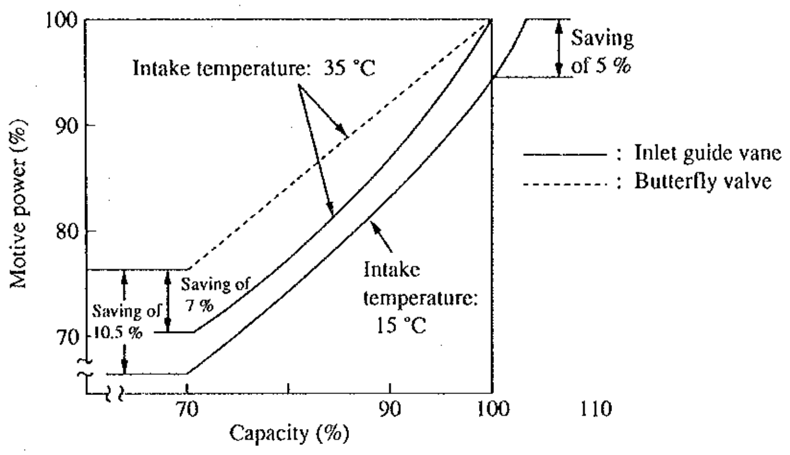
For the dry screw type, the intake valve throttle control method is rarely used because the energy conservation effect is less significant as mentioned above and the discharge temperature rises. The system using the slide valve is effective, but at the same time involves a problem of oil infiltration because valve operation requires a small volume of oil.

For the turbo type, rise of the discharge pressure is controlled by reducing the intake valve. Although reduction with a butterfly valve is inexpensive, the intake pressure drops when the air consumption declines.

There is an inlet guide vane (IGV) system that does not reduce the intake pressure but performs a swing operation on the intake air to reduce the work of the first-stage impeller when the air consumption decreases. Figure 7.8 gives a comparison between the inlet guide vane system and butterfly valve throttle system.

Also available is a system that reduces the discharge-side diffuser. This system, however, is only used for one-stage compressors with a low discharge pressure.

Figue 7.8 Comparison between Butterfly Valve Throttle System and IGV System



(3) Inverter system

The rotational speed corresponding to the load is calculated according to the signal from the pressure sensor in the discharge line. Therefore, the compressor is run at the optimum rotational speed to supply air always at a constant discharge pressure. This system flexibly accommodates a fluctuations in air consumption, has only a small fluctuation in the discharge pressure and produces a significant energy conservation effect.

If the rotational speed is reduced for the turbo type, however, the discharge pressure drops and as a result the required pressure cannot be obtained. Therefore, speed control cannnot be applied.

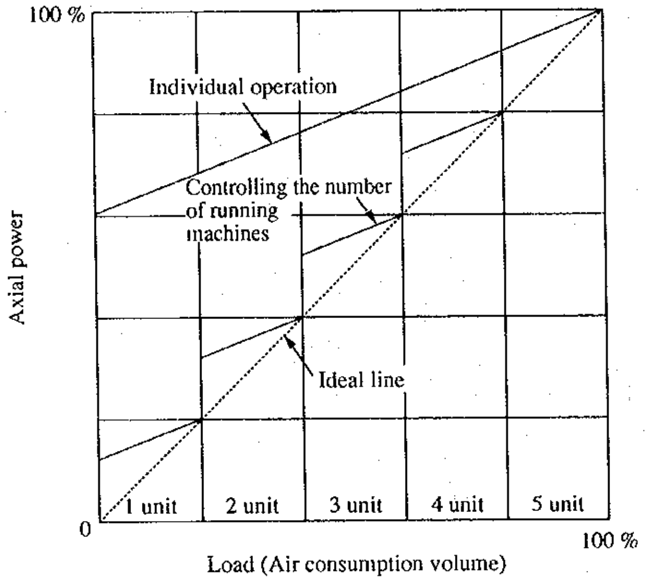
7.4.3 Controlling the Number of Operating Compressors

If two or more compressors are installed, the number of running compressors is controlled according to the load fluctuation for the following purposes:

a. To minimize the number of running compressors and reduce idling loss
b. To minimize the discharge pressure for operation at the proper pressure
c. To prevent action delay due to manual operation
d. To reduce maintenance man-hours by using centralized management

The number of running compressors should be minimized to match the amount with the air used and all except one compressor should be run on a full-capacity basis provided that one compressor only is run without a load. Figure 7.9 shows the load characteristics under control of the number of compressors. It is necessary to bring them to the ideal load characteristic under the widest load range possible.

Figure 7.9 Load Characteristic by Controlling the Number of Operating Machines



7.5 Energy Conservation Measures for Compressed Air Equipment

7.5.1 Reduction of Intake Temperature

For the displacement type, if the intake temperature drops by 20 °C, the axial power increases by 3 %. Theoretically, however, the actual discharge volume increases in proportion to the absolute temperature of the intake air and therefore it increases by 6.8 %. Thus, a 20 °C drop in temperature leads to a 3.8 % energy conservation.

For the turbo type, the axial power does not logically change unless the delivery pressure and intake volume flow rate change. Therefore, a drop in the intake temperature should naturally bring about an energy conservation effect equivalent to the increase in the mass flow rate. On the other hand, if the intake temperature drops, the specific gravity of air increases as well, and this may in turn cause the discharge pressure to increase. This is, however, determined by the load side. As a result, the discharge pressure does not change and only the intake volume flow rate increases. Thus, operation deviates from the designed point. The efficiency drops and only a 2 to 3 % energy conservation can be achieved with a 20 °C temperature drop.

The problem in indoor intake is the need to suppress indoor heat generation and drop the indoor temperature through ventilation. Indoor heat generation can be greatly reduced by exhausting motor heat directly to the outside or cooling the motor with water.

For outdoor intake, a cool place not exposed to direct sunlight should be selected for the intake port and reduction of the intake tube pressure loss and silencer installation should be examined.

7.5.2 Cooling Effect of Intercooler

Insufficient cooling by the intercooler takes air compression closer to adiabatic compression, thus increasing the motive power required for compression at the second and subsequent stages. A possible cause for the drop in efficiency of the intercooler may be reduction of the heat transfer efficiency due to deposits of scale or slime or shortage of the cooling water volume . Therefore, appropriate countermeasures such as washing the cooler periodicallyshould be planned.

7.5.3 Reduction of Discharge Pressure and Air Consumption

As shown in Table 7.3, reducing the discharge pressure leads to energy conservation. For example, if the discharge pressure is reduced from 0.7 MPa to 0.6 MPa, power will be reduced by about 8 % for one-stage compression.

Generally, many machines or tools may require different air pressure conditions for the same work even when they have the same capabilities. Therefore, it is important to standardize the operating pressures for the machines or tools in the entire factory to a lower pressure through careful examination in order to reduce the electricity requirements.

If the factory has equipment such as a press machine which requires high-pressure compressed air, it would be economical to install a dedicated booster.

Since reduction of air consumption leads to an approximately proportionate reduction of the power cost, use of compressed air for personal cooling and cleaning should be inhibited and the nozzle size at each location should be reviewed for a thoroughgoing management of the use conditions.

7.5.4 Air Leakage from Clearance, Hole, etc.

(1) Air leakage

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

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

where

g : Acceleration of gravity 9.8 $[m/s^2]$
γ : Specific weight of air $[kg/m^3]$
S : Effective cross section $[m^2]$
P_1, P_2 : Absolute pressure inside and outside vessel $[kg/m^2 \cdot abs]$

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

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

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, as such, reducing the service pressure surely reduces the leakage. Figure 7.10 shows the blow-off air amount from a small diameter orifice.

Figure 7.10 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 state (20 °C, 1 atmospheric pressure).

To apply practically, use selectively a value multiplied by 0.97 to 0.65 because values in Figure 7.10 are based when discharge coefficient c = 1.

Figure 7.10 Compressed Air Pressure and Blow-Off Air Amount from Nozzle

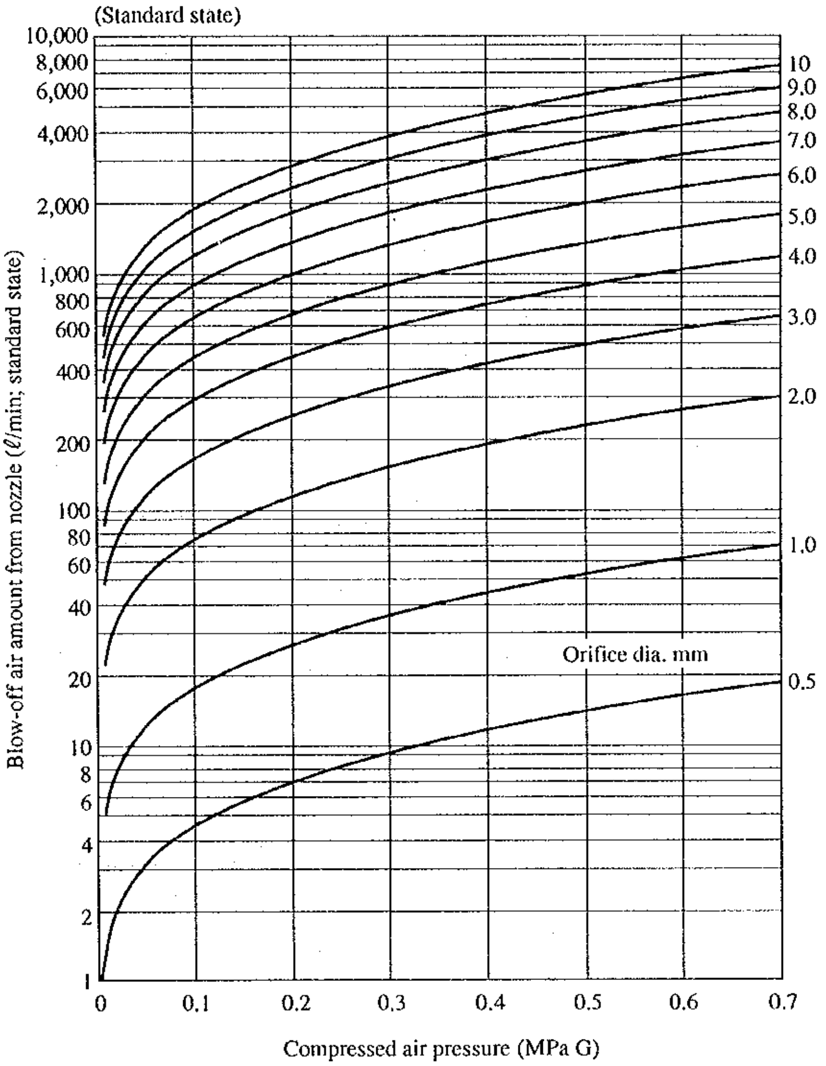
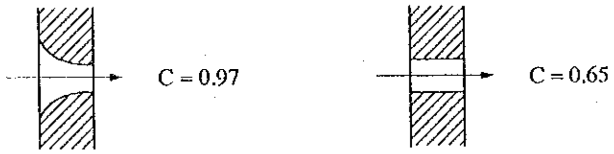


