

2.1 The SI System and Conversion Factors

The SI system (International System of Units) is a set of definitions and rules which provides an organic and consistent approach for obtaining the units for each quantity.

The SI system is based on seven basic and two supplementary units. The basic units are the following: the kilogram (mass), the meter (length), the second (time), the ampere (electric current), the kelvin (temperature), the candela (luminous intensity), and the mole (molecular substance). The supplementary units are the radian (plane angle) and the steradian (solid angle). The choice, which has been made by the General Conference on Weights and Measures, is always open to changes and integrations.

The SI basic and supplementary units are reported in Table 2.1. From these nine units any other SI units can be derived by using the following expression:

$$\text{Derived unit} = \text{m}^{\alpha_1} \times \text{kg}^{\alpha_2} \times \text{s}^{\alpha_3} \times \text{A}^{\alpha_4} \times \text{K}^{\alpha_5} \times \text{cd}^{\alpha_6} \times \text{mol}^{\alpha_7} \times \text{rad}^{\alpha_8} \times \text{sr}^{\alpha_9}$$

where the exponents $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_8, \alpha_9$ are positive or negative whole numbers. Each exponent is equal to zero when the derived unit does not depend on the corresponding basic or supplementary unit.

Table 2.2 shows the prefixes which must be used to derive multiples or submultiples of any SI unit. Table 2.3 shows a few derived units currently used.

It is worth noticing that EU (European Union) countries must use the SI units reported in Table 2.1 (they are obliged to by European Commission's recommendations and related national laws). This system has been adopted also by the International Organization of Standardization (ISO).

Table 2.4 lists commonly used units which, however, do not belong to the SI system. Technicians should refrain from using these units.

The table shows the conversion factors from these units to SI units; conversion between two non-SI units can be made by using the ratio between the conversion

Table 2.1 SI base and supplementary units

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	Ampere	A
Thermodynamic temperature	Kelvin	K
Luminous intensity	candela	cd
Molecular substance	mole	mol
Plane angle	radian	rad
Solid angle	steradian	sr

Table 2.2 Prefixes commonly used

Factor	Prefix name	Symbol
<i>Multiple</i>		
10^{18}	Exa	E
10^{15}	Peta	P
10^{12}	Tera	T
10^9	Giga	G
10^6	Mega	M
10^3	kilo	k
10^2	hecto	h
10^1	deka	da
<i>Submultiple</i>		
10^{-1}	deci	d
10^{-2}	cents	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

factors of the single units. This is valid also for temperature, if temperature changes are considered (as often occurs in many formulas).

Table 2.5 lists some parameters frequently used for technical calculations.

2.2 Primary Energy Measurement Units

The primary energy content of combustibles (solid, liquid, or gaseous) is expressed by Lower Heating Values or Higher Heating Values such as kJ/kg or kJ/m³ (SI units). There are other units in common use.

Table 2.3 Units derived from SI

Quantity	Unit	Symbol
<i>Space and time</i>		
Area	square meter	m^2
Volume	cubic meter	m^3
Velocity	meter per second	m/s
Acceleration	meter per second squared	m/s^2
Angular velocity	radian per second	rad/s
Angular acceleration	radian per second squared	rad/s^2
Frequency	Hertz	$\text{Hz} = \text{cycle/s}$
<i>Mechanics</i>		
Density	kilogram per cubic meter	kg/m^3
Momentum	kilogram meter per second	$\text{kg} \cdot \text{m/s}$
Moment of inertia	kilogram meter squared	$\text{kg} \cdot \text{m}^2$
Force	Newton	$\text{N} = \text{kg} \cdot \text{m/s}^2$
Torque, moment of force	Newton meter	$\text{N} \cdot \text{m}$
Energy, work, heat quantity	Joule	$\text{J} = \text{N} \cdot \text{m}$
Power	Watt	$\text{W} = \text{J/s}$
Pressure, stress	Pascal	$\text{Pa} = \text{N/m}^2$
<i>Electricity and magnetism</i>		
Electric charge	Coulomb	$\text{C} = \text{A} \cdot \text{s}$
Electric potential, voltage	Volt	$\text{V} = \text{W/A}$
Electric field strength	Volt per meter	V/m
Capacitance	Farad	$\text{F} = \text{C/V} = \text{A} \cdot \text{s/V}$
Current density	Ampere per square meter	A/m^2
Magnetic field strength	Ampere per meter	A/m
Magnetic flux	Weber	$\text{Wb} = \text{V} \cdot \text{s}$
Magnetic flux density	Tesla	$\text{T} = \text{Wb/m}^2$
Inductance	Henry	$\text{H} = \text{V} \cdot \text{s/A}$
Permeability	Henry per meter	H/m
Resistance	Ohm	$\Omega = \text{V/A}$
Conductance	Siemens	$\text{S} = \text{A/V}$
Magnetomotive force	Ampere	A
<i>Light</i>		
Luminous flux	lumen	$\text{lm} = \text{cd} \cdot \text{sr}$
Illuminance	lux	$\text{lx} = 1 \text{ m/m}^2$
<i>Viscosity</i>		
Kinematic viscosity	square meter per second	m^2/s
Dynamic viscosity	Pascal second	$\text{Pa} \cdot \text{s}$

