10.6 Pump

10.6.1 Purpose of Measurement

The purpose is to grasp the actual load operation status (flow rate, pressure, temperature, electricity consumption, etc.) as compared with the pump design performance.

10.6.2 Method of Measurement (See Figure 10.6.1)

Figure 10.6.1 Pump Measuring Points

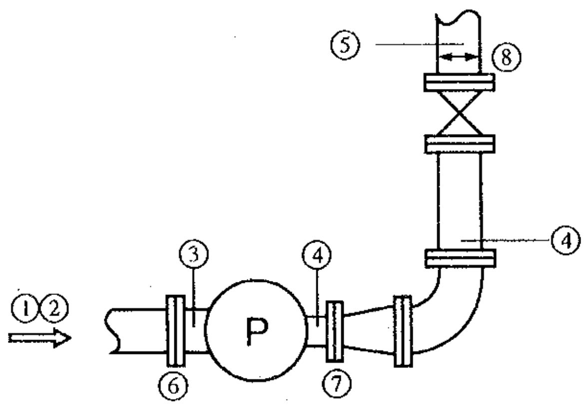


Table 10.6.1 Items to be Measured for a Pump and Measuring Equipment

Items to be Measured	Measuring Equipment	
① Fluid temperature	Thermometer	→ Specific gravity
② Flow rate	Ultrasonic flow meter	
③ Pump suction pressure	Pressure gauge	
④ Pump discharge pressure	Pressure gauge	
⑤ Pressure after passing through the flow control valve	Pressure gauge	
⑥ Pump suction port diameter		→ Suction sectional area → suction flow velocity
⑦ Pump discharge port diameter		→ Discharge sectional area → discharge flow velocity
⑧ Pipe diameter		→ Pipe internal sectional area → pipe internal flow velocity → calculation of total pump head
⑨ Voltage	Clamp meter	
⑩ Current	Clamp meter	
⑪ Electric power	Clamp meter	
⑫ Opening of a flow control valve	Visual check	→ Load

*When measurement on site is not available, use the reading on the local indicator.

Efficiency is calculated using the following shaft power calculation formula:

$$L = \frac{\gamma QH}{6120\,\eta}(1 + \alpha)$$

where

L: Shaft power [kW]
γ: Fluid weight per unit of volume [kg/m^3]
Q: Pump discharge volume [m^3/min]
H: Total pump head [m]
η: Pump efficiency
α: Tolerance

Figure 10.6.2 and Table 10.6.2 show the approximate values of η and α.

Figure 10.6.2 Standard Efficiency of General Purpose Pumps

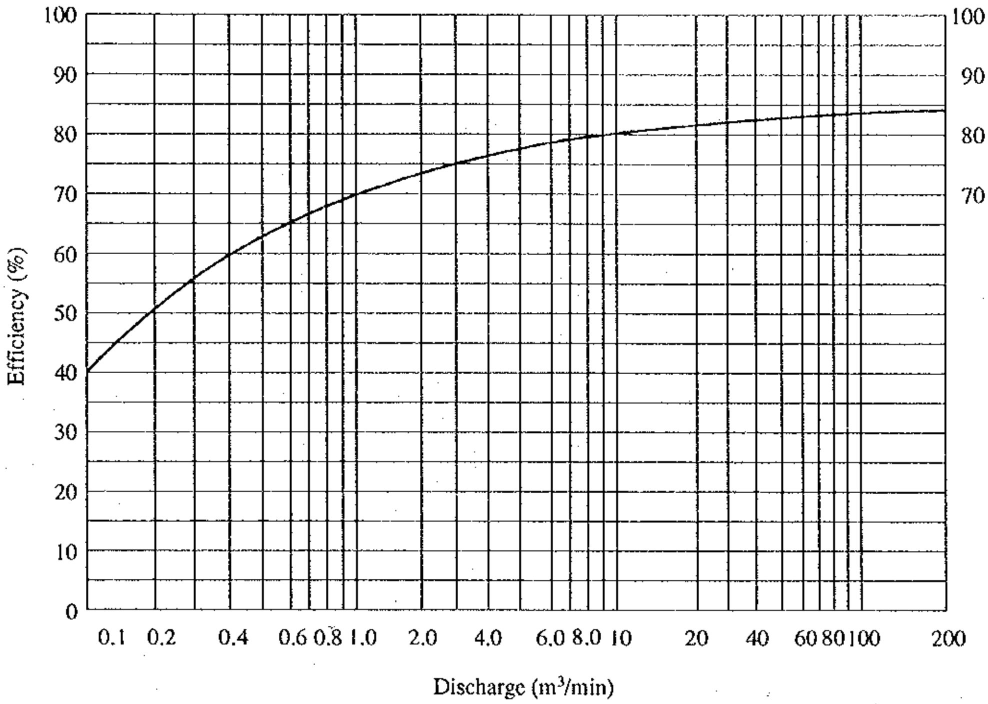


Table 10.6.2 Tolerances of Pumps

Pump Type		Tolerance (%): Fluctuation of Head is Relatively Small.	Tolerance (%): Fluctuation of Head is Relatively Large.
Volute pump	High head	15	20
	Medium, low head	10	15
Mixed flow pump		15	20
Axial flow pump		20	25

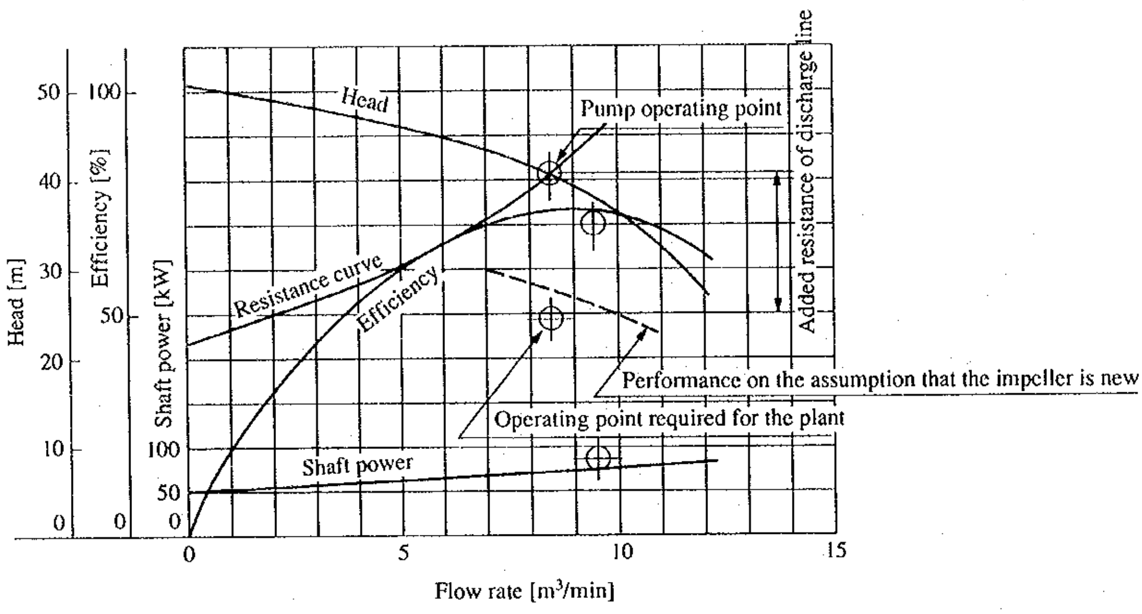
10.6.3 Method of Diagnosis

The head is calculated from the actually measured flow rate and pressure, and plotted on the pump performance curve of the manufacturer. Similarly, the flow rate and head required by the plant are recorded on the performance curve to help grasp the potential for energy conservation.

Energy conservation measures should be devised so that the current operation points coincide with the operation points required by the plant (Rotational speed control, impeller cutting, etc., for example).

Examples of pump performance curves are shown in Figure 10.6.3.

Figure 10.6.3 Pump Performance Curves



10.6.4 Energy Conservation Measures

Energy conservation measures to be taken for pumps include the following. (For details, see "IV. Guidelines".)

(1) Reduction of shaft power

Operating at the appropriate volume of water, preventing leakage, etc.

(2) Reduction of operating time

On/off runs.

(3) Replacement of pumps

A pump is replaced by one that matches the current load.

(4) Modification of impellers

Reducing the impeller outer diameter (Impeller cut)

(5) Control of the number of machines to be used

Managing the operation on a multiple machine basis

(6) Control of rotational speed

Introducing a variable frequency inverter or equivalent

(7) Adoption of high-efficiency equipment

Check List for Motor Driven Machine (1)
(30 motors of higher rank of output)

Date ____________
Surveyor ____________

Name of Shop		Location	No.
1	Name of Equipment	Number of similar Equipment	
②	Kind of motor	( ) AC ( ) Induction ( ) Wound Rotor ( ) Squirrel Cage ( ) Others ( ) Synchronous ( ) DC ( ) Series ( ) Shunt ( ) Compound	
③	Rating of Motor	Out put ______ kW Voltage ______ V Current ______ A Frequency ______ Hz RPM ______ rpm. Num. of Pole ______	
4	Starting method	( ) Full Voltage ( ) Star-delta (Y - △) ( ) Rotor-resistance ( ) Others	
5	Coupling Apparatus	( ) Direct ( ) Belt ( ) Gear ( ) Others Meterial ( ) Natural ______ Tension ______ ( ) Synthetic ______ Num. ______	
⑥	Load	( ) Pump ( ) Blower ( ) Compressor ( ) Others	
7	Kind and Density of Fulid	( ) Air ( ) Water ( ) Others ( ) Density (or Specific Gravity)	
⑧	Flow Control Method	( ) Automatic ( ) Valve ( ) Speed Control ( ) manual ( ) Damper ( ) Others	
⑨	Speed Control	( ) Motor ( ) Pole Change ( ) Voltage ( ) Mechanical ( ) Frequency ( ) Others	
10	Automatic Turn-off (when off load)	( ) Yes ( ) No	
11	Lubrication	time/year	
12	Filter cleaning	time/month	
13	Flow Chart of fluid		

Check List for Motor Driven Machine (2)

Date　　　　　Factory　　　　　Surveyor　　　　　(Blower. Pump)

Name of Shop		Location								No.		
No.	Name of Machine							Rating of Motor			kW, Pole	
	Actual Power				Temp. of Fluid	Flow m³/min Rated Actual	Pressure	Pipe dia.	Valve Position	Velocity of Fluid	Esti-mated load	Effici-ency
	Time	Volt V	Current A	Power kW	℃	Max. Min.	kg.cm²	(ID)		m/s		%

Name of Shop		Location								No.		
No.	Name of Machine							Rating of Motor			kW, Pole	
	Actual Power				Temp. of Fluid	Flow m³/min Rated Actual	Pressure	Pipe dia.	Valve Position	Velocity of Fluid	Esti-mated load	Effici-ency
	Time	Volt V	Current A	Power kW	℃	Max. Min.	kg.cm²	(ID)		m/s		%

Name of Shop		Location								No.		
No.	Name of Machine							Rating of Motor			kW, Pole	
	Actual Power				Temp. of Fluid	Flow m³/min Rated Actual	Pressure	Pipe dia.	Valve Position	Velocity of Fluid	Esti-mated load	Effici-ency
	Time	Volt V	Current A	Power kW	℃	Max. Min.	kg.cm²	(ID)		m/s		%

(1) Required Power of Blower

$$P = \frac{A \cdot Q \cdot PT}{6120 \cdot \eta} \quad (kW)$$

PT : Total Pressure (mmAq or kg/m²)
A : Allowance (1.1 - 1.3)
η : Efficiency of blower (0.72 - 0.78)
Q : Flow (m³/min)

Adequate Velocity of Fluid

Adequate Velocity	Velocity (m/sec)	Pressure (kg/cm²)
Air	8 - 15	1 - 2

(2) Required Power of Pump

$$P = \frac{A \cdot \gamma \cdot Q \cdot H}{6.12 \cdot \eta} \quad (kW)$$

A : Allowance (1.05 - 1.2)
γ : Density (kg/l)
Q : Flow (m³/min)
η : Efficiency of Pump
H : Head (m)

Adequate Velocity of Fluid

Adequate Velocity	Velocity (m/sec)	Pressure (kg/cm²)
Water	1.5 - 3.0	3.0 - 10

10.7 Management of Electricity

10.7.1 Purpose of Measurement

The purpose is to grasp the electricity consumption in the factory as a whole, and in each process, each line, and each electric facility.

10.7.2 Method of Measurement (See Figure 10.7.1)

Measurement time: On the basis of minute, hour, day or month

Figure 10.7.1 Measuring Points for Electricity Management

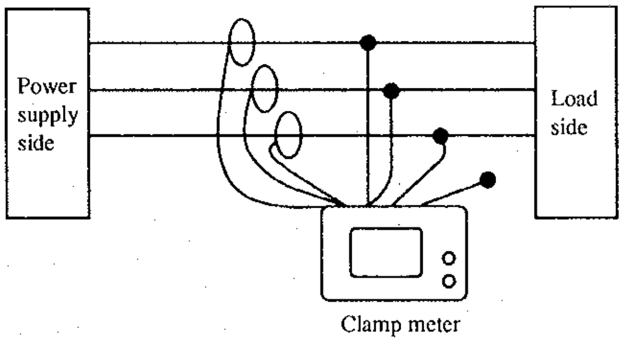


Table 10.7.1 Items to be Measured and Measuring Equipment

Items to be Measured	Measuring Equipment
① Watt-hour	Clamp meter
② Electric power	Clamp meter
③ Voltage	Clamp meter
④ Current	Clamp meter
⑤ Power factor	Clamp meter

10.7.3 Method of Diagnosis

(1) Grasping the load factor

Load factor is calculated based on the measurement data using the following equation:

Load curves such as those shown in Figure 10.7.2 are created.

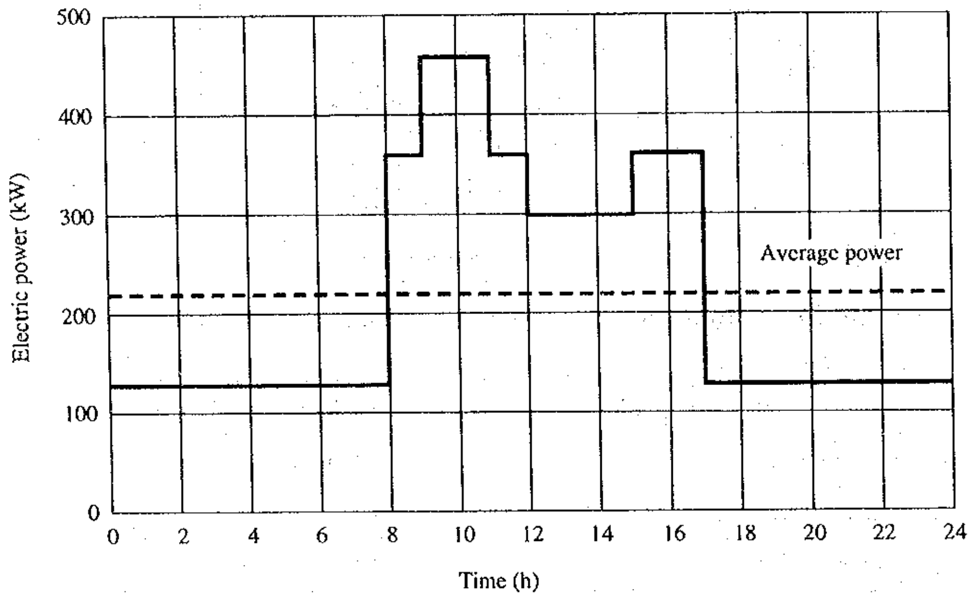
Based on this data, the method of reducing the maximum elctricity necessary for improving the load factor and the method of using electricity on an even basis are to be discussed.

$$\text{Load factor} = \frac{\text{Watt-hour consumed for the specified period (kWh)}}{\text{Maximum electric power (kW)} \times \text{period (day·hour)}} \times 100\ [\%]$$

or

$$\text{Load factor} = \frac{\text{Average electric power (kW)}}{\text{Maximum electric power (kW)}} \times 100\ [\%]$$

Figure 10.7.2 Load Curves



(2) Grasping voltage levels

Electric facilities are designed to perform most efficiently when they are used at their rated voltage.

Thus, the voltage at each portion of the power distribution system, from initial power receiving facilities to end terminals, should be checked, and adjustments should be made to bring the terminal voltage of each facility to its rated voltage.

(3) Grasping the power factor

The present factor should be grasped from the measurement data, and methods to install effective capacitors should be studied.

(4) Grasping the electricity intensity

The electricity intensity for each month should be compiled from operation records, etc.

Factors for monthly fluctuations should be understood and studied to find out whether or not there is room for further improvements.

$$\text{Electricity intensity} = \frac{\text{Amount of electricity consumption (kWh)}}{\text{Production amount (m, } m^2\text{, } m^3\text{, t, number of pieces, etc.)}}$$

10.7.4 Energy Conservation Measures

Energy conservation measures to be taken for electricity management include the following: (For details, see "IV. Guidelines".)

(1) Improving the load factor

The load should be shifted to operating hour under light loads, and equipment maintenance, load management, and use of load control devices should be carried out for this purpose.

(2) Improvement of power factor

Introduction of a power capacitor and other such measures should be taken.

(3) Improvement of electricity intensity

Operation record control, electricity control, equipment maintenance, process control, quality control, etc. should be performed.

(4) Reducing the electric charge

Check List for Electric Power Management (1)

Date ________
Surveyor ________

Factory Name ________
Electric Power Supplier ________
Electric System ________

(1) Phase ________ (2) Frequency ____ Hz (3) Receiving Voltage ____ V

1	General	
	(1) To be equipped with One line Diagram	Yes ( ) No ( )
	(2) Power Distribution Map	Yes ( ) No ( )
	(3) To be equipped with Main Electric Machine List	Yes ( ) No ( )
	(4) To record total power consumption every month	· from Utility service Yes ( ) No ( ) · from Non-Utility service Yes ( ) No ( )
	(5) To examine cause of power consumption variance	done ( ) Not done ( )
	(6) Content of contract with electric supplier	◎ Contract kW ____ kW ◎ Demand ____ kW Actual max. kW ____ kW ◎ Demand Charge ____ PLN per kW ◎ Energy Charge ____ PLN per kW ◎ Contract Power Factor ____ % Actual Power Factor ____ % Power Factor bonus or penalty Yes ( ) No ( ) ◎ Time Zone Charge ____ % ◎ Seasonal Charge ____ PLN per kW · Discount for Load Control ____ PLN per kW · Others Yes ( ) No ( )
	Annual change of contract	
	(7) Voltage and frequency of source	· Voltage ____ V (Rating) range of fluctuation (__~__) · Frequency ____ (Rating) range of fluctuation (__~__)
	(8) Organ. of electric energy conservation	
	(9) Problem to be solved in electric system (concretely)	

Check List for Electric Power Management (2)

2	Electric power consumption rate (EPCR)	
	(1) To calculate EPCR by major product monthly (annually)	Yes ( ) No( )
	(2) To calculate EPCR by process or use	• Process Name • EPCR ______kWh/______ • Ratio of Electric Power Charge per Production Cost ______%
	(3) To be equipped with Main Electric Machine	Yes ( ) No( )
	(4) Numerical EPCR target	• Process Name • Target of EPCR ______kWh/______
	(5) Interruption time of service per year	• by Fault Supplier side ____/year____time cause Factory side ____/year____time cause • for Maintenance ____/year____time • Others ____/year____time cause
	(6) Defective ratio of product	______%
	(7) Grasp condition of power system	

	Max. power	Power consumption	Power factor
○ Total factory	Yes ( ) No( )	Yes ( ) No( )	Yes ( ) No( )
○ Each trans.	Yes ( ) No( )	Yes ( ) No( )	Yes ( ) No( )
Each line	Yes ( ) No( )	Yes ( ) No( )	Yes ( ) No( )
Each process	Yes ( ) No( )	Yes ( ) No( )	Yes ( ) No( )
Each use	Yes ( ) No( )	Yes ( ) No( )	Yes ( ) No( )
Each building	Yes ( ) No( )	Yes ( ) No( )	Yes ( ) No( )
Others	Yes ( ) No( )	Yes ( ) No( )	Yes ( ) No( )

	(8) Calibration of meters	• On board Yes ( ) No( ) interval • Standard Yes ( ) No( ) interval

Check List for Electric Power Management (3)

3	(1) To record daily and monthly power consumpt. by process or use (annually) (2) To make daily and monthly load curve (annually) (3) To cut peak demand or shift load (4) To calculate load factor	Yes ( ) No( ) Yes ( ) No( ) Yes ( ) No( ) Yes ( ) No( )
4	Power factor (1) Monthly variance of power factor (2) To improve power factor by condenser (3) Power factor control system	January ~ December Yes ( ) No( ) connection point Capacity : Yes ( ) No( ) manual ( ) automatic ( )
⑤	Substation Receiving transformer	

Capac. (kVA)	No. Unit	Phase	Voltage (pry/sry)	Total loss	No load loss	load loss	Power fluct.	p. f fluct.	Operating hour/M(Y)

Test report	Yes ( ) No( )

Check List for Electric Power Management (4)

5

(1) Meters on a receiving panel
- equipped or not
- Kept in good or not

	Voltage	Ampere	kW	kWh	kvar	kvarh	Hz	p.f
primary								
secondary								

(2) Load by use

(2)-1 Capacity

Machine	Blower	Air Compressor	Pump	Heater	Lighting	Air Condi.	Others	Total
kW %	kW %	kW %	kW %	kW %	kW %	kW %	kW %	kW 100.0%

(2)-2 Actual power

Machine	Blower	Air Compressor	Pump	Heater	Lighting	Air Condi.	Others	Total
kW %	kW %	kW %	kW %	kW %	kW %	kW %	kW %	kW 100.0%

(3) To measure transformer load — Yes ( ) No( )

(4) To divide transformer by use — Yes ( ) No( )

(5) To turn off transformer when off load — Yes ( ) No( )

⑥ Distribution system

Name of equipment ________________ Use for ________________

Capac. (kVA)	No. Unit	Phase	Voltage (pry/sry)	Total loss	No load loss	load loss	Power fluct.	p. f fluct.	Operating hour/M(Y)
Test report			Yes ( ) No( )						

Check List for Electric Power Management (5)

6	(1) To measure each branch circuit load (2) Voltage drop of each branch circuit load (3) Balance in three phases	Yes ( ) No( ) Voltage in a panel : E1 $\frac{E1 - E2}{=} \times 100$ ____ % Voltage at end use : E2 Voltage ____ : ____ : ____ Current ____ : ____ : ____
7	Motor (1) To measure load of motor over 7.5 kW (2) To lubricate gear and motor periodically (3) To turn off motor when off load (4) To improve power factor by condenser	 Yes ( ) No( ) Yes ( ) No( ) Yes ( ) No( ) Yes ( ) No( )
8	Motor driven machine (1) Flow control of blowers or pumps (2) To check leakage of air or water (3) To keep pressure of compressed air (4) To keep delivery pressure of pump adequately	 Motor speed control Operation numbers control Damper or valve control Others Yes ( ) No( ) Yes ( ) No( ) Yes ( ) No( )

10.8 Boiler

10.8.1 Purpose of Measurement

The purpose is to measure the items necessary for boiler heat balance.