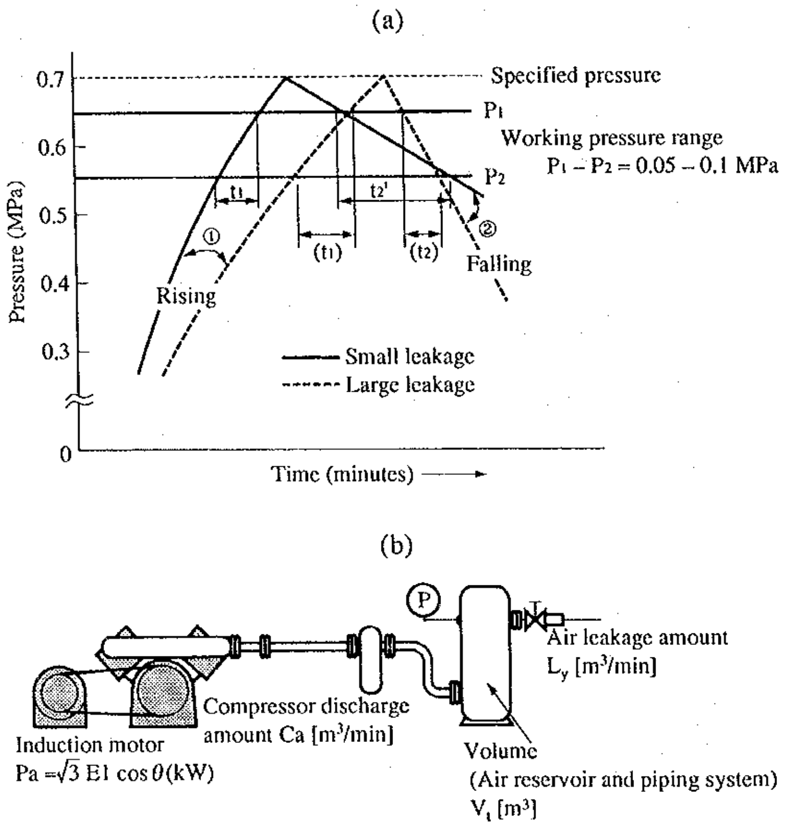
Figure 7.11 Shape of Orifice and Value of Discharge Coefficient



(2) Measurement of air leakage

It is possible to measure air leakage of the compressed air piping system in the following way: first, operate a compressor with the end closed and the pressure gradually rises as shown by (①) in Figure 7.12 (a). Stop the compressor at the specified pressure and let stand as-is, then the pressure will lower the air leakage as shown by (②). In the case of (a), it shows that the solid line has less leakage than the dotted line.

Figure 7.12 Pressure - Time Curve



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

Assuming that pressure range (P_1 to P_2)is treated as a pressure to be practically used (0.05 to 0.1 MPa), and t_1, t_2 are treated as shown in the figure, the following equation is formed.

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

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

When air leakage L_y is determined from the above equation,

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

Air leakage factor L_p (%) is

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

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

Table 7.4 shows an example of the results of air leak measurement through sound. The total number of air leaks in the factory is 81. Most leaks occurred at joints followed by auxiliary machines and the like, accounting for 70 % of the total leaks. These, however, do not include drive peripherals such as cylinders for machines.

Table 7.4 Results of Air Leakage Survey

Machine category	No. of leakages			
	Leak amount			Total(%)
	Large	Medium	Small	
1. Pipings	0	4	1	5 (6.2)
2. Joints	0	14	8	22 (27.2)
3. Auxiliary machines	0	9	6	15 (18.5)
4. Direction controller	0	3	7	10 (12.4)
5. Drives	1	0	0	1 (1.0)
6. Pneumatic tools	0	6	2	8 (10.0)
7. Others	0	16	4	20 (24.7)
Total	1	52	28	81(100.0)
Estimated amount of leak [L/min]	@200 200	@50 2,600	@10 280	
		3.080		

7.5.5 Management of Compressed Air Equipment

Precautions for management of compressed air system are as follows:

(1) Management of compressor

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

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

b. Is not generated heat of compressors unusually high?

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

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

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

f. Is not the intake side filter clogged?

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

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

i. Is the air tank drain ejector operating normally?

j. Is the intercooler operating normally?

(2) Control of pressure

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

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

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

c. What is the proof pressure of the line?
: the pressure at which the control equipment will be damaged.

Set the pressure switch, safety valve and relief valve after knowing the above matters. Items to check in this case are as follows.

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

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

c. Is the regular operating normally?

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

(3) Control of drain

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

Check Items:

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

b. Is the automatic drain apparatus operating normally?

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

(4) Inspection of pipings

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

Check Items:

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

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

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

8. ENERGY CONSERVATION IN MOTORS

8. MOTORS

The measures for motor energy conservation are mainly classified into the following two cases:

(1) Energy conservation by newly establishing or by greatly remodelling load and motor equipment.

(2) Eenergy conservation by intensifying the management aspect of the existing equipment or by remodelling it in a small scale.

Each of these will be discussed below:

8.1 Energy Conservation by Newly Establishing Load and Motor Equipment

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

8.1.1 Basic Expressions Relating to Motor-driven Force Applications

Basic expressions which must first be understood when considering the motor energy conservation are shown in Table 8.1.

Table 8.1 Basic and Practical Expressions Relating to Motor Application

Formulation Item	Basic expression	Practical expression	Description of symbols
1 Power and torque	$P = \omega T$	$\begin{cases} N[\text{rpm}] = \dfrac{60}{2\pi}\omega \\ T_g[\text{kg}\cdot\text{m}] = \dfrac{T}{g} = \dfrac{T}{9.81} \end{cases}$ $P_k[\text{kW}] = \dfrac{N[\text{rpm}]}{973} \times T_g[\text{kg}\cdot\text{m}]$	P : Power (W) P_k: Power (kW) T : Torque (N-m) T_g: Torque (kg·m) ω : Angular velocity (rad/sec) N : Rotating speed (rpm)
2 Moment of inertia and acceleration torque	$J\dfrac{d\omega}{dt} = T$	$GD^2 = 4J$ $T_g[\text{kg}\cdot\text{m}] = \dfrac{1}{375}\ GD^2 \cdot \dfrac{dN}{dt}$	J : Moment of inertia (kg·m²) GD²: Flywheel effect (kg·m²)
3 Acceleration time	$t = \int_0^{\omega_0} \dfrac{J}{Ta} d\omega[\text{sec}]$	$\overline{Ta} = \dfrac{\int_0^{\omega_0} Ta(\omega)d\omega}{\omega_0}$: $t_a[\text{sec}] = \dfrac{1}{365}\ \dfrac{GD^2N^2[\text{rpm}]}{P[W]}$	t : Time required for acceleration (sec) t_a : Time required for completion of acceleration (sec) Ta: Acceleration torque (kg·m) $\overline{Ta}$: Mean acceleration torque (kg·m)

8.1.2 Load Condition in the Selection of Motors

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

How a motor must be under various conditions of load, or what to be the allowable conditions are summarized in Table 8.2. When the conditions shown here are clear, it is possible to select the motor and also to select the control equipment to follow it.

Table 8.2 Conditions for Motor Selection

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

While motor systems are classified into DC, induction and synchronous machines in Table 8.2, induction and synchronous machines here are considered to be constant-speed drive systems for commercial power source. A thyristor motor applied to a synchronous machine and a frequency control method applied to an induction machine belong to the DC machines for system. Main items for selection of motors are described in the following sub-section 8.1.3:

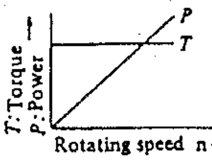
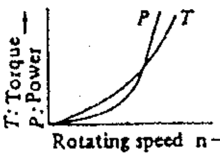
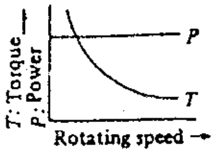
8.1.3 Torque Characteristics of Load

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

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

As examples of typical torque-speed characteristics, there are three types. The first is constant-torque type in which the torque is constant in spite of the speed, the second is torque increasing type in which the torque is in proportion to the speed or its square, or cubic 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 8.3.

Table 8.3 Class of Load and Torque Speed Characteristic

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

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

8.1.4 GD^2 of the Load

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

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

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

Accordingly, the starting time is

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

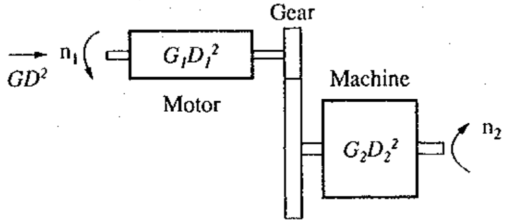
where N_o: Full-load rotation number

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

When GD^2 of motors: $G_1D_1^2$, GD^2 of machines: $G_2D_2^2$ and reduction ratio: $n_1/n_2 = n$ as shown in Figure 8.1, GD^2 converted to the motor side is:

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

Figure 8.1 Conversion of Flywheel Effect



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

8.1.5 Time Characteristics of the Load

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

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

(1) Continuous rating

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

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

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

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

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

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

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

This is graphed in Figure 8.2. Also, the thermal time constant normally will be as shown in Table 8.4.

Next, when the motor is separated from the power source and stopped, substituting Q = 0 in equation (3) and $\theta = \theta_0$ at t = 0,

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

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

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

Figure 8.2 Temperature Rise Curve of Motor

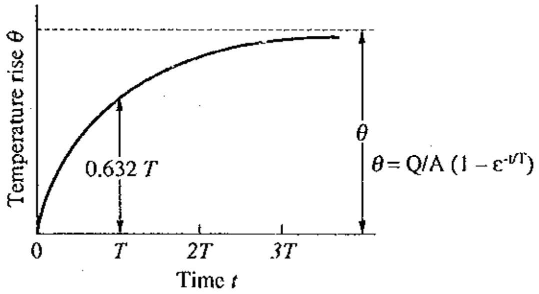


Table 8.4 Example of Thermal Time Constant

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

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

(2) 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.

(3) 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 8.5).

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

Table 8.5 Frame Number Application Table

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

ED: Einschetdauer (Germany)

(4) Calculation of output by the root mean square method

Rated output of a motor is selected from the timely characteristics of the load, but when the load varies irregularly, it is rather difficult to determine the motor output. However, when the load varies continuously and periodically, the root mean square method is often used as a simple output calculation method.