Table 2.4 SI units and conversion factors

To convert from	Symbol	To	Symbol	Multiply by
<i>Length</i>				
foot	ft	meter	m	0.3048
inch	in	meter	m	0.0254
mile	mi	meter	m	1,609
<i>Area</i>				
square foot	ft ²	square meter	m ²	0.0929
square inch	in ²	square meter	m ²	0.004645
<i>Volume</i>				
cubic foot	ft ³	cubic meter	m ³	0.02832
cubic inch	in ³	cubic meter	m ³	0.00001639
USA liq gallon	gal	cubic meter	m ³	0.0037854
Liter	L	cubic meter	m ³	0.001
<i>Mass</i>				
pound	lb	kilogram	kg	0.45359
ton(short)	ton	metric ton, tonne	t = 10 ³ kg	0.9072
ton(long)	ton	metric ton, tonne	t = 10 ³ kg	1.016
barrel(oil)	barrel	metric ton, tonne	t = 10 ³ kg	0.137
<i>Force</i>				
pound-force	lbf	Newton	N	4.448
kilogram-force	kgf	Newton	N	9.807
<i>Pressure</i>				
pound-force/ square foot	lbf/ft ²	Pascal	Pa	47.8788
pound-force/ square inch	lbf/in ²	Pascal	Pa	6,895
kilogram-force/ square meter	kgf/m ²	Pascal	Pa	9.807
bar	bar	Pascal	Pa	100,000
atmosphere	atm	Pascal	Pa	101,325
mm H ₂ O	mm H ₂ O	Pascal	Pa	9.7739
inch H ₂ O	in H ₂ O	Pascal	Pa	248.7
<i>Speed, velocity</i>				
foot/second	ft/s	meter/second	m/s	0.3048
foot/min	ft/min	meter/second	m/s	0.00508
mile/hour	mi/h	meter/second	m/s	0.4469
kilometer/hour	km/h	meter/second	m/s	0.2777
<i>Acceleration</i>				
foot/second ²	ft/s ²	meter/second	m/s ²	0.3048
<i>Energy, work</i>				
British thermal unit	Btu	Joule	J	1,055
foot pound-force	ft lbf	Joule	J	1.356
calorie	cal	Joule	J	4.1868
Watthour	Wh	Joule	J	3,600
<i>Power</i>				
Btu/hour	Btu/h	Watt	W	0.2931
Btu/second	Btu/s	Watt	W	1,055
horsepower	hp	Watt	W	745.7
calorie/hour	cal/h	Watt	W	0.0011628

(continued)

Table 2.4 (continued)

To convert from	Symbol	To	Symbol	Multiply by
<i>Refrigerant</i>				
capacity tons	tons	Watt	W	3,520
frigorie/hour	frig/h	Watt	W	0.0011628
<i>Torque</i>				
pound-force foot	lbf ft	Newton meter	N · m	1.356
kilogram-force meter	kgf m	Newton meter	N · m	9.807
<i>Density</i>				
pound/cubic foot	lb/ft ³	kilogram per cubic meter	kg/m ³	16.018
<i>Volume flow rate</i>				
cubic foot/minute	ft ³ /min	cubic meter per second	m ³ /s	0.00047
<i>Specific energy</i>				
Btu/pound	Btu/lb	Joule/kilogram	J/kg	2,326
calorie/kilogram	cal/kg	Joule/kilogram	J/kg	4.186
<i>Specific heat</i>				
Btu/pound °F	Btu/lb °F	Joule/kilogram K	J/kg K	4.186
calorie/kilogram °C	cal/kg °C	Joule/kilogram K	J/kg K	4.186
<i>Light</i>				
footcandle	fc	lux	lx	10.764
<i>Temperature</i>				
Celsius °C change	°C	Kelvin change	K	1
Fahrenheit °F change	°F	Kelvin change	K	5/9
Note that conversion between two non SI units can be made by using the ratio between the conversion factors of the single unit				
Examples				
To convert from	To	Multiply by		
Celsius change	Fahrenheit change	1/(5/9)		
Btu/h	cal/h	0.2931/0.0011628		

The quantity of combustibles is generally referred to TOE (Ton Oil Equivalent) by using the Lower Heating Value (41,860 kJ/kg).

Primary energy (hydro, geothermal, nuclear, or other renewable energy sources) from which electric energy is produced is converted into TOE on the basis of the specific consumption (kJ/kWh) of conventional fuel-fed utility power plants. Typical values range between 6,600 and 10,500 kJ/kWh (corresponding to 6,256 and 9,952 Btu/kWh) if both power plant and distribution line losses are taken into account; lower values correspond to combined cycles with gas turbines, whereas higher values to boilers and steam condensing turbines fed by solid coal.

