A

ABE fermentation Another name for the *Weizmann process used for the production of acetone, butanol, and ethanol using the acid-resistant bacterium *Clostridium acetobutylicum.*

ablation The removal of material by *erosion, *evaporation, or *chemical reaction. For short-term protection against high temperatures as a form of fire protection or fireproofing of process equipment, sacrificial materials are used such that during a fire there is resistance and protection to the equipment beneath for a sufficient period of time.

ablimaton *See* SUBLIMATION.

abscissa The horizontal or x-coordinate in a two-dimensional Cartesian coordinate system such as a chart or graph. The *ordinate is the vertical or y-coordinate.

absolute Denoting a number or a measurement that does not rely on a standard reference value.

absolute density The mass per unit volume of a substance. It is the density of the actual substance and does not include any free space that may be between particles. The SI units are $kg\,m^{-3}$.

absolute error The difference between a measured value and its true value.

absolute filter A type of filter used to remove all particles that may be present in the flow of gas into or out of a process. Absolute filters are used for ensuring the sterile flow of air or oxygen to biological reactors as well as for clean rooms and sterile cabinets used for analytical work. Unlike an *air filter, the pore sizes are smaller than the expected particle size. With a typical uniform pore size of 0.2 μm, the pressure drop is greater than that of air filters made from fibrous materials.

absolute humidity The amount of water in air expressed as the mass of water vapour per unit mass of dry air for a particular temperature and pressure condition. The SI units are $kg_{water}\,kg_{air}^{-1}$.

absolute pressure The measurement of gas or air pressure relative to the pressure in a total vacuum. In comparison, the *gauge pressure is measured above atmospheric pressure, which is variable.

absolute roughness (Symbol ε) The roughness of a solid surface expressed as the average height of undulations and imperfections. It is measured using an instrument that draws a stylus over the surface. The roughness of the inner surface of a pipe wall used to transport fluids with turbulent flow has the effect of increasing frictional pressure drop. Expressed

as a ratio with internal pipe diameter, it is used in determining the friction factor of fluids flowing in pipes with turbulent flow. *See* RELATIVE ROUGHNESS.

absolute temperature *See* KELVIN.

absolute viscosity *See* VISCOSITY.

absolute zero The lowest possible thermal energy state of a material. This corresponds to 0 K.

absorbed dose *See* DOSE.

absorber 1. A material that is capable of stopping ionizing radiation. *Alpha particles can be readily stopped by a sheet of paper whereas beta radiation can be resisted by a centimetre of aluminium. Gamma radiation is absorbed by materials with a high density, such as steel and concrete. Neutron absorbers include boron, hafnium, and cadmium and are used in the control rods in nuclear reactors. **2.** A shortened name for an *absorption tower or column.

absorption A mass transfer process in which one or more gases in a gaseous mixture is transferred into a liquid solvent or a solid. It is the most common form of separation of low molecular weight materials. Absorption is often used to remove gases from gas streams that may be harmful downstream or when released from the process. The **absorption factor** is used to determine the ease with which a component will absorb into the liquid phase and is based on liquid and vapour flow rates as well as the vapour liquid equilibrium for the component. For example, ammonia can be absorbed from a gas stream using water as the scrubbing liquid. *Compare* ADSORPTION.

absorption tower A tall vertical column containing a packing material in which a gas is absorbed by intimate contact with a liquid flowing downwards under the influence of gravity. The gas can be admitted either countercurrent or cocurrent to the flow of liquid in which one or more of the gaseous components are absorbed into the liquid. The minimum flow rate of scrubbing liquid required to achieve an absorption duty requires an infinite height of packing. In practice, a higher liquid rate is used to achieve a compromise between capital cost (i.e. height of column) and the operating cost (i.e. liquid flow rate). It is also known as a *scrubber.

absorptivity The portion of radiant thermal energy falling on a surface which is converted to heat with the remainder being either reflected or transmitted. The absorptivity is dependent on the wavelength of the energy and the properties of the surface including colour. *Compare* REFLECTIVITY; TRANSMISSIVITY.

accelerant A substance used to initiate and develop a fire. Flammable liquids are the most common form of accelerants.

acceleration (Symbol a) The rate of change of speed or velocity with respect to time. If the acceleration is constant then the final velocity, v, of a body that is initially moving with a velocity u after time t, is $v = u + at$. If the acceleration is not constant, then the acceleration can be found from:

$$a = \frac{dv}{dt} = \frac{d^2s}{dt^2}$$

where s is the distance moved by the body. In the case of motion in a circle, the acceleration is v^2 / r and directed to the centre of the circle of radius r.