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

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

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

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

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

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

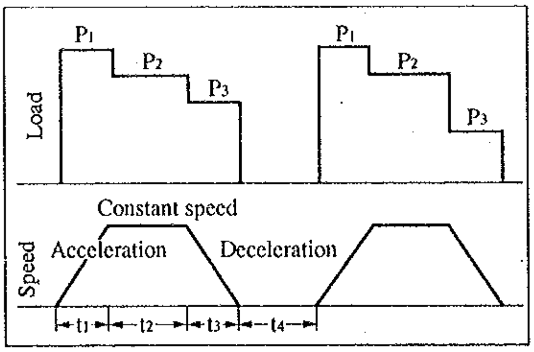
$$\text{Hence, } P_a = \sqrt{\frac{P_1^2 t_1 + P_2^2 t_2 + \cdots + P_n^2 t_n}{T}} \quad \text{.......} \quad (6)$$

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

For example, the equivalent load when a motor with a continuous rating is used for intermittent load as shown in Figure 8.3 is determined in the following way:

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

Figure 8.3 Example of Periodic Load



However, α is heat extraction coefficient and its value is as shown in Table 8.6.

Also,

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

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

Table 8.6 Example of Cooling Coefficient Values

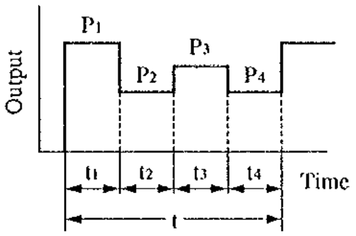
Type of motor	During stop	During acceleration	During operation	During deceleration
Open type AC motor	0.2	0.5	1	0.5
Enclosed type AC motor	0.3	0.6	1	0.6
Totally enclosed fan cooling type AC motor	0.5	0.75	1	0.75
Separately-cooling AC motor	1	1	1	1

(5) Determination of motor capacity

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

For example, in continuous operation as shown in Figure 8.4,

Figure 8.4 Example of Load Curve (1)



P_1 = 100 kW, t_1 = 10 minutes
P_2 = 50 kW, t_2 = 15 minutes
P_3 = 80 kW, t_3 = 10 minutes
P_4 = 50 kW, t_4 = 20 minutes

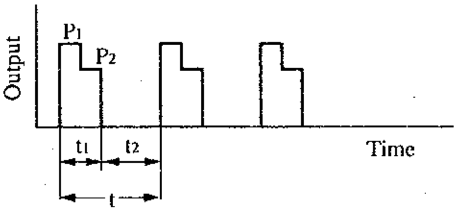
From equation (6), the required motor output P is

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

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

When a motor for crane is periodically used as shown in Figure 8.5.

Figure 8.5 Example of Load Curve (2)



P_1 = 50 kW 1.5 minutes
P_2 = 30 kW 1.5 minutes
t_1 = 1.5 + 1.5 = 3 minutes, t_2 = 7 minutes,

the root mean square load in operation is

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

Accordingly, a motor corresponding to 40 % ED 45 kW may be selected from Table 8.5.

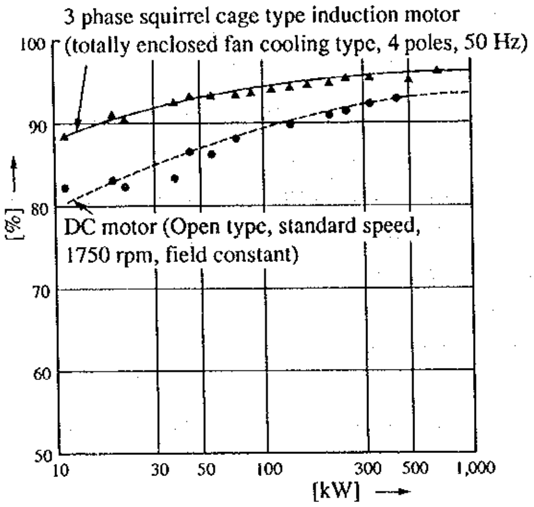
8.1.6 Class, Efficiency and Power Factor of Motors

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

(1) DC and induction motors

Figure 8.6 shows the comparison in efficiency between DC and induction motors. As can be seen from the figure, the efficiency of the DC motor is 5 to 8 % lower than the induction motor for small capacity machines 100 kW or less and 2 to 3 % lower for 300 to 100 kW. This DC motor, being of the separately-ventilated type, must be essentially evaluated including loss of the blower for cooling. Since, however, this value is omitted, the efficiency actually tends to lower further.

Figure 8.6 Comparative Example of Efficiency for Induction Motor and DC Motor

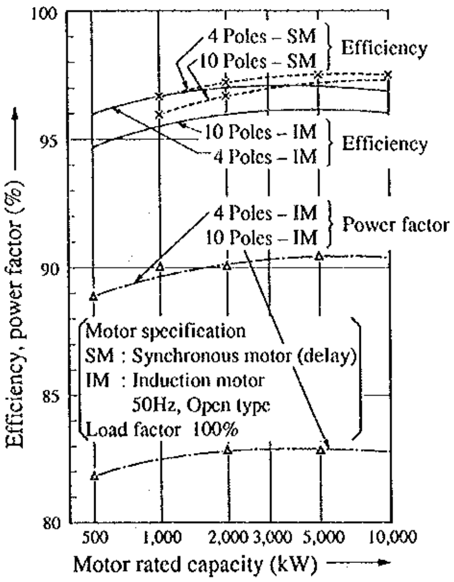


The DC motor is capable of operating in accordance with the load characteristic and also in easily controlling the speed or torque because it can be easily provided with various characteristics by means of excitation systems. On the other hand, the DC motor has the following defects; the efficiency is lower than AC motors such as induction and synchronous motors, etc.; it has difficulties in maintenance and in environment-proof because of a current collecting mechanism.

(2) Synchronous and induction motors

Figure 8.7 shows the comparison in efficiency between synchronous and induction motors.

Figure 8.7 Comparative Example of Efficiency and Power Factor between Synchronous and Induction Motors



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

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

Since, however, the synchronous motors including excitation power source equipment for the field system are expensive, generally selection should be studied, with the following points:

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

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

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

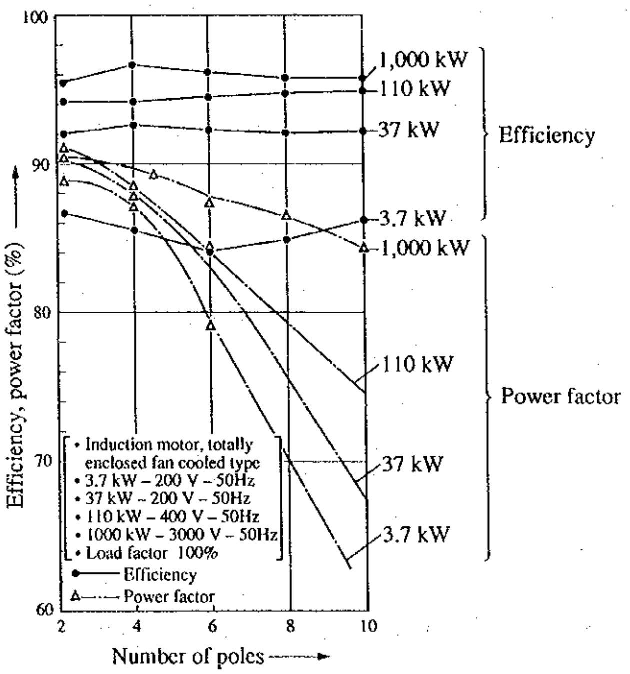
d. Generally, for 5 MW or less, induction motors are superior in simple starting and power source composition.

e. Generally, for salient-pole synchronous motors, the starting torque is not so large as for induction motors; it should be, therefore, noted that they are diffcult to start up with large inertia moment or torque loads.

(3) Induction motor and its number of poles

Figure 8.8 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.

Figure 8.8 Relation between Number of Pole, Efficiency and Power Factor of Induction Motors



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 the rotating speed of the opposite machine. Generally, for motors with the same output, the larger the number of poles is, the larger the volume and weight become.

Since the weight is closely related to the amount of materials used and material manufacturing expenses, it may represent a tendency of cost. Accordingly, since the larger numbers of poles generally raise the cost, it is better not to make the number of poles unnecessarily larger. Otherwise, the initial investment will be larger and uneconomical.

Motors are rarely directly coupled to the opposite load machine and usually, a reducer lies between them.

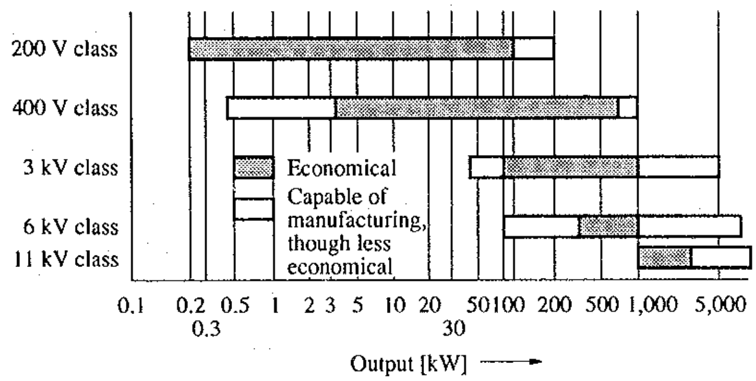
When a four-pole motor is selected with reference to the reducer, there will be no problem in respect of cost and power factor. But when a motor with larger numbers of poles is selected, it should be determined by taking into consideration the equilibrium between the efficiency merits of the drive system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

8.1.7 Selection of Motor Voltage

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

Figure 8.9 shows the optimum range of motor capacity for each voltage taking into consideration the technical problems and economical efficiency. The shaded portion in this figure indicates a comparatively economical range containing few problems in manufacturing technique, and the range shown with a white frame is the range in which it is possible to manufacture technically if the economical efficiency is ignored to a certain degree.

Figure 8.9 Optimum Output Range of Motor



8.1.8 Adoption of High-efficiency Motors

In recent years, high-efficiency motors with iron and copper losses reduced by 20 to 30 % have been sold on the market. They have been developed by improving the low-voltage squirrel cage type induction motors through adoption of flat rolled high grade magnetic steel plate (silicon steel) and optimization of design with leaving the frame number and external dimensions as the present standard. Although the initial investment will be somewhat higher, they will deserve studying for adoption for long-time operating motors.

Figure 8.10 and Figure 8.11 show comparison in efficiency between high-efficiency motors and standard type motors which are being manufactured at present. It should be noted in Figure 8.11 that the high-efficiency motors are remarkable in the improvement of efficiency at light load.