10.8.2 Method of Measurement (See Figure 10.8.1) .

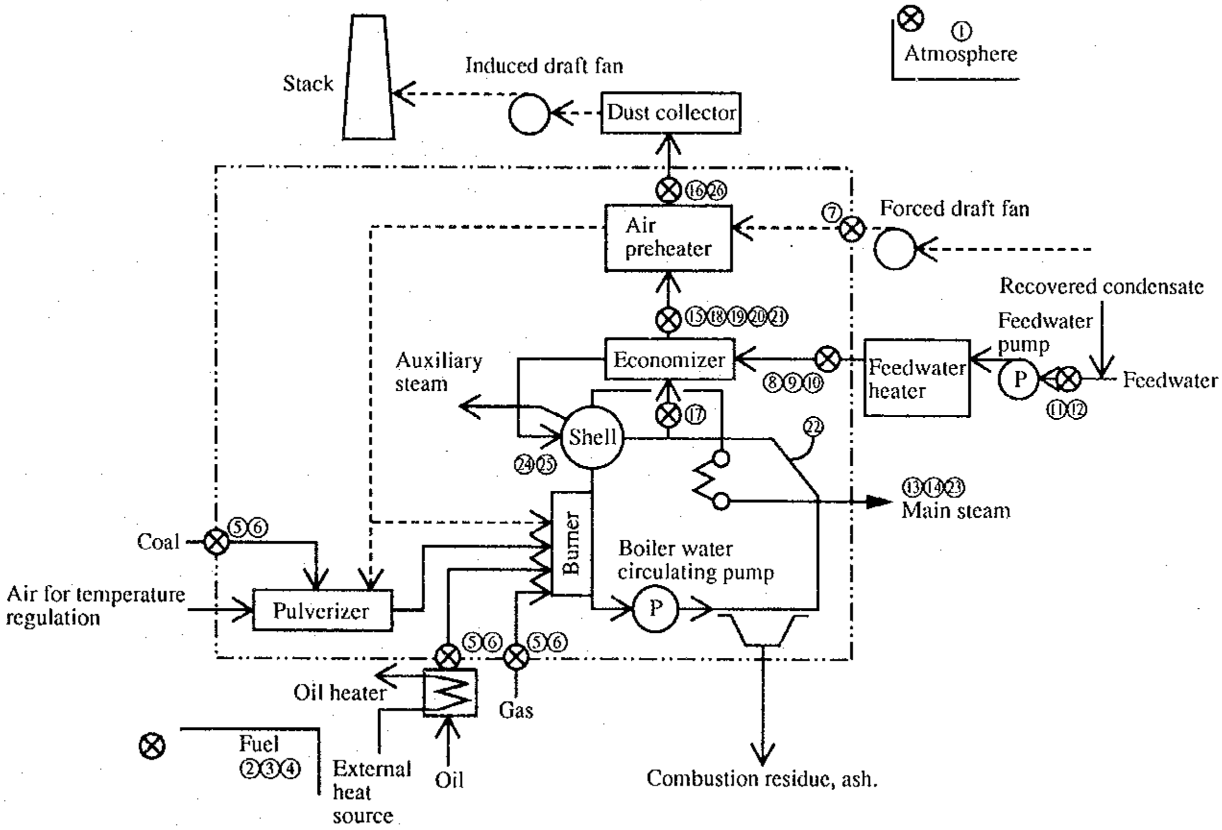
An outline of the applicable boiler is entered in the list shown in Table 10.8.1. (The measurement method conforms to JIS B 8222(1993).)

Measurement interval: Every 30 minutes

Measurement time : 2 hours or more (4 hours or more for a coal-fired boiler)

Notes : The boiler should be kept operating under the same condition for one hour or more.
Neither blowing nor soot blowing should be performed.

Figure 10.8.1 Boiler Measuring Points



—··—··— Range of heat balance ⊗ Measuring points

Table 10.8.1 Equipment Outline

Factory name and address			
Boiler manufacturer name			
Boiler serial No. and date of manufacture			
Boiler body	Type and model		
	Maximum continuous (rated) steam generation		t/h
	Maximum working pressure		kgf/cm^2
	Normal pressure		kgf/cm^2
Economizer	Type		
	Heating area		m^2
Air pre-heater	Type		
	Heating area		m^2
Combustion equipment	Type		
	Burner capacity		kg/h
	Number of burners		
	Fire grate area		m^2
Combustion chamber	Combustion chamber volume		m^3
Draft system	Draft method		
	Forced draft fan	Type	
		Capacity	$m^3/min(°C)$
		Pressure	mmAq
	Induced draft fan	Type	
		Capacity	$m^3/min(°C)$
		Pressure	mmAq
	Stack	Size (Diameter × height)	m × m
		Names and number of equipment in common use	

Table 10.8.2 Items to be Measured and Measuring Equipment

	Items to be Measured	Symbol	Unit	Measuring Equipment
①	Atmospheric temperature	t_{aO}	°C	Bar thermometer
②	Fuel components			
	Carbon	c	kg/kg·fuel	Laboratory analytical value
	Hydrogen	h	kg/kg·fuel	Laboratory analytical value
	Oxygen	o	kg/kg·fuel	Laboratory analytical value
	Sulfur	s	kg/kg·fuel	Laboratory analytical value
	Nitrogen content	n	kg/kg·fuel	Laboratory analytical value
	Ash content	a	kg/kg·fuel	Laboratory analytical value
	Water content	w	kg/kg·fuel	Laboratory analytical value
③	Lower calorific value of fuel	H_l	kcal/kg	(Calculated from higher calorific value Hh)
④	Specific heat of fuel	c_f	kcal/kg°C	
⑤	Fuel temperature	t_f	°C	Thermometer
⑥	Fuel flow rate	W_f	kg/h	Flow meter
⑦	Combustion air temperature	t_{ab}	°C	Thermometer
⑧	Feedwater temperature	t_w	°C	Thermometer
⑨	Feedwater flow rate (Steam flow rate)	W_w	kg/h	Ultrasonic flow meter
⑩	Feedwater pressure		kg/cm^2g	Pressure gauge
⑪㉔	pH of feedwater and boiler water		pH	pH meter
⑫㉕	Electric conductivity of feedwater and boiler water		μ S/cm	Conductivity meter
⑬	Temperature of generated steam	t_s	°C	Thermometer
⑭	Pressure of generated steam	P_s	kg/cm^2g	Pressure gauge (Reading)
⑮	Exhaust gas temperature (AH inlet)	t_{g1}	°C	Thermocouple
⑯	Exhaust gas temperature (AH outlet)	t_{g2}	°C	Thermocouple
⑰	Exhaust gas temperature (Boiler body outlet)	t_{g3}	°C	Thermocouple
⑱	Exhaust gas O_2	(O_2)	%	O_2 meter
⑲	Exhaust gas CO_2	(CO_2)	%	CO, CO_2 meter
⑳	Exhaust gas CO	(CO)	%	CO, CO_2 meter
㉑	Exhaust gas pressure		mmH_2O	Digital fine differential pressure gauge
㉒	Boiler surface temperature		°C	Surface thermometer
㉓	Temperature of the heat-insulated surface of steam pipe		°C	Surface thermometer
㉖	Unburnt carbon content in dust (For a coal-fired boiler)	u_d	Weight %	Laboratory analytical value

10.8.3 Method of Diagnosis

In order to perform a heat balance based on the measured value and calculated value, heat input, heat output and heat loss amount are calculated to obtain the boiler efficiency.
Heat consumption state can be identified by completing the heat balance sheet.

(1) Oil-fired boiler

a. Heat input

1) Lower calorific value of fuel: H_l [kcal/kg]

$$H_l = H_h - 5.9\,(9h + w) \qquad \text{.......... (1-1)}$$

H_h: Higher calorific value [kcal/kg]
h : Hydrogen content in fuel [Weight %]
w : Water content in fuel [Weight %]

2) Heat input of fuel: Q_f [kcal/kg]

$$Q_f = c_f \cdot (t_f - t_{ao}) \qquad \text{.......... (1-2)}$$

c_f: Specific heat of fuel [kcal/kg°C]
t_f : Fuel temperature at burner inlet [°C]
t_{ao}: Reference temperature (Outside air temperature or ambient temperature) [°C]

3) Heat input of combustion air: Q_a [kca/kg]

$$Q_a = m \cdot A_o \cdot c_a \cdot (t_{ab} - t_{ao}) \qquad \text{.......... (1-3)}$$

m: Air ratio

$$m = \frac{21}{21 - 79\left[\frac{(O_2) - 0.5\,(CO)}{(N_2)}\right]} = \frac{21}{21 - (O_2)} \qquad \text{.......... (1-4)}$$

$$(N_2) = 100 - [(CO_2) + (O_2) + (CO)]$$

(CO_2), (O_2), (CO), (N_2): Carbon dioxide (Carbonic gas), oxygen, carbon monoxide, and nitrogen in the dry combustion gas [Volume %]

A_o: Theoretical air volume [m³/kg]

$$A_o = \frac{1}{100}\left[8.89c + 26.7\left(h - \frac{o}{8}\right) + 3.3s\right] \quad \text{(1-5)}$$

c, h, o, s, n, a, w: Carbon, hydrogen, oxygen, sulfur, nitrogen, ash content, and water content in fuel [Weight %]

$c + h + o + s + n + a + w = 100$ [%]

c_a: Specific heat of air = 0.31 [kcal/m^3·°C]

t_{ab}: Combustion air temperature (Outlet of forced draft fan) [°C]

t_{ao}: Reference temperature (Outside air temperature or ambient temperature) [°C]

4) Feedwater heat input: Q_w [kcal/kg]

$$Q_w = \frac{W_w}{W_f} \cdot c_w \cdot (t_w - t_{ao}) \quad \text{(1-6)}$$

W_w: Feedwater flow rate [kg/h]
W_f : Fuel consumption rate [kg/h]
t_w : Feedwater temperature [°C]
c_w : Specific heat of water ≒ 1 [kcal/kg°C]

5) Total heat input: Q_{in} [kcal/kg]

$$Q_{in} = H_l + Q_f + Q_a + Q_w \quad \text{(1-7)}$$

b. Heat output

1) Calorific value of generated steam: Qs [kcal/kg]

$$Q_s = \frac{W_s}{W_f} \cdot (h_s - h_w) \quad \text{(1-8)}$$

W_s: Amount of generated steam = Ww [kg/h]
W_f: Fuel consumption [kg/h]
h_s : Enthalpy of generated steam [kcal/kg]
h_w : Enthalpy of feedwater [kcal/kg]

When no superheater is available: $h_s = h'' - (1 - x)\, r$ .... (1-9)

h'':Enthalpy of saturated steam [kcal/kg]
r: Latent heat of vaporization [kcal/kg]
x: Dryness of steam (based on 0.98 when no measurement is performed)

2) Heat loss due to exhaust gas: L_g [kcal/kg]

$L_g = G \cdot c_g \cdot (t_{g2} - t_{a0})$ .... (1-10)

G: Volume of actual exhaust gas per kg of fuel [m³/kg]

$G = G_o + G_w + (m - 1) A_o$ .... (1-11)

G_o: Volume of theoretical dry exhaust gas [m³/kg]

$$G_o = \frac{1}{100} [8.89c + 21.1 (h - \frac{o}{8}) + 3.3s + 0.8n] \quad \text{......} (1\text{-}12)$$

G_w: Volume of water vapor in exhaust gas [m³/kg]

$$G_w = \frac{1}{100} [1.24 (9h + w)] \quad \text{......} (1\text{-}13)$$

m : Air ratio .... (1-4)

A_o: Theoretical air volume [m³/kg] .... (1-5)

c_g: Specific heat of exhaust gas ≒ 0.33 [kcal/Nm³·°C]

t_{g2}: Temperature of exhaust gas at AH outlet [°C]

$$\therefore G = \frac{1}{100} (5.6h + 0.7o + 0.8n + 1.24w) + mA_o \quad \text{......} (1\text{-}14)$$

When no elemental analysis is performed, air volume Ao per kg of fuel and exhaust gas volume Go can be obtained using the following simple equations:

$$A_o = \frac{12.38}{10,000} \cdot H_l - 1.36 \ [m^3/kg] \quad \text{......} (1\text{-}15)$$

$$G_o + G_w = \frac{15.75}{10,000} \cdot H_l - 3.91 \ [m^3/kg] \quad \text{......} (1\text{-}16)$$

H_l: Lower calorific value of fuel [kcal/kg]

3) Other heat loss: L_r [kcal/kg]

$L_r = Q_{in} - (Q_s + L_g)$ .... (1-17)

(2) Coal-fired boiler

a. Fuel composition

$$c = \frac{100 - w}{100} \times c_o \ [\%] \qquad n = \frac{100 - w}{100} \times n_o \ [\%]$$

$$h = \frac{100 - w}{100} \times h_o \ [\%] \qquad a = \frac{100 - w}{100 - w_1} \times a_1 \ [\%]$$

$$s = \frac{100 - w}{100} \times s_o \ [\%] \qquad o = 100 - (c + h + s + n + a + w) \ [\%]$$

c, h, s, n, a, o : Contents of carbon, hydrogen, combustible sulfur, nitrogen, ash, and oxygen on an operation basis (Weight %)

w : Total water content (on an operation basis) [%]

w_1 : Water content by proximate analysis (constant humidity basis) [%]

a_1 : Ash content by proximate analysis (constant humidity basis) [%]

c_o, h_o, s_o, n_o [%]: Elemental analysis value (Dry basis)

$c_1 = c - c_2$: Content of carbon actually combusted [%] .... (2-1)

$c_2 = a \cdot u/(100 - u) \fallingdotseq a \cdot u_d/(100 - u_d)$: Unburnt carbon content [%] .... (2-2)

a : Ash content in fuel used [%]
u : Average unburnt carbon content in residue [Weight %]
u_d: Unburnt carbon content in dust [Weight %]

b. Heat input

1) Lower calorific value of fuel: H_l [kcal/kg]

Higher calorific value $H_h = \frac{100 - w}{100 - w_1} \times H_o$ [kcal/kg] .... (2-3)

H_o: Higher calorific value on constant humidity basis [kcal/kg]

Lower calorific value $H_l = H_h - 5.9\,(9h + w)$ [kcal/kg] .... (2-4)

2) Heat input of fuel (When fuel is preheated by external heat source): Q_f [kcal/kg]

$$Q_f = c_f\,(t_f - t_{ao}) \quad \text{.......... (2-5)}$$

c_f: Specific heat of coal = 0.25 [kcal/kg°C]
t_f : Coal (pulverized) temperature after heating [°C]
t_{ao}: Reference temperature (Outside air temperature or ambient temperature) [°C]

3) Heat input of combustion air: Q_a [kcal/kg]

$$Q_a = m \cdot A_o \cdot c_a \cdot (t_{ab} - t_{ao}) \quad \text{.......... (2-6)}$$

m: Air ratio

$$m = \frac{21}{21 - 79\left[\frac{(O_2) - 0.5\,(CO)}{(N_2)}\right]} = \frac{21}{21 - (O_2)} \quad \text{.......... (1-4)}$$

A_o: Theoretical air volume [m³/kg]

$$A_o = \frac{1}{100}\left[8.89c_1 + 26.7\left(h - \frac{o}{8}\right) + 3.3s\right] \quad \text{.......... (2-7)}$$

$$c_1 = c - c_2\ [\%] \quad \text{.......... (2-1)}$$

c_a: Specific heat of air = 0.31 [kcal/m³·°C]

t_{ab}: Combustion air temperature (at the outlet of forced draft fan) [°C]

t_{ao}: Reference temperature (Outside air temperature or ambient temperature) [°C]

4) Feedwater heat input: Q_w [kcal/kg]

$$Q_w = \frac{W_w}{W_f} \cdot c_w \cdot (t_w - t_{ao}) \quad \text{.......... (2-8)}$$

W_w: Feedwater flow rate [kg/h]
W_f: Fuel consumption rate [kg/h]
t_w : Feedwater temperature [°C]
c_w : Specific heat of water = 1 [kca/kg°C]

5) Total heat input: Q_{in} [kcal/kg]

$$Q_{in} = H_l + Q_f + Q_a + Q_w \quad \text{.......... (2-9)}$$

c. Heat output

1) Absorption heat of generated steam (Effective heat output): Q_s [kcal/kg]

$$Q_s = \frac{W_s}{W_f}(h_s - h_w) \quad \text{(2-10)}$$

W_s: Generated steam volume per kg of fuel [kg/h]
W_f: Fuel consumption [kg/h]
h_s : Enthalpy of generated steam [kcal/kg]
h_w : Enthalpy of feedwater [kcal/kg]

When no superheater is available: $h_s = h'' - (1 - x)\, r$ .... (1-9)

2) Exhaust gas heat loss: L_g [kcal/kg]

$$L_g = GC_g (t_{g2} - t_{ao}) \quad \text{(2-11)}$$

G: Volume of actual exhaust gas per kg of fuel [m^3/kg]

$$G = G_o + G_w + (m - 1) A_o \text{ [m}^3\text{/kg]} \quad \text{(2-12)}$$

G_o: Theoretical dry exhaust gas volume [m^3/kg]

$$G_o = \frac{1}{100}[8.89c_t + 21.1(h - \frac{o}{8}) + 3.3s + 0.8n] \quad \text{(2-13)}$$

G_w: Volume of water vapor in exhaust gas [m^3/kg]

$$G_w = \frac{1}{100}[1.24(9h + w)] \quad \text{(2-14)}$$

m : Air ratio .... (1-4)

A_o: Theoretical air volume [m^3/kg] .... (2-7)

c_g: Specific heat of exhaust gas = 0.33 [kcal/$Nm^3 \cdot °C$]

t_{g2}: Exhaust gas temperature at AH outlet [°C]

When no elemental analysis is performed, air volume Ao per kg of fuel and exhaust gas volume Go can be obtained using the following simple equations:

$$A_o = 1.01 \cdot \frac{H_l}{1{,}000} + 0.56\ [m^3/kg] \quad \text{.......... (2-15)}$$

$$G_o + G_w = \frac{0.904\, H_l}{1{,}000} + 1.67\ [m^3/kg] \quad \text{.......... (2-16)}$$

3) Heat loss due to incomplete combustion gas: L_2 [kcal/kg]

$$L_2 = 30.1\ [G_o + (m - 1)\ A_o]\ (CO) \quad \text{.......... (2-17)}$$

This applies also to both liquid and gas fuel except that the unit is [kcal/Nm³]for gas fuel.

