11.6.4 Resistance of Feed Pipe

Generally, resistance of feed pipes is calculated by Darcy's formula (formula (4)) when the feed pipe is rather short.

$$H_f = \lambda \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \quad\quad\quad\quad\quad\quad\quad\quad\quad\quad (4)$$

H_f : Resistance of feed pipe (m)
λ : Loss factor
L : Length of feed pipe (m)
D : Inside diameter of pipe (m)
v : Velocity in pipe (m/s)
g : Gravity acceleration 9.8 m/s^2

The value of λ is normally set as $\lambda = 0.02 + 1/2,000D$, which is multiplied by a modulus determined by the smoothness of the internal face of the feed pipe. For this calculation, the loss factor by Colebrook's experimental formula, as shown in Figure 11.39, will facilitate the procedure.
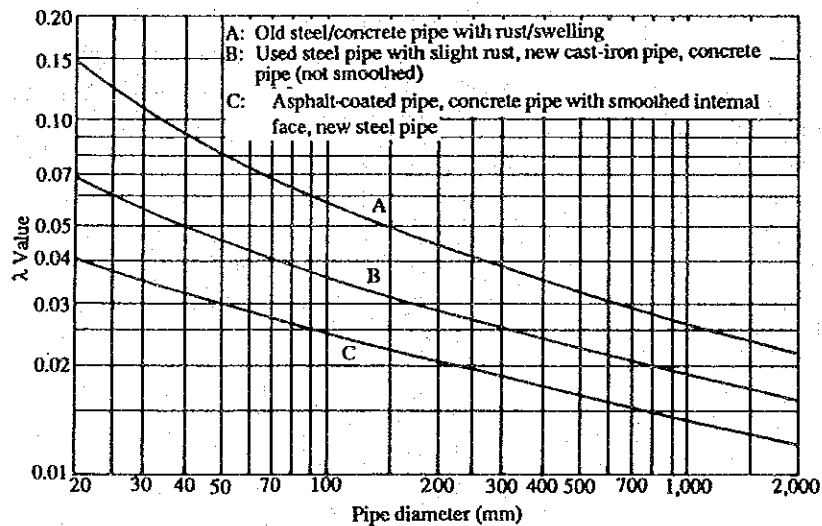

Figure 11.39 λ values by colebrook

11.6.5 Pump Performance when the Outside Diameter is Worked Upon

Volute pumps, like the frame number of motors, fabricate impellers according to the pump specification, within the ranges of a certain flow rate and head as a single barrel. Therefore, in cases where specifications are prepared in prospect of the future but have too much leeway performance for the time being as previously mentioned, it is economical to first fabricate the impeller according to a broken line in Figure 11.40, and then make a new one when the flow rate later becomes insufficient due to increase of line resistance.
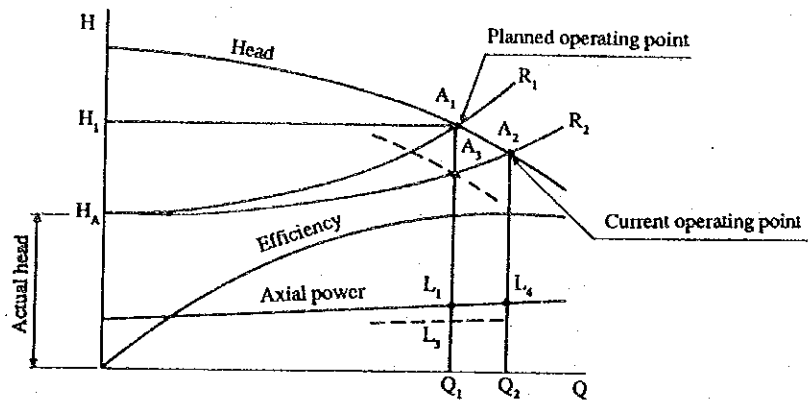
Figure 11.40 Pump performance and resistance curve

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

Change of performance when the outside diameter D_1 of the impeller of an operating pump is worked to D_2 as shown in Figure 11.41 is illustrated in Figure 11.42. When the outside diameter of the impeller is worked from D_1 to D_2 in Figure 11.41, the flow rate, head and power are obtained by equations (5), (6)and (7), respectively.
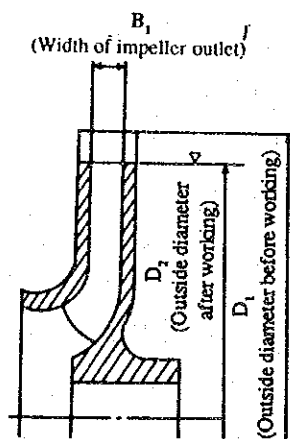

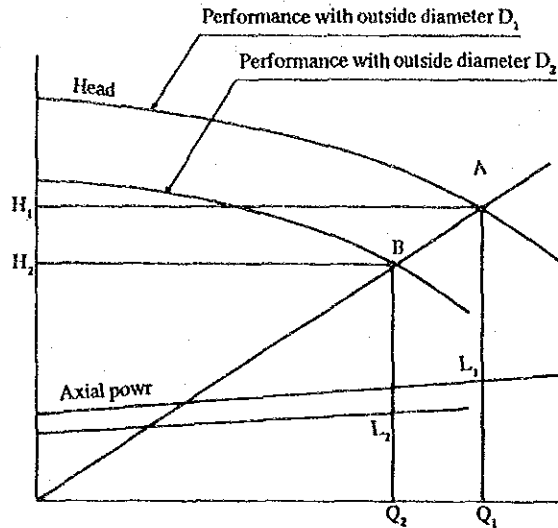**Figure 11.41 Working on the outside diameter of impeller**

Figure 11.42 Change of performance by working on impeller diameter

$$\frac{Q_2}{Q_1} = \left(\frac{D_2}{D_1}\right)^2 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (5)$$

$$\frac{H_2}{H_1} = \left(\frac{D_2}{D_1}\right)^2 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (6)$$

$$\frac{L_2}{L_1} = \left(\frac{D_2}{D_1}\right)^4 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (7)$$

Connect an optional point A, on the Q-H curve of outside diameter D1, to the origin with a line, and obtain a point B from $H_2 = (D_2/D_1)^2 \times H_1$, or $Q_2 = (D_2/D_1)^2 \times Q_1$. Determine several points for the performance of outside diameter D_2 in the same manner, and prepare the Q-H curve of outside diameter D_2 by connecting these points. Likewise, calculate the power from $L_2 = (D_2/D_1)^4 \times L_1$, and obtain a point L_2 on the vertical line BQ_2. Determine several points in the same manner, and prepare the power curve by connecting these points.

* Points to be noted on working the diameter of the impeller

1) As the impeller is balanced during fabrication, it should be re-balanced after worked.

2) For cases when the work ratio of the outside diameter of the impeller, $(D_1 - D_2)/D_1 \times 100\%$, exceeds 20%, the equations (5), (6) and (7) will sometimes not apply, not enabling pumping.

3) Note that working on the outside diameter is not necessarily available depending on the materials of the impeller, such as pressed stainless steel.

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11.6.6 Rotating speed control of pump

Rotating speed control may be adopted for purposes as process control, flow rate control of pumps, or energy conservation. As methods of rotating speed control for pump drive motors, there are various methods as described in 11.3.2 (3). To perform rotating speed control, relations of the equations (8), (9), (10) are established by supposing the rotating speed of the pump to be N_0 and N_1, the flow rate Q_0 and Q_1, the pump head H_0 and H_1, and the axial force L_0 and L_1:

$$\frac{Q_1}{Q_0} = \frac{N_1}{N_0} \qquad \cdots \cdots \cdots (8)$$

$$\frac{H_1}{H_0} = \left(\frac{N_1}{N_0}\right)^2 \qquad \cdots \cdots \cdots (9)$$

$$\frac{L_1}{L_0} = \left(\frac{N_1}{N_0}\right)^3 \qquad \cdots \cdots \cdots (10)$$

Figure 11.43 shows changes in characteristics of the pump when the rotating speed is changed, where the flow rate, head and axial power are changed in a manner so that the expressions (8), (9) and (10) show their relations to the rotating speed. When the resistance curve of the feed pipe is R_3 in Figure 11.43, and when the rotating speed of the pump is changed from N_0 to N_1 and N_2, the operating point of the pump is changed from A_3 to B_3 and C_3, and the flow rate from Q_3 to Q_2 and Q_1.

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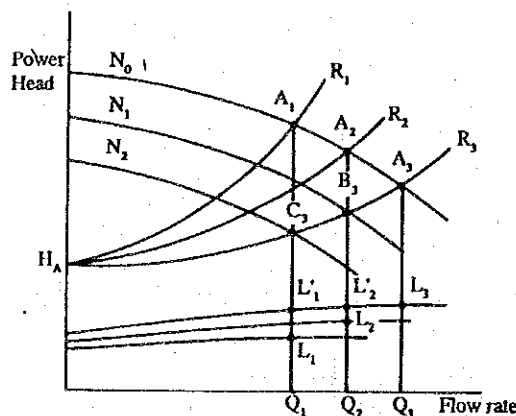

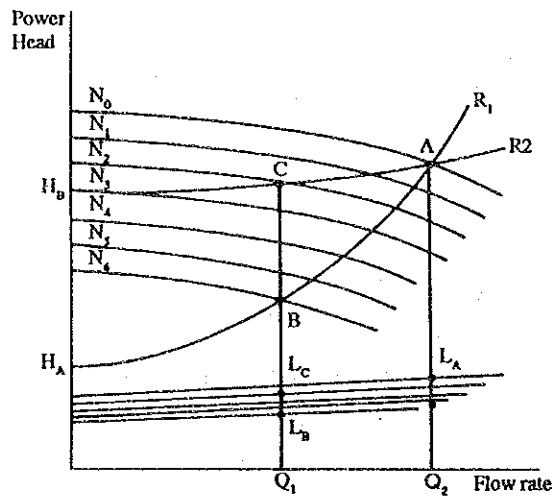**Figure 11.43 Changes of characteristics by change of rotational speed**

Figure 11.44 Difference of axial power by actual head power

Provided, however, it should be noted that, as the above description applies only when the actual head is small like H_A and the line resistance is large as shown in Figure 11.44, rotating speed would not result in a significant electric power conservation if made when the line resistance is small and the actual head is H_B.

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

Suppose that the pump is operating on the operating point A of Figure 11.45. The resistance curve can be determined from the actual head Ha and the total head H_0. On the resistance curve, the total head is H_2 and operating point C when the discharge is Q_2.

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

Supposing the quadratic curve to be,

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

the modulus a is obtained from the point C,

$$a = H_2/Q_2{}^2$$

When factors of Figure 11.45 are substituted,

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

Therefore, curve CB is expressed as,

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

The point of intersection of this curve with the pump performance curve at the rotating speed N_1 would be point B. From the figure, the discharge $Q_1 = 1.7 m^3/min$, total head $H_1 = 28.2$ m, and axial power $L_1 = 10.8$ kW.
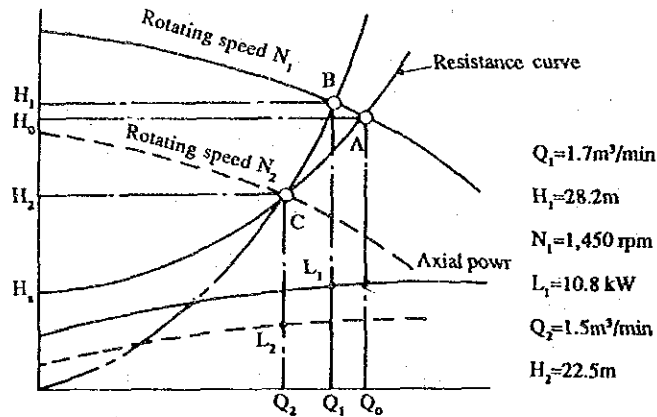
Figure 11.45 Change of pump performance by rotating speed

To determine a rotating speed of the pump for reaching the operating point C required by the facility, it is calculated by equation (9), as,

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

Here, the axial power is obtained from equation (10), as

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

As the axial power is 11.0 kW at point A of Figure 11.45, it is reduced to 7.7 kW by changing the rotating speed.

11.6.7 Pump unit control

Even if flow control is performed by operating the valve of a large-capacity pump when the required volume of water varies seasonally or by time, or by rotating speed control, the max. efficiency point of the pump is in a zone with large flow rate, and the efficiency is low in zones with small flow rates. In such a case as shown in Figure 11.46, the number of pumps may be made multiple to perform parallel operation for cases requiring a large volume of water and use only one pump in cases requiring a small volume of water, so that operation can always be performed in zones with high pump efficiency, resulting in electric power conservation. However, it is necessary to make sure of the operating point in order to avoid overload of motor.
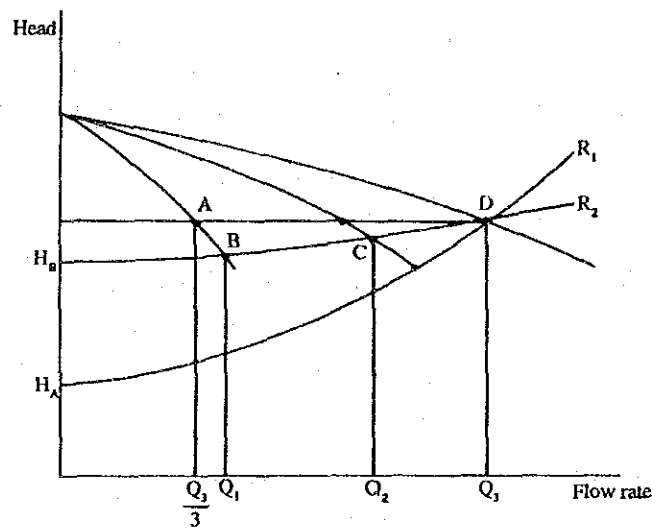
Figure 11.46 Parallel operation characteristics of pump

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

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

11.6.8 Electric power conservation measures of pump

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

The electric power saving flow of pumps is shown in Figure 11.47.