Figure 8.10 Efficiency Comparison of 3 Phase Squirrel Cage Type Induction Motor (Output Capacity)

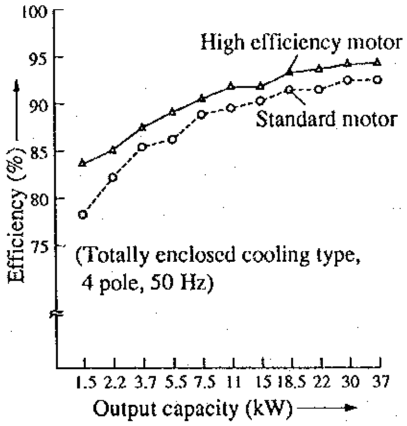


Figure 8.11 Efficiency Comparison of 3 Phase Squirrel Cage Type Induction Motor (Load Factor)

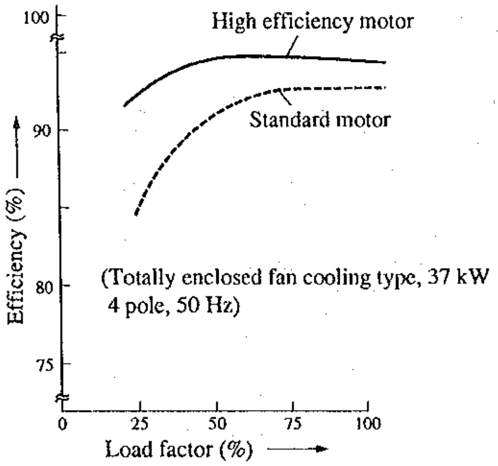
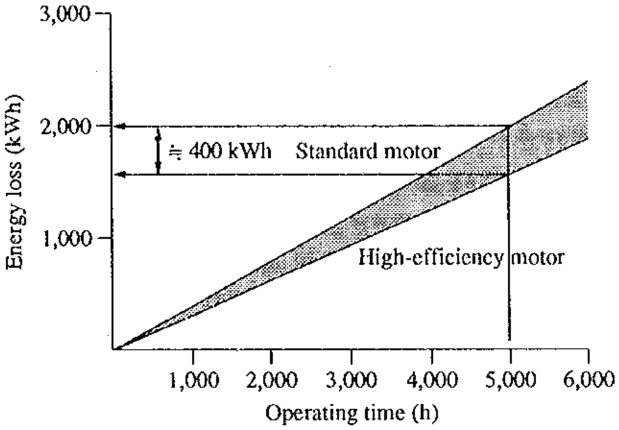


Figure 8.12 shows an example of achieving an energy conservation effect for high-efficiency induction motors.

Motor specifications: Totally enclosed fan cooled type, 2.2 kW, 4 poles, 200 V, 50 Hz, 100 % load

Figure 8.12 Energy Conservation Effect for High-efficiency Motors



This figure shows that energy conservation of about 400 kWh can be achieved by operating this type of motor, for example, 5,000 hours per year.

8.1.9 Rotating Speed Control of Induction Motors

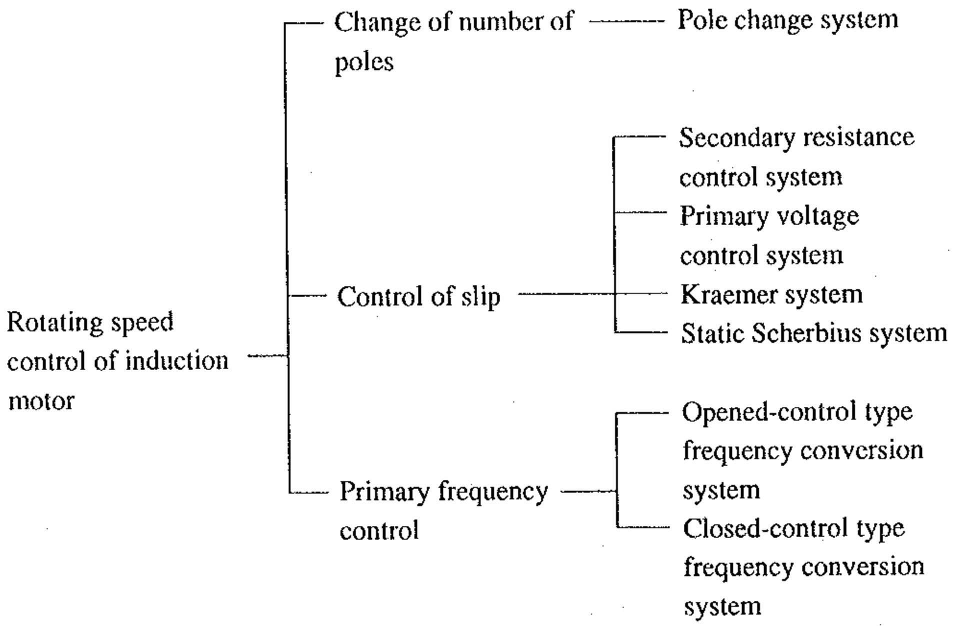
As described in sub-section 8.1.3, there are three types of motor loads: the constant-torque load, decreasing-torque load, and constant-output load. Among them, the fluid machine load belongs to the decreasing-torque load. The torque is a function of the angular speed and proportional to the square of the rotating speed, and therefore the power is proportional to the cubic of the rotating speed. Since the flow rate is proportional to the rotating speed, if the flow rate decreases on a fluid machine, the power is reduced in proportion to the cubic of the rotating speed by reducing the rotating speed as a result of rotating speed control. Thus, a substantial energy conservation effect can be expected. Additionally, rotating speed control is also used for the constant-torque load for cranes, etc.

Generally, the rotating speed of the induction motor is represented by the following equation:

$$N = \frac{120f}{P}(1 - S) \quad \cdots\cdots (7)$$

As shown above, rotating speed control of the induction motor is attained by changing one of three elements; the number of poles (P), slip (S), or primary frequency (f). Figure 8.13 shows the rotating speed control methods categorized for these control elements.

Figure 8.13 Classification of Rotating Speed Control



(1) Changing the number of poles

This speed control method changes the number of poles (P) of the motor step-wise as shown in the equation (7). The rotating speed is changed by changing the number of poles between 2 and 5. The speed change ranges from 1:1.5 to 1:8. This method is used to control the speed step-wise.

(2) Secondary resistance control

If the secondary resistance on the wound-rotor type induction motor is changed, torque characteristics change as a result of proportional shifting. By using this feature, the speed control is attained by changing the balance point with the load torque. This method allows the rotating speed to be changed continuously. However, if the rotating speed is reduced by increasing the secondary resistance, heat loss by the secondary resistance increases and efficiency drops.

(3) Primary voltage control

This speed control method changes the primary voltage of the motor by combining the induction motor with a thyristor. By using the feature that the toque volume is proportional to the square of the voltage, the rotating speed is changed continuously. Stable operation at a low speed is possible, while, on the other hand, the efficiency and power factor decrease.

(4) Kraemer system

The secondary output of the induction motor is converted into a direct current by a silicon rectifier. By driving the DC motor connected to the induction motor, the direct current is converted into a mechanical output. Since loss is not caused by control, efficiency is high. The variable range is 1:2 or less. This system is suitable for the constant-output operation within a small range.

(5) Static Scherbius system

This control method reversely converts the secondary output of the induction motor with an inverter and then returns the resulting power to the power supply. Speed control is attained through inverter phase control. Since loss is not caused by control, efficiency is high. The variable range is 1:2 and said to be economical. This method is used for variable speed control within a small range.

(6) Primary frequency control

This speed control method changes the primary frequency (f) of the induction motor. By using an inverter or cyclo-converter, the frequency is changed and the rotating speed is changed continuously. As power devices acquire higher performance, variable speed systems, each using an inverter, are widely used for large industrial machines to small household machines. Since this system is particularly useful for modification of existing equipment, it is described in detail in sub-section 8.2.3.

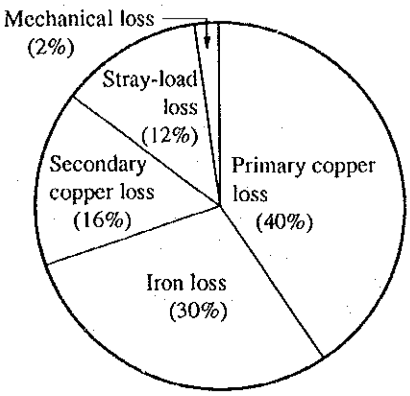
8.2 Energy Conservation by Remodelling the Existing Equipment in a Small Scale

8.2.1 Induction Motors and Voltage Control

Although generally induction motors are most widely used because they are low cost and simple to handle, it should be noted that supply voltage fluctuation gives the great influence on the efficiency of these motors.

Figure 8.14 shows one example of loss of a three phase induction motor with a comparatively small capacity. As can be seen from this figure, a greater part of the loss is copper and iron losses which account for 86 %. Accordingly, the impact of supply voltage fluctuation on the induction motor will be clarified by investing these two.

Figure 8.14 Loss Analysis Example of Standard 3 Phase Induction Motor



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

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

where

W_c: Copper loss
r_1 : Resistance of primary winding each phase (Ω)
r_2' : Resistance of secondary winding each phase (primary side converted value) (Ω)
I'_2 : Load current (A)

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

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

where

ω_0: Synchronous angular velocity
V_1: Supply voltage
T : Load torque

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

$$W_c \fallingdotseq (r_1 + r'_2)\frac{\omega_0^2 T^2}{3V_1^2} \text{ (W)} \quad \text{.......... (10)}$$

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

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

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

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).

$$W = \left(k'_1 + \frac{k'_2}{f}\right)V_1^2 + (r_1 + r'_2)\frac{\omega_0^2 T^2}{3V_1^2} \text{ (W)} \quad \text{.......... (12)}$$

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:

$$V=\sqrt[4]{\frac{(r_1+r'_2)\omega_0^2}{3(k'_1+\frac{k_2}{f})}}\cdot\sqrt{T}(V) \quad\cdots\cdots (13)$$

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

Figure 8.15 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 adverse 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 will swift to the right when the load factor is high, and it will swift to the left when the load factor is low.

Figure 8.15 Tendency of Loss against Applied Voltage

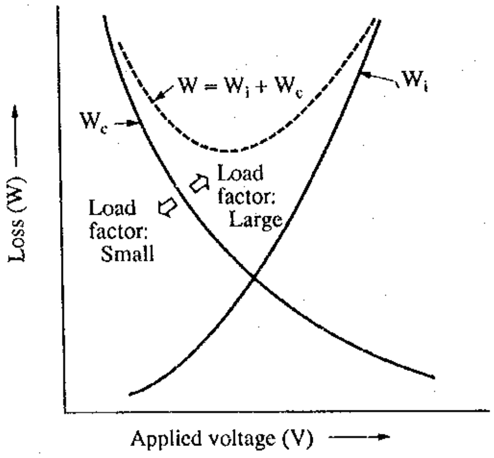


Figure 8.16 shows one example of the efficiency curve when the survey voltage is actually changed with a motor. As shown in the figure, the efficiency during voltage fluctuation exhibits varied tendencies according to the load factor. When the load factor is high, the highest efficiency is shown at the rated voltage, while, when the load factor is low, the efficiency lowers as the voltage increases.