acceleration due to gravity (Symbol g) The acceleration experienced by a body due to the Earth's gravitational field. The acceleration is normally taken as 9.806 65 m s^{-2} although it does vary by small amounts over the Earth's surface and with altitude.

acceleration phase The rapid growth of the culture of microorganisms in a bioreactor prior to the *log phase. After the medium within a bioreactor has been inoculated with a small population of microorganisms, there is an initial *lag phase of no growth in which they adjust to their new environment. Cell division then occurs at an increasing rate until the maximum growth rate is reached. The log or exponential phase corresponds to the rapid cell division such that the logarithm of the population increase with time is constant. As the substrate eventually becomes exhausted, this is then followed by a deceleration phase prior to the *stationary phase.

accelerator A substance that alters the rate of a chemical reaction such as a *catalyst.

accumulator A device used to smooth the rate of flow from a reciprocating pump and prevent the destructive effects of *water hammer from occurring. It consists of a vessel located on the pipe close to the pump with a *non-return valve preventing return flow back to the pump. The vessel contains a gas or a bladder bag although some use springs. As the pump discharges, some of the fluid enters the accumulator compressing the gas or spring. At the point of valve closure, the gas or spring expands allowing the accumulated volume to discharge through the pipe.

accuracy A measure of the closeness or agreement of a numerical value to a true value. It is expressed as either *significant figures or decimal places depending on whether proportional or absolute accuracy is important. For example, a number written as 5.425 normally assumes that the four figures are meaningful. It would be incorrect to write the number to a precision of five significant figures unless the *error in the estimate is indicated such as 5.4250 ± 0.0005. *Compare* PRECISION.

acentric factor A parameter used in *equations of state to estimate physical and thermodynamic properties. It is used to characterize the acentricity of molecules in reduced-state correlations along with reduced pressure and reduced temperature.

acetate process A process for the production of cellulose fibres used for textiles. There are two methods: **1.** The cellulose is obtained from wood pulp and dissolved in carbon disulphide and sodium hydroxide. The thick brown liquid that contains cellulose xanthate is forced through orifices into acid. The xanthate decomposes to leave a cellulose fibre known as viscose rayon. **2.** The cellulose obtained from wood pulp and cellulose acetate is formed by dissolving in acetone. The solution is forced through orifices and the solvent is allowed to evaporate leaving a cellulose fibre of acetate rayon.

ACHEMA (Ausstellungstagung für chemisches Apparatewesen) A triennial trade fair for chemical technology and biotechnology held in Frankfurt, Germany.

SEE WEB LINKS

- Official website of ACHEMA.

Acheson process A process used for the production of graphite. It involves heating coke mixed with clay to a very high temperature. At a temperature in excess of 4,000°C,

silicon carbide is formed leaving graphite. It is named after the American inventor Edward Goodrich Acheson (1856–1931) who patented the process in 1896.

acid A chemical compound or material containing hydrogen that has the tendency to lose protons and form hydrogen ions in solution. Solutions of acids have *pH values less than 7.

acid egg An egg-shaped vessel used to transport highly corrosive acids. The container has inlet and outlet pipes and is filled with a charge of liquid to be transported. Another pipe is used to admit compressed air or another gas. The pressure of the gas on the liquid surface forces the liquid through the discharge pipe that extends down into the liquid. The acid egg is not very efficient as the compressed air or gas is usually blown off when the operation is completed. *See* MONTEJUS.

acid gas Natural gas, which consists mainly of methane, but also contains significant amounts of carbon dioxide, hydrogen sulphide, and other acidic contaminants. Natural gas from offshore reservoirs that contain these corrosive and toxic contaminants are required to be removed or reduced at the platform before export using an *amine gas treating process. *Compare* SOUR GAS.

acid number A measure of the acidity of oils such as crude oil, mineral oils, and biodiesels. It is expressed as the mass in milligrams of potassium hydroxide titrated in one gram of the oil required to neutralize it.

acid rain A precipitation of rain that has a pH below that of typical rain, which is around pH 5.6. Rainwater is naturally acidic due to the absorption of carbon dioxide from the air to form carbonic acid. However, rainwater will also absorb other gases such as sulphur dioxide and various oxides of nitrogen that have been released into the atmosphere as pollutant gases through processes such as the combustion of fossil fuels and from car exhausts. The dissolved gases form sulphuric and nitric acids with pH values of less than 5.0 and have an adverse effect on trees and plants. Acid rain causes damage to leaves and increases the acidity of the soil preventing further growth. The water run-off into rivers and lakes also prevents freshwater fish from thriving, leaving the water sterile, and has a major impact on the ecosystem.