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

(1) Reduction of required flow rate

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

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

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

Determining objective facility — Listing of pump facilities

Determining procedure
(Generally select pumps of larger capacities)

Field survey

① Possibility of varying the flow rate in
   correspondence with the operational pattern
② Degree of valve throttling
   (Whether the working flow rate and pressure are too low
   for the pump specification)

Collection of specific data
Actually required flow rate and pressure
Actually required flow rate pattern

Study of possible measures — Comparison of possible systems (investment cost, running cost, restrictive conditions), and determining of measure

Execution of the measure
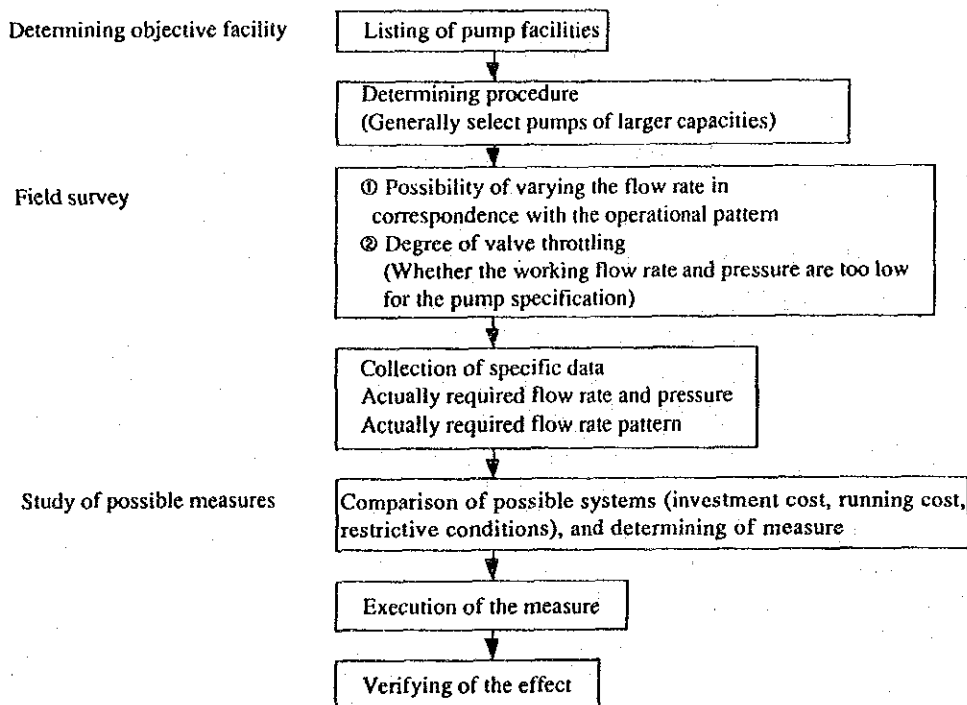
Verifying of the effect

Figure 11.47 Electric power conservation flow of pumps

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

(2) Reduction of pipe resistance

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

i) Friction loss of direct pipe

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

ii) Loss at piping elements

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

iii) Loss at valves

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

(3) Efficient flow rate control

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

i) Intermittent operation

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

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

ii) Pump unit control

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

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

iii) Rotating speed control

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

iv) Replacing pumps

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

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

v) Replacing the impeller

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

11.7 Lighting

11.7.1 Factory Lighting

(1) Purpose of factory lighting

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

A) Improved operation efficiency

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

B) Improved operation safety

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

C) Thorough shop management

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

D) Improved operator's morale

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

(2) Good factory lighting

Good factory lighting has the following factors:

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

For proper illuminance, the necessary value is determined by content of the operation, size of the object and color, etc. Values specified in Table 11.26 are recommended as illuminance standard values in Japan. For the aged, these standard values should be somewhat increased.

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

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Table 11.26 Illumination Standard

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

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

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

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

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

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

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11.7.2 Energy Conservation for Lighting

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

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

Where
E : Illuminance (lx)
A : Area of room (m²)
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 U 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),

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

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.

11.7.3 Concrete Measure for Energy Conservation
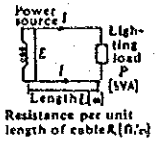
(1) Reduce the lighting time

Concrete measures are:
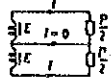
a. Lights-out while unnecessary, including noon recess

b. Individual lights-out near windows

c. Provide many switches for individual lights-out.

d. Lights-out in quiet areas

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

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

(2) Reduce the distribution line loss

Since the distribution line loss greatly varies with the distribution system (See Table 11.27), it is desirable to compare and study well for determination when establishing new equipment. Besides, to increase voltage level in the distribution line and to improve of power factor, etc. must be studied.

Table 11.27 Comparison of loss by wiring system

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

NOTE: Each cable size is same.

(3) Keep the illuminance proper

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

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

(4) Use high-efficient luminaires

Luminaires here mean stabilizers, lamps and light reflectors. Table 11.28 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.

Table 11.29 and Table 11.30 show features and general applications of various lamps.

Table 11.28 Example of stabilizer characteristic (for 400W mercury lamp)

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

Table 11.29 Special features and applications of various lamps

Class of lamps	Special features	Scope of size (W)	Main performance of standard quality				Applications
			Efficiency (lm/w)	Color temperature (K)	Color rendering index (Ra)	Life	
Incandescent lamp	• Stable light color • Possible to light as-is. • Instantaneous lighting high luminance	Several W ~ Several kW	100 W				Residence, store, office
			15	2,850	100	1,000	
Tungsten halogen lamp	Small-size, high efficiency and long life lamp	Several 10 W ~ Several kW	For general use 500 W				For floodlamp, for automobiles, for projection, for photography, for copying machine, studio
			21	3,000	100	2,000	
Fluorescent lamp	• High efficiency and long life • A wide variety of light colors • Little glare	4 ~ 220 W	White 40 W				Residence, office, store
			82	4,500	69	10,000	
Mercury lamp	High efficiency, long life, high luminance lamp	40 ~ 2 kW	400 W				For floodlamp (baseball ground, golf course)
			51	5,800	23	12,000	
Fluorescent mercury lamp	Mercury lamp with luster improved	40 ~ 1 kW	400 W				Roads, factory, street lighting, arcade lighting
			56	4,100	44	12,000	
Choreless mercury lamp	Mercury lamp requiring no stabilizer	160, 250, 500 W	500 W				For works, stores
			27	3,000	42	6,000	
Halide lamp	Higher efficiency and lustrous lamp than mercury lamp	250 ~ 1 kW	400 W				Gymnasium, factory, shopping street, open space, park
			80	4,500	65	9,000	
High lustrous halide lamp	High lustrous, high luminous lamp	250 ~ 400 W	400 W				Gymnasium, lobby, hall
			50	5,000	92	6,000	
Low pressure sodium lamp	Highest efficiency, yellow, luminous lamp	35 ~ 180 W	180 W				Tunnel, high-way, switch-yard
			175	1,740	44	9,000	
High pressure sodium lamp	Highest efficiency, luminous lamp for general lighting	150 ~ 1,000 W	360 W				Gymnasium, high-celling factory, warehouse, roads, open space
			120	2,100	29	12,000	

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

Table 11.30 Selection of lamps from standpoint of typical applications

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

(5) Improving utilization factor

Table 11.31 shows an example of the utilization factor table. Room index RI in this table is calculated in the following equation:

Table 11.31 Example of utilization factor

Ceiling	80%									50%								
Wall	60%			30%			10%			60%			30%			10%		
Floor surface	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%	40%	20%	10%
Room index	Utilization factor																	
0.60	45	.42	.40	.31	.30	.30	.26	.25	.25	.41	.39	.38	.30	.29	.29	.25	.25	.25
0.80	.56	.51	.49	.41	.39	.38	.35	.34	.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	.28	.75	.72	.78	.72	.70
5.00	1.09	.88	.82	.96	3.8	.77	.91	.79	.78	.91	.82	.79	.88	.78	.78	.82	.76	.73
10.00	1.13	.93	.86	1.08	.90	.84	1.05	.89	.82	.97	.87	.83	.94	.85	.81	.92	.84	.80

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

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

Where
W : Width of room (m)
L : Depth of room (m)
H : Height of light source from the working plane (m)

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

(6) Improving maintenance factor

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.

Fig. 11.48 and Fig. 11.49 show the lowering tendency of the luminous flux of lamp itself and the lowered luminous flux when dirt accumulates on luminaires respectively.
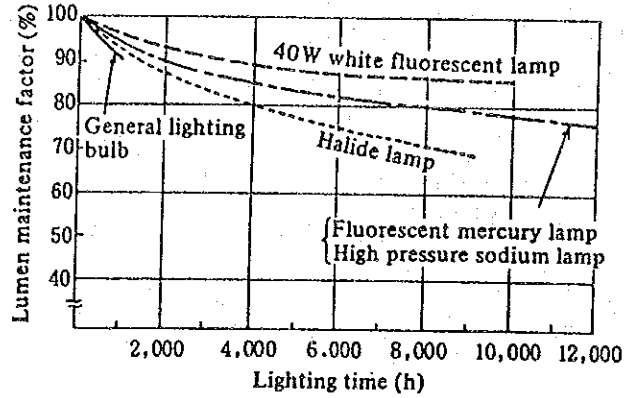

Figure 11.48 Lumen maintenance characteristic of various light sources
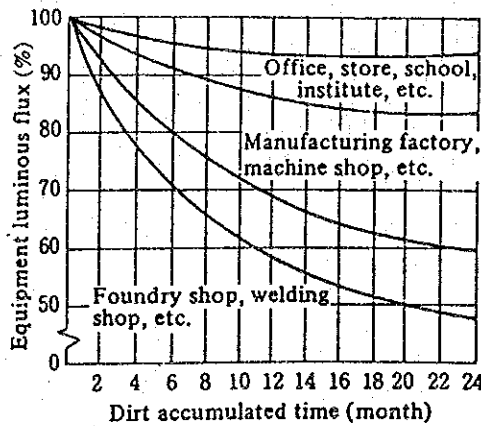

Figure 11.49 Lowered lumen when dirt accumulated on lamp and lighting equipment

(7) Others

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

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

11.8 Electric Heating Systems

11.8.1 Types of Electric Heating Systems

The electric heating systems are classified as shown in Table 11.32. Their common features are as stated below.

a. High temperature

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

b. High heating efficiency

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

c. Quick heating

It is possible to change the direct electric power to heat in an object heated and conduct quick heating by raising the electric power density.

d. Easy temperature control

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

e. Easy atmospheric control

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

Table 11.32 Type and main applications of electric heating systems

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

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11.8.2 Energy conservation for heating systems

(1) Conversion of the heat source

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

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

(2) Correction of the capacity of equipment

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

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

(3) Reinforced heat insulation

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

11.9 Heat Pump

11.9.1 Heat pump system

Electricity is not directly converted to heat but used as power source to convey heat in a heat pump system. Therefore, a heat source is always required.

Basically heat flows from a higher temperature place to a lower temperature place. The same is true for water; water flows from a higher level to a lower level. However, using a pump, water is allowed to flow from a lower level to a higher level. Because of functioning as a pump, a term "heat pump" was coined.

As shown in Figure 11.50, a vapor compression heat pump system needs a compressor, condensor, evaporator and expansion valve. The heat pump system performs heating operation by warming air or water through heat reaction in the condensor. On the other hand, by switching refrigerant circuits, the system can perform cooling operation by cooling air or water using cooling reaction in the evaporator. That is, the system can perform heating and cooling by alternating the heat radiation side and heat absorbing side.
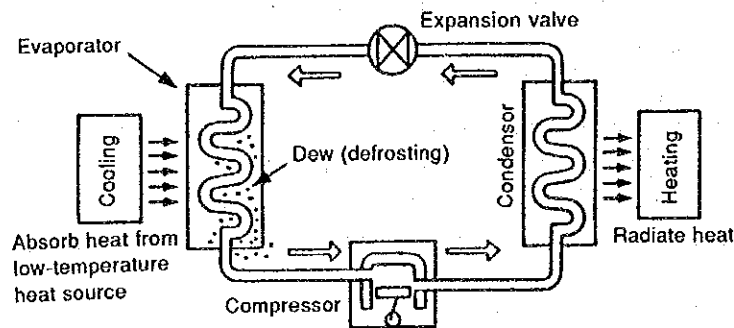

Figure 11.50 Configuration of heat pump system

An absorption heat pump is driven by heat energy.