Figure 8.16 Example of Efficiency during Voltage Fluctuation of Induction Motor

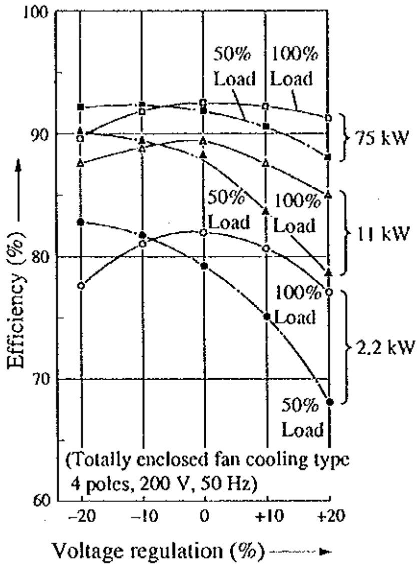
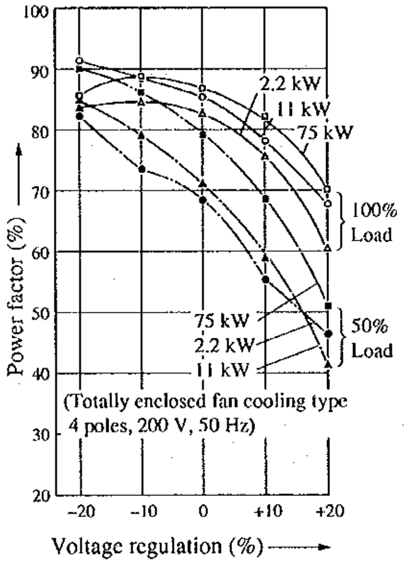


Figure 8.17 shows the change in the power factor of induction motors when the supply voltage fluctuates. The power factor increases as the voltage drops, because the exciting current of induction motors is in proportion to the supply voltage.

Figure 8.17 Example of Power Factor during Voltage Fluctuation of Induction Motor



What has been described until now is summarized in Table 8.7.

Efficiency and power factor during supply voltage fluctuation have been described in the foregoing. When the above are actually applied to motors in operation within the field, the following items should be studied together.

Table 8.7 Effect of Voltage Fluctuation on Induction Machine

		Voltage fluctuation		
		90 % Voltage	Proportional relation	110 % Voltage
Starting torque Stalling torque		–19 %	V^2	+21 %
Synchronous speed		Remain unchanged	Constant	Remain unchanged
% slip		+23 %	$1/V^2$	–17 %
Full-load speed		–1.5 %	–	+1 %
Efficiency	Full load	–2 %	–	Slightly increased
	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 decreased	–	Slightly increased

(1) Study when the supply voltage is lowered

To operate with the supply voltage lowered below the rated voltage, it is necessary to check accelerating torque during starting and the value of the peak load because the starting torque and maximum torque decrease at a rate of the square of the voltage as shown in Table 8.7.

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, the line loss of distribution line, etc. Care should be taken. Therefore, the lower limit of the supply voltage should be determined within a range not to exceed the motor rated current.

(2) Study when the supply voltage is raised

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

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

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) where s represents sliding 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.

8.2.2 Prevention of Idle Running and Reduced Starting Loss

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

(1) Deterioration and output drop of motors due to multi-frequency starting should be restricted within a range so that they can be used as usual.

In the case of large-capacity motors 100 kW or more and motors with high GD^2 as a load such as blower, etc., it is recommended to consult with the motor manufacturer.

(2) Electric energy during starting should not exceed the electric energy during idle running.

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

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 generally expressed by the following equation:

$$W_\ell = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_0^2 (S_1^2 - S_2^2)(1 + \frac{r_1}{r_2'}) \frac{T_m}{T_m - T\ell} \quad \cdots\cdots \quad (14)$$

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

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

$$W_\ell = \frac{1}{2} \cdot \frac{GD^2}{4} \omega_0^2 (1 + \frac{r_1}{r_2'}) \frac{T_m}{T_m - T\ell} \quad \cdots\cdots \quad (15)$$

Where

r_1 : Primary resistance of induction motor (Ω)
r'_2 : Secondary resistance of induction motor (Primary side converted value) (Ω)
T_m: Accelerating torque of induction motor (Mean value) (N·m)
T_ℓ : Mean torque of load in acceleration (N·m)
ω_0: Synchronous angular velocity

b. Reducing method of starting loss

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

1) Start with a higher motor generated torque.

2) 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.

3) Increase the secondary resistance when starting.

   When a wound-rotor type induction motor is used, inserting a high external resistance when starting will not only greatly reduce the entire motor loss including the external resistance, but also restrain rotor heat and starting current.

4) Change the synchronous angular velocity ω_0.

Changing the synchronous angular velocity ω_0 of induction motor together with a rise in the motor speed greatly reduces the loss during starting.

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

Taking the case of two-step pole change induction motors, we will explain. First, starting with the low-speed side winding, accelerate to the synchronous angular velocity ω_{0L} of the low-speed winding (Number of poles: P_L), and switching to the high-speed winding side, accelerate to the synchronous angular speed ω_{0H} of the high-speed winding (Number of poles: P_H). Total loss of the motor during this period $W_{2\ell}$ will be determined as follows. For simplification, it is assumed in equation (14) that $r_1 = 0$, $T_\ell = 0$.

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

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

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

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

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

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

The following measures are effective in preventing idle running.

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

8.2.3 Control of Induction Motor Rotating Speed

As mentioned earlier, control of induction motor rotating speed is widely used for energy conservation of pump, fan, blower and motor for crane.

Of the rotating speed control systems shown in Figure 8.13, the primary frequency control system (VVVF) can be materialized from the standpoint of remodelling the existing equipment and as such it will be described.

The primary frequency control system controls the primary voltage and frequency of the motor at the same time, by means of a frequency converter, to change the synchronous speed.

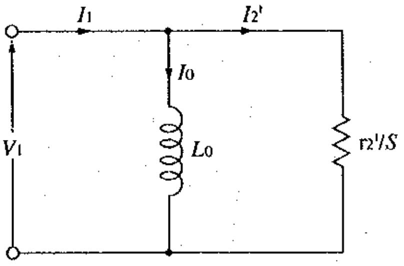
This control system is mainly divided into opened-control and closed-control types. Of these, the opened-control type is open-loop control in which the converter frequency is determined based on frequency instructions from a setting apparatus irrespective of changes in state such as the motor rotating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

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

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

The simple equivalent circuit prepared under this condition is shown in Figure 8.18.

Figure 8.18 Simple Equivalent Circuit of Induction Motor at Slip ≒ 0



Equivalent circuit during operation near synchronous speed

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

$$I_1 = I_0 + I'_2 \text{ [A]} \quad \cdots\cdots (19)$$

$$I_0 = \frac{V_1}{\omega_0 L} \text{ [A]} \quad \cdots\cdots (20)$$

$$I'_2 = \frac{SV_1}{r_2'} = \frac{S\omega_0}{r_2'}\frac{V_1}{\omega_0} \text{ [A]} \quad \cdots\cdots (21)$$

$$T = \frac{3SV_1^2}{\omega_0 r_2'} = 3\frac{S\omega_0}{r_2'}\left(\frac{V_1}{\omega_0}\right)^2 \text{ [N}\cdot\text{m/rad]} \quad \cdots\cdots (22)$$

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

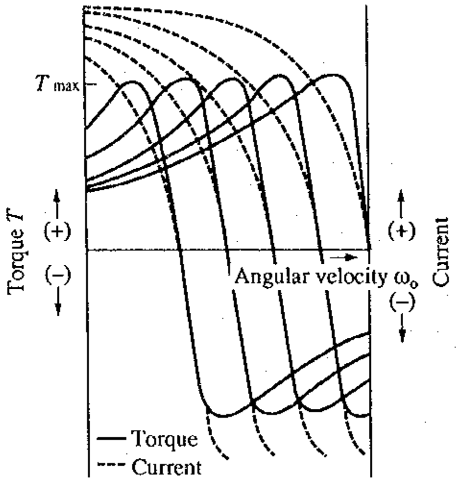
$$\phi = \frac{V_1}{K_v \omega_0} = K_1 I_0 \ [W_b] \qquad (23)$$

where

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

When control (V/f constant control) is performed so that the ratio of voltage V_1 to frequency ω_0 in the above characteristic equation is constant, the motor torque, current I_0, I_2 and magnetic flux ϕ become constant at constant slip frequency $S\omega_0$. Figure 8.19 shows torque-speed characteristic curve at this point and the maximum torque T_{max} becomes constant against speed ω_0.

Figure 8.19 Torque-Speed Characteristics of V/f Constant Control



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

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

As problems raised from introduction of an inverter, the following can be named: troubles by harmonic waves, troubles by speed control of general purpose motors, and troubles by operation switching between direct and inverter operations. Table 8.8 shows troubles and measures accompanied with the introduction of an inverter.

Table 8.8 Troubles and Measures Accompanied with Introduction of Inverter

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

8.2.4 Other Countermeasures

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

8.2.5 Calculation Example for Rotating Speed Control

As an example of actual calculation, Table 8.9 shows a comparison between the power-saving effect achieved by discharge valve control and that achieved by primary frequency control when the present discharge volume is reduced from 9.3 m^3/min to 4.2 m^3/min for a pump of which the discharge volume is 10.3 m^3/min, the pump head is 62 m, and the motor output is 230 kW

Table 8.9 Comparative Example for Calculating Energy Conservation Effects

Method	Discharge volume [m^3/min]	Pump head [m]	Rotating speed [rpm]	Pump efficiency [%]	Shaft power [kW]	Power consumption [kW]	Power saving [kW]
Actual state	9.3	67	1,485	61	167	175	–
Discharge valve control	4.2	75	1,485	39	132	139	Δ 36
Primary frequency control	4.2	42	1,114	47	61	68	Δ107

In this example, the effect of electricity conservation by primary frequency control is three times larger than that by discharge valve control although reduction in the discharge volume is same. Thus, rotating speed control is superior in terms of the electricity conservation effect, but the investment cost for discharge valve control is much smaller. Based on the investment effect derived from these, the best electricity conservation method should be selected.

9. ENERGY CONSERVATION IN TRANSFORMERS

9 TRANSFORMERS

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

(1) Transformer efficiency

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

(3) Selection of transformer taps

9.1 Selection of Transformers

9.1.1 Transformer efficiency is expressed by the following equation:

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

Where

η : Efficiency (%)
n : Load factor
p : Rated capacity (kVA)
$\cos\theta$: Power factor
W_i : Iron loss
W_c : Copper loss

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

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

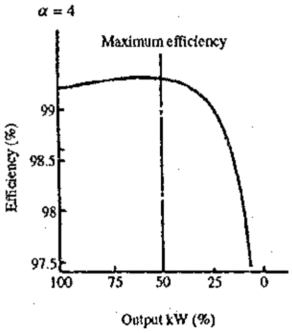
The loss ratio is generally 2 to 5 as shown in Table 9.1. However, it may exceed 10 in the energy conservation type transformers as described later.