Table 2.5 Parameters frequently used

Description	Other systems		SI system
	kcal/kg °C	Btu/lb °F	kJ/kg K
<i>Specific heat</i>			
Water	1	1	4.18
Superheated steam ^a	0.5	0.5	2.09
Air	0.24	0.24	1
Iron	0.114	0.114	0.477
Copper	0.092	0.092	0.385
Mineral oil	0.486	0.486	2.034
<i>Density^b</i>		lb/ft ³	kg/m ³
Water		62.5	1,000
Air (standard conditions)		0.08	1.29
Mineral oil		57.75	925
Iron		490	7,850
Copper		557.5	8,930
Natural gas		0.047	0.750

^aAverage value in industrial boiler. In air-water mixture (see Chap. 13) the specific heat of superheated steam equals 1.8 kJ/kg K (steam pressure <0.1 MPa)

^bDensity is referred to standard conditions: 0.1 MPa (1.013 bar, 14.5 psi), 273.15 K (0 °C; 32 °F) for air, and 288.75 K (15.6 °C; 60 °F) for natural gas

For an ideal gas, but widely accepted for most real gases, basic relationships (where V is the volume) are:

$$pV = \text{constant} \cdot T$$

The density of air at T_1 (K) and at standard pressure is: air density (T_1) = $\frac{1.293}{\left(\frac{T_1}{273.15}\right)}$

Notice that in some countries and in some applications the standard conditions can be different from the previous ones. For natural gas: 288.75 K (15.6 °C; 60 °F) and 0.1 MPa (14.5 psi). The user should ascertain the reference conditions for each application

Tables 2.6 and 2.7 report values from international statistics and conversion factors.

Some definitions, which will be discussed in detail in later chapters, are summarized below in order to allow a clearer understanding of Chap. 2:

- Heating value. This is a measure of the heat any given fuel can release during the combustion process.

Combustion of fuels consisting of carbon, hydrogen, and sulfur requires oxygen, which normally comes from atmospheric air. It starts at different ignition temperatures depending on the fuel. Typical values range between 573.15 and 973.15 K (300–700 °C, 572–1,292 °F).

Once ignition temperature has been reached, combustion continues until all the fuel or oxygen has been consumed.

Hydrogen, combined with oxygen, produces water (roughly 9 kg of water for 1 kg of hydrogen), which is discharged as liquid water as well as water vapor into the atmosphere together with combustion gaseous waste at the same temperature;

- Higher Heating Value (HHV), also called Gross Heating value. This is the number of heat units measured as being liberated when unit mass of fuel is burned in oxygen saturated with water vapor in a bomb in standard conditions, the residual materials being gaseous oxygen, carbon dioxide, sulfur dioxide and

Table 2.6 Lower and Higher Heating Values of solid, liquid, and gaseous fuels

Fuels	Average values			
	Lower	Higher	Lower	Higher
<i>Solid fuels</i>	<i>kJ/kg</i>		<i>Btu/lb</i>	
Vegetal fuels	10,465	16,700	4,499	7,180
Pitch lignite	18,000	24,000	7,738	15,478
Standard coal	29,302	33,500	12,598	14,403
Charcoal	31,395	34,750	13,498	14,941
Cokery coke	29,302	33,000	12,598	14,188
Gas coke	26,790	32,650	11,518	14,038
Petroleum coke	34,744	37,250	14,938	16,015
<i>Liquid fuels</i>	<i>kJ/kg</i>		<i>Btu/lb</i>	
Crude oil	41,860	44,400	17,997	19,090
Petroleum condensates	44,372	47,000	19,077	20,207
Light petroleum distillates	43,534	46,150	18,717	19,842
Gasoline	43,953	46,600	18,897	20,035
Jet fuel	43,534	46,150	18,717	19,842
Refined kerosene	43,116	45,700	18,537	19,648
Gasoil	42,697	45,250	18,357	19,455
Fuel oil	41,023	43,500	17,637	18,702
Liquid hydrogen	120,070	141,800	51,621	60,964
Propane	46,296	50,235	19,904	21,597
Liquefied petroleum gas (LPG)	46,046	49,700	19,797	21,368
<i>Gaseous fuels</i>	<i>kJ/m^{3a}</i>		<i>Btu/ft^{3a}</i>	
Natural gas	34,325	38,450	921	1,032
Methane	34,285	38,000	953	1,057
Cokery gas	17,791	19,900	478	534
Blast furnace gas	3,767	4,200	101	113

^a0.1 MPa (14.5 psi), 288.75 K (15.6 °C; 60 °F) for natural gas and 273.15 K (0 °C; 32 °F) for other gases

Table 2.7 Conventional densities of liquid fuels

Fuels	kg/m ^{3a}	lb/ft ^{3a}
Gasoline	734	45.8
Gasoil	825	51.5
Oil	925	57.7
LPG	565	35.3
Natural gas ^a	0.75	0.047
Standard coal	800	43.9
Vegetal fuels	400	24.3

^a0.1 MPa (14.5 psi), 288.75 K (15.6 °C; 60 °F) for natural gas

nitrogen, ash, and liquid water (the water produced during the combustion is assumed to be discharged as liquid water). The standard conditions are defined by ISO. The international reference temperature for combustion is 25 °C (77 °F), but in some countries different temperatures are used;

- Lower Heating Value (LHV), also called Net Heating Value. This is the number of heat units measured as before, the residual materials being gaseous oxygen, carbon dioxide, sulfur dioxide and nitrogen, ash, and water vapor (the water produced during the combustion is assumed to be discharged as water vapor). The water vapor enthalpy, which is completely wasted, is not taken into consideration.