activated carbon A compound of powdered or granular amorphous carbon mainly made from coconut shells. It has a very high specific surface area used to adsorb vapours and gases. With a surface area typically of around 1,000 m^2 per gram, it is widely used to adsorb vapours and gases. The amount of substance that can be adsorbed is proportional to the absolute temperature and pressure. The activated carbon can be reactivated for reuse using steam to strip the adsorbents and recover the carbon. Activated carbon is used in water and air purification, and used in gas masks for the removal of harmful gases. It is also known as **activated charcoal** and **active carbon**.

activated sludge process A process used in the treatment of sewage and wastewater. *Sludge is formed when air is bubbled through the sewage resulting in the aggregation of flocs. These contain denitrifying bacteria that are capable of decomposing organic substances. Aeration ensures a high level of dissolved oxygen and helps to reduce the *biological oxygen demand. Stirring of the sludge can also aid the process.

activation energy (Symbol E_a) The minimum energy required to activate one mole of a substance to cause a *chemical reaction to take place. For a chemical reaction to proceed,

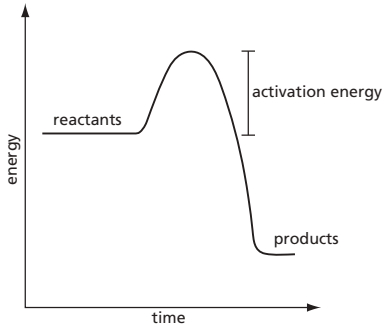

Fig. 1

the reactants are converted to products in which the energy increases to a maximum and falls to the energy of the products (see Fig. 1). The activation energy is the difference between the maximum energy and the energy of the reactants and is therefore the energy than needs to be overcome. *See* ARRHENIUS EQUATION.

active site 1. An available location on the surface of a *catalyst available for reactants to bind and result in a *chemical reaction taking place. The active site can be blocked by a chemical agent or *poison thereby reducing the effectiveness of the catalyst. **2.** On the surface of an enzyme, the active site is the location to which a substrate binds. The binding of the substrate to the enzyme is dependent on the conformation or 3-D shape of the protein. Inhibition prevents the binding from taking place by altering the conformation thereby preventing the substrate from binding, or by blocking the site.

activity 1. The change in one condition to another expressed as a ratio. Examples include *water activity, and chemical activity. The activity of a chemical reaction is used in place of concentration in equilibrium constants for reactions involving non-ideal gases and solutions. **2.** A quantitative term used to characterize the number of atomic nuclei that disintegrate in a radioactive substance per unit time. It is measured in *becquerel (Bq) where one Bq is equal to one disintegration per second. The unit of activity replaces the former unit of the curie (Ci) where one Ci is equal to 37×10^{10} Bq. The specific activity is the activity per unit mass of a pure radioisotope. **3.** (Symbol U) The amount of an enzyme present in a biologically catalyzed reaction. It is usually expressed in terms of units of activity based on the rate of the reaction that the enzyme catalyzes. The international unit of activity is the amount of enzyme that will convert one μmol of substrate to a product in one minute under defined conditions. These are usually 25°C and the optimum pH. **4.** A thermodynamic parameter that measures the so-called active concentration of a substance, a, in a chemical system, and is in contrast to the molecular concentration, c. It is related $a = fc$ where f is a dimensionless parameter and approaches unity in dilute solutions.

activity coefficient (Symbol γ) A correction factor that allows for the deviation from ideal behaviour of a gas or solution.

ADC *See* ANALOGUE-TO-DIGITAL CONVERTER.

additive A substance added in a small amount to another or mixture to improve the performance or properties in some way. Additives are added to polymers to enhance their stabilizing properties. Additives are added to foods as preservatives, and to enhance colour and flavour. Additives can also provide corrosion resistance, alter surface tension, and viscosity etc.

adiabatic A thermodynamic process that takes place without heat transfer to or from an external source. When a fluid is compressed adiabatically, there is an increase in temperature of the fluid. Likewise, **adiabatic cooling** occurs when the pressure of the fluid is reduced without any heat exchange to the surrounding. **Adiabatic expansion** of a fluid occurs without any heat transfer with the surroundings. **Adiabatic compression** is the compression of a gas without any transfer of heat to the surroundings. It results in an increase in the temperature of the gas undergoing compression.

adiabatic efficiency 1. The ratio of the work required for adiabatic compression to the real work input. **2.** The ratio of kinetic energy of a fluid through a valve to the kinetic energy obtained through the process of *adiabatic expansion.