The mechanism is the same as in the vapor compression type in that it utilizes evaporation and condensation of operation media. However, it uses absorption liquid in order to pressure low-pressure vapor, which then abosorbs vapor and is transferred to a high pressure portion. By adding heat externally, the operation media is vaporized again. The absorption liquid is recycled by returned back from high-pressure side to low-pressure side. Hence, the basic configuration of an absorption heat pump includes an absorber, liquid pump and generator, instead of a compressor.

11.9.2 Features of heat pump system

(1) Features of heat pump system

- One unit can perform heating and cooling.

- Energy efficiency is excellent.

- Ease of control and ease of operation can contribute to labor-saving.

- Because no combustion accompanies, it is highly safe and clean.

- Because it does not require any related facilities (chimney, oil reservoir, etc.) as in the case of boilers, installation space can be saved.

- Electricity is the only required energy as utility.

(2) Coefficient of performance (COP)

The figure of Coefficient of Performance, or COP, is used to express the relationship between heat output from the heat pump and power required for the heat pump.

$$\text{Coefficient of performance}(\varepsilon) \text{ (COP)} = \frac{\text{Heat output (kcal / h)}}{\text{Power required (kWh / h)} \times 860(\text{kcal / kWh})}$$

This expression is used to determine the efficiency of the heat pump and to obtain required power for necessary heat amount.

It may be meaningless if fuel consumption heat amount required to generate power for heat pump operation is larger than the direct combustion. In general the fuel consumption heat amount is 2,250 kcal for 1 kWh power generation.

Heat output of a heat pump with COP (ε) is 860 ε (kcal/kWh) for required power of 1 kWh. The figure 860 is heat output from 1 kWh electric heater.

To realize energy consrvation from a heat pump, at least the following equation needs to be satisfied.

860 ε > 2,250
ε > 2.62

According to the heat pump operation fact research report for industry use (March, 1988) offered by the Heat Pump Technology Center of Japan, the COPs of actually operating heat pumps range from 3 to 20, all exceeding 2.62. This means contribution to energy conservation.

11.9.3 Application range of heat pump

(1) Building airconditioning by regenerative heat pump

It is assumed that the load of air conditioning per day represents the area enclosed by thick line in Figure 11.51. The capacity of building air conditioning is conventionally determined based on the time period of maximum load (14:00 in the figure). In case of the regenerative system, however, about 50% of the air conditioning load is reserved at night and utilized in the daytime. Thereby, the facility capacity can be lessened and the facility can be operated constantly at high load areas. As a result, high efficiency can be established.
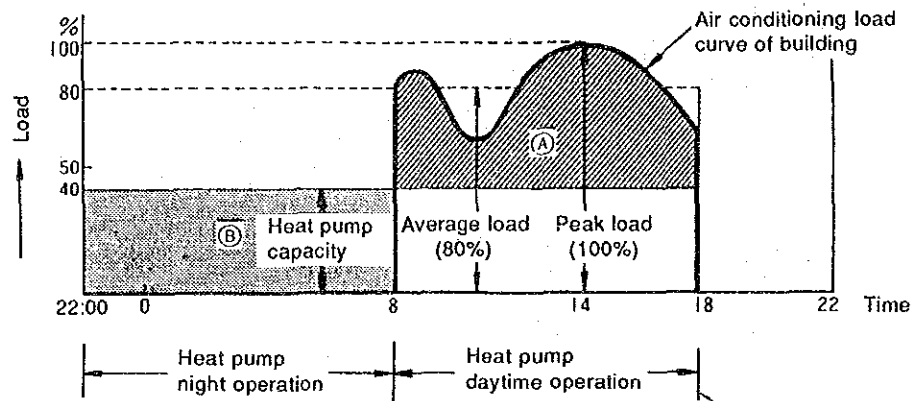

Figure 11.51 Cooling load characteristics curve

As shown in Figure 11.51, the heat pump is operated at night from 22:00 to 8:00 a.m. and warm and cool water equivalent to 50% (portion Ⓐ in the figure) of heat load is reserved in the heat storage tank. In the daytime, while the heat pump is operated, warm or cool water (portion Ⓑ in the figure) in the heat storage tank is pumped up to the air conditioner. Then warm or cool air is fed for air conditioning.

Thus, the heat pump capacity can be reduced and the facility cost becomes less. This brings high facility operation rate and efficient operation. In addition, the following advantages can be expected:

• As a result of reduction in facility capacity, the contract power amount can be graded down and then demand charge is reduced. Further, night-use incentive may reduce the operation cost.

• The heat pump can be installed on the rooftop, resulting in efficient use of building areas.

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- Automatization is easy for energy conservation.

- Combustion is not required; it is superior in safety and fireproof. It is also effective for environmental protection.

(2) District heating and cooling by a heat pump

Unutilized energy source in cities (urban waste heat) tends to increase year by year. This is because most of the energy supplied to cities is eventually wasted. The most of waste heat is of low temperature of less than 50 °C, generating sources of which are urban facilities such as subways, sewage treatment facilities, incinerators, power plants and substations, houses, factories, etc.

A number of advantages can be brought by using waste heat as heat source for the heat pump.

(2)-1 Advantages of district heating and cooling

- Air pollution by combustion facilities and thermal pollution by waste heat can be reduced, resulting in envinronmental improvement.

- Urban waste heat and heat in atmosphere, rivers and sea water can be recycled for the use of heat source to the heat pump. Thus, a system with high efficiency of energy conservation can be built. It will be also possible to effectively reduce the capacity of heat source facilities and lower the cost by introducing a heat storage system and combining heat load.

- Handling and storing of dangerous items such as petroleum fuel can be eliminated, so that centralized control will promise safety of the facilities.

(2)-2 Method of district heating and cooling system

① Centralized system

As shown in Figure 11.52 (a), the centralized system produces heat in a central plant at temperatures close to what is required by the demand site. Then it transfers heat to each local site. It is suited for city areas where load density is high and local piping length is relatively short.

② Distributed system

As shown in Figure 11.52 (b), heat pump temperature of heat source can be lowered (15 - 20 deg. C) and heat loss of the heat source water supplied can be reduced. Hence, cost of heat insulation work can be saved. This system is suited for areas where heat load is low and demanding sites expand widely.

③ Centralized and distributed system

In the case that a site in the centralized system area requires high temperature heat, heat source temperature is raised at the substation on the demand site. If the demand site is located nearby, heat is transferred through a dedicated line from the center plant.

The above-mentioned heat-pump-type district heating and cooling system will greatly contribute to waste heat recycling in city areas.
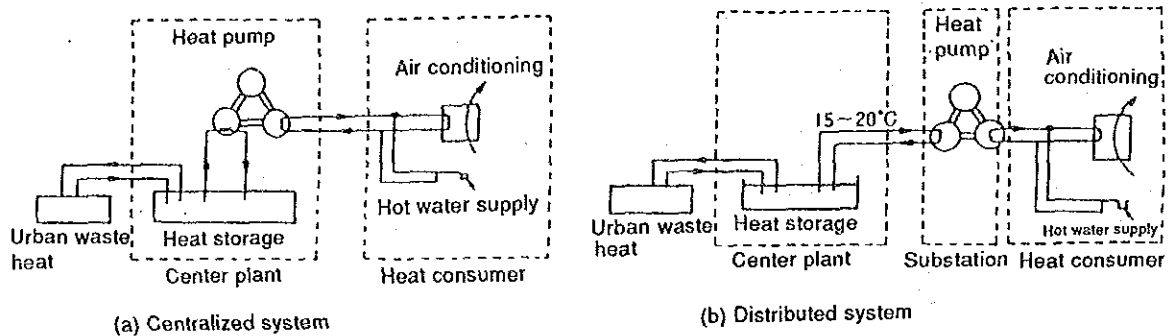

(a) Centralized system   (b) Distributed system

Figure 11.52 Heat-pump-type local air conditioning system

(3) Heat pump application to the industry

The application effect expected from a process largely depends on the stance to introduce the system; e.g., where to apply the heat pump system in the existing production process, or whether to implement the multi-function heat pump system as an indispensable element in the planning and design of a process.

For home appliances, because temperatures for air conditioning and hot water supply are considered almost constant, the system configuration of a heat pump may be relatively simple. For industry use, on the other hand, the heat pump system is required to fit to various conditions of production processes. The planning and design of the heat pump system varies in a thousand different ways depending on sectors and production processes.

Therefore, it is important on one hand to know the trend of heat energy utilization in each sector of the industry. On the other hand, however, when introducing a heat pump system, it is also important to conduct a deliberate planning; finding applicable points in the production process, reviewing material balancing (economic distribution of utilities, etc.) in the process concerning energy and production, and obtaining advantages from quality-improved products through improved quality control accuracy of energy.

Figure 11.53 shows a flow of heat utilization mainly with a heat pump .

The characteristics of heat pump usage cover a wide range of applications such as general air conditioning that mainly controls indoor temperature and humidity, a system that raises energy efficiency and economic effect by vaporizing separation of liquid, as is seen in the latent heat recycling heat pump for industry use, as well as a system that replaces combustion heating with heat pump heating and contributes to environmental improvement.
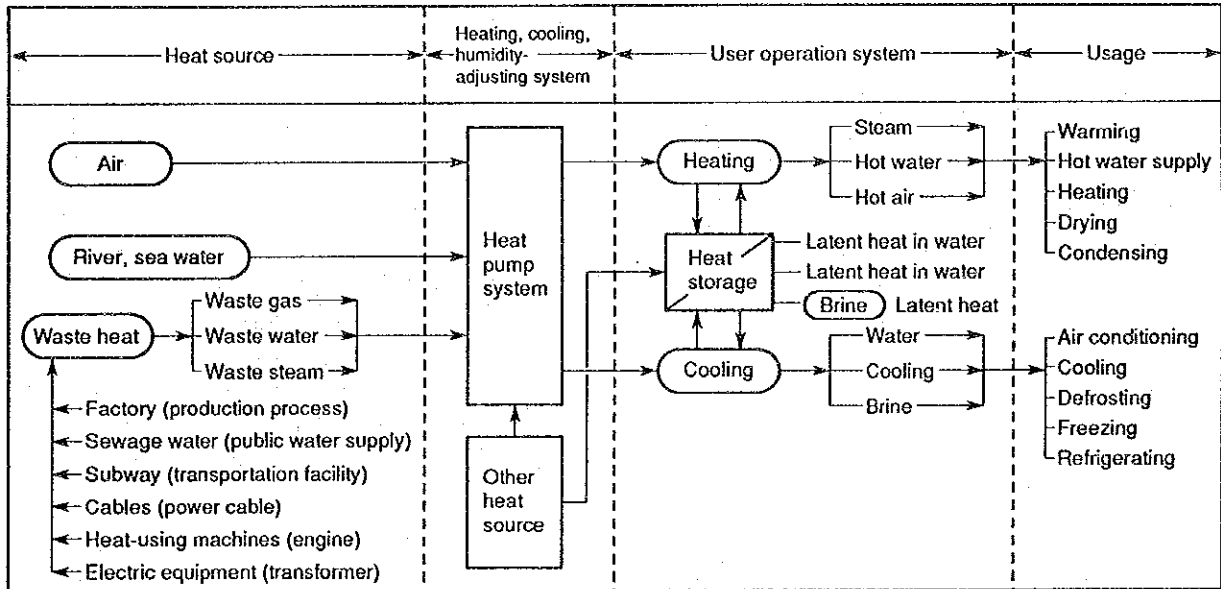

Figure 11.53 Heat flow diagram using a heat pump system

Table 11.33 shows the outline of the heat pump system performance. As for compressors, the main equipment of the system, rotary and reciprocating-types are employed for small size main equipment, and turbo and screw-types are employed for large size compressors.

Heat media is freon gas in general. However, special materials (water, hydrocarbon family material) are used for high temperatures (more than 100 °C).

Table 11.33 Performance of heat pump

Type of heat pump	General-purpose heat pump			Latent heat recycling heat pump		Super-heat pump
				Direct	Indirect	
Heat source	Air (sensible heat)	Air (sensible heat)	Waste heat, etc.	Waste heat (latent heat)	Waste heat (latent heat)	Waste heat, etc.
Application	Air conditioning, hot water supply, etc.	Air conditioning, hot water supply, etc.	Warming, hot water supply, drying, heating	Food, chemical factory	Food, medicine, photos, plating factory	Various factories, local heat supply
Heat media	Freon (R-22, R-12, etc.)	Freon (R-22, R-12, etc.)	Freon (R-22, R-114, etc.)	Water, etc.	Water, hydrocarbon, freon, etc.	Non-azerotropic mixture
Applied temperature	20 ~ 60°C	20 ~ 60°C	60 ~ 110°C	80 ~ 120°C	15 ~ 185°C	150 ~ 300°C
COP	About 3	About 4	About 4 - 5	About 10 - 20	About 2.5 - 6	About 6 - 8
Compressors	Rotary, reciprocating, screw, turbo, etc.	Reciprocating, screw, turbo, etc.	Reciprocating, screw, turbo, etc.	Turbo, roots, screw, etc.	Turbo, screw, reciprocating, etc.	Multi-stage turbo, etc.
Characteristics	For air conditioning use		For high temperature and heat recovery	High temperature, high efficiency, evaporation separation, concentration.	High temperature, high efficiency, heat recovery, low-temperature concentration, etc.	Under development

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Table 11.34 shows major applications and installations by technology utilized.