2.3 End User Energy Measurement Units

The energy entering a site goes through many transformations before reaching end users (this energy is commonly called final energy). Units referring to transformed energy rather than to purchased energy (fuels and electric energy) are conveniently used at this stage. Table 2.8 lists the typical ranges of values for the commonest ratios between end user and purchased energy, which depend on the efficiency of the transformations as well as on the level of energy exploitation:

- kg steam/kg fuel;
- kg hot water/kg fuel;
- cubic meter compressed air/kWh consumed by mechanical compressor;
- kJ available for the process/kWh consumed by mechanical compressor;
- Others.

Table 2.8 Ratios between end users energy and purchased energy (see also Chaps. 18 and 20)

Types of transformation		Transformation coefficient	Unit	Note
To convert from	To			
Oil	Steam	12–14	kgsteam/kgoil	Boiler
Natural gas	Steam	9–11	kgsteam/Sm ³	Boiler
Electricity	Cold fluid (HVAC)	12,000–16,000	kJ/kWh	Compressor
Electricity	Cold fluid (below ice point)	3,000–10,000	kJ/kWh	Compressor
Electricity	Compressed air (0.8 MPa)	9–10	Sm ³ /kWh	Compressor
Electricity	Heat	3,600	kJ/kWh	Resistor
Electricity	Heat	10,000–16,000	kJ/kWh	Heat pump
Oil	Electricity	4–7	kWh/kg	Utility plant
Oil	Electricity	8.5–9.5	kWh/kg	Cogeneration plant
Electricity	Water storage	250–300	t · m/kWh	Pump
Electricity	Lighting	50–100	lm/W	Lamps

2.4 An Outline of the Main Measurement Techniques

Energy measurement is important because on the one hand it is a means of improving energy management and control of plant operations and on the other it determines the incidence of energy cost on the total cost of production.

Energy can be found in many different forms:

- Solid, liquid, and gaseous fuels;
- Electric energy;
- Fluids by which heat is distributed throughout a site, such as steam, hot water, hot oil, heated air, etc.;
- Fluids by which motive power is distributed throughout a site, such as compressed air, compressed oil, etc.

All these energies can be measured by means of two categories of system:

- Meters that measure energy flow over time by performing the integral function inside the instrument;
- Transducers of instantaneous values such as flow and power. Energy is then calculated by means of independent systems able to perform an integral function. Notice that it is also possible to calculate energy if physical parameters such as temperature, pressure, etc. are measured and models of the phenomena are known.

2.4.1 Liquid and Gas Measurements

Flow meters for combustibles and other fluids, both liquids and gas, can be grouped in volume meter; velocity meter; head meter; pitot tube; vortex; rotameter; sonic meter; magnetic meter; Coriolis and thermal mass flow meters; others.

Notice that these meters always measure volume flow rate at actual temperature and pressure. In the case of gas, the meter indication must be corrected, generally inside the measurement system, in order to obtain volume flow rate in standard conditions by taking into account pressure and temperature as follows:

$$q_s = q \times \frac{p}{p_s} \times \frac{T_s}{T} \times \frac{Z_s}{Z}$$

where

q_s = standard condition volume flow rate (Sm³/s)

q = meter indication actual volume flow rate (m³/s)

p_s = standard atmospheric pressure (0.1013 MPa)

p = absolute actual pressure (MPa)

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T_s = standard temperature (273.15 K)

T = actual gas temperature (K)

Z_s, Z = compressibility factors.

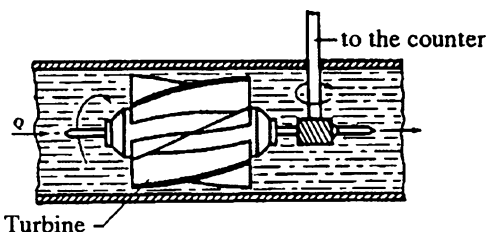
Mass flow rate is then obtained:

$$m \text{ (kg/s)} = q_s \times \rho_s$$

where

ρ_s = mass density at standard conditions (kg/Sm^3).

Fig. 2.1 Velocity meter with a turbine rotor



1. Volume meter. Volume meters generally operate on the principle of giving an indication proportional to the quantity that has flowed into fixed-volume containers over time. With alternate filling and emptying of the container, an indication of how many times the container is filled and emptied can easily be transferred to a counter with a calibrated dial in order to determine flow quantity.

Gasoline and gas meters were widely used in the past, but now they are outdated; other types of volume meters are still in use.

The error ranges from 0.5 % to 2.5 % depending on the meter model; a good degree of accuracy can be obtained from full capacity down to zero (working range 100:1).

Notice that volume meters can be installed anywhere along the pipe, but particular attention must be paid to floating solid matter. Filters must be installed and they should be cleaned on a routine basis.

2. Velocity meter. The quantity or the volume of the fluid is derived by means of a velocity measure that is transferred to a counter, generally calibrated in rates of total flow.

The operating principle is as follows: the meter has an orifice with a shunt circuit around it. Fluid flows through it and compels a turbine or a helix to rotate (see Fig. 2.1). The rotation speed, which is proportional to the fluid velocity, is transmitted to a counter calibrated in rates of flow through the orifice (volume flow rate = velocity $\times$ area).