adiabatic flame temperature The theoretical temperature of a flame during the combustion of a fuel in oxygen considered when there is no loss of energy. The temperature is dependent on whether the combustion process occurs at either constant pressure or constant volume. At constant pressure, the adiabatic flame temperature is due to the complete combustion of the fuel with no heat transfer or changes in kinetic or potential energy. Constant volume combustion results in a lower flame temperature since some of the energy is otherwise used as work to change the pressure.

adiabatic flash Another name for *flash evaporation, which involves the rapid isenthalpic evaporation of a saturated liquid into a liquid and vapour by the reduction in pressure.

adiabatic process A physical or chemical process without the loss or gain of heat. The **adiabatic equation** $pV^{\gamma} = k$ describes the relationship between the pressure of an *ideal gas and its volume where γ is the ratio of the specific heat capacities of the gas and k is a constant.

adiabatic saturation temperature The equilibrium temperature attained when a liquid and gas are brought into contact with no work or heat transfer done.

adjutage A tube inserted into a vessel to obtain a measure of its pressure or to allow the discharge of its contents.

adsorbate A substance that is adsorbed from a gas or liquid onto a solid surface or **adsorbent** during an *adsorption process.

adsorption A process in which components in gases, liquids, or dissolved substances are selectively held on the surface of a solid. It is used to remove components that may otherwise be harmful if released into the environment or may cause process difficulties further downstream such as causing the poisoning of a catalyst. Adsorption usually takes place in *fixed beds.

adsorption isotherm The relationship between the mass of *adsorbate taken up per unit mass of adsorbent at constant pressure, if a gas, or at constant temperature, if in a solution. The *BET, *Langmuir, *Freundlich, and *Temkin adsorption isotherm equations

are empirical equations used to describe the surface available for adsorption at constant pressure for gases and constant temperature for solutions.

advection The natural movement of a fluid such as air resulting in horizontal motion caused by local pressure differences. It differs from *convection since it does not include the effects of diffusion.

aeration The introduction and movement of air or oxygen at a low flow rate through a liquid medium such as a *bioreactor or *activated sludge process. Aeration is used to provide oxygen to microorganisms that are responsible for biologically catalyzed reactions. The oxygen is usually introduced through a *sparger as small bubbles that have a high surface area. Aeration is used to promote effective mass transfer of the oxygen to the liquid medium and therefore microorganisms.

aeration number A dimensionless number, N_a, used in the aeration-mixing of bioreactors and relates the gas flow rate, G, to the impeller speed, N, and diameter, D, as:

$$N_a = \frac{G}{ND^3}$$

aerobic process A biochemical process involving microorganisms that require the presence of oxygen, usually in the form of air. Many organisms require the presence of oxygen to survive and grow, such as plants, animals, and many microorganisms. They are dependent on oxygen for the breakdown of sugars into carbon dioxide and water, and for the release of energy through aerobic respiration. In comparison, anaerobic respiration releases energy in the absence of oxygen.

aerogel A highly porous material based on metal oxides or silica. It has a very low density below 10 kg m^{-3} and has excellent heat and electrical resistance as well as acoustic properties. Aerogels can be formed using the process of *supercritical drying using carbon dioxide to remove a solvent such as ethanol used in their formation. Being supercritical and without a gas–liquid interface, it avoids the crushing effects of capillary forces on the porous structure during a conventional drying process.

aerosol A dispersion of fine droplets of liquid or particles of solid within a gas such as air. The particles are often very small and colloidal in size. An aerosol spray can contains propellants that are liquefied under pressure and used to create an aerosol when released into the air.

agglomeration The process of bringing a suspension of small or fine particles together to form larger and more coarse particles or aggregates.

aggregated fluidization *See* FLUIDIZATION.

aggregation The formation of large groups of molecules or particles. With particles, aggregation consists of both *flocculation and *coagulation.

agitated vessel A vessel in which the contents are stirred by mechanical means through the use of an agitator, paddle, or stirrer. Impellers and propellers are commonly used to provide good mixing characteristics. It is also known as a **stirred tank**.

agitation intensity A measure of the power consumption of the shaft of an agitator used to mix a liquid in a stirred tank or *agitated vessel. Agitation intensities are expressed

as the power supplied per unit volume of liquid. The SI units are W m^{-3}. The magnitude of the agitation intensity is dependent on the nature of the liquid being stirred. Biological solutions containing flocculating materials are significantly affected by the level of agitation.

agitator A simple stirring device used to provide turbulence and mixing of the contents of a vessel containing a liquid. It is typically used to provide homogeneity, provide good oxygen transfer in fermentation vessels, and in the prevention of particles settling.