Table 9.1 Efficiency of 3 Phase High Voltage Medium Capacity Transformer

Primary 6.6/3.3 kV, Secondary 400/200 V

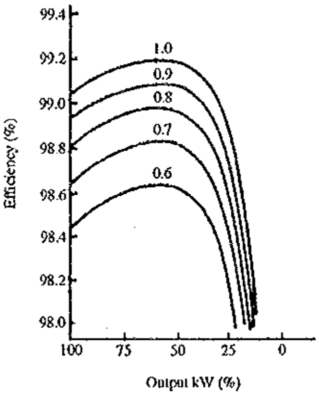
Rated capacity kVA	Company A				Company B			
	Efficiency (%)	Iron loss (kW)	Copper loss (kW)	Loss ratio	Efficiency (%)	Iron loss (kW)	Copper loss (kW)	Loss ratio
300	98.2	0.9	4.6	5.1	97.9	2.2	4.2	1.9
500	98.27	1.3	7.5	5.8	98.1	2.7	7.0	2.6
750	98.36	2.0	10.5	5.3	98.2	3.2	10.6	3.3
1,000	98.52	2.5	12.5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

Figure 9.1 Transformer Efficiency (Example)



Also, the transformer efficiency varies with the load power factor in equation (1) and lowering the power factor reduces the efficiency. This example is shown in Figure 9.2.

Figure 9.2 Relation between Power Factor and Efficiency (Example)



Note: Figure indicates power factor.

The difference of efficiency due to the transformer capacity is shown in Figure 9.3 and Figure 9.4.

Figure 9.3 Example of Efficiency of 50 Hz Single Oil Immersed Transformer

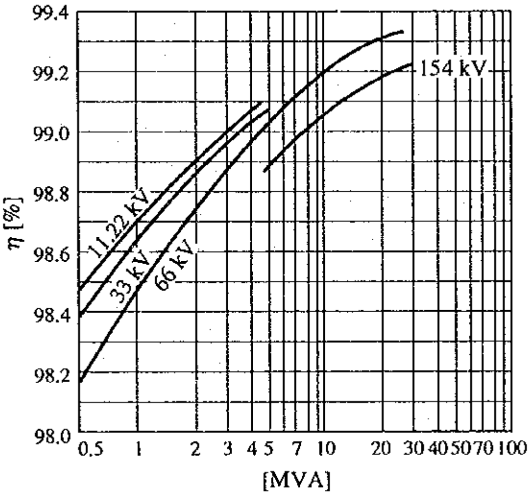
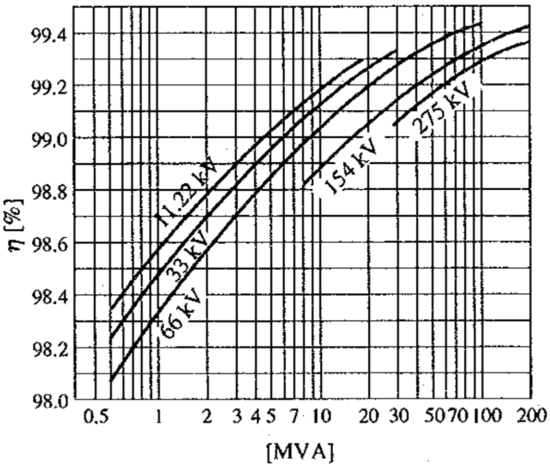


Figure 9.4 Example of Efficiency of 50 Hz 3 Phase Oil Immersed Transformer



9.1.2 All day efficiency of transformers

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

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

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.

9.1.3 Energy Conservation Type Transformers

(1) Low-loss type magnetic steel plate transformer

This type of transformer uses a flat rolled magnetic steel plate that has a smaller iron loss than the conventional flat rolled silicon steel plate and whose magnetic field is further sub-divided by laser irradiation, and makes the current density still lower in order to reduce the load loss. Table 9.2 shows comparisons with a conventional general-purpose transformer with respect to losses, etc. The magnetic steel type transformer is competitive with amorphous iron core transformer in terms of the total of the fixed and operating costs unless the load factor is especially low, and thus it is employed as a medium or larger transformer. According to recent research result, a magnetic steel plate transformers with iron loss of nearly the same level as amorphous magnetic body has been developed, and thus its application for industrial use is expected.

Table 9.2 Comparisons between a Low Loss Type Transformer and a General-purpose Transformer in Various Specifications (Three-phase, 60 Hz, 500 kVA)

Item	Unit	Low-loss type transformer	General-purpose transformer
No-load loss	W	750	1,090
Load loss	W	5,540	7,000
Efficiency	%	98.75	98.40
Outside dimensions	mm	1,250 × 800 × 1,360	1,280 × 810 × 1,365
Oil amount	L	360	290
Weight	kg	1,540	1,210

(2) Amorphous iron core transformer

Performance tests on the amorphous magnetic material were conducted in 1980's with regard to its possible use as the iron core for power transformers. As a result, it was verified that the amorphous magnetic body has a reliability equivalent to that of a conventional silicon steel plate transformer. Following are the characteristics of the amorphous magnetic body when it is to be used as the iron core for transformers.

(Advantages)

- Small iron loss: Approximately one-sixth that of a silicon steel plate transformer
- Small no-load current
- High permeability
- Superior in high-frequency characteristics

(Disadvantages)

- Low in saturation magnetic flux density
- Poor space factor: Approximately one-tenth that of a silicon steel plate
- Annealing conditions are complicated and also annealing makes it fragile.

These characteristics make the material and processing costs higher as compared with those of the silicon steel plate transformer in spite of smaller iron loss, thus limiting the manufacture of amorphous transformers only as small-size mass production type transformers.

Table 9.3 shows comparisons in losses with a silicon steel plate transformer under the same specifications (single-phase, 50 Hz, 30 kVA, and 415 V/210 - 105 V). Figure 9.5 and Figure 9.6 show a relationship between load factor and loss/efficiency for each of the two types of transformers, respectively.

Table 9.3 Comparison of Losses due to Iron Core Material

	Amorphous iron core transformer	Silicon steel plate iron core transformer
No-load loss (W)	21	124
Load loss (W)	427	440
Total loss (W)	448	564

Figure 9.5 Load Factor and Loss/Efficiency of Amorphous Iron Core Transformer

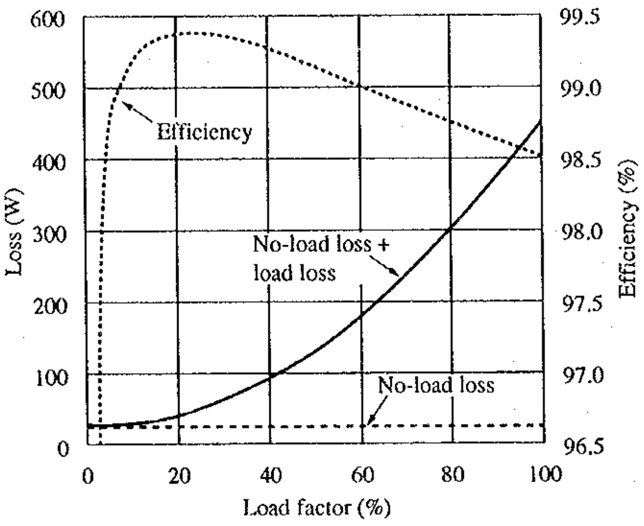
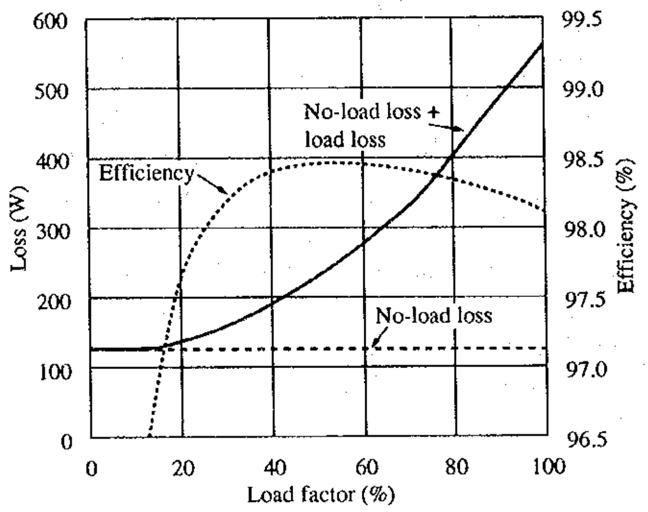


Figure 9.6 Load Factor and Loss/Efficiency of a Silicon Steel Plate Transformer



9.2 Efficient Operation of Transformers

9.2.1 Stopping of light-load transformers

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

(Example) When there are two 500 kVA transformers

In the case where each transformer has a load factor of 40 % as shown in Figure 9.7, the merit when one transformer is stopped is calculated. The transformer's characteristics are presumed to be of company A, specified in Table 9.1.

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

Iron loss = 1.3 (kW)

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

Hence,

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

After stop of transformer No. 1,

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

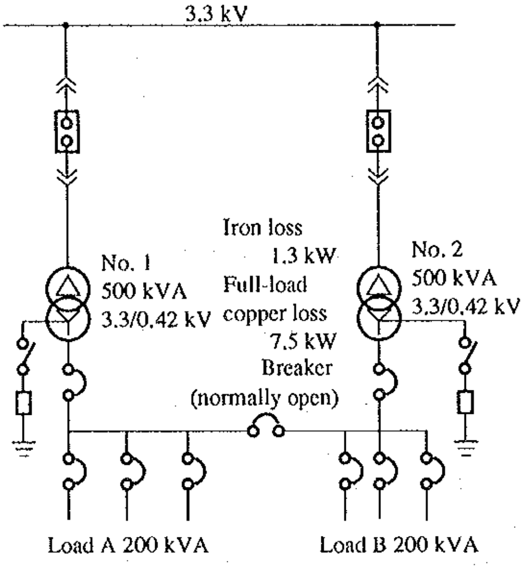
$$\text{Copper loss of transformer No.2} = \text{Full-load copper loss} \times \left(\frac{\text{Load factor}}{100}\right)^2$$

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

Total loss = 1.3 + 4.8 = 6.1 (kW)

Stopping one transformer increases the loss by 1.1 kW.

Figure 9.7 Method to Use Two 500 kVA Transformer



9.2.2 Control of the number of transformers

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

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

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

where

W_N: Overall loss (kW)
W_i : Iron loss of one transformer (kW)
W_c : Copper loss of one transformer (kW)
P_L : Load capacity (kVA)
N : Number of transformers
Q : Capacity of one transformer (kVA)

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

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

When $W_n > W_{N-1}$, (N−1) units operation is better for loss decreasing. Therefore, the following equation is obtained.

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

where

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

α: Loss ratio

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

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

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.

9.2.3 Stopping of transformers at night and on holidays

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

9.3 Selection of Transformer Taps

Low-voltage transformers or main power lines have many loads and it is not easy to supply the voltage close to the rating of each load. However, it is important to optimize the transformer taps and endeavour to get as close as possible.

Observing how motors are being operated in factories, full-load operations are few and 50% to 80% of the load is generally seen. Relation between voltage fluctuation and load state of an induction motor is as shown in Table 9.4 and Table 9.5. When all loads for the transformer are motors, it is desirable to select the taps in the light of these.