Table 11.34 Application and Installation fields

Technology	Application field
Air conditioning	Houses, buildings, housing complex (department store, school, hospital, public facilities), factories, clean room, public plantation, plant farming facility, etc.
Hot water supply	Pool, public bath, hotel, golf field, dying factory, ham factory, broiler factory, road heating, snow melting, etc.
Heating, cooling	Wine production, plantation facility, fish breeding, dairy farming, chemicals production, food, plating, etc.
Drying, humidity adjustment	Wood, fish, vegetables, fibers, gelatine, printed matters, peat, sewage, rubber products coating, etc.
Condensing, vaporization separation	Saccharated liquid, milk, glycerine, amino acid, antibiotic substance, agricultural chemicals, pulp, beat sugar, rayon fiber liquid, various waste liquid, etc.
Heat recycline	Organic solvent distillation, inorganic chemicals distillation, ethanol distillation, propylene, propane distillation

Waste heat utilization temperature distribution by sector is shown in Figure 11.54. Temperature of waste heat ranges 40 to 100 °C in a process. The shape of waste heat is vapor, hot water, air or gas (air containing solvent, dust), most of them including waste materials from the process.

Used temperature ranges 50 - 60 to 160 °C in a process. In the petrochemical industry and steel industry, waste heat source extends 500 to 1,500 °C high-temperature areas. Effective use of these waste heat is a subject for the future technological development.
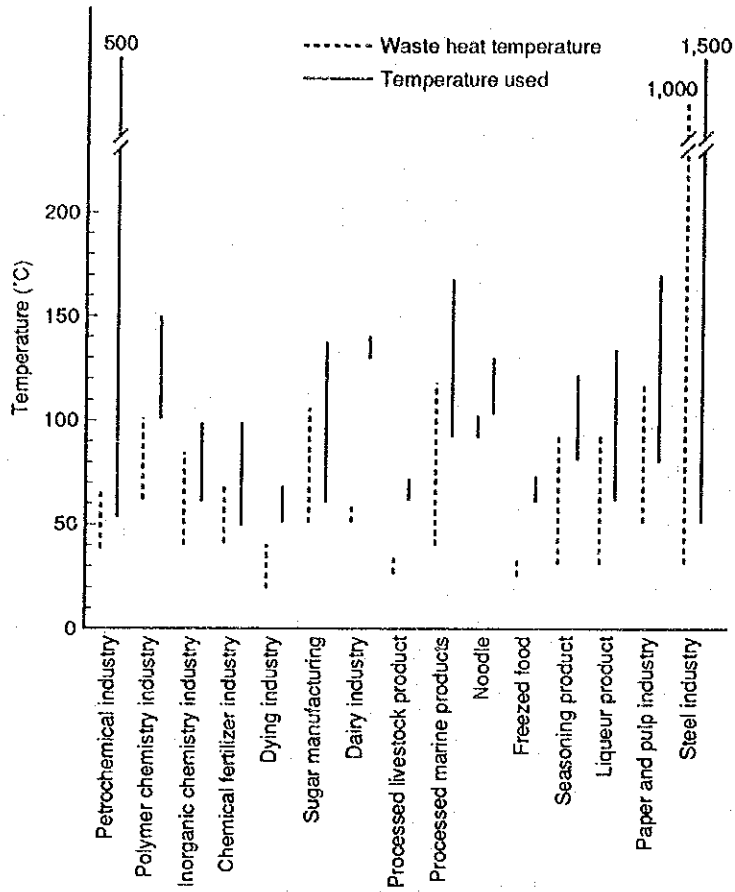
Figure 11.54 Heat utilization temperature distribution by sector

Table 11.35 shows each temperature level and heat demand rate of some industrial sectors. As is found in the table, sectors other than chemical industry and rubber manufacturing industry use heat level of 100 - 150 °C.

Table 11.35 Temperature level used by sector (%)

Temperature Sector	Less than 100°C	~ 150°C	~ 183°C	More than 183°C
Food, tabaco industry	2.5	62.3	16.6	18.6
Fiber industry	0.4	50.3	49.3	0
Wood, wooden product manufacturing	1.1	9.3	6.6	83.0
Pulb paper processing industry	0	85.9	4.1	0
Chemical industry	4.8	26.9	50.0	18.8
Rubber product manufacturing	0	26.3	53.4	20.4
Leather product	0	100.0	0	0
Ceramic and stone manufacturing	0	85.6	14.4	0

Table 11.36 shows application examples of heat pumps currently used, effect of energy conservation, COP of the system, applied places and used temperatures.

According to the table, VRC systems that use latent heat as heat source show high values of COP, 4.5 to 26. High efficiency of energy conservation is realized.

The heat pump system employed in a production process provides different cost performance largely depending on the cost of petroleum (Heavy oil, raw oil, naphtha, light oil) or gas (LPG, LNG) used as heat source. It is important to select investment timing to make the best use of the introduction of a heat pump system.

Heat pump systems for heating or cooling should be used systematically and comprehensively in combination with high temperature heat storage (hot water heat storage, hydrate heat storage) and low temperature heat storage (ice heat storage, inorganic salt and water). Thereby, energy efficiency is raised higher. It also provides reduction of initial cost and running cost, and other advantageous points such as labor-saving and space-saving. Further, larger effects than the aspect of energy utilization can be expected in other aspects such as improvement of product quality, improvement of yielding rate, speeding up of production, and environmental protection by recycling of waste heat and waste materials.

Table 11.36 Heat pump system application and advantages of energy conservation effect

	Applied place	Type	Temperature used (°C)	COP	Energy conservation effect	Comments
Drying and concentration	Drying of peat	VRC	130~180	4.5	About 75% reduction	4-stage turbo: Water content 60% → 10%, 3 → 14kg/cm²g
	Drying of gelatin	C	30~40	—	About 50% reduction	Quality: Water content 67% → 13%
	Drying of laminated processed paper	C	40~50	About 4	About 50% reduction	Improved controllability of capacity
	Drying of golf balls	C	H40 C15	$6.24 \left(\frac{2.56}{3.68}\right)$	About 50% reduction	Quality
	Drying of fruits and vegetables	VRC	100		About 56% reduction	Quality: Water content 90% → 12%
	Drying of seaweed	C	20~30		About 14% reduction	Quality: Safety
	Calcination of beer malt	C	65~	4	About 58% reduction	Quality
	Concentration of oil raw materials	VRC	100	15	About 93% reduction	Density: 10% → 50%
	Concentration of pulb	VRC	100	21	About 90% reduction	Density: 8% → 40% (3EF 40% → 70%)
	Concentration of wheat juice	VRC	100	7	About 50% reduction	About 10% vaporized
	Concentration of waste whisky	VRC	100	20		Density: 3% → 35% 1 → 1.23kg/cm³·g
	Concentration of amino acid	VRC	88~90	21~25	About 90% reduction	Density: 35%wt → 60%wt
	Concentration of gelatin	VRC	60~70	19		
	Concentration of anti-biotic substance	IVRC	25~30	18		Improvement of controllability and productivity
	Concentration of coarse phosphoric acid	IVRC	20	6	About 50% reduction	Density: 25% → 48%
	Concentration of sugar liquid	VRC	93	21~26	About 66~75% reduction	Density: 7% → 48%
Distillation	Ethyl alcohol purification	VRC	73~105	5.6	About 66% reduction	
	Organic solvent purification	VRC	100	15	About 90% reduction	
	BTX purification	VRC	145	6		Demonstration plant
Heating and cooling	Preprocess before coating	C	52	5	About 30% reduction	Closing, quality
	Tofu production process	C	0			Ice heat storage, quality
	Eel breeding pond heating	C	3		About 33% reduction	Use of nighttime power service
	Dying hot water supply	C	50		About 60% reduction	Production speed: 4 times/day → 5 times/day
	Hot water supply for broiler	C	65	4.8	About 56% reduction	Refrigerating waste heat recycling

Note: VRC: Vapor recompression, C: compress-type, IVRC: Indirect type, Quality: quality improvment, 3EF: tripple effect can

11.10 Air Conditioning

11.10.1 Introduction

Air conditioning refers to control of air conditions of rooms or plants to their optimal states fit for its usage and purposes. As other indices for judging the quality of a room atmosphere, there are acoustic impression, visual impression and sense of freedom, but air conditioning has nothing to do with them unless the facility factors affect them adversely.

Air condition of rooms to be controlled include the following 4 factors.

(1) Temperature

The room air is either cooled or heated for control to the prescribed value of the dry-bulb thermometer.

(2) Humidity

The room air is controlled to the prescribed comfortable relative humidity.

(3) Cleanliness

The room air is removed of dusts below the allowable dust concentration, and at the same time it is maintained so that fume, CO_2, odor, toxic gases, etc. are kept below the allowable concentration.

(4) Distribution

To facilitate uniform distribution of conditioned air in the room, a proper air flow is produced and a constant temperature condition of the whole room is maintained.

Purposes of this air-conditioning can be classified largely into a) hygienic air-conditioning and b) process air-conditioning.

a) Hygienic air conditioning

Hygienic air-conditioning means to maintain the room air in a state which maintains the hygienic environment for the human body and gives a sense of comfort and amenity namely to maintain the room air to a state suited for people living or working there. The 2 major factors governing the optimal air condition are temperature and humidity. Figure 11.55 shows the comfortable zones during winter and summer in Japan.

Meanwhile, apart from this figure, it is considered desirable to keep the room temperature not so greatly different from the outdoor temperature and to keep the humidity at a lower level. And, the difference between room and outdoor temperatures is considered most suitable when it is 5° ~ 7°C.

For general office work, design conditions are set at 18° ~ 22°C and 30% ~ 50% (R.H) during heating, and 25° ~ 28°C and 50% ~ 60% (R.H) during cooling. When energy conservation is given priority, values near the lower limit of the given values, namely 18°C and 40% during winter, and 28°C and 50% during summer are adopted.
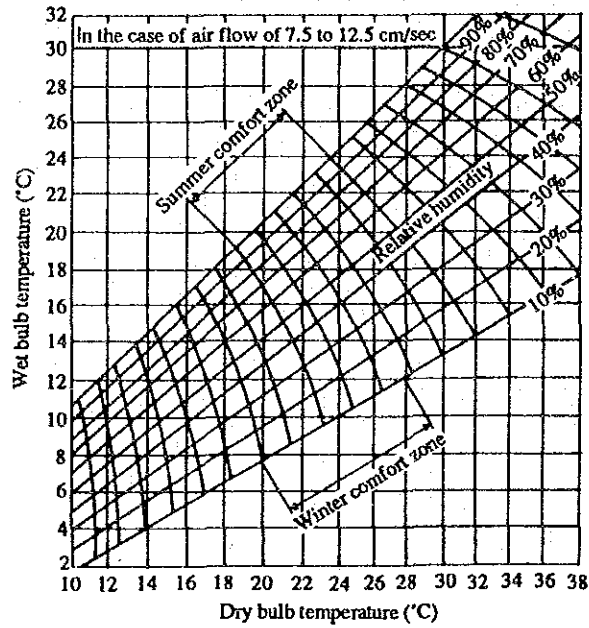

Figure 11.55 Comfort zone

b) Process air conditioning

Of processes of industrial production, many including processes from raw materials to completion and storage of products require independent conditions for retaining the facility and quality. As processes often require coexistence of operators, workers there, process air conditioning should take factors of hygienic air conditioning into consideration. Generally, process air conditioning precedes, and for the human body hygienic performance is assured by local air conditioning and other means.

Table 11.37 shows typical design air conditioning states of various industrial processes. However, the table shows mere guidelines, and individual design should be determined by thorough study.