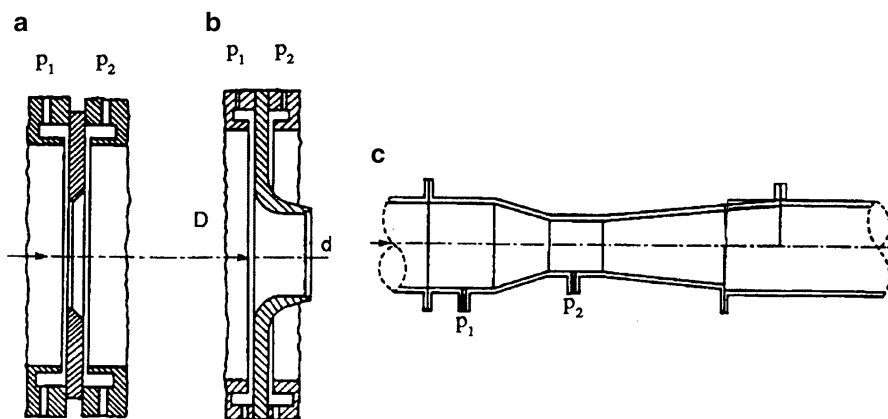


Fig. 2.2 Different types of head meters. (a) Thin plate orifice; (b) sharp edge orifice; (c) Venturi tube. Upstream (p_1) and downstream (p_2)

The meter can be installed anywhere along the pipe; in bypass installation, the counter is calibrated by taking into account the diameters of the orifice and the nozzle of the main pipe.

Overloads up to 150–200 % of rated capacity are handled temporarily without loss of accuracy.

Both volume and velocity meters are able to work with liquid and gas, but they are not interchangeable (for instance, if gas flows through a meter originally designed for a liquid, the rotor velocity will be too high and mechanical damage may occur).

3. Head meter. The operating principle is based on the measurement of a differential pressure (pressure losses) between two points of the pipe; this is produced by introducing an orifice or a nozzle. In this way fluid speed increases and pressure decreases.

The differential pressure between the two points is proportional to the square of the mass flow rate, thus:

$$q = \alpha \times S \times \sqrt{(p_1 - p_2)/\rho}$$

where q = volume flow rate (m^3/s), α = instrument flow coefficient (expansibility factor for gas included), S = section of the orifice or the nozzle (m^2), ρ = fluid mass density (kg/m^3), p_1, p_2 = upstream and downstream pressures (Pa).

Head meters differ with the type of device producing a differential pressure:

- Thin plate and sharp edge orifices (see Fig. 2.2a, b). An orifice with a diameter d is inserted by means of two shafts anywhere along the pipe with a diameter D . Values of the diameter ratio d/D ranging from 0.05 to 0.7 and straight pipes upstream and downstream are required. The length of the straight pipes must be at least $20D$ upstream and $5D$ downstream;

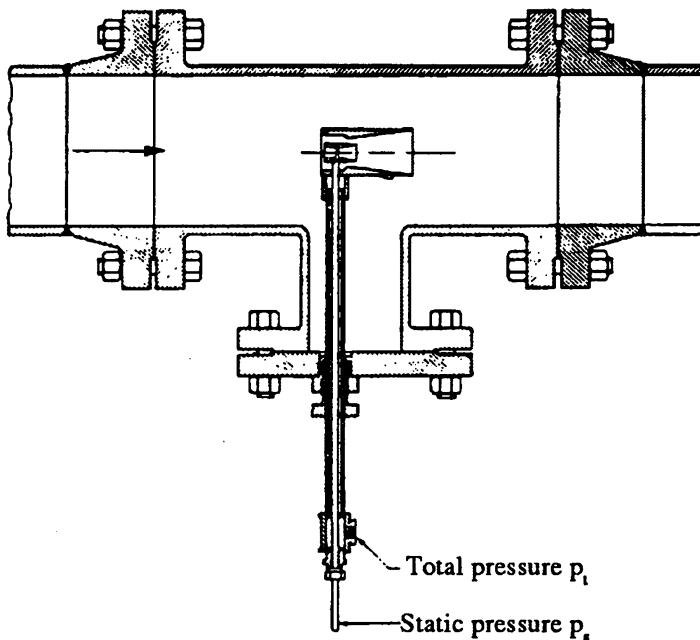


Fig. 2.3 Pitot tube

- Venturi tube (see Fig. 2.2c). This meter uses a Venturi nozzle which permits flow measurement with low differential pressure values. Then shorter straight pipes upstream and downstream are required, generally less than $15D$.

Notice that the error of head meters is generally less than 2 %, but increases as the meter works in the lowest part of the scale because of the squared relationship between flow and differential pressure. Care must be taken not to oversize the full-scale capacity on the basis of the real flow rate; a good degree of accuracy is obtained from full capacity down to 25 % (working range 4:1).

4. Pitot tube (see Fig. 2.3). This operates on the principle that the total pressure p_t , detected at a small orifice facing into the flow, is the sum of static and dynamic pressures. The static pressure p_s can be detected by a measurement orthogonal to the direction of the flow. The dynamic pressure is then obtained by subtraction. Notice that straight pipes are required upstream and downstream in order to avoid turbulence near the point of measurement.