(CO): Carbon monoxide in dry basis combustion gas [Volume %]

4) Heat loss due to unburnt carbon in residue: L_3 [kcal/kg]

$$L_3 = 81\ c_2 \quad \text{.......... (2-18)}$$

c_2: Unburnt carbon content [%]

5) Other heat loss: L_r [kcal/kg]

$$L_r = Q_{in} - (Q_s + L_g + L_2 + L_3) \quad \text{.......... (2-19)}$$

(3) Gas-fired boiler

a. Heat input

1) Lower calorific value of fuel: H_l [kcal/Nm³·fuel]

$$H_l = H_h - 470\ G_w \quad \text{.......... (3-1)}$$

H_h: Analysis value (Higher calorific value) [kcal/Nm³·fuel]

G_w: Volume of water vapor in fuel [m³/Nm³·fuel]

$$G_w = \frac{1}{100}\ [(h_2) + \frac{1}{2}\ \Sigma n\,(C_mH_n) + w_v] \quad \text{.......... (3-2)}$$

(h_2), (C_mH_n), Wv: Hydrogen, hydrogen carbonate, and water vapor content in fuel [Volume %]

2) Heat input of combustion air: Q_a [kcal/Nm³·fuel]

$$Q_a = m \cdot A_o \cdot c_a \cdot (t_{ab} - t_{ao}) \quad \text{.......... (3-3)}$$

m: Air ratio .... (1-4)

A_o: Theoretical air volume [m³/Nm³·fuel]

$$A_o = \frac{1}{21} [\Sigma (m + \frac{1}{4} n) (C_m H_n) + \frac{1}{2} co + \frac{1}{2} (h_2) - O_2] \quad \text{.......... (3-4)}$$

co, o_2: Carbon monoxide and oxygen content in fuel [Volume %]

c_a : Specific heat of air = 0.31 [kcal/m³·°C]

t_{ab}: Combustion air temperature (at forced draft fan outlet) [°C]

t_{ao}: Reference temperature (Outside air temperature or ambient temperature) [°C]

3) Feedwater heat input: Q_w [kcal/Nm³·fuel]

$$Q_w = \frac{W_w}{W_f} \cdot c_w \cdot (t_w \cdot t_{ao}) \quad \text{.......... (3-5)}$$

W_w: Feedwater flow rate [kg/h]
W_f : Fuel consumption [Nm³/h]
t_w : Feedwater temperature [°C]
c_w : Specific heat of water ≒ 1 [kcal/kg°C]

4) Total heat input: Q_{in} [kcal/Nm³·fuel]

$$Q_{in} = H_l + Q_a + Q_w \quad \text{.......... (3-6)}$$

b. Heat output

1) Calorific value of generated steam: Q_s [kcal/Nm³·fuel]

$$Q_s = \frac{W_s}{W_f} (h_s - h_w) \quad \text{.......... (3-7)}$$

W_s : Amount of generated steam = W_w [kg/h]
W_f : Fuel consumption [Nm³/h]
W_w: Flow rate of feedwater [kg/h]
h_s : Enthalpy of generated steam [kcal/kg]
h_w : Enthalpy of feedwater [kcal/kg]

When no superheater is available: $h_s = h'' - (1 - x)\, r$ .... (1-9)

2) Heat loss due to exhaust gas: L_g [kcal/Nm³·fuel]

$L_g = G \cdot c_g (t_{g2} - t_{ao})$ .... (3-8)

G: Volume of actual exhaust gas per Nm³ of fuel [m³/Nm³-fuel]

$G = G_o + G_w + (m - 1) A_o$ [m³/Nm³· fuel] .... (3-9)

G_o: Theoretical dry base exhaust gas [m³/Nm³·fuel]

$$G_o = \frac{1}{100} [\Sigma (4.76m + 0.94n)(C_mH_n) + 2.88 co + 1.88 (h_2) + y - 3.76 O_2]$$ .... (3-10)

G_w: Volume of water vapor in fuel [m³/Nm³·fuel]

$$G_w = \frac{1}{100} [(h_2) + \frac{1}{2} \Sigma n (C_mH_n) + W_v]$$ .... (3-2)

m : Air ratio

A_o: Theoretical air volume [m³/Nm³·fuel]

$$A_o = \frac{1}{21} [\Sigma (m + \frac{1}{4}n) (C_mH_n) + \frac{1}{2}co + \frac{1}{2} (h_2) - O_2]$$ .... (3-4)

c_g: Specific heat of exhaust gas ≒ 0.33 [kcal/Nm³·°C]

t_{g2}: Exhaust gas temperature at AH outlet [°C]

t_{ao}: Reference temperature (Outside air temperature or ambient temperature) [°C]

y : Incombustible gas [Volume %]

Here, the following relationship is established among the fuel components:

$\Sigma (C_mH_n) + co + h_2 + o_2 + y + w_v = 100$ (%)

When no elemental analysis is performed, air volume Ao per Nm³ of fuel and exhaust gas volume Go can be obtained using the following simple equations:

$$A_o = \frac{11.2}{10,000} \cdot H_l \text{ [m}^3\text{/Nm}^3 \cdot \text{fuel]}$$ .... (3-8)

$$G_o + G_w = \frac{12.25}{10,000} \cdot H_l \text{ [m}^3\text{Nm}^3 \cdot \text{fuel]}$$ .... (3-9)

3) Other heat loss: L_r [kcal/Nm³·fuel]

$$L_r = Q_{in} - (Q_s + L_g) \quad \text{(3-10)}$$

[Remark] When heat loss due to radiation, L_{ra}, is considered:

The heat loss in the case of a coal-fired boiler is obtained as follows. (which also applies to oil-fired and gas-fired boilers)

$$L_r = Q_{in} - (Q_s + L_g + L_2 + L_3 + L_{ra})$$

where

$$L_{ra} = \frac{1}{100} \cdot l_r \cdot H_l = \frac{1}{100} \cdot l_{rh} \cdot H_h$$

l_r : Radiation heat loss in lower calorific value H_l [%]
l_{rh}: Radiation heat loss in higher calorific value H_h [%]
(See Table 10.8.3.)

Table 10.8.3 Typical Values of Radiation Heat Loss in Water Tube Boilers and Drum Boilers

Boiler Type	Capacity and Structure	Heat Loss due to Radiation (*) at the Rated Load (Based on Higher Calorific Value)
A	Water tube boilers and smoke tube boilers of rated output of 5 MW or more	0.3 %
B	Water tube boilers and smoke tube boilers of rated output from 2 MW to less than 5 MW	0.5 %
C	Water tube boilers and smoke tube boilers of rated output of less than 2 MW	1.0 %
D	Smoke tube boilers of the brickwork structure and of the dryback type, and boilers with the brickwork bottom	1.5 %
E	Water tube boilers of the brickwork structure with the water-cooled wall	2.0 %
F	Water tube boilers of the brickwork structure without a water-cooled wall	2.5 %
G	Lancashire and Cornish boilers of the brickwork structure	4.0 %

* The percentages of radiation heat loss (%) in the heat input under the rated load are indicated.(**)
**The percentage at the load other than the rated one must be multiplied by the following.

$$\left(\frac{\text{Fuel consumption at rated load}}{\text{Fuel consumption at actual load}}\right)$$

Table 10.8.4 and Table 10.8.5 summarize the results of the above heat balance.

Table 10.8.4 Measurement Results (1/2)

Test Date and Time			
Person in charge			
Weather and outside air temperature			°C
Dry bulb and wet bulb temperatures of the outside air			°C
Testing time (hour)			h
Load factor			%
Fuel	Kind and brand of fuel		
	Mixing ratio		
	Operating temperature		°C
	Water content or total water content		%
	Proximate analysis	Analysis value	%
		Actual value	
	Element analysis	Analysis value	%
		Actual value	%
	Calorific value	Measured value	kcal/kg (or m^3)
		Actual value	kcal/kg (or m^3)
	Consumption	Total consumption	kg (m^3)
		Consumption per hour	kg (m^3)/h
Combustion system condition			
Feed-water	Total amount of feedwater (compensated value)		kg
	Feedwater amount per hour		kg/h
	Feedwater amount per unit quantity of fuel		kg/kg
	Economizer inlet temperature		°C
	Boiler body inlet tempearture		°C
	(Condensate recovery rate)		%
Generated steam	Pressure		kgf/cm^2
	Temperature		°C
	Dryness of saturated steam		%
	Generated steam volume	Total volume (Compensated value)	kg
		Per hour	kg/h
		Value on an hourly basis	kg/h
Combustion air	Air volume per unit quantity of fuel		m^3/kg (or m^3)
	Temperature/ pressure	Inlet of air preheater	°C, mmAq
		Outlet of air preheater	°C, mmAq
		Outlet of forced draft fan	°C, mmAq
		Inlet of furnace	°C, mmAq
	Air ratio	Outlet of boiler body	
		Outlet of air preheater	

Table 10.8.4 Measurement Results (2/2)

Exhaust (Combustion) gas	Exhaust gas volume per unit quantity of fuel		m^3/kg (or m^3)
	Temperature and pressure	Outlet of boiler body	°C, mmAq
		Inlet of air preheater	°C, mmAq
		Outlet of air preheater	°C, mmAq
	Gas analysis	Outlet of economizer	(CO_2), (O_2), (CO) Volume %
	Unburnt content in residue		%
	Quantity of residue per unit quantity of fuel		kg/kg
Smoke condition			
Auxiliary machine	Electricity consumption		kW
	Steam consumption		kg/h

Table 10.8.5 Heat Balance Sheet (Example of coal-fired boiler)

Heat Input			Heat Output			
Item	kcal/kg of fuel	%		Item	kcal/kg of fuel	%
(1) Lower calorific value of fuel (H_l)			Effective heat output (Q_s)	(1) Heat absorbed by generated steam (Q_s)		
(2) Heat input of fuel (Q_f)			Heat loss (L_l)	(1) Heat loss due to exhaust gas (L_g)		
(3) Heat input of combustion air (Q_a)				(2) Heat loss due to incomplete combustion gas (L_2)		
(4) Heat input of feedwater (Q_w)				(3) Heat loss due to unburnt carbon in residue (L_3)		
				(4) Other heat loss (L_r)		
				Sub-total L_l		
Total $H_l + Q_f + Q_a + Q_w$		100	Total $Q_s + L_l$			100

Note: Radiation heat loss may, in some cases, be included in the items of heat loss. (See "Remarks" in the text.)

10.8.4 Analysis of Boiler Water Quality

An analysis of water quality of industrial purpose boilers is given below.

(1) Purpose of Measurement

The purpose is to study whether the quality of each of feedwater and boiler water for boilers is properly managed or not.

pH control : The pH value of the feedwater needs to be controlled in order to prevent corrosion in the water supply system. The pH value of the boiler water needs to be controlled in order to prevent corrosion inside the boiler.

Electric conductivity: This factor is measured as an index for the concentration of electrolytes present in the feedwater and boiler water.

(2) Method of measurement

(Water quality analysis here is in accordance with JISB B 8223 (1989).)

Measurement points : ⑪, ⑫ (feedwater) and ㉔, ㉕ (boiler water) in Fig.10.8.1
Measurement instruments: pH meter and conductivity meter

(3) Method of diagnosis

The measured water quality should be compared with the standard to see if it is suitable. As reference, the water quality standard of JIS is provided in Tables 10.8.6 through 10.8.8.

a. Drum boilers (vertical boilers, flue boilers and smoke tube boilers)

Table 10.8.6 Quality of Feedwater and Boiler Water for Drum Boilers

Category	Maximum working pressure [kgf/cm²]	10 or less	From more than 10 up to 20 or less
	Kind of makeup water	Softened water (1)	
Feedwater	pH (at 25 °C)	7 to 9	7 to 9
	Hardness ($mgCaCO_3/L$)	1 or less	1 or less
	Fats and oils (mg/L)	(2)	(2)
	Dissolved oxygen (mgO/L)	(2)	(2)
Boiler water	Processing system	Alkaline process	
	pH (at 25 °C)	11.0 to 11.8	11.0 to 11.8
	Electric conductivity (μS/cm) (at 25 °C)	4500 to 4000 (or less)	3500 or less

(1) City water, industrial water, underground water, river water, lake water, etc.
(2) It is desirable to keep them at a low level.

1) Purpose of feedwater control

pH : is controlled in order to prevent corrosion of a feedwater supply system.

Hardness : is controlled in order to prevent the accumulation of sludge inside the boiler as well as reduction in thermal efficiency due to a deposit of scales on the heating surface.

Oils and fats : are controlled in order to prevent foaming of boiler water.

Dissolved oxygen: is controlled in order to prevent corrosion of metals around the water side of the entire boiler plant.

2) Purpose of boiler water control

pH : is controlled to prevent corrosion and scale deposits

Acid consumption: is controlled to control pH of the boiler water indirectly and to prevent scale deposits due to silica

Total residue on evaporation and electric conductivity:
are controlled to prevent a carryover and accumulation of sludge

Figure 10.8.2 shows the relationship between pH and acid consumption of boiler water.

Figure 10.8.3 shows the relationship between the total residue on evaporation and carryover.

Figure 10.8.2 Relationship between pH and Acid Consumption (pH8.3) of Boiler Water

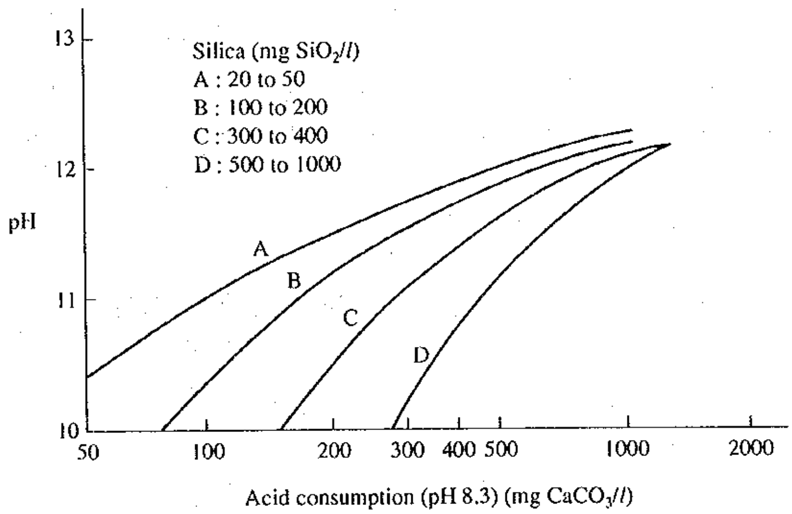
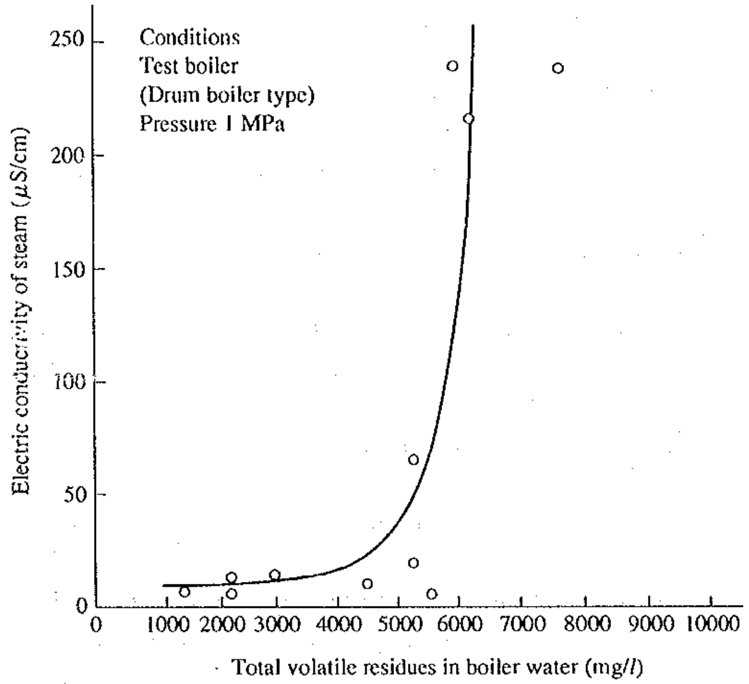


Figure 10.8.3 Relationship between Total Residue on Evaporation and Carryover of Boiler Water (Example)



b. Water tube boiler

Table 10.8.7 Quality of Feedwater and Boiler Water for Water Tube Boilers

Category	Maximum working pressure [kgf/cm²]	10 or less	From more than 10 up to 20 or less
	Kind of makeup water	Softened water	
Feedwater	pH (at 25 °C)	7 to 9	7 to 9
	Hardness (mgCaCO$_3$/L)	1 or less	1 or less
	Fats and oils (mg/L)	(2)	(2)
	Dissolved oxygen (mgO/L)	(2)	(2)
Boiler water	Processing system	Alkaline process	
	pH (at 25 °C)	11.0 to 11.8	11.0 to 11.8
	Electric conductivity (μS/cm) (at 25 °C)	4500 to 4000 (or less)	3000 or less

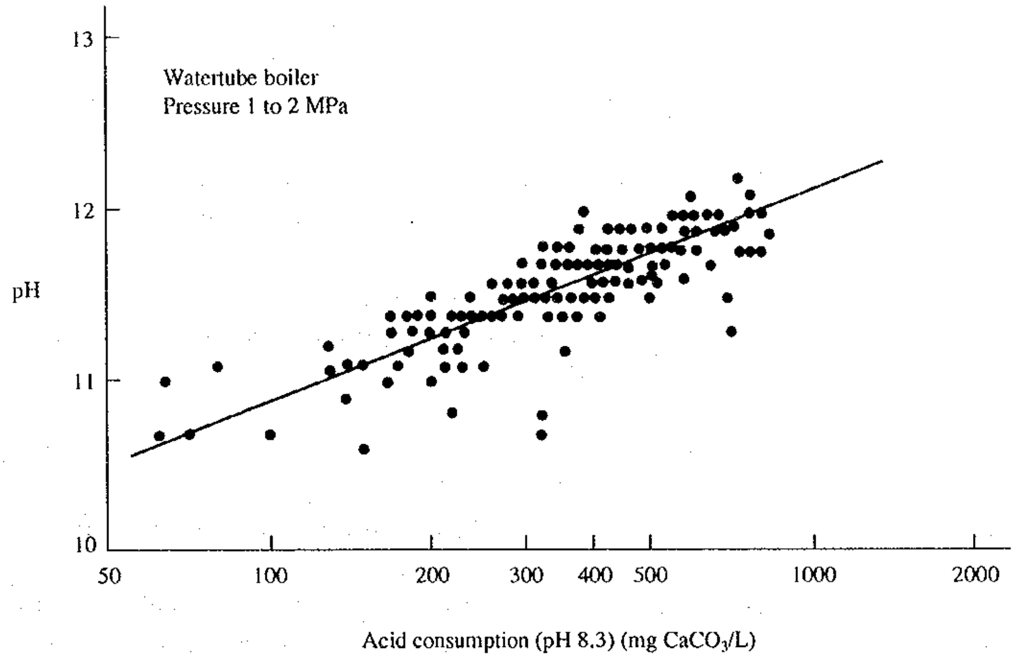
(2) It is desirable to keep them at a low level.

1) Purpose of feedwater control: Same as item a. in 1)

2) Purpose of boiler water control: Same as item a. in 2)

Figure 10.8.4 shows a relationship between pH and acid consumption (pH 8.3) of boiler water.