Table 11.37 Example of process air conditioning

Classifica-tion	Process	Temperature (°C)	Relative humidity (%)	Classifica-tion	Process		Temperature (°C)	Relative humidity (%)
Color printing	Bronze plating room	24-27	45-50	Food	Manufacture of butter		16	60
	Plate preparation	24	45-50		Coffee substitute		24-27	40-45
	Printing room	24-27	45-50		Milling		—	60
					Macaroni		21-27	38
Printing	Book binding	21-24	45		Mayonnaise		24	40-50
	Form	24-27	45-50		Mushroom prowing room		14-27	75
	Printing room	24-27	45-50					
	Web press	24-27	50-55	Brewing	Storage of grains		16	35-40
	Paper storage	20-23	50-60		General manufacture		16-24	45-65
	Photographic printing	21-23	40-50		Aging room		18-22	50-60
					Beer fermentation room		3-4	50-70
Optics	Melting room	24	45		Beer malthouse		10-15	80-85
	Abrading room	27	80					
				Confection-ery	Chewing gum	Cooling	22	50
Plywood	Manufacture	—	55-60			Drying	49-60	50
	Gluing	—	55-60			Wrapping and storage	21-24	45-60
					Candy	Manufacture	18-27	35-50
Rubber	Storage	14-24	40-50			Cooling	24-27	40-45
	Cementing	27	25-30			Product storage	16-24	45-55
	Dipping	24-27	25-30			Dry fruits storage	10-13	50
	Manufacture	32	—		Chocolate	Bar manufacture	18	45-50
	Sulfurization	26-28	25-30			Center cream manufacture	24-29	50
						Nougats	18	50
Laboratory	Animal laboratory	24-27	40			Starch room	24-29	50
	Central analysis room	23	50			Wrapping	18	50
						Product storage	16-24	40-50
Photograph	Manufacture of ordinary film	23-24	24-40					
	Printing	23-24	65-70	Tobacco	Cigarette	Raw material storage	27	75-78
	Finished product storage	16-27	45-50			Cutting	24-27	80
	Developing	21-24	60			Cut tobacco storage	27-29	60-65
						Manufacturing room	21-27	55-65
Bakery	Base mixing	24-27	45-55			Wrapping room	27-29	50
	Base fermentation	27	70-80			Truck removing room	27	70-75
	Bread cooling	21	70-80			Sweating	49	80
	Bread wrapping	18-24	50-65					
	Powder storage	21-27	50-60	Cotton spinning	Roving		21-24	50-55
	Cake freezing	21-27	45-50		Spinning		21-24	55-65
					Drawing		21-24	55
Precision machinery	Gear cutting	24-27	45-55		Picker		21-24	45-50
	Precision parts	24	45-55		Roving		21-24	50-60
	Precision assembly	20-24	40-50		Warp spinning		24-27	50-65
	Precision test room	24	45-50		Weft spinning		24-27	50-65
					Cotton reel		24-27	60-70
Pharmacy	Capsuling	24-27	25-40		Twister		21-24	65
	Colloid	21	30-50		Woven textile		24-27	70-85
	Deliquescent salt	27-32	15-40		Fabric storage		24-27	65-75
	Gelatin capsule	26	40-50					
	Powder product	24-27	5-35	Jute spinning	Fabric conditioning room		24-27	90-95
	Tablet forming	21-27	35-40		Spinning		24-27	60
	Tablet furbish coating	24-27	35-40		Woven textile		26-27	80
	Serum	23-26	45-50		Preparation		18-20	80
	Powder material drying	24-71	20		Roving and spinning		24-27	60
	General pharmacy room	21-27	10-50					
				Match	Manufacture		22-27	45-50
Electricity	Manufacture of thermostat	24	50-55		Storage		15	50
	Manufacture of insulating material	24	65-70					
	Assembly of electron tubes	20	40					
	Cable insulation	40	5					
	Transformer coil winding	16-24	15-35					

11.10.2 Composition of Air Conditioning System

The final means for performing air conditioning is the air, and generally air conditioning is performed by letting out the air with proper temperature, moisture and cleanliness from blowing outlets into rooms. And there are various devices for achieving this aim, of which a composition of a relatively large-scale air conditioning system is shown in Figure 11.56. Here descriptions are given mainly on cooling, based on this composition.
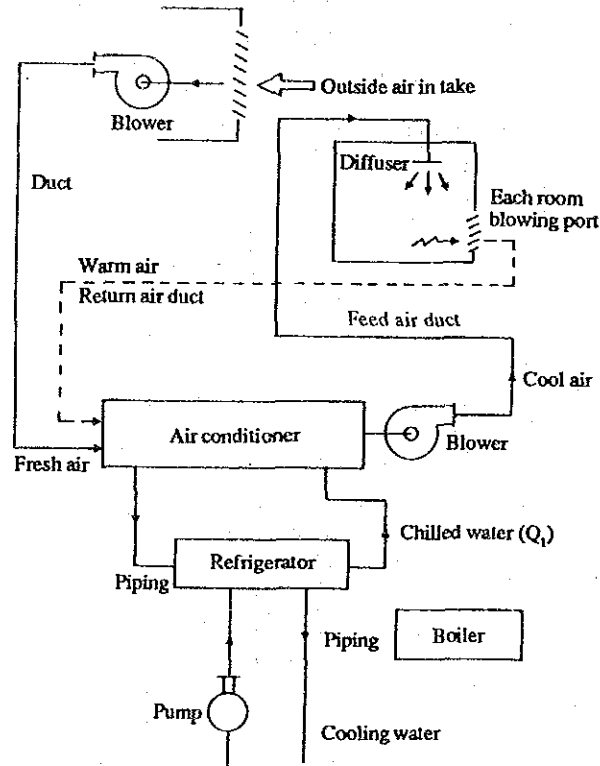

Figure 11.56 Composition example of large scale air conditioning system (during cooling)

During cooling, heat load flows from the outside into the room, which is transferred from air to chilled water within the air conditioner and carried to the heat source unit (refrigerator), and after pumped up by the refrigerator, is discharged through the cooling tower into the atmosphere.

During heating, oil or gas is burnt by boiler, and this heat, after transferred to warm water, is carried to the air conditioner, and supplied into the room by means of air conditioner.

(1) Heat source unit

The heat source unit supplies warm water (heating medium) or chilled water (coolant) to the air conditioner. Heat source units for heating the heating medium include boiler, regenerator tank, heat pump, etc., and that for cooling the coolant include the refrigerator. Besides them are heat exchangers, pumps, blowers and pipings as auxiliary equipment.

(2) Air conditioner

A unit for preparing the blow air to a temperature, moisture and cleanliness suited for the required room conditions. It therefore is equipped with various equipment within for purifying, cooling, temperature reducing, heating, humidifying, blowing, etc.

(3) Supply unit

A unit for supplying fluid and gas is composed of blower, pump, duct, piping, etc. That is, the air conditioned through the air conditioner is supplied through the duct to a room to be cooled. And, the warm room air is absorbed by negative pressure of the blower and sent into the air-conditioner.

(4) Diffuser

Installed at the outlet or inlet of the duct, composed of blowing outlet, suction port, muffler, damper, etc.

(5) Switch board, control panel, monitor panel

These are electric facilities for operating, controlling and monitoring the air conditioning system.
The above-mentioned units are not necessarily installed separately, and there are systems which combine several units in one or those in which all of them form a single unit, like a package-type air-conditioner, depending on the scale of air-conditioners.

11.10.3 Heat Load of Air Conditioning System and Its Calculation

Figure 11.57 shows the inflow sections of heat load to a room.

Table 11.38 lists the type and composition of heat load, and calculation formulas corresponding to Fig. 11.57. Additionally, accumulated heat load is generated during ordinary intermittent operation, which is accumulated in the building framework by invasion of external heat during the night when the air conditioner is stopped and is gradually flown away as load after resuming operation. Both heating load and cooling load are largely affected when operation is stopped during the night and during the day respectively by heat accumulation.

Figure 11.58 shows a cooling load example at a plant office. Construction of the building is as shown in Figure 11.59.

According to Figure 11.58, load due to heat transfer is the largest, followed by lighting, external air, solar radiation and human body in that order.
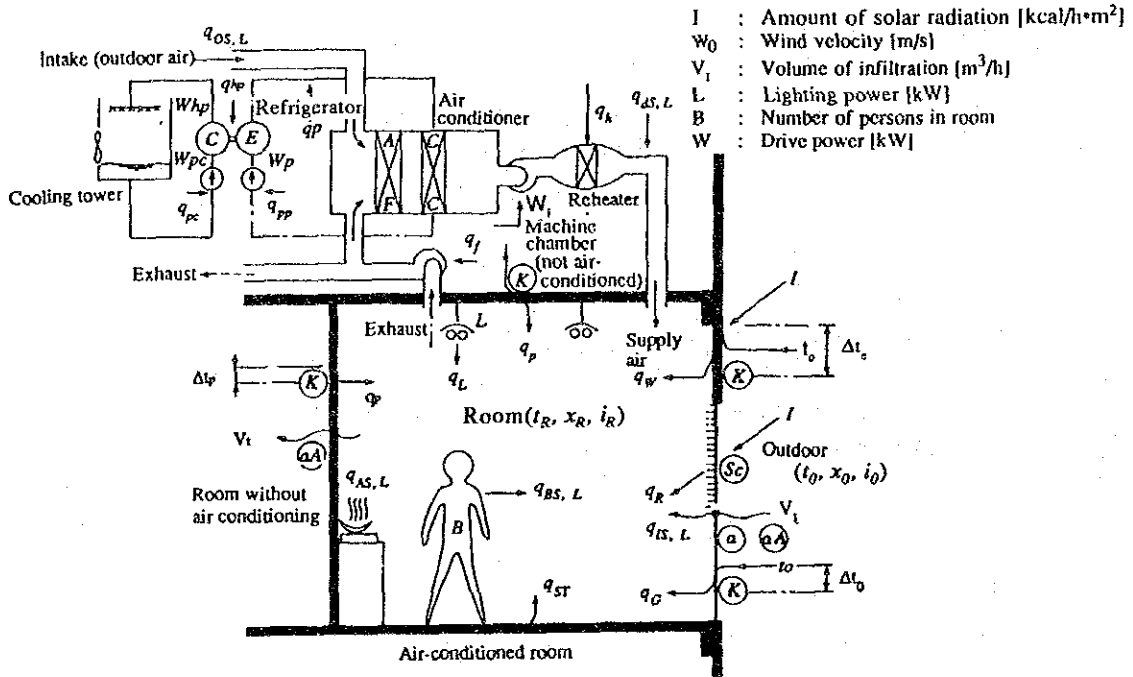

I	:	Amount of solar radiation [kcal/h·m²]
W_0	:	Wind velocity [m/s]
V_I	:	Volume of infiltration [m³/h]
L	:	Lighting power [kW]
B	:	Number of persons in room
W	:	Drive power [kW]

Figure 11.57 Type of heat load and inflow sections (cooling)

Load due to human body	11%	
Load due to solar radiation	15%	
Load due to external air	15%	
Load due to lighting	16%	
Load due to heat transfer	43%	Total 17,045 kcal/h

Figure 11.58 Example of air conditioning load in factory office (during cooling)

Corridor

0.9 m   0.9 m

Outside

Window   2nd floor of 3 storied reinforced
          concrete building
          (Height of ceiling 3 m)
                              Office

Next room

7.5 m

Venetian blind (Intermediate color)

Next rooms, the lower and
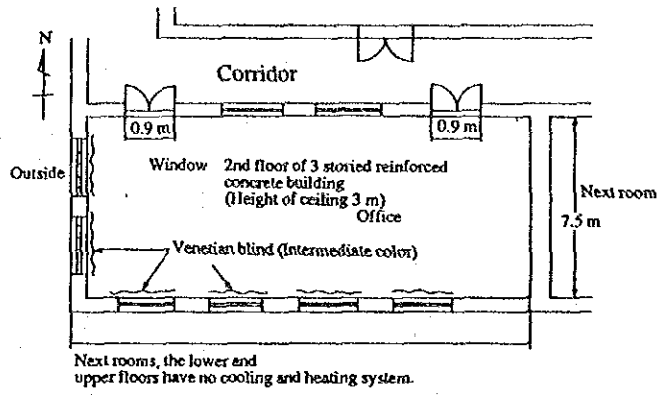upper floors have no cooling and heating system.

Figure 11.59   Example of office

Table 11.38 Types and composition of air conditioning heat loads, and calculation formulas

Type of load	Symbol	Calculation formula — Sensible heat load	Calculation formula — Latent heat load	Remarks
Glass-transmitted solar radiation	q_R	$S_c \cdot A \cdot I$		S_c: Shield modulus, A: Area, I: Standard solar radiation gain
Transfer through external wall and roof	q_W	$K \cdot A \cdot \Delta t_e$		K: Heat transfer coefficient $\frac{1}{K} = \frac{1}{\alpha_i} + \Sigma \frac{d_i}{\lambda_i} + \frac{1}{\alpha_o}$ kcal/h·m²·°C
Transfer through external wall glass	q_G	$K \cdot A \cdot \Delta t_o$		α_i: Indoor heat transfer rate = 8 kcal/h·m²·°C; α_o: Outdoor heat transfer rate = 20 (summer), 30 (winter) [kcal/h·m²·°C]
Infiltration	$q_{IS,L}$	$0.28V_i \cdot \Delta t_o$	$715V_i \cdot \Delta x_o$	d_j: Thickness of j-layer of component member, λ_j: Thermal conductivity [kcal/m·h·°C]
Accumulated heat load	q_{ST}			For all-day air conditioning $q_{ST}=0$; Δt_e: Effective temperature difference (°C)
Lighting	q_L	$860b \cdot L$		b: Ballast coefficient, incandescent lamp b=1.0, fluorescent lamp b=1.2, L: Lighting power [kW]
Human body	$q_{HS,L}$	$h_s \cdot B$	$h_L \cdot B$	h_s, h_L: Sensible heat and latent heat generated from a human body, B: Number of persons
Equipment	$q_{AS,L}$	q_{AS}	q_{AL}	Use measured value (facility capacity × load factor)
External air load	$q_{OS,L}$	$0.28V_o \cdot \Delta t_o$	$715V_o \cdot \Delta x_o$	V_o: Amount of air intake $\Delta t_o = t_o - t_R$ $\Delta x_o = x_o - x_R$
Duct heat reception and leakage	$q_{dS,L}$	$(K \cdot A \cdot \Delta t)$ $(0.28V_D \cdot \Delta t_D)$	$(715V_o \cdot \Delta x_o)$	V_D: Amount of leaked air; 5-20% of RL
Fan heat	q_f	$860W_f$		W_f: Fan drive power [kW]
Reheat load	q_h	q_h		Use measured value of reheat quantity
Piping heat reception	q_p	$(K \cdot A \cdot Dt)$		Δt: Difference between water temperature and ambient temperature
Pump heat	q_{pp}	$860W_p$		W_p: Pump drive power; 2-5% of ACL
Accumulator tank loss	q_{ac}	$(K \cdot A \cdot \Delta t)$		5-15% of HACL (Total 1-day value)
Refrigerator drive power	q_{np}	$860W_{np}$		For heat pump, it is included as part of heat source (during heating)
Cooling water pump heat	q_{pc}	$860W_{pc}$		W_p: Pump drive power [kW]
Boiler waste heat	q_r	$\left(\dfrac{1}{\eta} - 1\right)$ HACL		η: Boiler efficiency

Left-side grouping (rotated labels):
- Room load RL — Outdoor load / Internal load
- External air load
- System load — Duct system load / Piping system load / Heat source system load
- Air conditioner load ACL
- Heat source unit (boiler, refrigerator, etc.) load HACL
- Heat source (oil, etc.) and heat sink (cooling lower-atmosphere air) load

11.10.4 Energy conservation of air conditioning facility

For air conditioners, the load to be air conditioned is determined first, and secondly a suitable air conditioning system for this load is selected. Therefore, in considering energy conservation of an air conditioning facility, reducing the cooling load (1st step), and selecting an energy-saving air conditioner or system for the remaining cooling load (2nd step) are very important. Here, measures are considered mainly in relation to existing buildings.