Fluids without solid matter are required. Flow speed must be relatively high, because low speed involves a differential pressure too slight to measure easily. A squared relationship exists between flow and differential pressure, as in head meters.

The basic operating formula is as follows:

$$q = \alpha \times K_v \times S \times \sqrt{(p_t - p_s)/\rho}$$

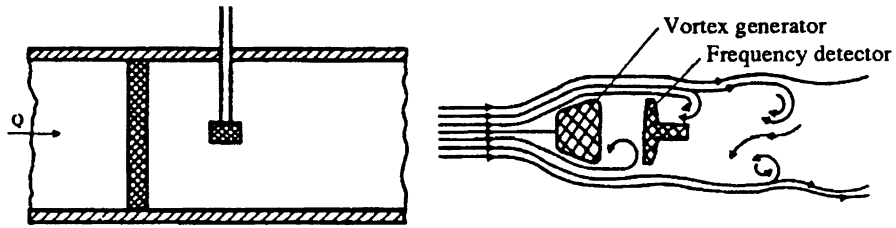


Fig. 2.4 Vortex meter

where q = volume flow rate (m^3/s), α = instrument flow coefficient (expansibility factor for gas included), S = section of the orifice or the nozzle (m^2), K_v = velocity coefficient which depends on the Reynolds number, ρ = fluid mass density (kg/m^3), p_t , p_s = total and static pressures (Pa).

5. Vortex (see Fig. 2.4). The operating principle is based on Karman's law, which concerns vortices produced by a fluid. A vortex generator, which is an appropriately shaped solid, is placed inside the pipe and the fluid vortex frequency is detected. The working equation is as follows:

$$q = S \times V = S \times (K_m \times f)$$

where q = volume flow rate (m^3/s), S = section of the pipe (m^2), V = fluid velocity (m/s) which is equal to the vortex frequency f (Hz) multiplied by the vortex meter constant (K_m = Karman constant).

Vortex meters are able to measure volume flow rates (mass flow rates are derived by introducing the volume flow rate at standard condition and the related mass density) of gas, liquid, and vapor. A good degree of accuracy is obtained from full capacity down to 10 % (working range 1:10). In the case of gas, a correction factor as with velocity meters is required. It is generally elaborated inside the measurement system to give the value of the standard volume flow rate and the real value of the mass flow rate.

6. Rotameter. This operates on the principle that a flowing fluid exerts a force proportional to the flow. A rotameter is a vertical conic tube in which a ball or any other calibrated device made of plastic or glass moves freely. The calibrated device is subject to two opposite forces: the force of gravity which works downwards and the fluid force which works upwards. The device moves vertically and indicates the rate of the fluid flow.

Notice that no straight pipes upstream or downstream are required; the only condition is that fluid must flow upwards from below.

The rotameter is suitable for measuring low rates of flow and must be differently calibrated for each kind of fluid.

7. Sonic and magnetic meter. The operating principle of a sonic meter is based on the fluid property of propagating a sound at a speed which depends on fluid volume, pressure, and temperature.

Electric pulses are generated and transformed into sonic ones through the fluid; the sonic pulses are then detected and the fluid speed is calculated. The flow is calculated as fluid speed multiplied by area, as already shown for the velocity meters.

A magnetic meter works on the basis of Faraday's law which says that at the ends of a conductor (the fluid in this case) moving inside a magnetic field there is an electromotive force linearly depending on both the conductor speed and the magnetic field itself. This meter, which does not require the pipes to be cut, can be used only with liquid with a conductivity of not less than 500 $\mu\text{S}/\text{mm}$.

8. Coriolis mass meter, thermal mass meter. Coriolis meter is based on the controlled generation of Coriolis forces inside parallel tubes, where vibrations (ω) are detected. The mass flow rate is proportional to ω^2 . In a thermal mass flow rate the mass flow is directly proportional to the rate of heat absorbed by the flow stream.
9. Other systems based on different principles are also available but it is not necessary to describe all of them in detail. They can readily be found in specialized books.

Table 2.9 shows basic operating parameters able to qualify flow meters and their applications. Note that the commonest devices are head meters, with orifice or Venturi tube, Pitot tube meters, vortex meters, and thermal mass flow meters. The choice among them depends on the fluid to be measured and on the accuracy required.

2.4.2 Electric Energy Flow Measurements

Equipment for measuring energy flow and power demand in the distribution system consists of conventional voltmeters, ammeters, and kilowatthour meters. Potential transformers (PT) or current transformers (CT) are generally installed to reduce the level of voltages and currents for technical as well as for security reasons. Current is generally stepped down to 5 A or less, line voltage to 120 V or 100 V or less.

Specific equipment, which performs combinations of the abovementioned functions, is also available to provide kilovarhour, kilovoltamperehour, kilowatt, kilovoltampere, and power factor.

Typical connection schemes of the three basic meters are shown in Fig. 2.5, where basic relationships between current, voltage, and power are also illustrated.