Table 9.4 Effect of Voltage Fluctuation on Induction Motor

	Voltage fluctuation	
	90 % Voltage	110 % Voltage
Starting torque, Maximum torque	–19 %	+21 %
Synchronous speed	Remain unchanged	Remain unchanged
% Slip	+23 %	–17 %
Full-load speed	–1.5 %	+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 9.5 Relation between Voltage Fluctuation and Loading State of Induction Motor

		Voltage fluctuation	
		90 % Voltage	110 % Voltage
Efficiency	Full load	–2 %	Slightly increased
	3/4 Load	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 %

10. ENERGY CONSERVATION IN FACTORY HEATING SYSTEM

10. FACTORY HEATING SYSTEM

10.1 Air-conditioning for a Large-space Factory

A large space is generally interpreted as a room of large volume. In terms of air-conditioning technology, however, it is often a high ceiling rather than large volume that is a matter of concern. Therefore, a large space here is interpreted as "a building space with a high ceiling and large volume". In this regard, 4 or 5 meters or higher is used as a guide for a ceiling height, while 2,000 m^3 or more is considered for the volume.

Many modern factories have a large space due to the possible factors described below.

- An increase in production scale (mass production). (Ex.: Spinning factory)
- Continuous and automatic production processes. (Ex.: Automobile assembly factory)
- Upsized production equipment (Ex.: Large-scale machine assembly factory and aircraft factory)
- Increase in loads of various kinds, such as generation of heat and dust, generally involved in production processes (Ex.: Casting factory)

A large space, from the standpoint of air-conditioning, is characterized by the tendency of easily generating a temperature inbalance in the upper and lower parts of the room.

10.1.1 Characteristics of Production Equipment

This section describes the characteristics of air-conditioning in terms of process and equipment using some of the typical large-space machine factories as examples.

(1) Casting, forging and quenching processes

In the factory there are metal melting furnaces, finishing machines used to remove burrs adhered on castings, sieves used for the sand to be recycled, etc. A large amount of dust and heat is produced in the factory as a whole, thus easily deteriorating the working environment. While ventilation and local ventilation are generally used to improve the working environment, spot cooling, as well as local exhaust and blockage of radiation heat by a screening plate, is often performed for workers near melting, casting and quenching furnaces where smoke and heat occur.

In either case, the main purpose of air-conditioning here is to improve the operating environment. Some of the factories of late are made windowless to prevent pollution and to improve the working environment, so that air conditioning is available at the main section.

(2) Machining

In machining factories, forming, cutting, machining, grinding and other similar process for metal are performed by using machines. There are many large-scale factories with large spaces, such as automobile parts machining factories. These factories are equipped with many machine tools in a large space, which involve heat generation, evaporation of cutting lubricant, mist generation and dust generation during cutting and grinding. While these factories generally require ventilation and local ventilation, air-conditioning equipment is often installed in order to improve the working environment. Also in some cases, working environment requirements have to be ensured for high-grade machining, such as NC (numerically controlled) machine tools and FMS (flexible manufacturing systems). In full-scale auto-parts shops, automation has led to the reduction of workers, thus raising concern about how to provide efficient air-conditioning for dispersed workers and how to cope with a change in the work position associated with the line change.

For high-precision machining of 1 μm or less, the temperature needs to be kept at a constant level in order to maintain accuracy. Additionally, a proper humidity should be maintained to prevent the generation of rust and corrosion due to steam condensation and generation of static electricity. Since high-precision machine factories require a constant temperature/humidity and dust-free environment, many of them are made windowless to allow thorough air-conditioning.

(3) Assembly

While assembly factories generally have less dust and mist than machining factories, fumes are produced during the electric welding or soldering process. In this case, local ventilation is required.

An assembly process reportedly accounts for 65 % to 70 % of the total number of man-hours needed for machining, thus constituting a principal part of a machining factory operation. Although an increasing number of assembly factories have reduced the number of workers through introduction of conveyor robots, assembly processes still require a larger number of workers than other processes.

In small-size electronic/electric device assembly shops, entire heating (i.e.heating the entire area concerned) is in many cases implemented for higher density of workers, production reasons, etc. Also, local heating is provided to heat only the area surrounding the assembly line where most of the workers are concentrated as in the case of an automobile assembly shop. Assembly processes of precision machines often require constant temperature/humidity condition and high degree of air cleanliness for production reasons.

(4) Painting

In a painting process, where a jet of paint is directed toward an object to be painted, ambient temperature/humidity conditions greatly affect the finishing performance and productivity. In many cases, therefore, air-conditioning has to be carried out strictly. Since the painting process also involves the evaporation of solvents and generation of dust due to paint particles, a suitable distribution of draft has to be devised to avoid possible safety and quality problems. The exhaust from the painting process is not allowed to be discharged as it is; it has to be processed through an air washer or by other similar means.

(5) Inspection/measurement

Generally, loads such as dust generation and exhaust gas occur less frequently except in the special cases of chassis, dynamo, etc. in automobile factories although inspection and measurement of products are conducted in various ways. However, there are industrial standard temperatures specified for the measurement which is affected by the ambient temperature/humidity factors. It is not economical to maintain a large space at a constant temperature/humidity in order to inspect and measure small products. In such cases, therefore, a constant-temperature oven or thermostatic chamber is often installed in order to ensure the required temperature/humidity conditions in the oven or chamber, while general heating is provided mainly for the workers in the remaining space.

10.1.2 Characteristics of Large-space Production Facilities and Planning for Air-conditioning Equipment

(1) Characteristics of large-space production facilities

The characteristics of large-space production facilities cannot be defined simply as they widely differ depending on the production process. Most common characteristics may be as follows:

a. Liable to generate temperature fluctuations in the upper and lower parts of the room

b. A large heat load produced from the internal part due to production equipment

c. A lower density of workers for the high ceiling conditions

d. Generating a large heat locally as well as hazardous gas and dust

e. Limitation in the arrangement of equipment due to moving cranes and hoist

f. Limitation in the arrangement of air outlets for air-conditioners due to large-size manufacturing equipment

g. Operation requiring a longer time: 24-hour operations in some cases

(2) Equipment planning for a large space

A temperature difference in the upper and lower parts in the room tends to occur easily when the ceiling is high and the internal heating is small as in the case of large-size vehicle assembly shops. In such situations, therefore, heating equipment planning is very important.

Heating equipment is roughly categorized into the warm-air heating type and radiation heating type. Generally, in warm-air heating for a space with a high ceiling, it is difficult to effectively heat only the occupied area because of a draft effect. Thus in many such cases, radiation heating is employed.

There are two types of radiation heating systems: the panel heater type which circulates steam or hot water through ducts or pipe, and infrared radiation heating which uses electricity or gas. Generally, the panel heater system using steam or hot water is employed for heating the entire area where there are many workers and the working positions are not fixed. On the other hand, infrared radiation heating by gas, electricity, etc. is locally used in some cases when working positions are fixed and strong heat radiation is required because of poor air-tightness of a building.

Also warm-air heating is employed when a building is adequately air-tight and the ceiling is comparatively low. Warm-air heating includes two types: central heating system using "air furnace + duct" and individual heating system using unit heaters. The central system is used when outside air needs to be introduced and space for a duct is available. The unit heater system is used when duct space is unavailable.

Entire heating is recommended even for large-space machining and assembly factories where the heat generated by the equipment accounts for 20 % or less of the total load or the workers' positions are not specifically determined and thus a line change takes place frequently. Area air-conditioning or spot air-conditioning is used when the equipment generates a large amount of heat and the workers' positions are relatively fixed. It should be noted, however, that spot heating is unsuitable for heating because of the draft problem.

10.1.3 Factory Heating

(1) Type and overview of heating equipment

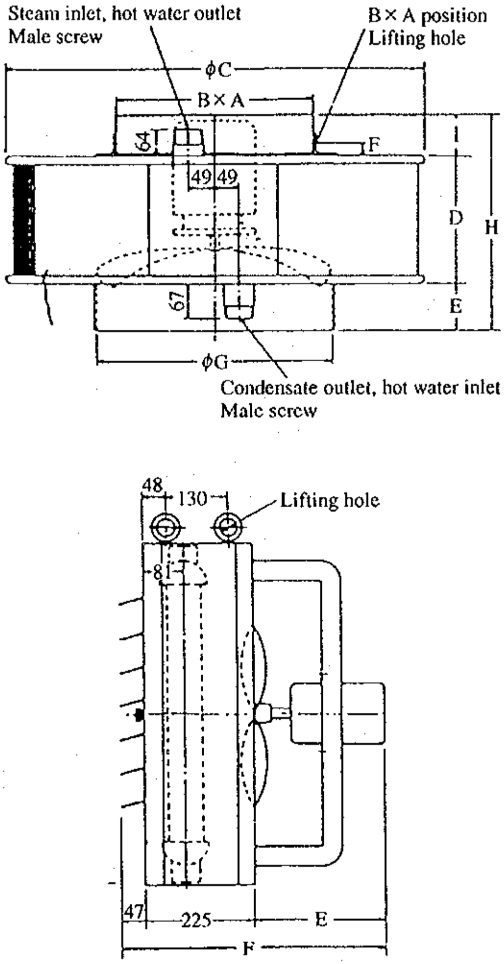
Table 10.1 shows the heating equipment generally used for large-space production facilities.

Table 10.1 Types of Factory Heating System

- Factory heating
  - Convection type heating
    - Unit heater ①
    - Warm-air heating ②
  - Radiation type heating
    - Panel heating ③
    - Infrared heating ④

Among the above, heating by unit heater ① is performed by setting up small-size units made up of a fan, coil and outlet combination as shown in Figure 10.1 at various locations.

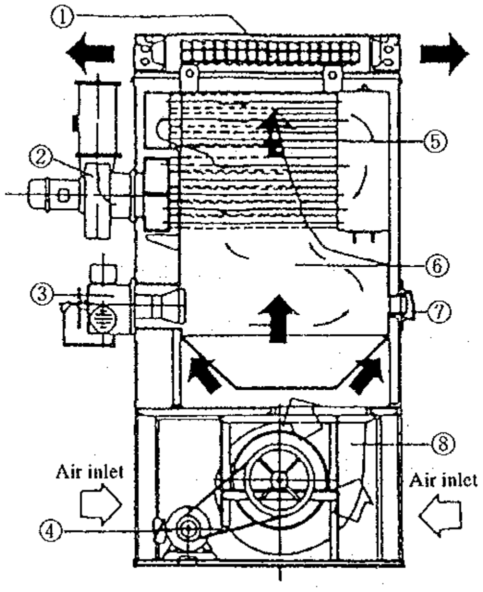
Figure 10.1 Unit Heater



The heat source in this figure is steam. Recently, however, ceiling-mounted small-size gas- or oil-fired "air furnaces" are also available, which may generically be referred to as "unit heaters".

In warm-air heating ②, warm air, generated by a gas- or oil-fired air furnace as shown in Figure 10.2 or generated by a steam coil/hot water coil/electric heater, is distributed to the fan and the duct.