Figure 10.8.4 Relationship between pH and Acid Consumption (pH 8.3) of Boiler Water



c. Once-through boiler

Table 10.8.8 Quality of Feedwater and Boiler Water for Once-through Boilers

Category	Type of boiler	Single-tube boiler	Multi-tube boiler
	Maximum working pressure [kgf/cm²]	From more than 10 up to 30 or less	From more than 10 up to 30 or less
	Kind of makeup water	Softened water (1)	Softened water (1)
Feedwater	pH (at 25 °C)	10.5 to 11.0	7 to 9
	Hardness (mg$CaCO_3$/L)	1 or less	1 or less
	Fats and oils (mg/L)	(2)	(2)
	Dissolved oxygen (mgO/L)	(2)	0.5 or less
	Electric conductivity (μS/cm) (at 25 °C)	4000 or less	—
Boiler water	Processing system	—	Alkaline process
	pH (at 25°C)	—	11.0 to 11.8
	Electric conductivity (μS/cm) (at 25 °C)	—	3000 or less

(1) City water, industrial water, underground water, river water, lake water, etc.
(2) It is desirable to keep them at a low level.

1) Purpose of feedwater control

pH : is controlled to prevent corrosion of a feedwater supply system.

Hardness : is controlled to prevent the accumulation of sludge inside the boiler as well as reductions in thermal efficiency due to deposits of scales on the heating surface.

Oils and fats : are controlled to prevent foaming of boiler water.

Dissolved oxygen: is controlled to prevent corrosion of metals around the water side of the entire boiler plant.

Total residue on evaporation and electric conductivity:
are controlled to prevent a carryover and accumulation of sludge.

2) Purpose of boiler water control

pH : is controlled to prevent corrosion and scale deposits.

Acid consumption: is controlled to control pH of the boiler water indirectly and to prevent deposits of scale due to silica.

Total residue on evaporation and electric conductivity:
are controlled to prevent a carryover and accumulation of sludge.

10.8.5 Energy Conservation Measures

The following energy conservation measures should be taken for boilers. (For details, see "IV. Guidelines".)

(1) Control of air ratio

Maintaining the proper temperature of fuel oil, inspection and maintenance of burners, prevention of air entry, adjustement of air volume, automatic control, etc.

(2) Recovery of waste heat

Heat recovery of exhaust gas, recovery of steam condensate, etc.

(3) Prevention of radiation heat

Providing heat insulation on the boiler body, feedwater pipe, valves, flanges around the boiler, etc.

Check List / Steam System

Boiler Date: ____________

Factory / Company: ______________________________

Written by: ______________________________

General Information:

Name of boiler house ______________________________

No. of boilers installed ______________________________

Steam connected to
(process/turbine/heating) ______________________________

Concept of steam system (diagram, handwritten)

____

Specification (designed):

	Unit			
Boiler No.				
Boiler type				
Manufactured by				
Installed at				
Run into commissioning at				
Fuel				
Steam pressure				
Steam temperature				
Evaporation				
Kind of fuel				
Super heater attached?				
Economizer attached?				
Air heater attached?				
Heating surface				

Main body				
Super heater				
Economizer				
Air heater				
Air heater type				
Combustion facilities				
Type				
Capacity				
Draft system				
Type				
Capacity				
Fuel characteristics Unit				
Composition (C, H, N, O, S) **				
Water content **				
Ash content **				
Heat value, gross **				
Heat value, net **				
Volatile matter content				
Size of coal				
Annual Working Condition:				
(If written in general inquiry, next items not to be filled-out.)				
Yearly working days or hours				
Daily running hours				
Winter (heating period)				
Other seasons				
Annual consumption / generation				
Fuel				
Steam				
Feed water				
Power generated				
Steam to process				
Steam to heating				

Check List / Steam System

Factory:

Typical Operating Condition (for heat balance calcuation):

Unit No.		
Steam **		
Pressure **		
Temperature **		
Generation or boiler water supply **		
Fuel		
Consumption **		
Temperature **		
Exhaust gas temperature at after air-heater **		
Exhaust gas oxygen (if available), O2 %		
measured at		
Exhaust gas carbon monoxide (if available), CO %		
measured at		
Combustion residue (kg/kg-wet coal) **		
Carbon content of combustion residue		
Exhaust temperature of combustion residue		
Boiler water blow-down ratio		

Symbol "**": Essential for the calculation

Exhaust gas composition can be measured in the field audit period.

Check List / Steam System

Turbine

Date: ____________

Factory / Company: ______________________________

Written by: ______________________________

General Information:

Name of turbine house ______________________________

No. of turbine installed ______________________________

Steam comes from ______________________________

Steam connected to

Extraction ______________________________

Back pressure ______________________________

Concept of steam line (diagram, handwritten)

Specification (designed):

	Unit			
Turbine No.				
Turbine type				
Generator, type				
Capacity				
Main steam, flow				
Pressure				
Temperature				

No.1 extraction, flow				
Pressure				
Temperature				
No.2 extraction, flow				
Pressure				
Temperature				
Back pressure				
Pressure				
Temperature				
Condenser, type				
Vacuum				
RPM				
Turbine / generator				

Annual working condition:

(If written in general inquiry,

next items not to be filled-out.)

Yearly working days or hours				
Daily running hours Winter (heating period)				
Other				

Annual generation / consumption

Main steam				
Power generated				
Extraction No.1				
Extraction No.2				

Check List / Steam System

Factory:

Typical Operating Condition:

No. of unit ______________________

Power output

Generator end ______________________

Main steam

Pressure ______________________

Temperature ______________________

Flow-rate ______________________

Extraction No.1

Pressure ______________________

Temperature ______________________

Flow-rate ______________________

Extraction No.2

Pressure ______________________

Temperature ______________________

Flow-rate ______________________

Condenser

Vacuum ______________________

Cooling water for condenser

Temperature in ______________________

out ______________________

Check List / Steam System

Future Date: ________

Factory / Company: ______________________

Written by: ______________________

Problems now going or in your mind:

On

Combustion ______________________

Steam turbine ______________________

Instrumentation ______________________

Maintenance ______________________

Heat insulation ______________________

Condensate recovery from process ______________________

Steam supply/utilize system ______________________

Power generation ______________________

Other ______________________

Plans or idea for future improvement, if any (please write freely)

____

Gas sampling nozzle:

Is exhaust gas sampling nozzles available for O2 and CO analyzing during our audit ?

At before / after of air preheater

At after combustion chamber

10.9 Steam Piping

10.9.1 Purpose of Measurement

The purpose is to grasp the radiation heat loss from the steam pipe.

10.9.2 Method of Measurement (See Figure 10.9.1)

Figure 10.9.1 Steam Pipe Measuring Points

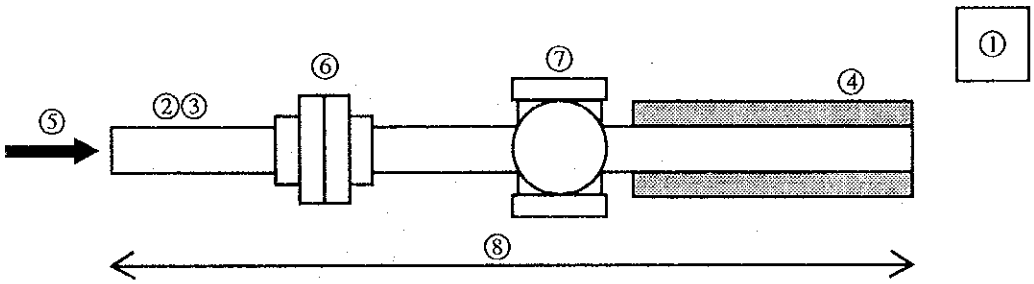


Table 10.9.1 Steam Pipe Measuring Points

	Items to be Measured	Measuring Equipment
①	Outside air temperature	Thermometer
②	Pipe inner diameter	
③	Pipe outer diameter	Vernier caliper
④	Outer diameter of heat-insulated cylinder	Tape measure
⑤	Steam temperature, pressure	Reading, thermocouple pressure gauge
⑥	Size and number of flanges	
⑦	Size and number of valves	
⑧	Pipe length	
⑨	Outer surface temperature of heat-insulated cylinder	Surface thermometer

10.9.3 Method of Diagnosis

(1) Diagnostic method based on a data sheet

The radiation heat loss from a bare or uncovered steam pipe is obtained based on the measured steam temperature according to Figure 10.9.2. Steam temperature should be checked with the saturated temperature at the steam pressure.

Then, the total radiation heat loss is calculated from the above heat radiation loss and the pipe length.

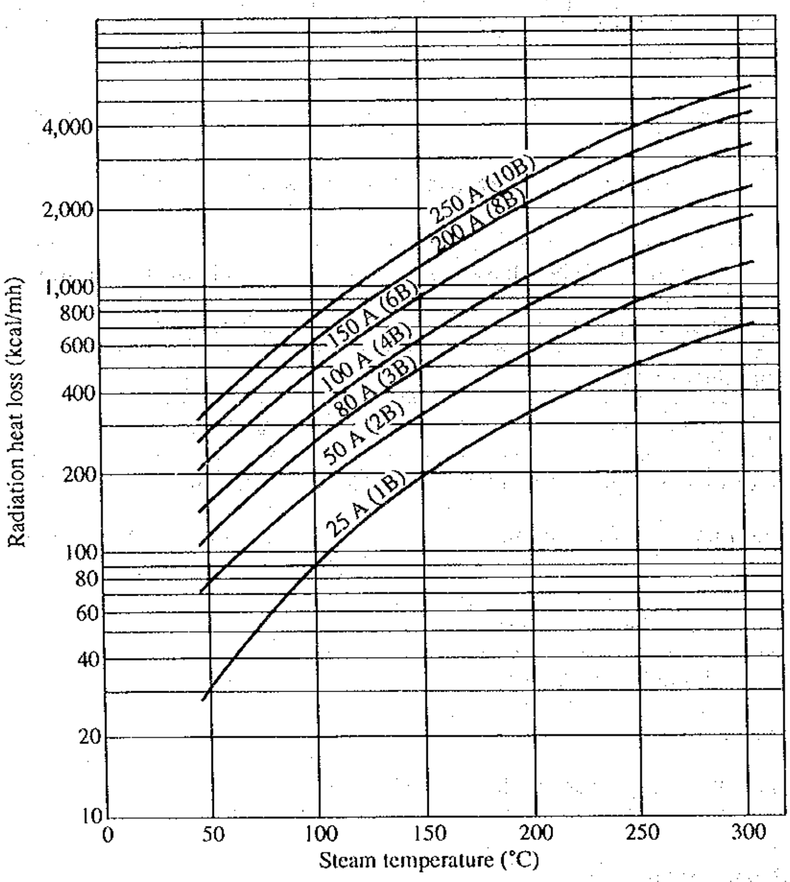
It should be noted, however, that metric values converted from Table 10.9.2 should be used for flanges, pressure reducing valves, etc.

The radiation heat loss from a heat-insulated pipe is obtained as well based on the above radiation heat according to Figure 10.9.3.

Then, the total radiation heat loss is calculated from the above heat radiation loss and the pipe length.

It should be noted, however, that the metric values converted from Table 10.9.2 should be used for flanges, pressure reducing valves, etc.

Figure 10.9.2 Radiation Heat Loss from Bare Steam Pipe



(When ambient temperature is 20°C)

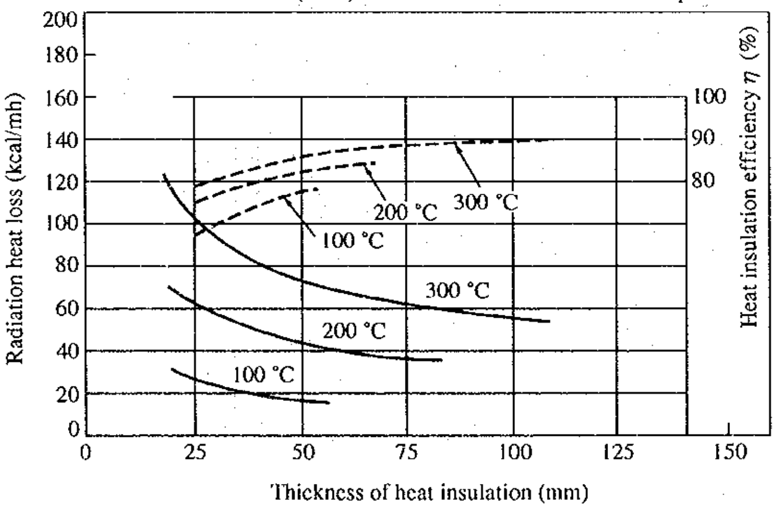
Table 10.9.2 Bare Pipe Length Equivalent to the Heat-insulated Surface Area of Piping Fittings

[m]

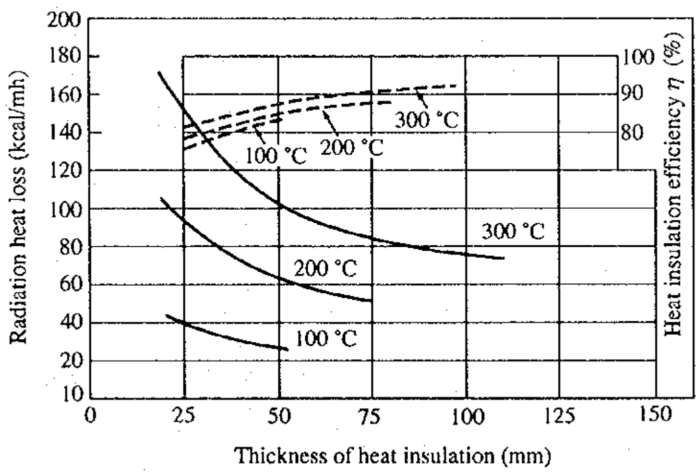
Kinds of piping fittings	15 A	20 A	25 A	40 A	50 A	65 A	80 A	100 A	125 A	150 A	200 A
Flange type globe valves (10 kg/cm²)	1.15	1.06	1.22	1.11	1.11	1.23	1.25	1.27	1.40	1.50	1.68
Flange type globe valves (20 kg/cm²)	1.24	–	1.21	1.20	1.28	1.50	1.56	1.58	–	1.78	1.87
Flange type gate valves (10 kg/cm²)	1.12	0.98	1.15	1.31	1.22	1.16	1.31	1.20	1.27	1.35	1.52
Flange type gate valves (20 kg/cm²)	1.29	1.13	1.32	1.23	1.53	–	1.63	1.50	–	1.92	–
Pressure reducing valves (10 kg/cm²)	1.96	1.71	1.67	1.49	1.55	1.60	1.66	1.58	1.91	1.76	1.81
Control valves (10 kg/cm²)	–	1.72	1.84	1.56	1.60	–	1.54	–	–	1.48	–
Flanges (10 kg/cm²)	0.50	0.46	0.53	0.47	0.44	0.42	0.42	0.39	0.44	0.45	0.44
Flanges (20 kg/cm²)	0.51	0.46	0.54	0.47	0.49	0.46	0.50	0.46	–	0.56	0.51

Figure 10.9.3 Heat Insulation Thickness of Steam Pipe and Radiation Heat Loss (1/3)

(Note) Parameters indicate the steam temperatures.

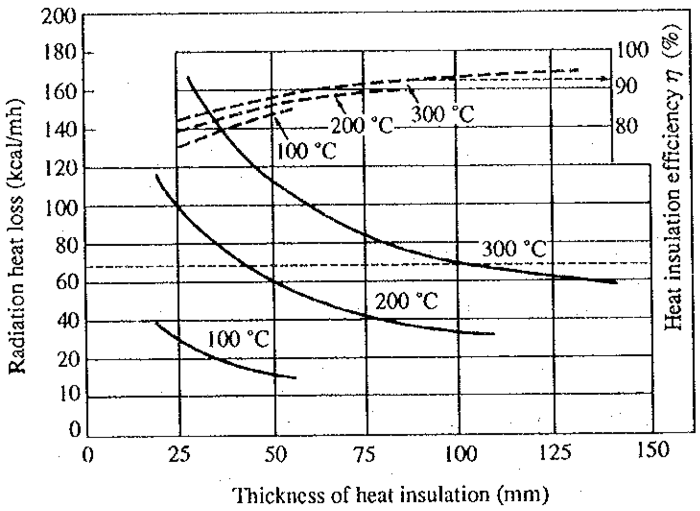


(1)
25 A (1B) Pipe

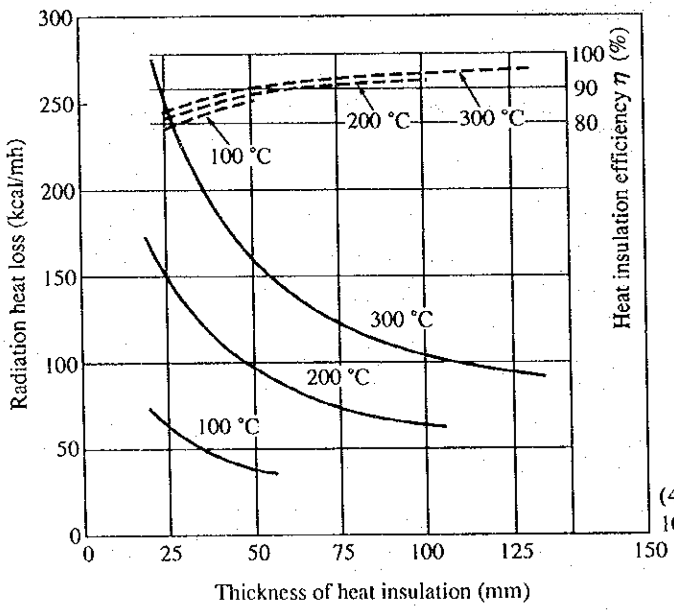


(2)
50 A (2B) Pipe

Figure 10.9.3 Heat Insulation Thickness of Steam Pipe and Radiation Heat Loss (2/3)

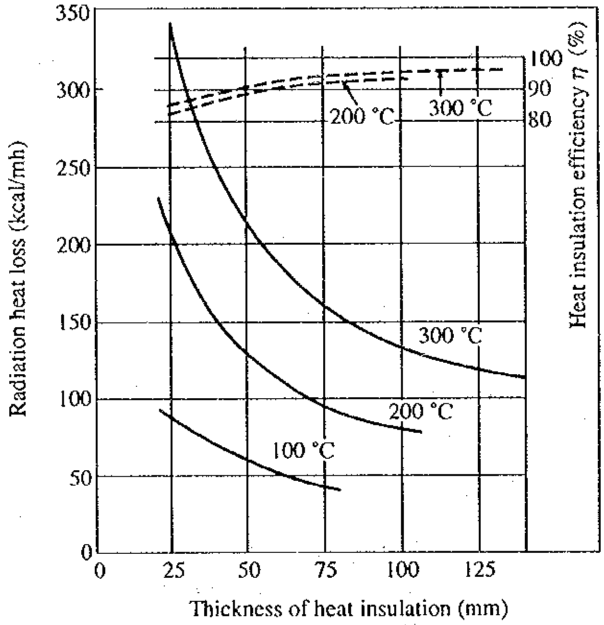


(3)
80 A (3B) Pipe

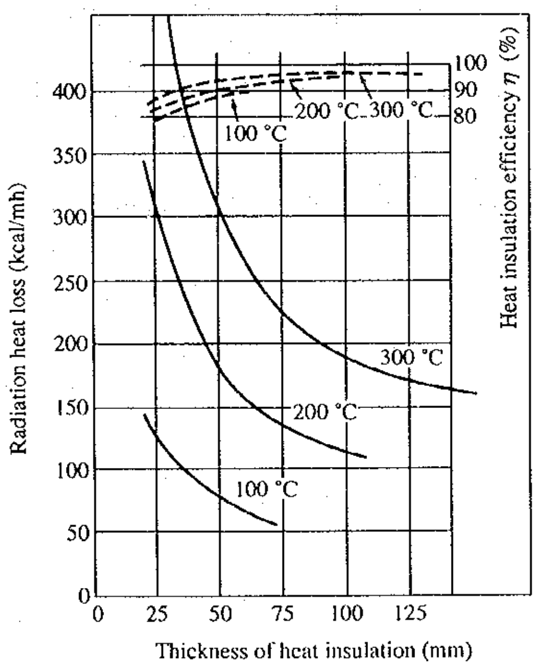


(4)
100 A (4B) Pipe

Figure 10.9.3 Heat Insulation Thickness of Steam Pipe and Radiation Heat Loss (3/3)



(5)
150 A (6B) Pipe

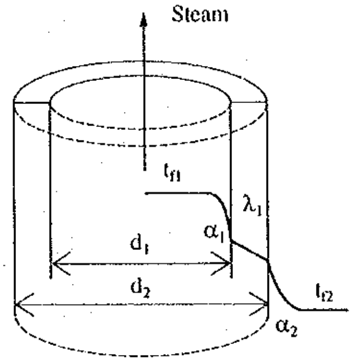


(6)
250 A (10B) Pipe

(2) Method of diagnosis based on calculation

The amount of radiation heat from a bare steam pipe per unit of length, Q[kcal/mh], is expressed in the following equation:

$$Q = \frac{2\pi(t_{f1} - t_{f2})}{\frac{2}{\alpha_1 d_1} + \frac{1}{\lambda_1}\ln\left(\frac{d_2}{d_1}\right) + \frac{2}{\alpha_2 d_2}}$$



where

t_{f1} : Steam temperature [°C]
t_{f2} : Outside air temperature [°C]
d_1 : Inner diameter of pipe [m]
d_2: Outer diameter of pipe [m]
α_1 : Heat transfer rate of fluid to pipe inner surface [kcal/m²h°C]
(Example: α_1 = 9,000 kcal/m²h°C)
α_2 : Heat transfer rate to the outside air from pipe surface [kcal/m²h°C]
(Example: α_2 = 15 kcal/m²h°C)
λ_1: Thermal conductivity of pipe[kcal/mh°C] (Example: λ_1 = 35 kcal/mh°C)

The total amount of radiation heat is calculated based on the calculated amount of radiation heat and pipe length.