(1) Heat insulation

The transfer heat load is expressed by $K \cdot A \cdot \Delta t_e$. The area A and effective temperature difference Δt_e are determined by the shape of building, weather condition and heat capacity, so when these cannot be changed, it is easiest to insulate the heat, that is, vary the heat transfer coefficient K. As methods of heat insulation, there are the following 3 methods.

a. Heat insulation of walls and windows

While external heat insulation has an advantage of being able to cut off heat without obstacles from the outside, internal heat insulation has disadvantages such as restrictions due to furniture or reduction of the room area.

b. Heat insulation of roofs and floors

c. Heat insulation of window glass

Heat insulation of window glass is done by doubling of window glass or doubling of window sashes. For the heat transfer coefficient, there is not so much difference as far as the number of window glasses is the same.

(2) Light shielding

The glass transmitted solar radiation load is expressed by $S_c \cdot A \cdot I$. The standard solar radiation gain is decided by weather condition and layout of the building, and methods are adopted for varying the shielding factor and window area.

a. Fitting blinds and curtains

It should be noted that the shielding effect is available only under the condition that sure open/close operations of blinds are carried out. Also, since the shield effect is connected with the use of day light, it is essential to obtain a method which makes the sum of cooling/heating energy and lighting energy at a minimum.

b. Fitting louvers and hoods

Provide fixed hoods, louvers, etc. outside windows with considerations made so as to shield solar radiation during the summer and not shield it during the winter.

c. Repairing window glass

Window glass is replaced with heat ray absorbing glass or reflecting glass, without having to change sashes, and the amount of transmitted solar radiation through window glass is reduced by bonding solar radiation adjusting film, to reduce cooling load.

(3) Preventing infiltration

Load q_I kcal/h due to infiltration is caused by natural ventilation, namely entrance of external air through crevices of windows and doors and the open and close operations, and it is expressed by the following formula.

$$q_I = 0.28V_I \cdot \Delta t_0 + 715V_I \cdot \Delta x_0$$
$$= 0.28n \cdot V \cdot \Delta t_0 + 715n \cdot V \cdot \Delta x_0$$

n : number of times for natural ventilation (see Table 11.39)
V: Room capacity (m³)

Table 11.39 Number of times for natural ventilation (n)

Class of room	n
1 wall surface facing outside air and having window or door	1
2 walls surface facing outside air and having window or door	1.5
3 walls surface facing outside air and having window or door	2
4 walls surface facing outside air and having window or door	2
Room without window facing the outside air or door	1/2 - 3/4

For air-tight window, 1/2 of this table shall be used. However, n shall be more than 1/2 in any case.

To reduce infiltration load, windows and doors may be sealed, and the number of (open/close) operations may be reduced, as practicable, much as possible by automatic doors. However, since Δt_0 will become negative when the outdoor temperature is below the room temperature during the nighttime, and it means more reduction of cooling load, and cooling effect is obtained by opening windows and doors to introduce external air.

(4) Producing heat values generated by equipment in the room

It is preferable not to place any equipment which generated heat inside the air-conditioned room. For lighting as well, adoption of local lighting and high-efficiency lamps and improvement of lighting appliances for more efficiency of lighting, or adoption of a ventilation system for disposing generated heat by lighting equipment separately, are desirable.

(5) External air load

The external air load q_o is produced by forced ventilation and is expressed by the following formula.

$$q_0 = 0.28V_0 \cdot \Delta t_0 + 715V_0 \cdot \Delta x_0$$

The ventilation volume V_0 is regulated mainly from the safety and hygiene for man. Suppose the allowable CO_2 concentration is 0.1%, the required volume of external air is approx. 30 m³/h/person.

At any rate, in order to reduce external air load, it is important to minimize the volume of ventilation within a range in which CO_2 concentration is below 0.1%.

Where there is a circulation system as shown in Figure 11.60, introduction of external air should be reduced, as much as possible, by recirculating within the system. The damper of the circulation system is increased in size to increase return air, and at the same time opening of the damper at the external air intake system is reduced to cut down on the intake volume of external air.

What should be noted in the system (Figure 11.60) is that the room pressure becomes negative against the outdoors when return air is made excessive, resulting in a state which readily allows invasion of air and dusts from outside. Therefore, it is desirable to maintain the room pressure in the positive state at 0.1 mm Aq ~ 1 mmAq against the outdoors.
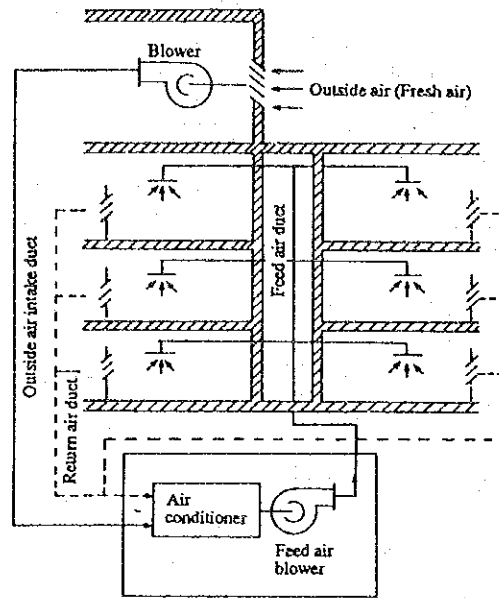
Figure 11.60 Air conditioning system when return air is available

(6) Alleviating the set room temperature

By raising the set temperature during cooling, cooling load by heat transfer from wall surfaces, which is proportionate to difference between temperatures inside and outside the room, is greatly reduced. In the case shown in Figure 11.58, for example, raising set temperature from 26°C to 27°C reduced cooling load by approx. 100 kcal/h.

(7) Review of room humidity

In the case of air conditioners having a dehumidifying function, alleviation of humidity condition is an effective measure toward energy conservation. According to the example calculations, variations of air conditioning load by varying humidity and by varying temperatures are as shown in Figure 11.61.

While approx. 4.2 kcal/h of load reduction can be attained when humidity is alleviated from 40% RH to 60% RH at 23°C, load reduction is approx. 0.7 kcal/h only when temperature is alleviated from 21°C to 25°C at relative humidity 50% RH - alleviation of humidity is about 6 times more effective as energy conservation. However, it should be noted that excessively high humidity would give uncomfortableness to man and affect on products quality adversely.
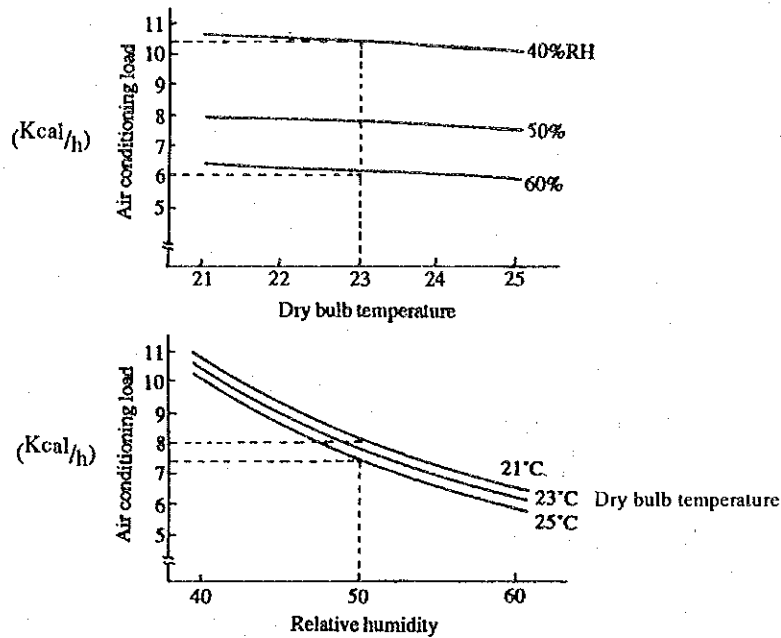
Figure 11.61 Energies required for temperature and humidity changes

(8) Improving control method

As mentioned before, control of heat load is available by method which varies flow rate, and by method which varies set temperature with flow rate set constant. Reduction effect of drive power for the fan and pump is larger in the former, and it results in energy conservation.

As control methods for flow rate, there are control of dampers and vanes, and various rotating speed controls. Power consumption is ranked as discharge damper control > inlet vane control > rotating speed control. As rotating speed control by VVVF is easily available for existing motor facilities with considerable effects, it should be studied first among other possibilities.

(9) Regular maintenance

a. Cooling water piping
Accumulation of scale and sludge in piping will increase resistance and require more pump output for the same flow rate. If the water quality is poor, it will naturally accelerate accumulation of scale and sludge. Therefore, control of water quality is necessary. Reference value for the control criterion are shown in Table 11.40.

Table 11.40 Quality Standard of Cooling Water
(Japan Refrigeration and Air Conditioning Industrial Association Standard)

	Item		Standard value for makeup water	Standard value for cooling water [1]	Tendency [3]	
					Corrosion	Scale
Standard item	PH (25°C)		6.0 ~ 8.0	6.0 ~ 8.0	O	O
	Conductivity	(μv/m)	200 or less	500 or less (1,000 or less)	O	
	Chlorine ion Cl	(ppm)	50 or less	200 or less	O	
	Sulfuric acid ion SO_4	(ppm)	50 or less	200 or less	O	
	Total iron Fe	(ppm)	0.3 or less	1.0 or less [2]	O	O
	M Alkalinity $CaCO_3$	(ppm)	50 or less	100 or less		O
	Total hardness $CaCO_3$	(ppm)	50 or less	200 or less		O
Reference item	Sulfur ion S	(ppm)	Not be detected	Not be detected	O	
	Ammonium ion NH_4	(ppm)	Not be detected	Not be detected	O	
	Silicon oxide SiO_2	(ppm)		50 or less		O

[1] Cooling water means water passing through condenser for both once through and circulation systems.

[2] Standard value for plastic piping shall be 0.5 ppm or below.

[3] Mark O in "Tendency" column indicates a factor concerning either corrosion or scale tendency.

b. Heat exchanger

When scale, sludge and microbes are generated in the evaporator and condensor by cooling water, they will be accumulated to drop the efficiency of heat exchange, and increase power consumption per refrigeration ton. Therefore, periodical cleaning is necessary.

c. Air duct

When filters are used for cleaning the air, periodical cleaning is inevitable. Clogging of filters increases pressure loss and reduce air volume to degrade cooling capacity. As air conditioners are quickly contaminated when installed at places under poor atmospheric conditions, cleaning is required at least once a week.

d. Others

It is desirable to reduce air-conditioning load, as possible, by performing reviews of air-conditioning zones through studies on unbalanced supercooling/superheating of rooms, review of air-conditioning levels at corridors, etc. in each season.

Also, in installing any air conditioning systems, studies should be made carefully, including appropriateness of installing heat accumulation tanks, appropriateness of using waste heat, selection of the most efficient air conditioning duct system, etc., all of which are realized by placing emphasis on reduction of the running costs.

12. Thermal Insulation Calculation with a Personal Computer

12. THERMAL INSULATION CALCULATION WITH A PERSONAL COMPUTER

(1) Outline

With the personal computer calculation sheet treated here, the calculation of the heat emission amount from the surface of steam piping etc. is executed on the basis of the theories of heat transfer engineering. Heat transfer is divided into conduction, convection, and radiation, and in actual life, these appear individually or in combination.

The heat emission amount is calculated according to the following two methods.

① A method where the heat emission amount is obtained from the temperature of the inner surface and the thickness of the insulating material

② A method where the heat emission amount is obtained from the surface temperature.

The thickness of the insulating material is selected according to the philosophy of the economic insulation thickness.

These calculations are executed with a personal computer and Lotus 123 as a spreadsheet, using the calculation sheet developed by the Energy Conservation Center. Here, the way of thinking and the use of the personal computer calculation sheet will be explained.

(2) Heat conduction

2-1 Basic formula

As shown in Fig. 12.1, when there is a solid wall with a thickness of b (m) and the temperature at both sides of the wall is held at t_1 (°C) and t_2 (°C), the amount of heat passing though the wall per unit time is expressed by formula (1).
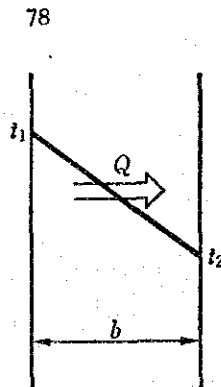
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Figure 12.1   Heat conduction

$$Q = \lambda A \frac{t_1 - t_2}{b} \qquad\qquad [kJ/h] \qquad\qquad \text{Equation (1)}$$

where A (m²) is the area of the wall.