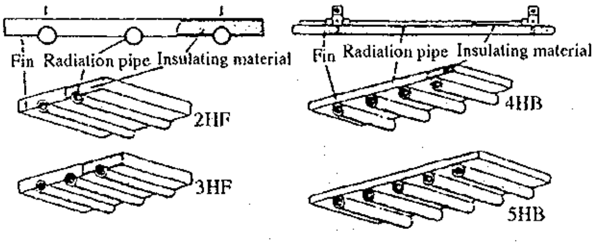
Figure 10.2 Air Furnace



①Warm-air outlet ②Exhaust gas fan ③Oil burner
④Motor for a blower ⑤Heat exchanger ⑥Combustion chamber
⑦Peep hole ⑧Blower

In panel heating ③, steam or hot water is supplied to a panel of a large surface area as shown in Figure 10.3 in order to provide heating through high-temperature (100 to 200 °C) heat radiation. The panel is usually installed on the ceiling.

Figure 10.3 Panel Heater



(a) Fin type ceiling-mounted panel heater
(b) Reflector type ceiling-mounted panel heater

In infrared heating ④, an infrared heater using gas or electricity as shown in Figure 10.4 and Figure 10.5 is installed to provide warm air by means of far infrared rays of 3 µmm to 400 µmm.

Figure 10.4 Gas Infrared Heater

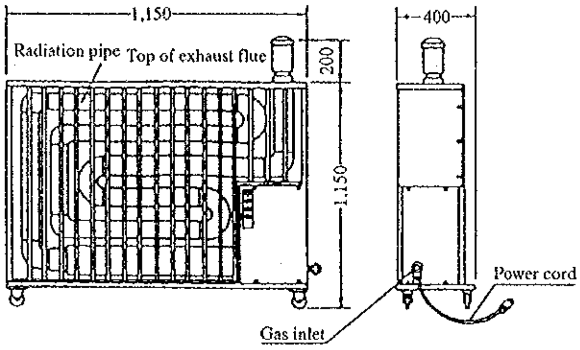
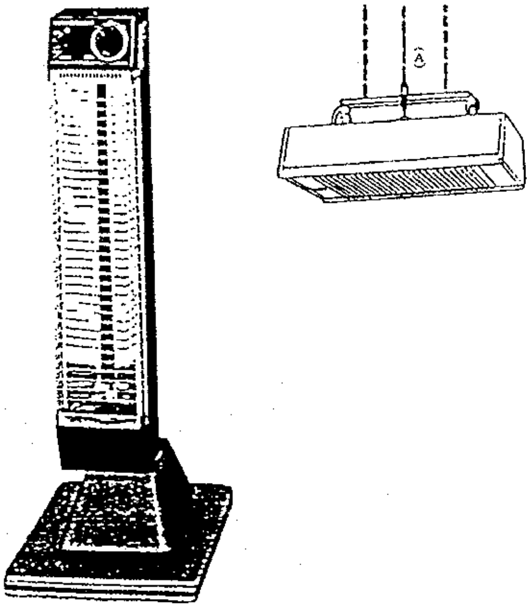


Figure 10.5 Air Infrared Heater



(2) Selection of a heating system

Various phenomena which do not occur in general office buildings are encountered in factory heating due to factory-specific characteristics. Such conditions sometimes put excessive load on equipment, or fail to maintain a proper environment. Generally the heating system is categorized as shown in Table 10.2.

Table 10.2 Types of Heating System

	Types	Heating sources	Energy sources	Radiator	Remarks
Centralized system	Hot water heating	Boiler Heat pump Regional heating	Fuel oil, kerosene, gas, electricity, coal, outside air, recovered waste heat	Radiator Convector Fan/coil/unit Tube radiator	Features ① The heat radiation area is larger than in steam heating ② The heat capacity of equipment is large and preheating takes a long time.
	Steam heating	Boiler	Fuel oil, kerosene, gas, electricity, coal	Radiator Convector	In addition to the characteristics opposite to those of hot water heating, this type of heating involves the following problems: ① Occurrence of water hammer ② Poor controllability
	Warm-air heating	Boiler Air furnace	Fuel oil, kerosene, gas, electricity	Heating coil	① Controllable air current ② Fresh air supply available. ③ The preheating time required for equipment is extremely short. ④ Increase in blower power.
		Heat pump Integrated heat recovery unit	Outside air, recovered waste heat	Heating coil	
	Radiation heating (Low temperature system)	Boiler (Hot water)	Fuel oil, kerosene, gas, electricity	Floor panel Ceiling panel Wall panel Warm-air floor heating	① High degree of comfort ② Even distribution of temperature ③ Large fuel savings (Low room temperatures allowed) ④ High equipment cost ⑤ Difficult to repair ⑥ The capacity cannot be adjusted for rapid changes.
Decentralized system	Forced convection unit	Unit ventilator	Electricity, gas, oil	Unit ventilator	Ceiling mounting The following types of mounting are used for the equipment for local heating.
	Natural convection unit	Unit heater	Electricity	Unit heater Baseboard heater	Wall mounting Floor mounting
	Radiation heating (High temperature system)	Combuster	Electricity, gas, oil	Radiation-convection panel	Local heating is available and there is no heat loss during transportation through heat medium.
		Electric resistor	Electricity, gas, oil	Heat radiation assisted by a reflector panel	
	Infrared heating	Incandescent lamp	Electricity		• The heat energy hardly heats the surrounding air and directly carries the heat to the human body, floor, machines, and other portions at which the infrared rays are directed. • Easily absorbed by water. (Thus, suitable for drying)
		Infrared lamp	Electricity		
		Gas infrared burner	Gas		

Heating equipment is largely categorized into centralized system and decentralized system. In centralized heating systems, hot-water heating is generally employed for small-scale buildings, while steam heating is recommended for large-scale buildings. Although it differs depending on the heating operation time, this judgment is based on the factors, that is, a large preheating load at the start of operation in the morning when hot-water heating is performed in large-scale buildings and the occurrence of accidents which can occur when the water in the pipe gets frozen. Thus, in situations free of these factors, hot-water heating may also be used. Steam heating is in many cases more economical in terms of equipment costs compared with the hot-water heating.

There are various types of warm-air heating: passing the steam or warm air generated by a boiler through a coil to heat the air, generating warm air by heat pumps, or system using air furnace, etc. In general, warm-air heating is relatively expensive compared with the foregoing steam heating in terms of equipment cost.

Radiation heating has various kinds of features as described in Table 10.2. The floor panel system serves as a very effective means for rooms with especially high ceiling. Radiation heating can offer adequate levels of comfort even though the air temperature in the room is low, and it is an economical system in terms of energy consumption. In general factories, however, it is in many cases practically difficult to install the panel heating (low temperature system) embedded in the floor slab because of the arrangement of equipment and machines and installation of an under-floor pit. Thus, high-temperature radiation heating (decentralized system) is often employed.

Unlike general systems for heating the surrounding air, infrared heating has the effect determined by the amount of radiation energy actually absorbed and also by raising the average radiation temperature (the average of the surface temperatures in the room). Although the surrounding air is somewhat heated by the convection from the object heated by radiation, the heating effect is mostly determined by the amount of radiation directly received. Therefore, a load calculation method different from the conventional one is required.

Considering such characteristics of the infrared heating system, it should be installed on the wall surface 4 to 5 m above the floor in high ceiling factories at an angle at which it can allow the maximum amount of direct radiation. This heating system can also be used when heating is needed without heating the surrounding air at places directly connected to the outside (take-in/take-out places, entrance halls) or places exposed to the outside air. The infrared heating also serves as an effective means for warehouses of steel products where the temperature is raised in order to prevent the condensation of water content as a preventive means against the generation of rust.

(3) Key points in planning the heating equipment

a. Entire heating and local heating

Basically, entire heating is employed when there are a large number of workers and their work positions are not fixed, whereas in the reverse situation, local heating is used.

b. Radiation type heating and warm-air heating

Radiation heating is more effective when the ceiling of a building is high or when the air-tightness of the building is poor. In the reverse situation, the use of warm-air heating should be considered.

c. Warm-air heating system should preferably be employed when more outside air needs to be introduced because of a large amount of local exhaust, etc.

d. Dispersed installation of small-size gas- or oil-fired units should be avoided in terms of maintenance control and safety.

e. Gas- or oil-fired unit heaters are not advisable for factories where there exists corrosive steam from the standpoint of fire prevention in the event of leakage.

f. Since the radiation surface temperature of infrared heating equipment is as high as 900 to 2000 °C, the infrared heating equipment should not be used in facilities where there exist flammable gas or dust particles.

g. The environment of the area near the entrance/exit of a factory tends to become worse and therefore installation of an air curtain should be considered.

(4) Points to be noted in designing of heating equipment

a. Unit heater

It should be noted that the heating effect of unit heaters varies depending on the installation height even when the number of heating units is the same.

Unit heaters should be installed mainly on the outer wall surface and also arranged intensively at the area near the entrance/exit.

b. Warm-air heating

A nozzle is installed at a warm-air outlet when the outlet is to be installed at a high position. In this case, an induction type nozzle which effectively induces the warm air to the outlet is also available.

c. Panel heating

Radiation panels should be arranged mainly on the outer circumference in order to compensate for the heat loss from the outer wall surface. Also they should be installed at places where radiation will not be obstructed by the structures or machines.

d. Infrared heating

Since infrared heating is high in the radiation density and gives warm air directly to the human body, it is often employed in places exposed to the outside air such as the loading work area at a warehouse.

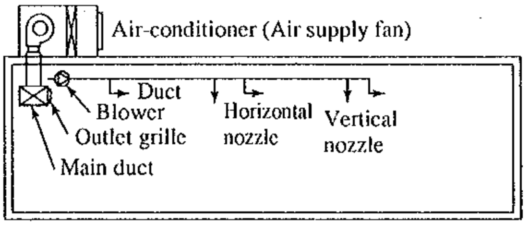
A stack should, if possible, be installed for gas-fired devices in order not to allow the exhaust gas to come into the room. When no stack is available, proper ventilation should be provided, while also care should be taken not to cause condensation of moisture inside the room.

e. Air jet system

An "air jet system" is available, which uses a special jet nozzle for air-conditioning/ ventilation of a large-space. This system is designed to transport the air not by a large duct but by utilizing the momentum (amount of motion) of the air sprayed out at high speed from the nozzle.

The configuration of this air jet system for air conditioning is as shown in Figure 10.6.

Figure 10.6 Configuration of Air Jet System



(5) Features of an air jet system and the problems

a. This system generates draft in a wide range in the low-velocity zone and thereby transports the air. Therefore, the system can effectively cope with the natural convection in a large space, thus allowing a comparatively favorable temperature distribution to be obtained during heating.

b. Since the induction effect by jet air is utilized, it cannot be used for the suction system in the space susceptible to contamination with oil mist.

c. This system is liable to be affected by a localized turbulent airflow because warm air is carried on a low-velocity air current.

d. Air jet nozzle

The amount of air jetted out from the air jet accounts for a few percent to ten and several percent and the jetting speed is often about 20 to 30 m/s.

Figure 10.7 shows an example of air jet nozzle.

Figure 10.7 Air Jet Nozzle