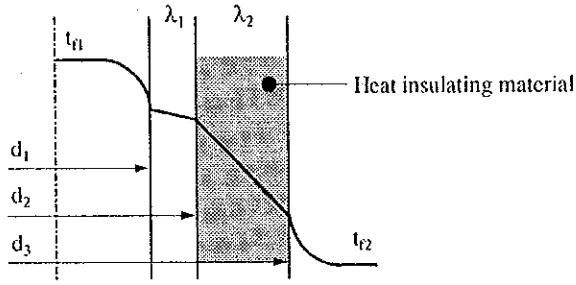
The metric values converted from Table 10.9.2 should be used for flanges, pressure reducing valves, etc.

The amount of radiation heat Q [kcal/mh] from a heat-insulated pipe per unit of length is expressed in the following equation.

$$Q = \frac{2\pi(t_{f1} - t_{f2})}{\frac{2}{\alpha_1 d_1} + \frac{1}{\lambda_1}\ln\left(\frac{d_2}{d_1}\right) + \frac{1}{\lambda_2}\ln\left(\frac{d_3}{d_2}\right) + \frac{2}{\alpha_2 d_3}}$$

The above equation is approximated as $\alpha_1 \gg \alpha_2$ and $\frac{d_2}{d_1} \fallingdotseq 1$ to obtain the following equation.

$$Q = \frac{2\pi(t_{f1} - t_{f2})}{\frac{2}{\alpha_2 d_3} + \frac{1}{\lambda_2}\ln\left(\frac{d_3}{d_2}\right)}$$



where

d_2: Outer diameter of pipe [m]

d_3: Outer diameter of a heat-insulated cylinder [m]

α_2: Heat transfer rate to the outside air from the heat-insulated cylinder surface [kcal/m²h°C] (Example: α_2 = 15 kcal/m²h°C)

λ_2: Thermal conductivity of a heat insulating material [kcal/mh°C] (Example: λ_2 = 0.1 kcal/mh°C)

The total amount of radiation heat (= QL) is obtained based on the calculated amount of radiation heat (Q) and pipe length (L).

The metric values converted from Table 10.9.2 should be used for flanges, pressure reducing valves, etc.

10.9.4 Energy Conservation Measures

Energy conservation measures to be taken for a steam pipe include the following:

(1) Optimization of steam pressure

Low-pressure steam should be used, or a similar measure should be taken.

(2) Optimization of pipe

The piping route should be reviewed, etc.

(3) Heat insulation of pipe

Heat insulation should be provided for flanges and reducing valves, and high-performance heat-insulating materials should be introduced. The amount of heat-insulating materials should be increased.

(4) Maintenance and inspection

Any breakage of heat insulation should be repaired and maintenance of steam traps should be performed, etc.

Check List / Steam System

Steam Piping

Date: ____________

Factory / Company: ____________

Written by: ____________

General Information:

Name of steam system ____________

Steam connected to
(process/turbine/heating) ____________

Concept of steam system (diagram, handwritten)

Specification (designed):

	Unit			
Pipe size (ID/OD)				
Pipe length (Total)				
Pipe material				
Insulation size (OD)				
Insulation material				
Steam temperature				
Steam pressure				
Numbers of flange (Type)				
Flange size				
Number of valve (Type)				
Valve size				
Pipe surface temperature				
Insulation surface temperature				
Ambient temperature				

APPENDIX (DESCRIPTION OF MEASURING EQUIPMENT (SUPPLEMENTARY))

1. METHODS FOR ANALYZING COMBUSTION EXHAUST GASES

Combustion exhaust gases, which are composed mainly of N_2, O_2, CO_2, and H_2O, may contain also trace constituents such as CO, SO_2, NO, NO_2, HCl and unburnt hydrogen carbonate depending on the fuel and combustion conditions. These gases may also contain particulate substances such as soot. Analyzing these components in a combustion exhaust gas is important for grasping an amount of combustion gas based on the assumed air ratio, calculating the heat loss by exhaust gas in heat balance, improving the combustion state, and so forth. Analyzers of these gases can be basically classified into chemical analyzers and physical analyzers, and classified as shown in Table 1.

A chemical CO_2 meter uses the property of CO_2 that it is very soluble in a strong alkali. Flue gas is introduced into an absorbing tank containing a strong alkali solution for absorbing CO_2, to obtain CO_2 concentration in % from a decrease in gas volume. Recently it is not commonly used in plants.

Physical analyzers utilize the differences of respective gases in density, viscosity, thermal conductivity, magnetism, reactivity, infrared absorbability, etc. Kinds of gas analyzers used for combustion control are listed in Table 1.

Table 1 Classification of Gas Analyzers

	Method of Measurement	Name of Analyzer	Measured Ingredients
Chemical gas analyzer	Absorption by solution	Hempel gas analyzer	CO_2, O_2, CO, N_2
		Orsat gas analyzer	CO_2, O_2, CO, N_2
Physical gas analyzer	Thermal conductivity method	Electric CO_2 meter	CO_2
		Unburnt gas meter	CO + H_2
	Specific gravity method	Specific gravity type CO_2 meter	CO_2
	Absorption of ultraviolet rays	Infrared gas analyzer	CO_2, CO, CH_4, SO_2,
	Electric conductivity	SO_2 automatic recorder	SO_2
	Electrochemical method	Zirconia type O_2 meter	O_2
		Galvanic cell type O_2 meter	O_2
	Magnetic method	Magnetic O_2 meter	O_2
	Gas chromatography	Gas chromatography	CO_2, N_2, H_2, O_2, CO, CH_4, SO_2, NO_2

1.1 Exhaust Gas Sampling Methods

When gas samples for analyzing gas components are taken from a flue, the matters specific to a component to be measured should be taken into consideration with JIS K0095 "Method for Sampling of Stack Gas" as the reference.

(1) Selection of gas sampling points

Measuring ports in the flue should be provided at the positions which conform to the specification in JIS Z8808 "Method of Measuring Dust Concentration in Flue Gas" avoiding places where air leaks into the flue, where dust is deposited in the flue, or places which are subject to frequent fall of dust. Several measuring ports should be set, depending on the size and form of the flue. However, if the analytical results are little different among respective measuring points, and gas concentrations are considered to be almost the same at the cross sections of respective sampling positions as in the flue for a boiler, then any one point can be selected for sampling.

(2) Structure of a gas sampler

A sampler is generally composed of a sampling tube, conduit, cooling dehumidifier, gas-liquid separating tube, condensed water trap, etc. The material of the sampling tube and conduit must not affect the analytical result of exhaust gas due to the chemical reaction or adsorption, etc. and must be resistant against corrosion. In case the water or gas component with high dew point in the exhaust gas should be condensed to clog the conduit, the sampling tube and conduit should be thermally insulated or heated as required.

To prevent the ingress of dust, etc. into the sample gas, the sampling tube should contain a filter as required, and furthermore, a fine filter medium should be used downstream of the gas-liquid separating tube. To avoid indication errors due to the disturbance by the deposition of condensed water or water content in the tube inside the analyzer, a cooling dehumidifier for cooling and condensing water, gas-liquid separating tube, condensed water trap, desiccant, adsorbent, etc. should be used as required.

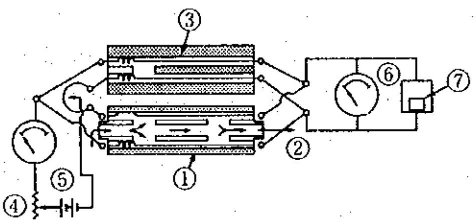
1.2 Analysis of Carbon Dioxide

(1) Thermal conductivity method

A meter using this method is also called electric CO_2 meter and this method is widely used. It applies that the thermal conductivity of CO_2 is very small compared with that of air.

As for the mechanism, as shown in Figure 1, current is fed through the thin platinum wires stretched in the gas chamber ① and air chamber ③, to heat them about 100°C. Since the thermal conductivity of the flue gas, high in CO_2 content, which is fed into the gas chamber, is smaller than that of air, the heat loss from the heated platinum wire is smaller in the gas chamber. Therefore, the temperature of the platinum wire in the sample gas chamber is higher than that in the reference gas chamber, to increase the electric resistance, and it is measured by a Wheatstone bridge and indicated by meter ⑥ or recorded by recorder ⑦.

Figure 1 CO_2 Meter Using Thermal Conductivity



① Sample gas chamber
② Gas passage
③ Reference gas chamber
④ Slide rheostat
⑤ Ammeter
⑥ Indicator
⑦ Recorder

(2) Specific gravity method

This is intended to measure the CO_2 content using the fact that the specific gravity of CO_2 is larger than that of air.

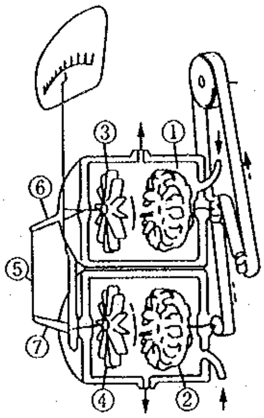
As shown in Figure 2, two impellers of the same form and speed are used. One impeller is revolved in an air chamber and the other one is revolved in a chamber fed with the flue gas mutually in reverse directions. The wind pressures generated by them are received by passive impellers of the same form respectively facing the above mentioned impellers. If air current of the same condition is blown to both the impellers, to actuate both, the force for turning the air arm downward and the force for turning the gas arm upward are the same, and the connecting rod connecting both the arms does not move.

However, if flue gas is fed into the gas chamber, the revolving torque of the gas arm becomes larger than that of the air arm due to the difference of both in specific gravity, which raises the connecting rod by the gas arm. The movement of the air and gas arms and the connecting rod due to the torque difference is indicated by a needle or recording pen attached at the passive impeller shaft for air.

At the bottom of the meter, a water tank is provided to always give the same humidity to gas and air.

In using of CO_2 meter for flue gas, if the composition of components other than CO_2 is different, it affects the specific gravity of the entire gas, which causes some error.

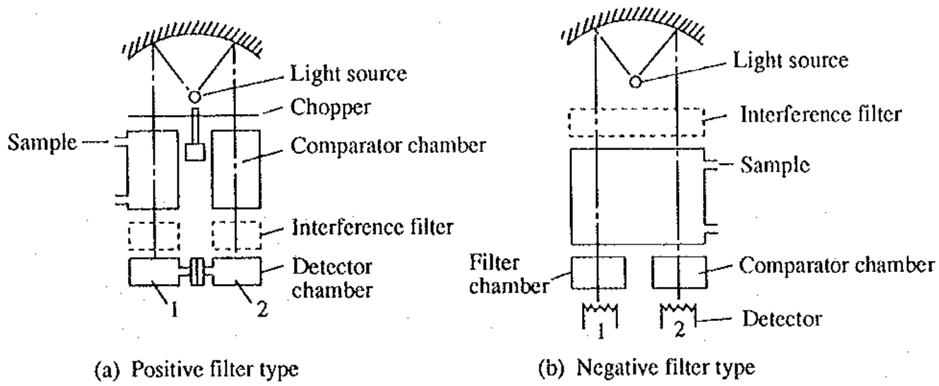
Figure 2 Specific Gravity Type CO_2 Meter



(3) Infrared gas analysis method

Most gases such as CO_2, CO and CH_4 except gases in which diatomic molecules, such as H_2, N_2 and O_2, have respectively peculiar absorption wavelength bands of infrared rays. This property is used in the method. An industrial infrared gas analyzer is either of a positive filter type or of a negative filter type. As shown in Figure 3, a positive filter type analyzer usually uses a heated nichrome wire as the heat source and the heat is divided into two rays by a reflector. One ray goes through a sample tank into detector 1, and the other goes through a comparator chamber (usually containing N_2) into detector 2. A reference gas for a component to be analyzed, for example, a reference CO_2 gas in case when the concentration of CO_2 content is to be measured, is sealed in the both detector chambers 1 and 2. (In recent years, also available is a simplified infrared gas analyzer which uses a semiconductor and solid filter instead of detector chambers.) The energy absorbed by detector chamber 2 remains the same, but the energy absorbed by detector chamber 1 depends on the concentration of the gas to be analyzed in the sample chamber. The difference of both the detector chambers 1 and 2 in the absorbed energy is taken out, for example, as the change in the capacity of the capacitor held between them, for indicating the concentration of the gas component analyzed. A negative filter type analyzer uses non-selective detectors. The filter chamber contains 100 % test gas, and the compensator chamber contains N_2, or the gas obtained by excluding the gas components to be analyed from the gas of the sample chamber. The difference between the outputs of both the detectors such as bolometers is measured to know the concentration of the test gas. (See JIS K0151 "Non-dispersive Infrared Gas Analyzer")

Figure 3 Infrared Gas Analyzer



1.3 Analysis of Oxygen

For automatic meters for continuously measuring the oxygen concentration in exhaust gas, it is preferable to use those specified in JIS B7983 "Continuous Analyzers for Oxygen in Flue Gas".

(1) Magnetic O_2 meter

The magnetic method continuously obtains oxygen concentration by using the attractive force generated when oxygen molecules, which are a paramagnetic material, are magnetized in a magnetic field, and includes a magnetic wind type and magnetic force type. The magnetic method can be used when the influence of the gas with high bulk susceptibility (nitrogen monoxide) is negligible.

a. Magnetic wind detecting type O_2 meter

In this type, the intensity of the magnetic wind generated when the oxygen molecules attracted in the magnetic field are partially heated to lose magnetism, is detected by a hot wire element.

b. Magnetic force detecting type O_2 meter

Dumbbell type : The displacement caused when a nonmagnetic dumbbell is extruded outside the magnetic field by magnetized oxygen molecules is detected.

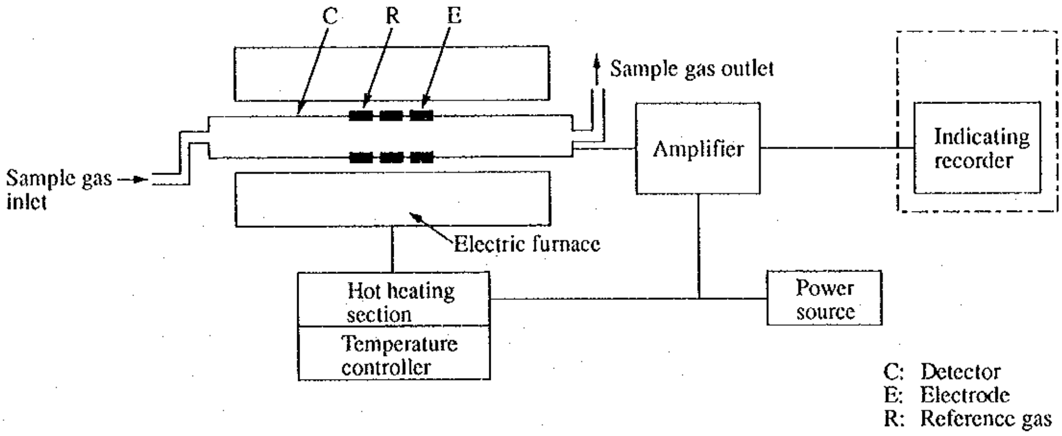
Pressure detector type : In a periodically intermittent magnetic field, the intermittent attractive force acting on oxygen molecules is detected as the back pressure variation of auxiliary gas flowing into the magnetic field at a constant rate.

(2) Electrochemical O_2 meter

The electrochemical method uses the electrochemical oxidation reduction reaction of oxygen, for continuously obtaining oxygen concentration and includes zirconia type and electrode type.

Zirconia type: In this type, electrodes are provided at both ends of a zirconia element heated to a high temperature, and the sample gas is fed to one of them while air is fed to the other, in order to give an oxygen concentration difference, and for detecting the electromotive force generated between both the electrodes. Figure 4 shows the structure of a zirconia type analyzer.

Figure 4 Structure of a Zirconia Analyzer



Electrode type: This type detects the electrolytic current generated when the oxygen diffused and absorbed in an electrolyzer cell through a gas permeable diaphragm is reduced on the surface of a solid electrode. This type can be further classified into a contact potential electrolysis type for giving reduction potential from outside, polarograph type, and galvanic cell type for forming galvanic cells.

1.4 Analysis of Carbon Monoxide

Carbon monoxide in exhaust gas can be analyzed by the follwing methods according to JIS K0098 "Method for Determination of Carbon Monoxide in Flue Gas".

(1) Oxidation condensation method

Sample gas is cooled by liquid air to remove the condensable components in the gas, and the remaining gas is fed through a gas oxidizing agent based on copper oxide, to oxidize carbon monoxide into carbon dioxide which is simultaneously condensed by liquefied air. In this case, the difference between gas pressures before and after oxidation condensation is measured (differential pressure method), or it is gasified once into a certain volume, and the pressure is measured (gasification pressure measurement method), for the determination of carbon monoxide.

(2) Gas chromatography

A certain amount of sample gas is taken and introduced into a gas chromatograph with a thermal conductivity type detector, and carbon monoxide concentration is obtained from the height of the peak shown in the chromatogram.

(3) Infrared gas analysis method (non-dispersion method)

The ray absorption of carbon monoxide in the infrared region is used, and the carbon monoxide concentration of the sample gas is measured using a non-dispersion type infrared gas analyzer.

(4) Detector tube method

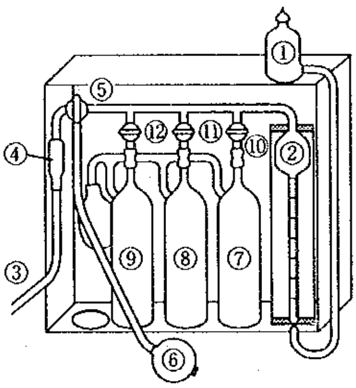
Sample gas is fed through a carbon monoxide detector tube which is a thin glass tube packed with a certain amount of a detecting agent, and the coloring achieved is used to determine carbon monoxide. This is a simple method for knowing the approximate carbon monoxide concentration of exhaust gas.

1.5 Other Analysis Methods

(1) Orsat method

Carbon dioxide, oxygen, and carbon monoxide in exhaust gas are analyzed by the absorption method using an Orsat gas analyzer. As absorbants, potassium hydroxide solution (CO_2), alkaline pyrogallol solution (O_2) and ammoniacal copper chloride soltion (CO) are used. The instrument is small in size and light in weight, being convenient to carry and is simple in operation. However, skill is required.