In equation (1), λ is called the "heat conductivity", and this is a specific value for insulating material etc., and in many cases it changes according to the temperature of the material.

When the wall has a multilayer construction as shown in Figure 12.2, expression as shown in equation (2) is possible as the temperature gradient is consecutive for the various layers and the amount of heat passing through each layer is the same.
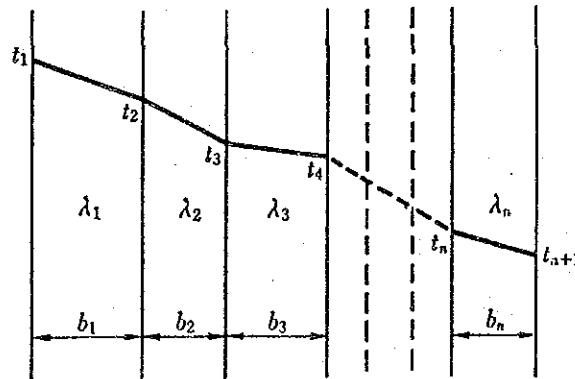
Figure 12.2 Heat conduction of a multilayer wall

$$q = \frac{t_1 - t_{n+1}}{\dfrac{b_1}{\lambda_1} + \dfrac{b_2}{\lambda_2} + \cdots\cdots + \dfrac{b_n}{\lambda_n}} \qquad\qquad [kJ/(m^2 \cdot h)] \qquad \text{Equation (2)}$$

As can be seen from equation (2), it is not necessary to calculate the temperatures of the intermediate wall boundary, and the transfer amount can be calculated by giving the surface temperatures of the two outer wall surfaces and the thermal conductivity and the thickness of the material of each wall.

2-2 Heat Conduction of Cylindrical Walls

When the wall surface is a cylinder, as shown in Figure 12.3, the cross section area changes with increase of the distance in radial direction. Accordingly, even when the heat transfer amount at the position of each radius is constant, the heat transfer amount per unit area differs according to the radius position. The heat transfer amount per unit length for the case of cylindrical walls is expressed by equation (3).
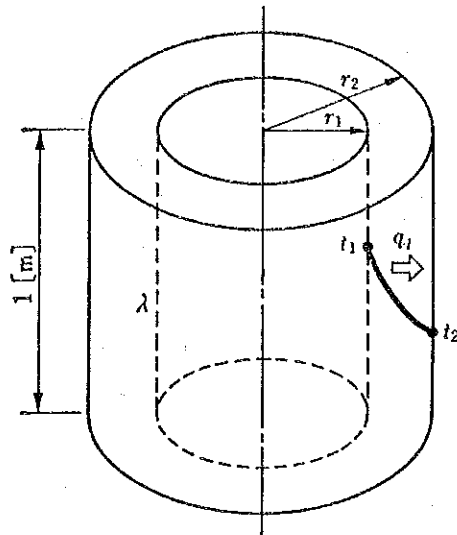
Figure 12.3   Heat conduction of a cylindrical wall

$$q_l = \frac{2\pi\lambda}{\ln\dfrac{r_2}{r_1}}(t_1 - t_2) \qquad\qquad \text{[kJ/m·h]} \qquad\qquad \text{Equation (3)}$$

where ln is the natural logarithm in equation (3).

The heat transfer amount for a multilayer cylindrical wall as shown in Figure 12.4 is given by equation (4).
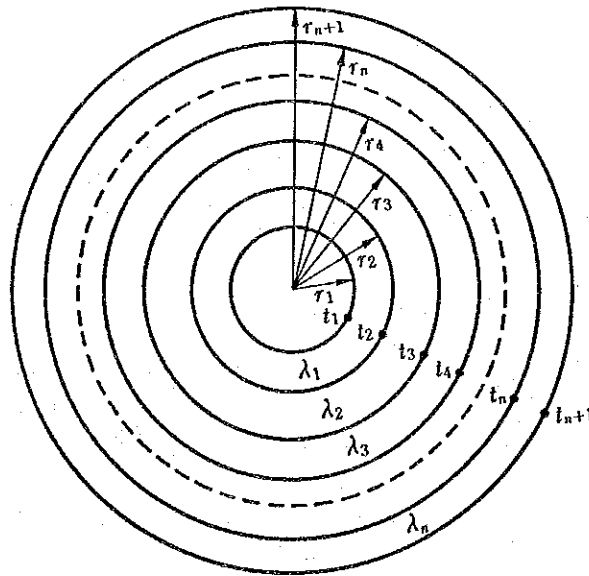

Figure 12.4   Heat conduction of a multilayer cylindrical wall

12-3

$$q_1 = \frac{2\pi(t_1 - t_{n+1})}{\dfrac{1}{\lambda_1}\ln\dfrac{r_2}{r_1} + \dfrac{1}{\lambda_2}\ln\dfrac{r_3}{r_2} + \cdots + \dfrac{1}{\lambda_n}\ln\dfrac{r_{n+1}}{r_n}} \qquad \text{[kJ/m·h]} \qquad \text{Equation (4)}$$

In this case also, in the same way as for a flat surface, the temperatures at the boundaries of each cylinder are not required for calculation of the heat transfer amount, and it is sufficient when the temperatures at the inner and the outer surface of the multilayer cylinder are known.

(3)   Heat transfer by convection

The heat exchange of a gas or a liquid at the surface of a solid body differs from the heat conduction in a solid body, and it is called "heat transfer by convection". In this case, the heat does not only move inside the fluid by means of heat conduction, but as it is also being transported by the moving fluid, the heat transfer amount becomes extremely large in comparison to heat conduction. The heat transfer amount also is influenced easily by the flow, and the heat transfer amount increases with increasing velocity of the fluid.

In the case of convection heat transfer as shown in Figure 12.5, the temperature difference and the heat transfer amount are proportional when the flow pattern of the fluid is the same, so that the heat transfer amount is expressed by equation (5).
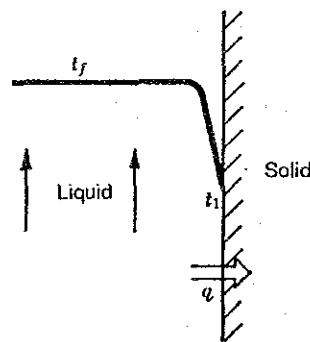

Figure 12.5   Heat transfer by convection

$$q = \alpha\,(t_f - t_1) \qquad \text{[kJ/(m}^2\text{·h)]} \qquad \text{Equation (5)}$$

In equation (5), α is a factor called the "heat transfer coefficient", which changes according to the fluid type and the flow conditions, and various calculation formulas have been proposed on the basis of experiments.

The dimensionless numbers defined in equation (6) are used to express the condition of flow and heat transfer.

$$Nu = \frac{\alpha L}{\lambda} \qquad \text{(Nusselt number)}$$

$$Re = \frac{wL}{\nu} \qquad \text{(Reynolds number)}$$

$$Pr = \frac{\nu}{a} \qquad \text{(Prandtl number)}$$

Equation (6)

α : Heat transfer coefficient $[kJ/(m^2 \cdot h \cdot °C)]$

L : Representative length   [m] (diameter for a tube, distance from the tip for a plate)

λ : Heat conductivity of the fluid $[kJ/(m \cdot h \cdot °C)]$

w : Fluid velocity   [m/h] or [m/s]

ν : Kinetic viscosity $[m^2/h]$ or $[m^2/s]$

a : Thermal diffusivity of the fluid $[m^2/h]$ or $[m^2/s]$ $(= \frac{\lambda}{c\gamma})$

c : Specific heat of the fluid $[kJ/(kg \cdot °C)]$

γ : Specific gravity of the fluid $[kg/m^3]$

3-1 Natural Convection

The flow of a fluid not caused by a fan or a pump, but by the density difference from temperature rise of the fluid in contact with a solid body is called "natural convection". The heat transfer coefficient with natural convection is expressed using the Grashof number, which is defined as follows.

$$Gr = \frac{L^3 g \beta (t_w - t_0)}{\nu^2}$$

Equation (7)

g : Gravitational acceleration $[m/s^2]$

β : Coefficient of volume expansion of the fluid $[1/K]$

t_w : Surface temperature $[°C]$

t_0 : Fluid temperature $[°C]$

With these equations, the value of the heat transfer coefficient of the fluid, the dynamic coefficient of viscosity, and the Prandtl number change according to the type and the temperature of the fluid, and for each fluid, the temperature relation can be expressed according to the following equation. In other words, the fourth order temperature equation for water is expressed as

$a + bt + ct^2 + dt^3 + et^4$,

while the third order temperature equation for air is expressed as

$a + bt + ct^2 + dt^3$,

and the coefficients in the equations are given by the following table.

Substance	Property value	a	b	c	d	e
Water	Thermal conductivity kJ/(mh°C)	1.869	13.28 × 10⁻³	−10.80 × 10⁻⁵	40.16 × 10⁻⁸	−6.484 × 10⁻¹⁰
	Dynamic viscosity coefficient (m²/s)	1.234 × 10⁻⁶	−2.021 × 10⁻⁸	1.619 × 10⁻¹⁰	−6.347 × 10⁻¹³	9.790 × 10⁻¹⁶
	Prandtl number	8.179	−0.1345	1.017 × 10⁻³	−3.663 × 10⁻⁶	5.148 × 10⁻⁹
Air	Thermal conductivity kJ/(mh°C)	0.08669	28.70 × 10⁻⁵	−14.29 × 10⁻⁸	6.559 × 10⁻¹¹	
	Dynamic viscosity coefficient (m²/s)	1.378 × 10⁻⁵	8.916 × 10⁻⁸	1.355 × 10⁻¹⁰	−1.566 × 10⁻¹³	
	Prandtl number	0.7177	−1.705 × 10⁻⁴	−4.403 × 10⁻⁷	2.924 × 10⁻⁹	

With use of these dimensionless numbers, the Nusselt number can be expressed by the following empirical equations.

a)   In case of a horizontal cylinder

$$Nu_m = 0.53(Gr \cdot Pr)^{1/4}$$

Equation (8)

b)   In case of a vertical plate

$$Nu_m = 0.13(Gr \cdot Pr)^{1/3}$$

Equation (9)

c)   In case of a horizontal plate facing up

$$Nu_m = 0.14(Gr \cdot Pr)^{1/3}$$

Equation (10)

d)   In case of a horizontal plate facing down

$$Nu_m = 0.27(Gr \cdot Pr)^{1/4}$$

Equation (11)

3-2 Forced Convection

With forced convection, the Nusselt number is expressed as follows by using the Reynolds number instead of the Grashof number.

a) When the fluid is flowing at right angle outside the tube (in case of a single circular tube and air as the fluid)

$$Nu = cRe^n \hspace{5cm} \text{Equation (12)}$$

with the values for c and n as shown in the following table.

Re	n	c
1 to 4	0.330	0.891
4 to 40	0.385	0.821
40 to 4,000	0.466	0.615
4,000 to 40,000	0.618	0.174
40,000 to 250,000	0.805	0.0239

b) When the fluid is flowing parallel to a flat plate

$$Nu = 0.037\ Re^{0.8}Pr^{1/3} \hspace{4cm} \text{Equation (13)}$$

- In these equations, the value of the heat transfer coefficient, the dynamic coefficient of viscosity, and the Prandtl number are given by the temperature polynominal in the same way as for the case of natural convection.

Various empirical equations have been proposed for the heat transfer coefficient in case of convection heat transfer, and the following equation for calculation of the heat transfer coefficient in case of convection heat transfer has been quoted from a publication of assistant professor Takamura.

(4) In addition to the above mentioned convection, heat transfer at the surface of a solid body also is executed by radiation. In the case of a small body being placed in a large space, as in the case of steam pipes etc. in a room, the heat transfer quantity by radiation from the body is expressed by equation (14).

$$q = 20.43\ \varepsilon \left\{ \left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4 \right\} \hspace{2cm} [kJ/(m^2 \cdot h)] \hspace{1cm} \text{Equation (14)}$$

Where T_1 is the absolute temperature of the body and T_2 is the absolute temperature of the ambient air. In equation (14), ε is a coefficient related to the body (the body and its surface condition) and the temperature of the body, and it is called the emissivity. As shown in equation (14), the heat transfer quantity by radiation is proportional to the difference between the fourth powers of the absolute temperatures. As radiation in many cases occurs simultaneously with convection and conduction, the heat transfer quantity by radiation for practical use also is expressed in the form of an equation proportional to the temperature difference. In other words, the heat transfer coefficient for radiation is expressed by equation (15).

$$h_r = \frac{20.43 \; \varepsilon \; \left\{ \left(\dfrac{T_1}{100}\right)^4 - \left(\dfrac{T_2}{100}\right)^4 \right\}}{t_1 - t_2} \qquad [\text{kJ/(m}^2\text{•h•}^\circ\text{C)]} \quad \textbf{Equation (15)}$$

When the heat transfer coefficient for radiation is defined in this way, the total heat emission quantity by convection and radiation is expressed by equation (16).

$$q = (h_r + h_c)(t_1 - t_2) \qquad\qquad [\text{kJ/(m}^2\text{•h)]} \qquad \textbf{Equation (16)}$$

In equation (16), h_r is the heat transfer coefficient for radiation and h_c is the heat emission coefficient for convection.