Notice that:

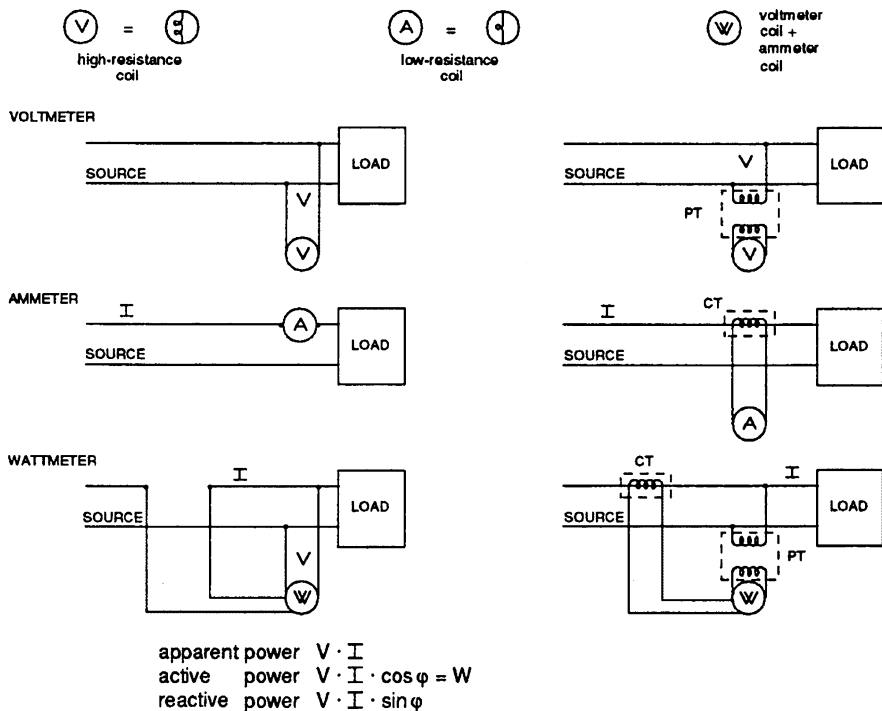
- Voltmeter is a high-resistance coil device and it must always be connected in parallel;
- Ammeter is a low-resistance coil device and it must always be connected in series with the current. With portable meters, clamp-around current transformers are generally used;
- Wattmeter, which measures real power, reactive or apparent power, is a combination of potential coils (parallel connected) and current coils (series connected);

Table 2.9 A review of the main flow meters

Type of device	Pipe diameter (mm)	Type of fluid to measure		Max pressure MPa	Max temperature °C	Reynolds number	Operating range	Typical accuracy (%)	Pressure losses (kPa)
		Liquid	Gas						
Volume meter	5–500	x	x	–	20 2,900 100 212	Any value	50:1	0.2–0.5	50–100
Velocity meter	10–600	x	x	–	10 1,450 200 392	>10,000	15:1	0.2–0.5	5–10
Head meters: orifice and Venturi tube	>50	x	x	x	50 7,252 500 932	>2,500	4:1	1–2	2,050
Pitot	>100	x	x	x	50 7,252 500 932	Any value	4:1	2–5	1–2
Vortex	25–200	x	x	x	10 1,450 200 392	>10,000	15:1	0.75–1.5	10–20
Rotameter	5–150	x	x	x	4 580 200 392	>10,000	10:1	2–3	5–10
Sonic meter	Any value	x	x	–	20 2,900 200 392	Any value	10:1	2–3	0
Magnetic meter	Any value	x	–	–	20 2,900 200 392	Any value	20:1	0.5	0
Cortolis mass meter	5–100	x	x	–	30 4,351 150 302	Any value	100:1	0.1–0.5	10–20
Thermal mass meter	>5	x	x	–	10 1,450 200 392	Any value	100:1	0.5–2	10–20

a

Single-phase connection



b

Three-phase connection

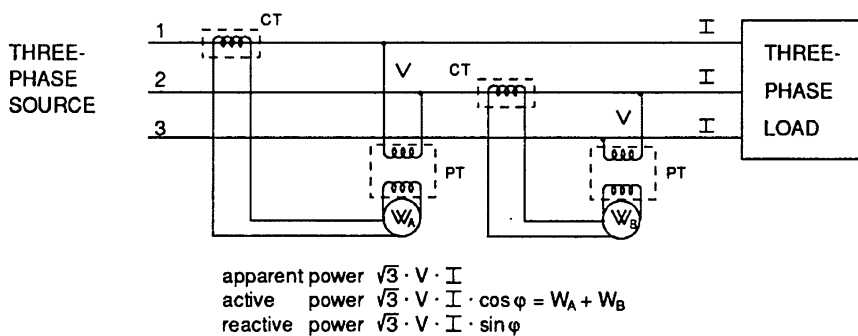


Fig. 2.5 Typical connection schemes: voltmeter, ammeter and wattmeter with single-phase line (a) and with three-phase line (b)

- When current transformers or potential transformers are used, the CT and the PT ratios must be taken into account. The meter readings multiplied by the meter constant and the CT or PT ratios (or both in the case of wattmeter) give the values of current, voltage, and power.

Typical CT ratios are 100:5, 1,000:5, 5,000:5. These values show how many amperes flow in the primary conductor or line conductor when a 5 A current flows in the secondary winding. For security reasons the secondary winding must never work with no-load, and consequently it must always be connected to a low-resistance ammeter or shorted by means of a jumper wire, screw, or switch on a CT shorting terminal strip.