Figure 5 Orsat Gas Analyzer



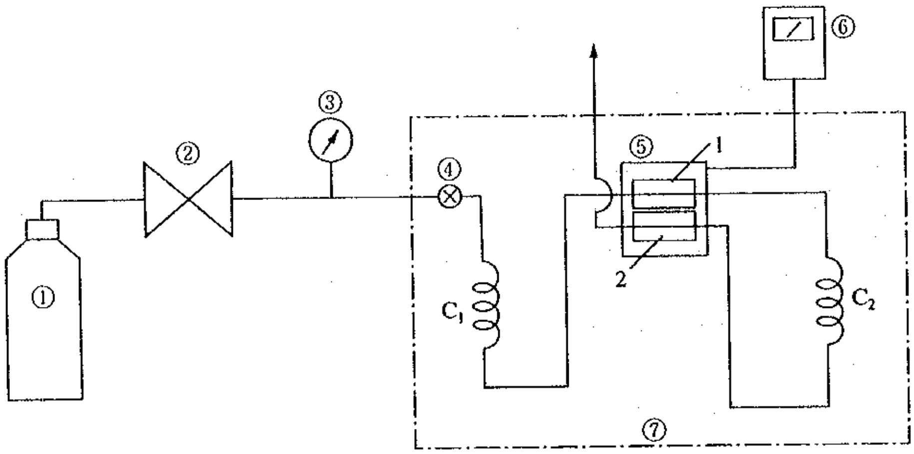
① Leveling bulb
② Gas burette
③ Sample tube
④ Filter
⑤ Three-way cock
⑥ Suction pump
⑦ Carbon dioxide absorbing bottle
⑧ Oxygen absorbing bottle
⑨ Carbon monoxide absorbing bottle
⑩ - ⑫ Cock

(2) Gas chromatography

Combustion gas can be analyzed also by using a gas chromatograph. Compared with the infrared gas analyzer, etc., this method is slow in the response speed and does not allow continuous analysis. However, if an automatic gas sampler is attached, automatic analysis can be made. Gas chromatography is suitable for analyzing a sample consisting of many components, and especially allows trace element analysis. Main components of combustion gas such as CO_2, O_2, CO, N_2, CH_4, SO_2, and NO_2 can be analyzed.

The gas chromatograph used has a thermal conductivity type detector, and a gas sample introducer or automatic gas sampler. The carrier gas used is either helium or nitrogen. Since the above components cannot be isolated and eluted by single packing column, it is convenient to use two columns different in isolation capability, and to isolate and determine by the intermediate cell method in which one column is installed upstream of a detector and the other column downstream of the detector in a thermoregulator as shown in Figure 6. It is recommended to pack C_1 column with silica gel or Porapak Q and C_2 column with Molecular Sieve 13X or 5A. In this case, the polarity of a sensor signal after passing through C_1 column is reversed to that after passing through C_2 column; therefore, the polarity of the recorder should be changed halfway (Refer to JIS K0114 "General Rules for Gas Chromatograph Analysis and JIS K2301 "Fuel Gas and Netural Gas – Methods for Chemical Analysis and Testing").

Figure 6 Intermediate Cell Type Gas Chromatograph



① Carrier gas
② Pressure valve
③ Pressure gauge
④ Sample gas inlet
⑤ Detector
⑥ Recorder
⑦ Thermoregulator

2. TEMPERATURE MEASUREMENT METHODS

2.1 Kinds and Selection of Thermometers

Temperature measurement methods include the contact method in which an object to be measured is brought into a thermally close contact with the sensing element of a thermometer, to keep the same temperature for measurement, and non-contact method in which the radiation of the object, etc. is used for temperature measurement. The features and requirements of thermometers for respective methods are shown in Table 2. For selecting a thermometer, the following items should be examined, to select a thermometer suitable for the purpose of measurement.

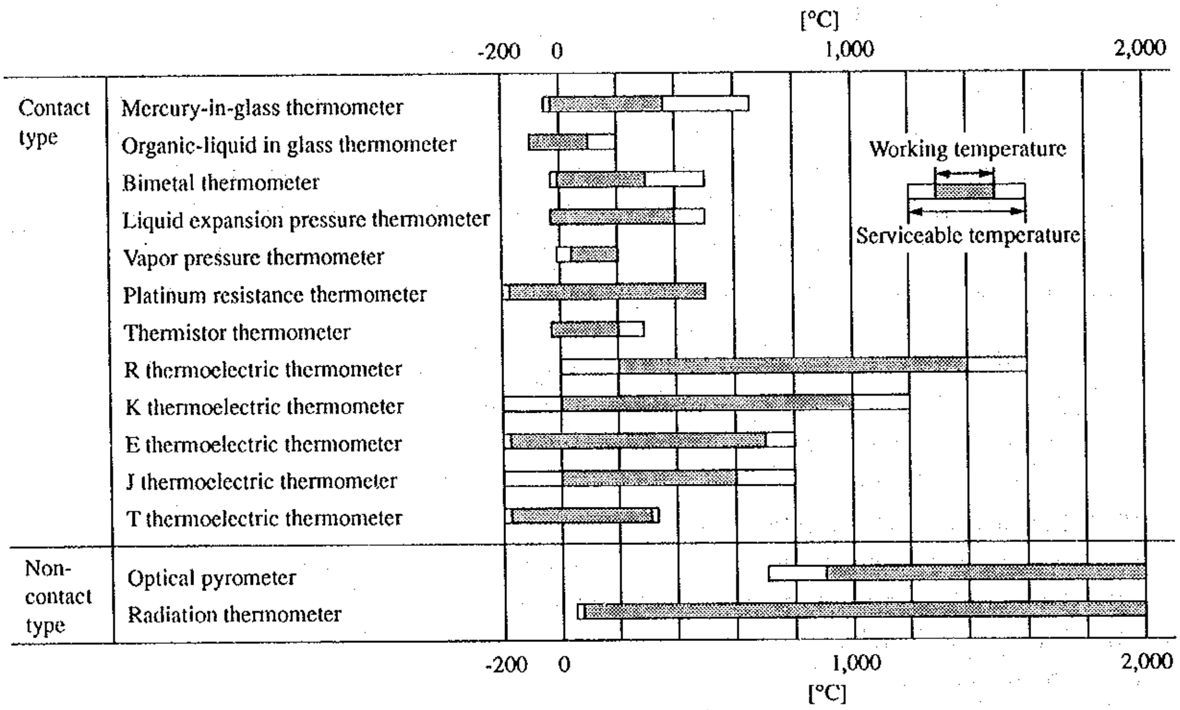
(1) The range of temperatures to be measured (working temperatures in principle).
(2) Accuracy and error possibly occurring in measurement.
(3) Material, form, size, etc. of the sensing section.
(4) Delay of indication.
(5) Easiness to read the indication.
(6) Necessity of telemetering, recording, alarm or automatic control.
(7) Durability, corrosion resistance and reliability.
(8) Easiness to handle.
(9) Interchangeability.

Kinds and working ranges of various thermometers are shown in Figure 7.

Table 2 Contact Method and Non-contact Method

	Contact Method	Non-Contact Method
Requirements	(1) The object to be measured should be kept in close contact with the sensing element. (2) The temperature of the object to be measured should not be substantially changed even by the contact with the sensing element.	The radiation from the object to be measured should sufficiently reach the sensing element.
Features	(1) If the sensing element is brought into contact, the temperature to be measured tends to be changed. Therefore, it is difficult to measure the temperature of a small object. (2) The temperature of a moving object is difficult to measure. (3) The temperature at an optional point can be measured.	(1) Since the sensing element is not brought into contact, the temperature to be measured is not changed. (2) The temperature of a moving object can also be measured. (3) In general, surface temperature is measured.
Temperature range	Temperatures lower than 1000 °C can be easily measured.	Suitable for measuring high temperatures.
Accuracy	In general, about 1 % of scale span.	In general about 10 degrees.
Delay	Generally large	Generally small

Figure 7 Kinds and Working Ranges of Various Thermometers (JIS Z 8710)



2.2 Liquid-in-glass Thermometer

Among various thermometers, this thermometer is the simplest to handle and the most inexpensive. Generally used liquid-in-glass thermometers are either enclosed scale type thermometers or bar thermometers. An enclosed scale type thermometer has a capillary tube and a scale plate of milky white glass behind it enclosed in one glass tube, and mostly has fine graduations, to allow accurate reading for the indication. Therefore, it is generally used for precise measurements. A bar thermometer has graduations directly stamped on a thick-wall capillary tube, and is generally higher in mechanical strength than an enclosed scale type thermometer.

JIS Z8705 specifies the temperature measurement methods using liquid-in-glass thermometers.

2.3 Pressure Thermometer

If mercury or any other liquid or gas enclosed in a sealed tube is heated, the pressure in the tube increases. The pressure is used to determine the temperature. As shown in Figure 8, the main components are a heat sensor to be inserted into the temperature measuring point, a Bourdon tube in the meter, and a capillary tube connecting them.

Though not high in accuracy, it is structurally strong and allows easier reading compared with the glass thermometer. Since it is suitable for telemetry, it allows measurements at a place apart from a dangerous place. It can also be used for automatic control.

Figure 8 Pressure Thermometer

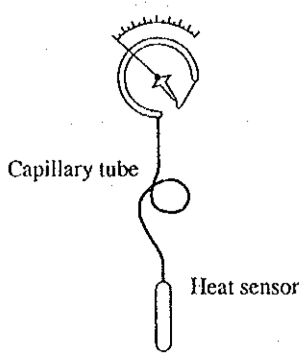


Table 3 shows the kinds and performance of pressure thermometers.

Table 3 Kinds and Performance of Pressure Thermometers

Kind	Liquid Expansion Type	Vapor Pressure Type
Enclosed material	Mercury	Volatile liquid
Scale range (°C)	–30 to 500	–20 to 200
Maximum length of capillary tube (m)	8 to 20	50
Sensibility	Good	Rather poor
Influence of capillary tube on temperature	A little	Nil
Influence of atmospheric pressure	Extremely little	A little at low pressure
Influence by the locations of heat sensor and meter	A little	Considerable at low pressure

2.4 Resistance Thermometer

(I) Resistance bulb

According to the rise of temperature, a metal wire changes in electric resistance, and there is a certain relation. Therefore, if a metal wire is brought into contact with an object to be measured, to be equal to the object in temperature, the electric resistance of the metal wire measured can be used for finding the temperature of the object.

The resistance bulb used should be desirably as large as possible in the change of resistance by temperature (temperature coefficient) and regular and stable in the change of value. To meet these requirements, a platinum wire is most excellent for precision measurement and has been used for a long time as a resistance bulb, but it is expensive which is a disadvantage.

Figure 9 Platinum Resistance Element

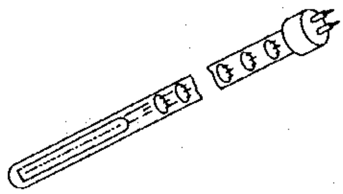


Figure 9 shows the most general platinum resistance element for precision measurement. A platinum wire of about 0.01 to 0.2 mm in diameter is folded at the center into two parallel lines, and wound around a crossed frame of mica plate or ceramic plate, and usually three or four lead wires are attached to remove the error otherwise caused by lead wire resistance.

The resistance wire may be used as it is, but generally is put in a protective tube made of glass, quartz porcelain or metal, etc., depending on the temperatures to be measured or the material to be measured.

A nickel resistance element is inexpensive, stable at room temperature and large in temperature coefficient, and therefore, it is often used next to platinum. However, it cannot be used at temperatures of 200 °C or higher.

A thermistor is a semiconductor prepared by mixing and sintering a metal oxide of nickel, manganese or cobalt etc., and the temperature coefficient of the thermistor changes, depending on the temperature. Therefore, it cannot be considered that the temperature coefficient is constant in a wide temperature range. However, the temperature coefficient of a thermistor at 25 °C is as large as about –2 to 6 %/°C, being about 10 times that of a platinum wire. For a measurement temperature range from about –50 to 350 °C, a small temperature sensing element can be made, and therefore the time delay is also small.

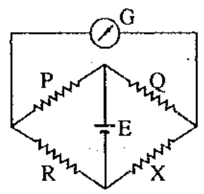
(2) Measuring instrument

a. Method by use of Wheatstone bridge: As shown in Figure 10, the four sides of Wheatstone bridge are resistances P and Q, variable resistance R and platinum wire resistance X, and if R is adjusted to let ammeter G indicate zero,

$$X = R \frac{Q}{P}$$

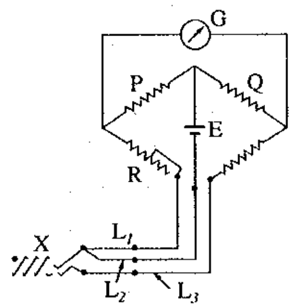
usually P = Q, hence X = R.

Figure 10 Wheatstone Bridge



For precise resistance measurement, the resistance of lead wires connecting the resistance bulb with the measuring instrument cannot be neglected. To eliminate the influence, lead wires are variously contrived. Figure 11 shows a case of three-wire connection.

Figure 11 Three Lead Wires



That is, if two lead wires L_1 and L_2 are taken from one end of the platinum wire coil and a lead wire L_3, from the other end (total 3 lead wires), and the respective resistances are L_1, L_2 and L_3, then

$$X + L_3 = R + L_1$$

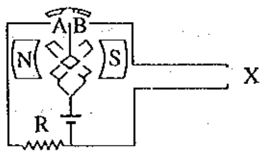
If $L_1 = L_3$, then we have X = R, and the value of R gives the resistance X of the coil.

b. Method by electronic automatic null balancing instrument: An electronic automatic null balancing mechanism is combined with a bridge circuit, to indicate or record the temperature by the zero method. The method includes an AC bridge type and a DC bridge type, depending on the measurement principle used. The AC bridge type is prone to cause an error due to the AC noise voltage induced in the resistance element or lead wires, and DC bridge type is more practically used.

c. Method by moving coil type ratio meter: Figure 12 shows a connection diagram for measuring the platinum wire resistance X, using a moving coil type ratio meter. Moving coils A and B are located between both the poles N and S of a permanent magnet, and the coil B contains resistance X of platinum wire.

If X is changed by a temperature change, the needle is deflected till the resultant magnetic field of both the coils A and B and the magnetic field of the permanent magnet reach a new equilibrium. This is widely used industrially.

Figure 12 Moving Coil Type Ratio Meter



d. Method by potentiometer: Resistance, i.e., temperature can be measured very accurately. This method is mainly used for precise measurement and calibration.

(3) Error by self-heating

In a resistance thermometer, since current flows in a resistance element, Joule heat is generated to raise the temperature. The magnitude is usually less than 0.2 °C, though depending on the resistance wire, and is mostly negligible.

2.5 Thermoelectric Thermometer

(1) Thermocouple

If metal wires of different kinds are bonded at both their ends as shown in Figure 13 and both the junctions are kept at different temperatures, a thermoelectromotive force is generated by a Seebeck effect. The electromotive force is measured using a DC millivolt meter or potentiometer, to know the temperature. Such a combination of metals is called a thermocouple. The cold junction is kept at 0 °C in an ice bath for base point, but in case of general plants, it is put in water, underground or atmosphere, to be kept at a constant temperature, and the other end (hot junction) is inserted into the measuring point.

Figure 14 shows the structure of a thermocouple.

Figuer 13 Principle of Thermocouple

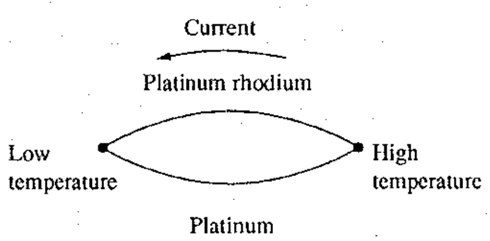
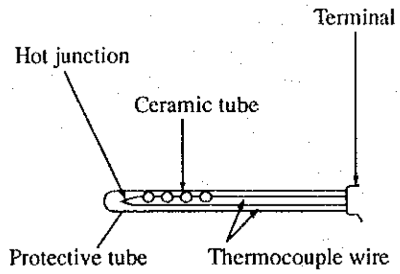


Figure 14 Thermocouple



(2) Requirements for thermocouple material

a. To be large in thermoelectromotive force which should rise continuously according to the rise of temperature.

b. To be stable in thermoelectromotive force, withstand long-term use and be free from hysteresis.

c. To be resistant against heat, mechanically strong even at high temperature, and resistant against corrosion in high temperature air and gas.

d. To be high in reproducibility, easily manufactured with constant characteristics and processed.

e. To be as small as possible in electric resistance and temperature coefficient, and also to be small in thermal conductivity.

f. To be smoothly available at low cost.

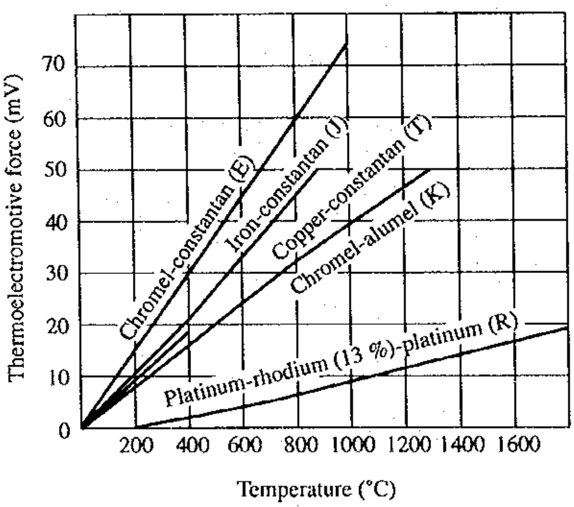
As materials satisfying these requirements, platinum-platinum-rhodium (JIS symbol: R.S.), chromel-constantan (E), chromel-alumel (K), iron-constantan (J), copper-constantan (T), etc. are used.

Figure 15 shows a thermoelectromotive force diagram of thermocouples specified in JIS.

Thermocouples for high temperature measurement include Ir-Ir·Rh (40 %) 2000 °C, W-Ir 2100 °C, W-W·Re (26 %) 2980 °C, etc.

Platinum-platinum-rhodium thermocouple is smaller than chromel-alumel thermocouple (K) in the thermoelectromotive force, but high in heat resistance and good in accuracy. It is resistant in oxidizing atmosphere but weak in the reducing atmosphere and metal vapor.

Figure 15 Thermoelectromotive Forces of Thermocouples Specified in JIS



(3) Compensating lead wire

As thermocouples are generally expensive, the part from the terminal of protective tube to the cold junction is substituted by a compensating lead wire.

A compensating lead wire is an electric wire which has the same characteristic as the electromotive force characteristic of the thermocouple at about the terminal temperature, and is mainly a combination of copper wire and copper nickel alloy wire. The electromotive characteristic is properly decided by nickel content.

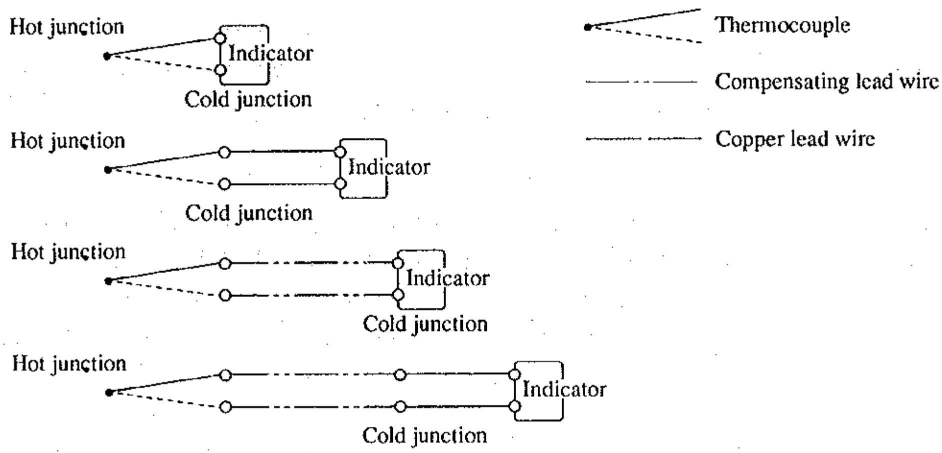
(4) Correction for cold junction temperature

The cold junction is kept at 0 °C in principle, but when it is difficult, the temperature is corrected as follows. That is, if an electromotive force of E (mV) is generated between the cold junction t_c kept at any other temperature than 0 °C and the hot junction t_H, the thermoelectromotive force e between 0 °C and t_c is obtained from the temperature vs. thermoelectromotive force curve or electromotive force table of the thermocouple used, and the temperature corresponding to E + *e* is obtained from the diagram or electromotive force table.

The thermocouple, compensating lead wire, copper lead wire and indicator can be connected by various methods as shown in Figure 16. The temperature at the cold junction in the respective connection methods is the correction temperature for the cold junction temperature.

There is also a meter which allows the cold junction temperature correction to be automatically carried out using a resistance wire or bimetal, etc. large in temperature coefficient.