(5) Overall Heat Transfer

5-1 Philosophy

When two types of fluids flow along the two surfaces of a solid body between them as shown in Figure 12.6, the heat transfer quantity from the high-temperature side to the low-temperature side is expressed as follows by combining the above explained relation equations.
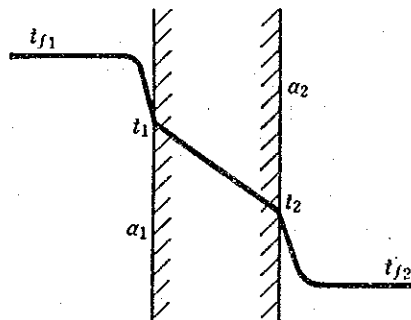

Figure 12.6 Overall heat transfer

$$q = \frac{t_{f1} - t_{f2}}{\dfrac{1}{\alpha_1} + \dfrac{b_1}{\lambda_1} + \dfrac{b_2}{\lambda_2} + \cdots\cdots + \dfrac{b_n}{\lambda_n} + \dfrac{1}{\alpha_2}}$$ [kJ/(m²•h)]   Equation (17)

where α_1 and α_2 are the heat transfer coefficients between the solid wall and the fluids on the high-temperature side and the low-temperature side, b is the thickness of the solid wall, and λ is the thermal conductivity of the solid wall.

The surface temperatures of the solid wall are given by equations (18) and (19), using the calculated heat transfer quantity.

$$t_1 = t_{f1} - \frac{q}{\alpha_1}$$ Equation (18)

$$t_2 = t_{f2} + \frac{q}{\alpha_2}$$ Equation (19)

In the case of a circular wall, the heat transfer quantity and the surface temperatures are expressed as shown in equations (20), (21), and (22).

$$q_1 = \frac{2\pi(t_{f1} - t_{f2})}{\dfrac{1}{r_1 \cdot \alpha_1} + \dfrac{1}{\lambda_1}\ln\dfrac{r_2}{r_1} + \dfrac{1}{\lambda_2}\ln\dfrac{r_3}{r_2} + \cdots\cdots + \dfrac{1}{\lambda_n}\ln\dfrac{r_{n+1}}{r_n} + \dfrac{1}{r_{n+1} \cdot \alpha_2}}$$

[kJ/m•h]   Equation (20)

$$t_1 = t_{f1} - \frac{q_1}{2\pi r_1 \cdot \alpha_1}$$ Equation (21)

$$t_2 = \frac{q_1}{2\pi r_{n+1} \cdot \alpha_2} + t_{f2}$$ Equation (22)

5-2 Calculation Sheet for the Overall Heat Transfer

With actual calculation, the heat transfer quantity can not be obtained easily, as the thermal conductivity of materials and the heat transfer coefficient for convection and radiation change according to the temperature. For example, the heat transfer coefficient of the surface depends on the surface temperature, and the surface temperature is calculated by means of the heat transfer coefficient. With a calculation sheet for multilayer insulation, first the surface temperature is assumed, and the heat transfer coefficient and the thermal conductivity of the material are obtained. Next, thus heat transfer coefficient and this thermal conductivity are used to calculate the heat transfer, and the surface temperature is calculated. These calculations are repeated until the surface temperature obtained in this way has approached the assumed surface temperature within given limits.

This calculation procedure used the Lotus 123 programming function called a macro, with notation on a work sheet and execution by specification from the keyboard. Accordingly, the work required by the user of the calculation sheet is only specification of calculation execution to the machine after the various preconditions have been set. The calculation sheet permits calculations for insulation with up to 3 layers.

(6) Economical Insulation Thickness

6-1 Philosophy

In the case of insulation of steam tubes etc., a most economical thickness exists for the thickness of the thermal insulation. In other words, when the insulation thickness is too large, this is economical from the point of view of thermal economy, but the work expense load increases. Reversely, when the insulation thickness is reduced, the work expense load is smaller, but the heat loss increases. Theoretically, there is an insulation thickness where the total of heat loss and work expense load becomes a minimum, and this is called the economical insulation thickness. Figure 12.7 shows an example for the change of the heat loss and the work expense load when the insulation thickness is changed.
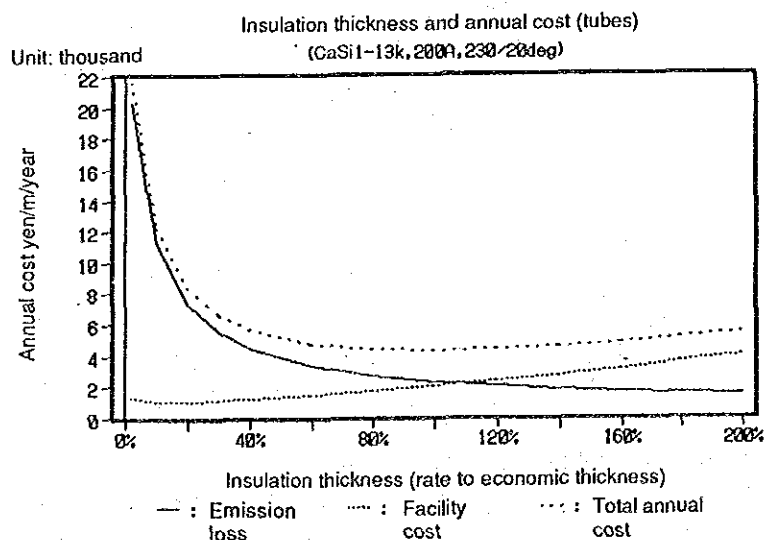

Figure 12.7   Insulation thickness and yearly expenses

As shown in this figure, there is an insulation thickness where the total of heat loss and work expense load becomes a minimum. The Japanese Industrial Standards (JIS) list calculation formulas for the economical insulation thickness, and the results for calculation of the economical insulation thickness are listed for several insulation materials on the basis of given preconditions. At the Energy Conservation Center Japan, a work sheet for calculation of the economical insulation thickness for various preconditions has been developed on the basis of the JIS philosophy. For these investigations, this calculation sheet has been used for the insulation calculations.

12-10

6-2 Explanation of the Calculation Sheet

a) Calculation of the radiation loss value

The heat loss quantity by radiation is calculated using the heat transfer calculation formula. The thermal conductivity of the insulation material is expressed by a third-order equation, and the coefficients of this third-order equation are read in by selection of the material. The loss value is calculated as the product of the radiation quantity and the heat unit price.

The heat unit price is not the heat unit price of the fuel, but for example in the case of a steam tube, it is the steam heat unit price lost by emission.

b) Calculation of the work expense load amount

The work expense load amount is obtained by multiplying the work expenses with the yearly amortization rate. The work expenses for insulation work are given by equation (23) according to the JIS.

$$P = 1.2 \ (12{,}000 \ X^{-k} + 100) \qquad\qquad [1{,}000 \ ¥/m^3] \qquad \text{Equation (23)}$$

with X: Insulation material thickness (mm)
      k : The value of the following table

Tube outer diameter (Inch)	k
1/2 to 3/4	1.09
1 to 2	1.13
$2\frac{1}{2}$ to 6	1.17
8 to 12	1.21
14 to flat surface	1.28

6-3 Calculation Method

On the work sheet, the radiation loss value obtained by the above calculation and the formula for the total amount of the yearly work expense load amount are differentiated by the thickness of the insulation material. Then the insulation thickness where the value of the differential coefficient becomes zero is the economical insulation thickness to be obtained. However, as this value can not be obtained as the solution of a numerical equation, the work sheet calculates an approximate solution by repeated calculations.

a) Use of the calculation sheet

First, the various preconditions are set, and then the calculations are executed by the macro. The conditions to be set are the numerical values enclosed in a bold frame of the work sheet screen shown in Figure 12.8. The outer diameter of the tube and the insulation material are set by selection from the menu.

```
                Economically optimum insulation  SI(Wh unit)
<Premises---Pipe/Surface>   <Pipe> (¥R:calc)              03/24      16:24
                            Eco thickness      Xp    | 0.055 | m
Inside temp      th.0  | 150 |   0.D of insulation  do    0.275   m
Room temp        th.r  |  20 |   I.D of insulation  di  | 0.1652 | m
Heat transfer  *alpha  |  12 |   Annual expense     Fp    2439   ¥/year
Heat price *       b   |   5 |   Heat loss / hour   Qp    78.4   /m/h
Annual interest    n   | 0.07|   Surface temp   th.pc    27.5   deg C
Working year       ■   |  10 |   H.conduct'y (avg)ramda.p 0.0521
Working hour      hr   |3000 |   Insul'n work pric   ap      233  th.¥/m^3
Deprec'tn rate   dep   14.2%     Insul'n material  |Calcium silicate 1-13 |
          * : Be aware of unit

                            <Plane surface> (¥S:calc)     03/24      16:24
                            Eco thickness      Xs    | 0.078 | m
Macro command:              Annual expense     Fs    3170   ¥/year
 ¥A Menu                    Heat loss / hour   Qs    82.0   /m^2/h
 ¥U Unit select  ¥P Print   Surface temp   th.sc    26.8   deg C
 ¥G Graph call   ¥X Line    H.conduct'y (avg)ramda.s 0.0520
                            Insul'n work pric   as      174  th.¥/m^3
 ¥L Protect    : Free :     Insul'n material  |Calcium silicate 1-13 |
```

Figure 12.8 Setting screen for the economical insulation calculation

6-4 Calculation Method

The Lotus 123 function for easy parameter study - What-if study - is used, and various characteristic analysis tables have been prepared. One of the most interesting points with the characteristic analysis is the relation between the heat unit price and the economical insulation thickness, and an example for this calculation is shown in Figure 12.9.
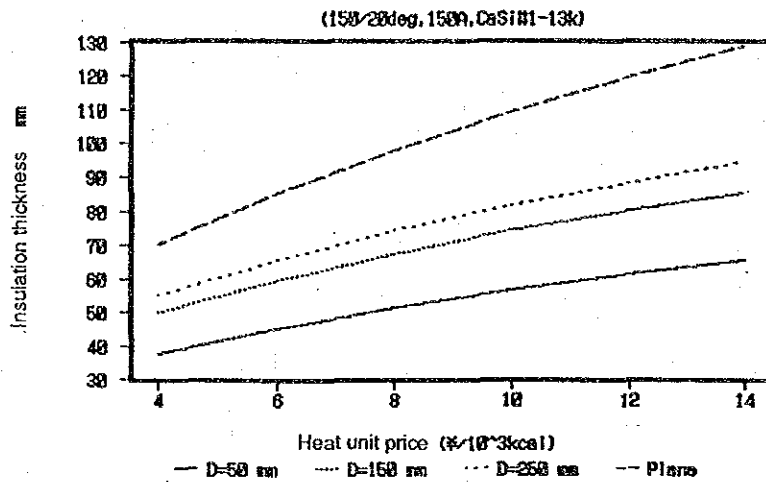
Figure 12.9   Heat unit price and economical insulation thickness

(7)   Calculation of the Radiation Quantity from the Surface Temperature

When the surface temperature of a body is known, the emission amount can be calculated from equation (24).

$$q = \alpha(t_f - t_1) \qquad\qquad [\mathrm{kJ/(m^2 \cdot h)}] \qquad \text{Equation (24)}$$

As heat transfer from the surface of a body is executed by convection and by radiation, so the heat transfer coefficient of equation (24) is the sum of the heat transfer coefficients of convection and radiation.   In the report, the above explained equations for the convection heat transfer coefficient and the radiation heat transfer coefficient are used to calculate the heat transfer quantity when the surface temperature is given.

(8)   Appendix Table

The appendix table shows the length of a tube with the same diameter, which has the same surface area as a valve or a flange. For example, the surface area of a 2″ globe valve for 20 bar is the same as that of a 2″ tube with a length of 1.28 m.

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Equivalent pipe length to valve or flange (Unit: m)

Piping Parts	$\frac{1}{2}$	$\frac{3}{4}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	4	5	6	8
Flanged Globe Valve (10bar)	1.15	1.06	1.22	1.11	1.11	1.23	1.25	1.27	1.40	1.50	1.68
Flanged Globe Valve (20bar)	1.24	–	1.21	1.20	1.28	1.50	1.56	1.58	–	1.78	1.87
Flanged Sluice Valve (10bar)	1.12	0.98	1.15	1.31	1.22	1.16	1.31	1.20	1.27	1.35	1.52
Flanged Sluice Valve (20bar)	1.29	1.13	1.32	1.23	1.53	–	1.63	1.50	–	1.92	–
Pressure Reducing Valve (10bar)	1.96	1.71	1.67	1.49	1.55	1.60	1.66	1.58	1.91	1.76	1.81
Control Valve (10bar)	–	1.72	1.84	1.56	1.60	–	1.54	–	–	1.48	–
Flange (10bar)	0.50	0.46	0.53	0.47	0.44	0.42	0.42	0.39	0.44	0.45	0.44
Flange (20bar)	0.51	0.46	0.54	0.47	0.49	0.46	0.50	0.46	–	0.56	0.51