Complex metering systems can also be introduced by using current and voltage transducers whose signals are elaborated by means of computers and transformed into electric power and energy. The introduction of computerized systems allows both the measurement of energy flow and the control of electric systems based on different optimization criteria.

These systems can also be integrated conveniently with flow and other physical parameter measurements in order to obtain complete process control. This approach, quite common in energy-intensive industry, is becoming popular also in many manufacturing sectors and in buildings (see Sect. 17.8).

2.4.3 Temperature, Pressure, and Other Measurements

Devices for measuring temperatures can be grouped according to the principle of operation and the temperature range. The commonest devices are liquid-in-glass thermometers, bimetallic thermometers, resistance temperature devices, thermocouples, infrared thermometers, and optical pyrometers. A correct choice must be based on temperature ranges, environmental conditions, and uses of the measurements for reporting or process control.

Figure 2.6 shows relationships among the Kelvin (K), Celsius ($^{\circ}\text{C}$), Rankine ($^{\circ}\text{R}$), and Fahrenheit ($^{\circ}\text{F}$) temperatures.

Devices for pressure measurement can be listed as Bourdon gage, diaphragm gage, and manometer. They measure the difference between the absolute pressure in a system and the absolute pressure of the atmosphere outside the measuring device. This difference is called differential or gage pressure. If the pressure of the system is lower than atmospheric pressure, the term vacuum pressure is used instead of gage pressure.

The Bourdon gage consists of a curved tube closed at one end with the other end connected to the pressure to be measured. When the pressure inside the tube is greater than the pressure outside, the tube tends to straighten and the amount of change in length or curvature can be translated into a gage reading.

The diaphragm gage is based on the detection of the diaphragm movement if the pressures against its two sides are different.

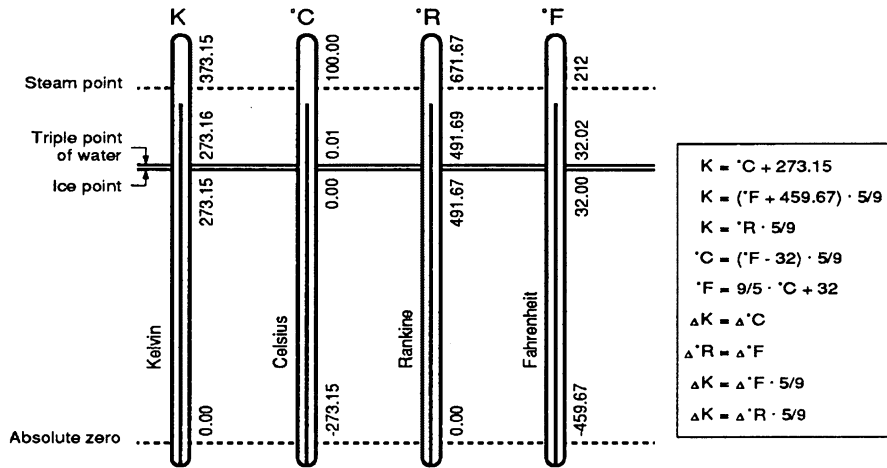


Fig. 2.6 Relationships among the Kelvin (K), Celsius (°C), Rankine (°R) and Fahrenheit (°F) temperatures

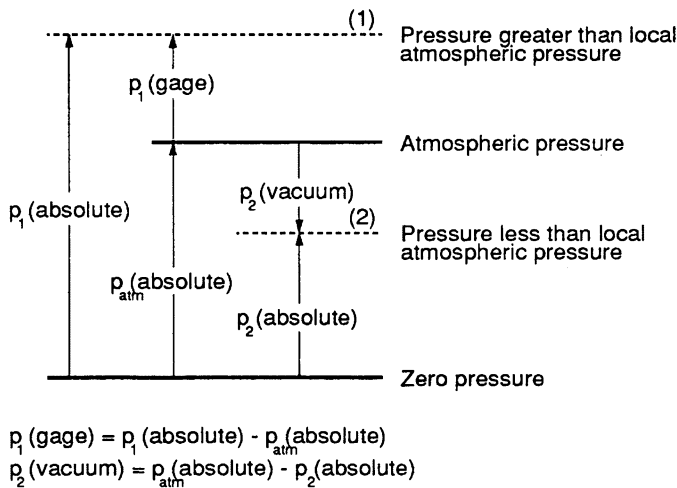


Fig. 2.7 Relationships among the absolute, atmospheric, gage and vacuum pressures

The manometer is a tube with liquid in it; one end is open to the air and the second end is exposed to a different pressure, so that the end with the higher pressure has a lower liquid level and the pressure difference is detected.

Figure 2.7 shows relationships among the absolute, atmospheric, gage, and vacuum pressures.

Other physical parameter measurements can be made to meet specific needs. A careful study of specialized books and manufacturers' technical specifications is suggested in order to make the right choice for each application.

Energy Conversion and Management

Principles and Applications

Petrecca, G.

2014, XXX, 326 p. 94 illus., 6 illus. in color., Hardcover

ISBN: 978-3-319-06559-5