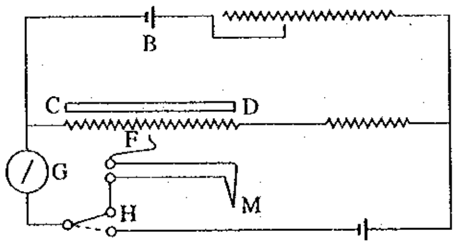
Figure 16 Various Connection Methods and Cold Junction



(5) Measuring instrument

When the thermoelectromotive force is measured by an ordinary potentiometer, as shown in Figure 17, the electromotive force generated from the thermocouple M is compared with a known constant current supplied from the dry battery B, and the position of the contact F on the slide rheostat C-D is adjusted to let the needle of the galvanometer G indicate zero. The position at that time indicates the temperature corresponding to the electromotive force of the thermocouple. The potentiometer uses a mechanical method for balancing the specified current and the thermoelectromotive force, and requires a relatively delicate galvanometer for detecting the unbalance. The detection is intermittent.

Figure 17 Potentiometer



Electronic type uses an electronic continuous balancer instead of the galvanometer, and the related mechanism is the same as the electronic balancer used for the resistance wire.

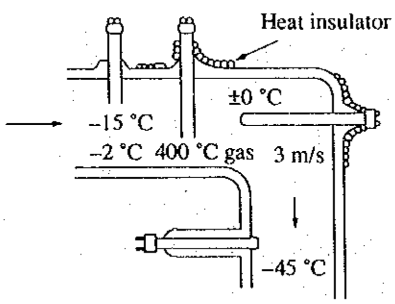
The electronic type is large in the torque for moving the needle, to allow expression on a large scale, thus allowing observation from a remote place, and the indication is reliable and highly accurate. Automatic recording is also easy, and a meter with a scale narrow in temperature range can also be manufactured. However, the structure is complicated.

(6) Error of thermoelectric thermometer

The electric error includes the error caused by the combination of a thermocouple and a meter, and the general error of an electric meter affected by temperature, magnetic field, etc. It also includes the secular change of the meter, and the error caused by the deterioration of the thermocouple.

What must be noted during use is thermal error. If a thermocouple is brought into contact with an object to be measured, the thermocouple may take away heat from the object, to lower the temperature of the measured object. In another case, when a thermocouple is inserted into the measuring point, heat is transmitted through the thermocouple and the protective tube. Figure 18 shows a case of such error.

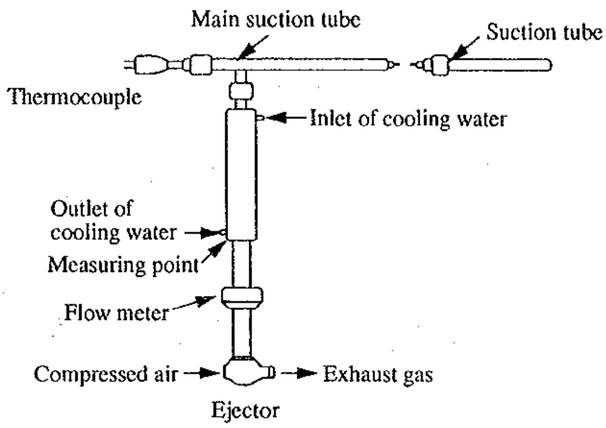
Figure 18 Caution for Use of Thermometer



Furthermore, since a thermocouple which senses the temperature of the measuring point may be subject to the radiant heat from a nearby object with a higher temperature or may give heat to an object with a lower temperature by radiation, an error is caused especially in the temperature measurement of gas.

Figure 19 shows a suction-pyrometer for preventing it. In the suction-pyrometer, the thermocouple is provided as a double tube for preventing the influence of thermal radiation, and gas is sucked at a high velocity toward the circumference of the thermocouple, for a better heat transfer to the thermocouple, and to know the temperature of the gas itself.

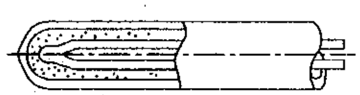
Figure 19 Suction Pyrometer



(7) Sheathed thermocouple

A sheathed thermocouple, as shown in Figure 20, has magnesia (MgO) or alumina (Al_2O_3) kept and solidified in the protective tube of the thermocouple and is made very thin in order to be flexible. Sheathed thermocouples of about 0.25 to 12 mm in diameter are also manufactured, and the radius of possible bending is 1 to 5 times the diameter. Since they are thin, they are suitable for local temperature measurement and small in time delay of indication. Furthermore, they do not disturb the temperature of the measured object.

Figure 20 Sheathed Thermocouple

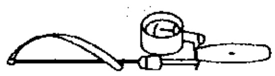


(8) Surface thermometer

As shown in Figure 21, the cold junction of the thermocouple is grasped by hand and the hot junction is brought into contact with the surface of an object, for surface measurement.

There is also a surface thermometer which is heated internally to prevent the temperature drop of the measured object otherwise caused by contact with the thermometer.

Figure 21 Surface Thermometer



2.6 Radiation Thermometer

An object higher in temperature radiates stronger heat. The radiant heat Q emitted from a unit area of an object with emissivity ε and absolute temperature T (K) into a space during a unit time is expressed by

$$Q = 5.67 \times \varepsilon \times \left(\frac{T}{100}\right)^4 \ [\text{W/m}^2]$$

The radiant energy is measured, to know the temperature.

Since the meter indicates the emissivity (blackness) of the black body as $\varepsilon = 1$, the real temperature of the measured object which is not a black body can be obtained by knowing ε of the measured object and dividing by $\sqrt[4]{\varepsilon}$.

Table 4 shows emissivities of some materials, which vary to some extent, depending on the temperature, state, etc. of each material.

Table 4 Surface Emissivities ε of Some Materials

Surface	Temperature Range (°C)	Emissivity ε
Iron oxide	500 to 1200	0.87 to 0.89
Silica brick	1000	0.80
Rough aluminium surface	25	0.055
Rolled steel sheet	21	0.675
Limestone	63 to 193	0.36 to 0.40

A radiation thermometer collects radiant energy by a lens or reflector, as shown in Figure 22. The former type is mainly used.

A lens radiation thermometer uses a lens transparent for the visible and infrared range of radiation. For the measurement of radiant energy, a thermocouple, a thermopile with many thermocouples assembled or bimetal, etc. is used. In this arrangement, consumable parts such as battery are not required, and a considerably large output is available. Therefore, the output voltage allows direct recording and can also be used for temperature control.

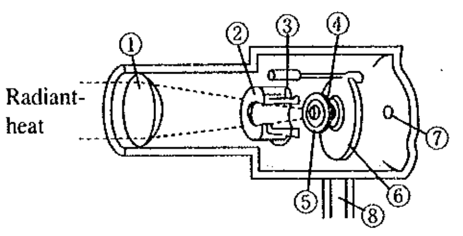
Notes for use:

(1) If smoke, water vapor or carbon dioxide, etc. exists between the thermometer and the measured object, an error is caused.

(2) If the temperature of the thermometer rises, an error is caused. Therefore, any proper air- or water-cooling device should be used.

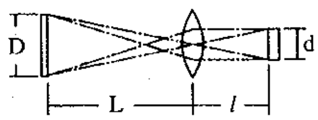
(3) It must be noted that each meter has its distance coefficient. As shown in Figure 23, if the distance from the measured object to the lens of the transmitter is L, the effective diameter of the measured object is D, the distance from the lens to the thermal sensitive material is *l*, and the size of the thermal sensitive material is d, then *l*/d is called the distance coefficient. It is usually 10 to 30. In this case, L and D must be selected to satisfy the relation of L/D < *l*/d.

Figure 22 Radiation Thermometer



① Objective lens
② Stop
③ Stop adjusting screw
④ Compensating resistor
⑤ Thermocouple
⑥ Terminal
⑦ Peep hole
⑧ Support

Figure 23 Distance Coefficient

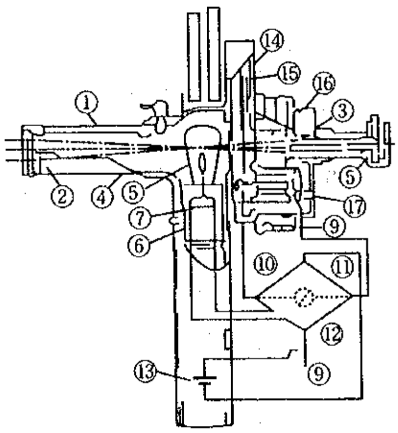


2.7 Optical Pyrometer

An optical pyrometer is a kind of radiation thermometer. The radiant energy of a specific wavelength (usually 0.65 μ red) in the radiation from a hot object is compared in luminance with that of a hot material (lamp filament) with reference temperature in the pyrometer, to know the temperature.

Figure 24 shows the internal structure of a filament dissipation type optical pyrometer most widely used.

Figure 24 Structure of Optical Pyrometer



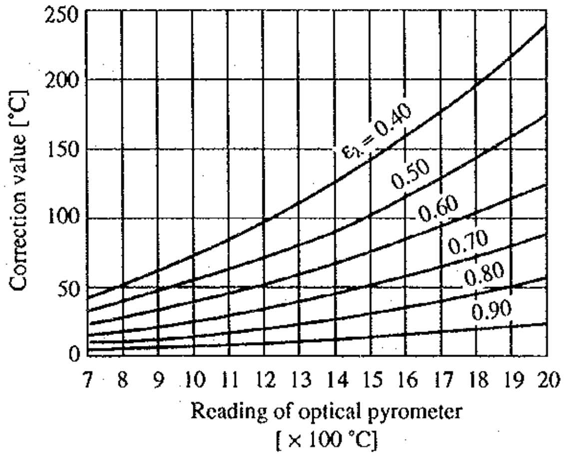
The entire structure is one telescope, and a reference lamp for comparison is located at the center. The telescope is turned toward the hot object to be measured, and the lens barrel is visually adjusted to superimpose the image of the object on the plane of the filament. Visually comparing the luminance of the object image with that of the filament through the red filter glass plate, and the filament current is adjusted by the resistance to make both the luminances equal. Since the relation between the filament temperature and filament current of the reference lamp is known beforehand, the temperature corresponding to the filament current can be obtained by reading the current flowing in the filament of the lamp using an ammeter. The temperature is indicated on the scale.

There is also another measuring method, in which with the luminance of the reference light source kept always constant by a constant current, the light from the hot object to be measured is made to pass obscure glass with a certain thickness or a polariscope, to weaken the luminance, for the adjustment to be equal to the luminance of the reference light source.

When the temperature of an object other than a black body is measured by an optical pyrometer, correction must be made to know the real temperature, by knowing the emissivity ε_λ of the object to wavelength 0.65 μ (red). Figure 25 is a correction table for it.

An optical pyrometer using a photoelectric cell or photoelectric tube to substitute human eyes is called a photocell pyrometer or phototube pyrometer.

Figure 25 Correction by Emissivity



2.8 Color Thermometer

In general, a material begins to emit light at a temperature higher than 700 °C, and changes from red to reddish yellow and further to bluish according to the rise in temperature. The reason is that according to the rise in temperature, the short wavelength (blue) component contained in ray increases, while on the contrary, the long wavelength (red) component decreases. To use a color temperature while a hot object is observed through a color filter, the filter is adjusted to weaken one of the radiant energies of two wavelengths until it is visually confirmed that the color of the hot object becomes the same as the reference color. This is in order to obtain the temperature of the hot object from the weakened degree of the radiant energy of one wavelength.

This principle is used by the color filter thermometer and bioptics thermometer. There is also a two-color thermometer which measures the ratio of radiant energies of two wavelengths using photoelectric tubes, etc. and automatically indicates and records the thermometer. A color thermometer is little affected by emissivity and the measured value is close to the real temperature.

2.9 Other Temperature Measuring Methods

(1) Seger cone

This is a triangular pyramid prepared by mixing clay, various silicates, and metal oxides. If it is heated, each specific ingredient is softened and deformed at a specific temperature. It is used, for example, to know the internal temperature of a furnace. It is affected by the heating rate, gas atmosphere in the furnace, gas flow velocity, temperatures of surrounding furnace walls, etc. It can be more convenient than ordinary thermometers, depending on the place of use. It is used in the ceramic industry, etc.

(2) Thermal paint

A thermal paint is applied to the portion to be measured, to know the temperature by using the property of the paint color that it changes at a predetermined temperature. Both reversible and irreversible paints are available.

(3) Bimetal thermometer

Two kinds of metals which are different in the thermal expansion coefficient are stuck together, and their bending caused by temperature change is transmitted to a needle. It can also be used for temperature control.

3. FLOW RATE MEASUREMENT

3.1 Kinds and Features of Flow Meters

Major methods for measuring the flow rate of a liquid or gas include volume method for measuring a volume or mass, differential pressure method using an orifice plate or nozzle throttle mechanism, area method for knowing the flow rate by changing the throttle area with the differential pressure kept constant, flow velocity method for knowing the flow rate from the revolution of a propeller, etc. in a liquid, method using a Pitot tube, method using vortexes of a fluid, hot wire method for measuring the absorbed heat of a fluid, etc. Kinds, features and accuracies of main flow meters used for heat control are listed in Table 5.

Table 5 Kinds, Features and Accuracies of Flow Meters

Measuring Method	Flow Meter	Features	Accuracy
Volume method	Wet gas meter	• Gas only can be measured. • Measuring range: 1 m/min to large flow rates	±0.5 %
	Dry gas meter	• There is no fear of freezing since water is not used. • Handling is simpler than with wet type.	±0.5 %
	Rotary piston type	• Measuring accuracy depends on the flow rate range and the nature of fluid. • Pressure loss is small.	Approximately ±0.5 %
	Oval flow meter Roots flow meter	• Volume flow rate can be measured irrespective of kind, viscosity and density of liquid. • Mainly for liquid.	±0.1 to 2 %
Flow velocity method (impeller method)	Axial flow type (Waltman type)	• In general, used for measuring the flow rate of city water.	Approximately ±4 %
	Venturi tube diversion	• Can measure large flow rates of water. • Apparatus is simple.	
	Turbine meter	• Small and can measure large flow rates.	0.2 to 1 %
Area method	Rotameter	• Effective measuring range is wide. • Flow rate at low Reynolds number can be measured. • Scale keeps almost linearity.	Approximately ±2 %
	Piston type flow meter	• Used for measuring fuel oil with high viscosity. • Allows telemetry.	
Measurement of velocity head	Pitot tube	• Simple and inexpensive.	
Throttle method (differential pressure method)	Orifice Flow nozzle	• Mechanism is simple. • Liquid, gas, vapor, etc. can be measured.	Approximately ±1 %
	Venturi tube	• Pressure loss is small.	
Vortex	Swirl meter	• For gas	
	Delta flow meter	• Measuring range is wide.	
Hot wire method	Thomas gas meter	• For gas	
Electromagnetic method	Electromagnetic flow meter	• No pressure loss. • Quick response.	Approximately ±2 %
Ultrasonic method	Ultrasonic flow meter	• No pressure loss.	

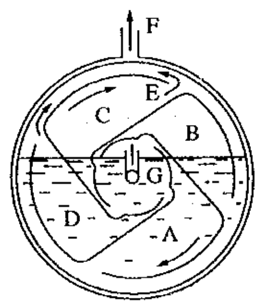
In the selection of a flow meter, the following should be considered.

(1) Temperature, pressure and density of fluid
(2) Magnitude and variation range of flow rate
(3) Solid content and pressure loss
(4) Corrosivity, harmfulness and flammability
(5) Accumulated value or momentary value
(6) Recorded value or indicated value
(7) Direct reading measurement or telemetry

3.2 Volume Method

A fluid is introduced into a container with a certain volume, to obtain the flow rate. Figure 26 shows a wet gas meter used to measure the flow rate of gas. This flowmeter has a rotary drum with four chambers A, B, C, and D installed in a horizontal cylinder filled with water up to a half. The gas entering from inlet G into the respective chambers sequentially replaces the water in the chamber. The buoyant force produced at this time rotates the drum to cause the gas in the drum to be replaced by water again and discharged from outlet F. This allows the number of rotations proportional to the flow rate to be obtained. Here, however, it should be noted that the water level should be constant; otherwise, the volume of the measuring chamber would change, thus causing an error in measurement. The measurement tends to be affected by vapor pressure, and therefore the water temperature should be accurately measured and compensated.

Figure 26 Wet Gas Meter



A dry gas meter usually has two drums made of synthetic rubber, and if one drum is filled with a gas, valve action occurs, to change the gas passage in the other way. The expansion and contraction of the synthetic rubber drums moves a metering mechanism. The dry type has advantages over the wet type so that freezing does not occur and that moisture does not go into the gas.

Figure 27 shows a rotary piston type flow meter. In the radial direction of a cylinder, one partition wall is provided, and the cutout of a rotary piston slides on it for eccentric motion with one point on the circumference of the piston kept always in contact with inner wall of the cylinder. The action is caused by the fluid pressure applied to the inside and outside of the piston, and the fluid is measured by the volumes inside and outside the piston.

Figure 27 Rotary Piston Type Flow Meter

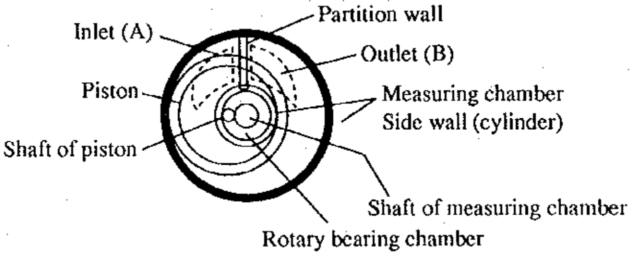
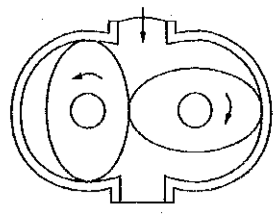


Figure 28 shows an oval flow meter. Two oval gear rotors are rotated by the difference between inlet and outlet pressures of a fluid, and from the number of revolutions, the flow rate is obtained. Various types and various flow rates transfer and indication methods are available.

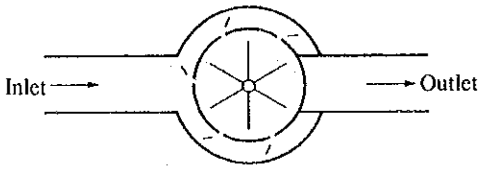
Figure 28 Oval Flow Meter



3.3 Flow Velocity Method

In this method, from a propeller, etc. rotated in a fluid by flow velocity, the flow rate is obtained. Figure 29 shows an impeller type flow meter, and it is available as a single box type or double box type. Waltman type flow meters are used for measuring large flow rates of city water, etc. For industrial use, turbine flow meters are generally used which belong to Waltman type.

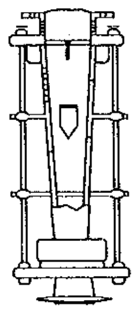
Figure 29 Impeller Type Flow Meter



3.4 Area Method

In this method, with differential pressure kept constant, the throttle area is changed to know the flow rate. Figure 30 shows a rotameter. When a fluid to be measured flows through a vertical tube with a bottom bore slightly smaller than the top bore, the buoy in the tube is pushed up to a height corresponding to the flow rate of the fluid and comes to a standstill. Graduations are given to indicate the momentary flow rate from the stationary position. When this flow meter is used, it must be noted that the measured value depends on the density, pressure, viscosity, etc. of the fluid. Various kinds are available for various conditions. If properly used, it is simple and convenient, and widely used in many fields.

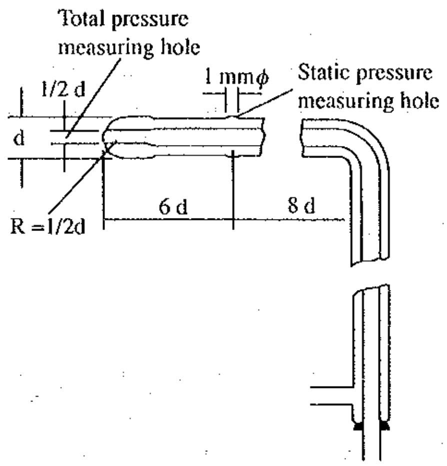
Figure 30 Rotameter



3.5 Method for Measuring Velocity Head

Figure 31 shows a Pitot tube. It has a hole in front, and if the hole is turned toward the flow of fluid, a pressure corresponding to the sum of the static pressure of the fluid at the point and the dynamic pressure for the velocity is generated. In this case, since only the static pressure of the fluid acts on a side opening, the difference h is measured by a proper pressure gauge, to know the flow velocity of the fluid, for obtaining flow rate Q.

Figure 31 Pitot Tube



$Q = A \cdot c\sqrt{2g \cdot h/\rho}$ [m³/s]

A: Sectional area of tube [m^2]
g : 9.8 [m/s^2]
h : Pressure difference (Pa) [mm/H_2O]
ρ: Specific gravity of fluid [kg/m^3]
c : Coefficient of flow

The measurement by a Pitot tube is simple, but if it is wrongly used, a large error is caused. That is, the Pitot tube must be set to straightly face the flow direction. The sectional area of the Pitot tube must be smaller than 1 % of the sectional area of the pipe line. Upstream of the Pitot tube, a straight tube portion as long as more than 20 times the tube diameter is required. When there is much dust, a double head Westone type Pitot tube is used, but it requires the coefficient of flow to be noted.

3.6 Throttle Mechanism Method

An orifice is a flow rate sensing element generally used for this method.

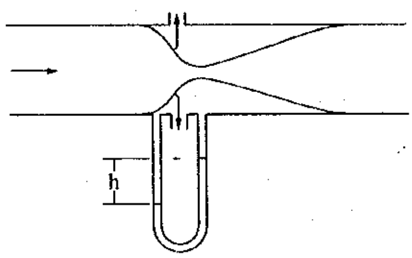
A throttling plate is inserted in a pipe line, and the pressure difference generated is measured, to obtain the flow rate according to Bernoulli's theorem. That is, as shown in Figure 32, in a straight tube, a throttling plate (orifice plate or nozzle plate) with a hole smaller than the sectional area of the tube is inserted, to restrict the flow, and from the difference between the pressures upstream and downstream of it, the flow rate is measured. It can be used for either a gas or liquid. If F is the sectional area of the hole of the throttle plate (m^2), h is $P_1 - P_2$ = the difference between the pressures upstream and downstream of the throttle plate (Pa), ρ is the specific gravity of the fluid (kg/m^3), c is the coefficient of discharge, and ε is the expansion coefficient of factor, then the mass M and the volume W of the fluid passing through the tube per unit time can be obtained from the following:

$$M = c \cdot \varepsilon \cdot F\sqrt{\rho (P_1 - P_2)} \quad [kg/s]$$

$$W = c \cdot \varepsilon \cdot F\sqrt{(P_1 - P_2)/\rho} \quad [m^3/s]$$

That is, they are proportional to the root of the differential pressure.

Figure 32 Throttle Plate Flow Meter



3.7 Hot Wire Method

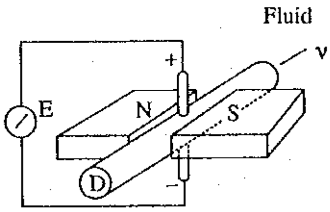
In the hot wire method by a hot wire flowmeter, a wire of metal such as tungsten or thin film is placed in the fluid flow, heated by application of an electric current, and thus the amount of heat taken away through convection is measured to obtain the flow rate. Generally, the flow rate is obtained from the heating value with the hot wire controlled and kept at a constant temperature. A hot wire flowmeter, which has a small sensing element and a frequency response up to several kHz, is suitable for measuring the fluctuations in the flow rate, but it is susceptible to the fluid temperature. A mass flowmeter, which is becoming increasingly popular in the recent years, is mainly used for measuring the flow rate of gas. In this method, a fluid resistance such as capillary is inserted in the main flow passage and a bypass tube is provided with a heater, upstream and downstream of which a detecting resistance wire is wound. When the heater is heated, a temperature rise on the upstream side differs from that on the downstream side due to the factors including fluid density, specific heat and flow rate. This difference in the temperature is detected to obtain the flow rate. This flow rate is a mass-based flow rate and therefore temperature and pressure exert no effect on the measurement value.

This method, which offers quick response and the output by electric signals, is, in many cases, used together with automatic valves as a flow controller. Additionally, since the sensing element does not come into direct contact with the fluid, this method can be used also for a corrosive fluid.

3.8 Electromagnetic Method

If a magnetic field is generated at right angles to the flow direction of a conductive fluid flowing in a tube on both sides of the tube as shown in Figure 33, an electromotive force E is generated in the direction perpendicular to the flow and magnetic field respectively.

Figure 33 Electromagnetic Flow Meter



If a conductive fluid flows in a tube of D in diameter at an average velocity v, and the intensity of the magnetic field is H, then the volume flow rate Q can be expressed by

$$Q = C \cdot D \cdot \frac{F}{H} \quad \text{(C: Constant)}$$

If the intensity of the magnetic field and the tube diameter are constant, the electromotive force is proportional to the volume flow rate.

The flow meter is characterized by a perfect freedom from pressure loss and a very quick response and usability inspite of ingress of some solid grains.

3.9 Method by Fluid Vortexes

The method was developed with attention paid to the phenomenon that the frequency of vortexes generated in a fluid is proportional to the flow velocity. Figure 34 shows a delta flow meter using the principle. Two thermal sensors are set in a triangular prism-like vortex generator, and the alternating change of von Karman's vortex street is taken as the change in the resistances of the sensors, for expressing as the flow rate.

Figure 35 shows a vortex flow meter which uses the same principle as the delta flow meter. It uses a cylindrical sensor and one very thin platinum wire as the sensing element (the delta flow meter uses thermistors), and therefore, is different in electric circuit configuration. Both are small in pressure loss due to their structures, and can be easily installed and removed. A purge type vortex flow meter is also available for use for a fluid containing dust or corrosive fluid in a flue etc.

Figure 34 Delta Flow Meter

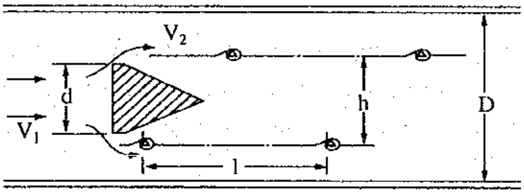


Figure 35 Vortex Flow Meter

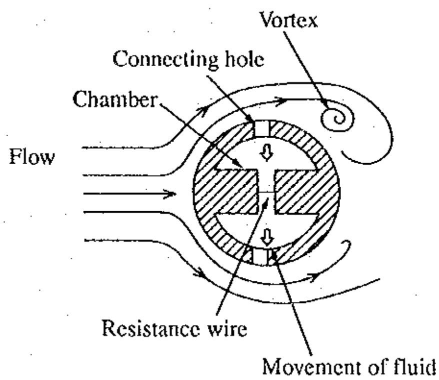
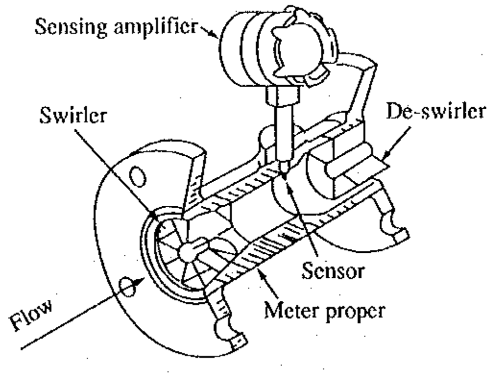


Figure 36 shows a swirl meter which is composed of a meter proper, swirler, de-swirler, sensor and sensing amplifier. The meter proper has internally Venturi tube structure. It was developed for gas. Each vortex generated by the swirler has a velocity distribution protruding at the axial portion and symmetrical around the axial center, and causes a braying motion at the neck portion of the Venturi tube. Since the number of revolutions at the velocity center (vortex center) is proportional to the actual volume of the gas, it is sensed by a thermistor, in order to indicate as the flow rate.

Figure 36 Swirl Meter



The de-swirler is provided to remove the influence on the downstream side, and restores the original condition free from vortexes.

All the flow meters are wide in measuring a range as a common advantage, and their respective features are used to widen their applications.

3.10 Other Flow Rate Measuring Methods

If an acoustic wave is generated in flow, the sound is propagated at a velocity equal to the vector of the sound velocity and the flow velocity. An ultrasonic flow meter uses this principle, to measure the propagation velocity, for measuring the flow velocity and rate. As for a laser flow meter, since a laser beam is in wavelength and monodirectional with uniform wave front, the scattering in a fluid is used to measure the flow velocity. It has such features as non-contact measurement and a good response.

4. MEASUREMENT OF PRESSURE

4.1 Kinds and Features of Pressure Gauges

Pressures gauges include liquid column type, elastic type, inverted bell jar type, ring type, electric type, etc., and their features and accuracies are listed in Table 6.

Table 6 Kinds, Features and Accuracies of Pressure Gauges

Measuring Method	Pressure Gauge	Features	Accuracy
Liquid column type	Mono-tube type	• Only once scale reading is required. • Influence of temperature is large.	8 mmHg (Users' tolerance)
	U-tube type	• Higher in accuracy than mono-tube type. • Tube diameter and temperature affect error.	8 mmHg (Users' tolerance)
	Mono-tube inclination type	• Straightness and inclination angle of tube exert a large influence.	Approximately 0.01 mmH_2O
Elastic type	Bourdon tube	• Simple in structure. So popularly used that it is a generally called pressure gauge which reminds people of Bourdon tube pressure gauge. • Measuring operation is simple and does not require skill. • Easy in handling and maintenance. • Telemetry and automatic recording are easy. • Allows measurement even in relatively severe conditions such as solid-containing fluid, corrosive fluid, etc. • Suitable for high pressure measurement and wide in measuring range. • Unsuitable for measuring slight pressure. • Since elasticity only is used, it is difficult to change the measuring difficult to change the measuring pressure range. • Errors due to creep, hysteresis or secular change are liable to be caused.	Approximately ±0.5 to 2.5 % of maximum pressure
	Diaphragm type	• Pressure receiving face is large. • Corrosion preventive measure can be easily taken. • Response is quick. • Maximum pressure is 2 kg/cm^2.	Approximately ±0.5 to 2.0 %
	Bellows type	• Measuring range can be changed. • Displacement is large. • Pressure tightness and temperature compensation can be easily realized.	Approximately ±0.5 to 2.0 %
	Capsular type	• Very sensitive to a slight pressure change. • Unsuitable for high pressure.	Approximately ±0.5 to 2.0 %
Inverted bell jar type	Single bell type	• Mechanical friction is small. • Impact vibration can be measured.	Approximately ±1 %
	Double bell type	• Higher in sensitivity and accuracy than single bell type.	Approximately ±0.5 %
Ring type		• Turning torque is large. • Measuring range can be adjusted. • At end connection, elastic resistance is liable to occur.	±1 % to 2 %
Electric type	Strain gauge type	• Sudden change can be followed. • Suitable for telemetry and multi-point measurement.	Approximately ±1.5 %
Piston type		• Measuring range can be adjusted.	Approximately ±1 %
Weight type		• Measuring range is wide. • Accuracy is high.	1/200 of marked quantity (Users' tolerance)

In the selection of a pressure gauge, the following should be considered;

(1) Measuring range: In the case of Bourdon gauge, etc., the measuring range should be 2/3 or less of the maximum graduation.

(2) Direct reading measurement or telemetry.

(3) Place of installation.

(4) To have a safety device, in the case of high pressure.

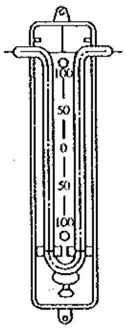
(5) Inspection should be carried out constantly to confirm that the indication is correct.

4.2 Liquid Manometer

(1) U-tube manometer

As shown in Figure 37, a glass tube is bent like U shape, and one end connects to a measuring point, while the other end connects to another pressure measuring port or is usually open to the atmosphere, regarded as a 1-atmosphere constant pressure chamber.

Figure 37 U-tube Manometer



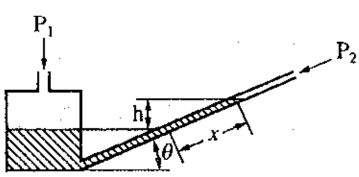
The measuring liquid used is usually water. However, for large pressure difference, mercury is used, and for small pressure difference, any liquid lighter than water is used. However, in this case, calculation of multiplying the differential pressure by the specific gravity of the fluid used is required. The liquid used for the pressure measurement is required to have such properties as (1) small viscosity, (2) small thermal expansion coefficient, (3) small capillarity, (4) certain chemical ingredients, etc.

Therefore, if a precise measurement is required, correction of temperature, gravity and capillarity is required.

(2) Mono-tube inclination manometer

As shown in Figure 38, this is a modification of U-tube manometer. The sectional area of P_1 side is very large compared with that of P_2 side, and the change of the liquid level in the container large in sectional area corresponding to the change of the liquid level in the thin tube can be neglected. Therefore the height of the liquid in the mono-tube is subtracted, and the length x corresponding to the pressure is enlarged by $1/\sin\theta$.

Figure 38 Mono-tube Inclination Manometer



Since x corresponds to h/sinθ where θ is the inclination angle, pressure P_1 can be obtained from the following equation:

$$P_1 = P_2 + \rho\, x \sin\theta$$

where ρ is the specific gravity of the liquid. Both types constant and adjustable in the angle θ of the inclined tube are available.

(3) U-tube manometer using two liquids

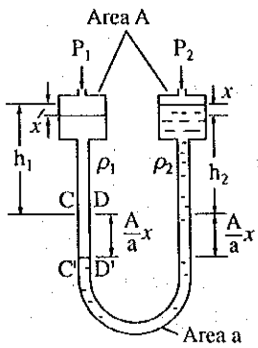
As shown in Figure 39, two liquids are used, to enlarge the differential pressure. The pressure difference can be calculated from:

$$\Delta P = P_1 - P_2 = \frac{A}{a} x \{(\rho_2 + \rho_1)\frac{a}{A} + (\rho_2 - \rho_1)\}$$

where A: Sectional area of pressure receiving chamber
a : Sectional area of measuring tube
ρ_1: Specific gravity of light liquid
ρ_2: Specific gravity of heavy liquid

If a/A and $\rho_2 - \rho_1$ are smaller, even a slight pressure difference can be enlarged more. For example, if A/a = 1000, specific gravity of alcohol ρ_1 = 800 kg/m^3, and specific gravity of petroleum ρ_2 = 810 kg/m^3, then the enlarging factor becomes about 81 times.

Figure 39 Two-liquid Manometer

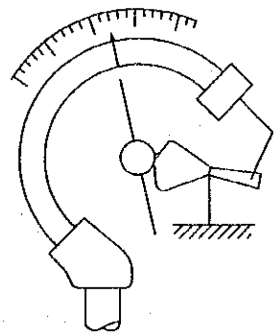


4.3 Elastic Pressure Gauge

(1) Bourdon gauge

As shown in Figure 40, a metallic pipe bent like a circular arc (or spiral, helix, any other form, etc.), and one end is fixed, while the other end is kept free. If an internal pressure is applied, the free end moves. The movement is enlarged by a lever or gear, to move the needle. Bourdon gauges are available in a wide accuracy range from superhigh accuracy to low accuracy. For various applications, various forms and sizes are available. Bourdon gauges are generally used in large quantities for industrial use.

Figure 40 Bourdon Gauge



(2) Instrument pressure gauges

Instrument pressure gauges are offered for measurement and control sensing in large plants and industrial processes, and are applied for measuring static pressure, differential pressure and absolute pressure. Either current transmission (4 to 20 mADC) or pneumatic transmission (20 to 100 kPa) is used. The gauges are standardized for indication, recording and arithmetic input respectively.

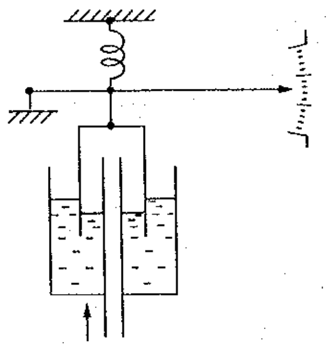
The pressure receiving element is a diaphragm made of a special metal, and a liquid material is contained between it and the sensing element, for transfer of pressure. The diaphragm is available in various forms, sizes and materials, for various working conditions and pressure ranges. The measuring range available is generally from about 20 mm water column to hundreds of atmospheric pressure. Zero adjustment, span adjustment and damping adjustment can be made.

4.4 Other Pressure Measuring Methods

(1) Inverted bell jar type manometer

As shown in Figure 41, this combines a beam with a bell. For industrial application, it is little used.

Figure 41 Inverted Bell Jar Type Manometer



(2) Strain gauge type pressure gauge

In general, a strain gauge is used as the sensing element. Strain gauge type pressure gauges are used mostly for special applications. The sensing means is characteristically small and quick in response rate. They are available for superhigh pressure to slight pressure. There are some using a semiconductor strain gauge or magneto-striction effect.

5. MEASUREMENT OF HUMIDITY

5.1 Kinds and Features of Hygrometers

The humidity of a gas can be measured by using a psychrometer, dew point meter, electric hygrometer, hair hygrometer, etc. Kinds and features of psychrometers are shown in Table 7.

Table 7 Kinds and Features of Psychrometers

Kinds	Advantages	Disadvantages
Simple psychrometer	Simple in structure	1. Does not directly indicate relative humidity. 2. Poor in accuracy. 3. Requires water.
Sling-type psychrometer	Convenient to carry.	1. Does not directly indicate relative humidity. 2. Requires much skill. 3. Requires water.
Asmann ventilated psychrometer	1. Allows a relatively high accuracy to be obtained at room temperature. 2. Convenient to carry.	1. Does not directly indicate relative humidity. 2. May sometimes be low in ventilation. 3. Requires some skill. 4. Requires water.
Meteorological Agency type ventilated psychrometer	Allows a high accuracy to be obtained at room temperature.	1. Does not directly indicate relative humidity. 2. Requires water.
Resistance thermometer type psychrometer	1. Indicates relative humidity directly. 2. Allows continuous recording and telemetering. 3. Can be used for automatic control. 4. Allows measurement at several positions by one indicator.	1. A simple calculation formula is used for direct indication of relative humidity, thus causing a large error in measurement of a wide range of operating temperatures and humidity. 2. Requires water.

5.2 Psychrometer

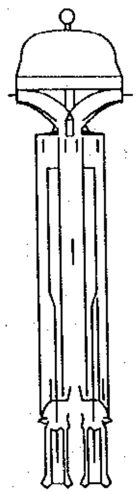
This meter is usually used. Two ordinary mercury-in-glass thermometers are placed in the air to be measured, and the bulb of either of them is wrapped with cloth wetted by water.

From the dry bulb temperature and wet bulb temperature, the humidity is obtained in reference to the psychrometer diagram.

The wet bulb indication of a stationary psychrometer is generally too high, affected by radiant heat, and does not coincide with the real wet bulb temperature. Therefore, there is also a device contrived to increase the velocity of the air around the wet bulb.

A sling psychrometer has the psychrometer mounted on one frame, and swung around the frame, to reach an equilibrium temperature.

Figure 42 Asmann Ventilated Psychrometer

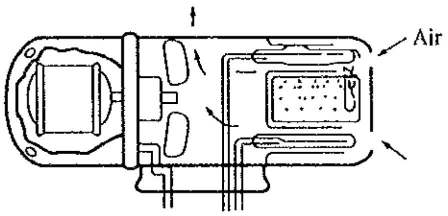


An Asmann ventilated psychrometer has a small spring revolved like the works of a watch at the top of the psychrometer, and it is revolved to cause an air current of about 2.5 m/s in flow velocity on the surfaces of the dry and wet bulbs.

5.3 Resistance Thermometer Type Hygrometer

As shown in Figure 43, the principle is the same as that of a psychrometer. Instead of mercury thermometers, resistance thermometers are used. The cold junction is wrapped with wet cloth, and the hot junction is exposed to air, to generate an electromotive force corresponding to the difference between dry and wet bulb temperatures. Remote indication and recording can also be realized.

Figure 43 Resistance Thermometer Type Hygrometer



5.4 Dew Point Meter

A cooling dew point meter has a smoothly polished metallic face placed in the air to be measured, and the metallic face is gradually cooled by feeding water inside or using the evaporation heat of ether, etc. At a certain temperature, the glossy face becomes cloudy with a thin film of dew. On the contrary, if the temperature of the metallic face which is cloudy with dew is gradually raised, the cloud disappears at almost the same temperature as before. The mean temperature of both is called a dew point. If the dew point is known, the humidity can be obtained from the water vapor table or humidity diagram.

The cloud by dew can be judged visually, or using a photoelectric tube or electric resistance.

A phototube dew point meter measures the cloud on the metallic specular gloss face using a phototube circuit, and allows recording.

5.5 Electric Hygrometer

If a hygroscopic conductive thin film (e.g., containing lithium chloride) is spread between two electrodes insulated from each other, the moisture around it is absorbed according to the increase of the humidity of the air around it, and it causes decrease in electric resistance. This principle is used in this hygrometer.

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