An agitator consists of blades attached to a rotating shaft. Impellers have flat blades and provide radial flow patterns whereas propellers provide axial flow movement. Paddle agitators consist of tilted flat blades providing a combination of radial and axial flow movement. Selection of the appropriate agitator depends on the processing requirements, the fluid properties, and the materials of construction.

AIChE *See* American Institute of Chemical Engineers.

air An odourless and colourless mixture of gases and vapours that surround the Earth. At sea level, the composition of dry air is mainly nitrogen (78.09 %) and oxygen (20.95 %), with an average relative molecular weight of 29. Other gases include argon (0.93 %), carbon dioxide (0.03 %), neon (1.8×10^{-3} %), helium (5.2×10^{-4} %), and lesser amounts of methane, krypton, hydrogen, nitrous oxide, xenon, and radon in decreasing amounts, respectively. Air is a common source of oxygen used in many processes such as *combustion.

air conditioning The process of controlling the environmental air conditions in buildings through control of the temperature and level of relative humidity, as well as through filtration of particles to provide human comfort. The movement and cleanliness of the air are also involved.

air filter A type of filter used to remove particles such as dust, soot, and microorganisms from the flow of air. They are often used for ensuring a sterile flow of air or oxygen to bioreactors as well as for clean rooms and sterile cabinets used for analytical work. The pore sizes of the filter are larger than the particle size to be removed such that the filter relies on the depth of the filter to entrap the particles within a fibrous mesh structure. Fibrous filters are relatively cheap and robust, and have a low pressure drop in comparison with *absolute filters.

air-lift A pumping device used to raise a liquid from a depth such as a well. It consists of a vertical pipe extending down into the well into which compressed air is injected at the bottom. As the air bubbles rise, the reduced hydrostatic pressure results in a flow of liquid up the leg. The air or gas is disengaged from the liquid at the top of the leg. It is used for raising oil from wells.

air-lift reactor A type of bubble column reactor into which air is sparged at the bottom as bubbles to promote oxygen transfer and cause circulation of the liquid. The reactor is cylindrical and mounted on its axis. It has an inner tube up which the air or oxygen rises. An external-loop air-lift-type reactor consists of a U-tube within which the sparging takes place promoting oxygen transfer and liquid circulation.

air lock 1. Trapped air or some other gas or vapour within a pipe that prevents the intentional flow of a liquid. **2.** The intentional seal in a process that relies on a differential pressure to prevent the undesirable loss of material.

air pollution The release of particles, vapours, and gases into the environment that are harmful to human health and to the environment such as plants, forests, and animals. Carbon dioxide is a product from the combustion of fossil fuels in power stations, vehicles, aeroplanes,

and numerous industrial processes, and is a greenhouse gas responsible for contributing to the warming of the Earth's atmosphere. Methane is another greenhouse gas as are chlorofluorocarbons (CFCs), which were once widely used as refrigerants and as aerosol propellants but are now banned due to their known damaging effect on the Earth's ozone layer. Sulphur dioxide is another product of the combustion of fossil fuels and is known as the cause of *acid rain.

In the UK, an Act of Parliament was introduced in 1956 to reduce the level of air pollution. It was a landmark in environmental protection and was responsible for reducing the level of smoke pollution as well as sulphur dioxide emitted into the environment.

In the US, the Clean Air Act introduced in 1963, together with its subsequent amendments as a federal law, has been responsible for controlling air pollution. Other governments have also taken measures to control air pollution and limit the emission of carbon dioxide and other greenhouse gases. The Kyoto Protocol is an international agreement between countries to reduce the emissions of carbon dioxide emissions and restrict or ban the emission of certain chemicals such as CFCs. One way of restricting carbon dioxide emissions is to raise the level of taxation on fuels so that people and industrial companies have greater incentives to conserve energy and pollute less.

SEE WEB LINKS

- Official website of Environmental Protection UK.

air separator A device used to separate solid or liquid particles from air in which centrifugal force is used. The device has a cylindrical body with a conical base. The particle-containing air enters tangentially and the particles leave from the bottom while particle-free air leaves from the top. It is also known as a *cyclone separator.

air-to-close A type of pneumatically operated control valve that automatically opens in the event of a loss of instrument air pressure. An **air-to-open** valve is a pneumatically operated control valve that automatically closes in the event of a loss of instrument air pressure. For example, the fuel supply to a furnace should automatically shut on air failure.

ALARA An abbreviation for **a**s **l**ow **a**s **r**easonably **a**chievable, it is a management tool used in the controlling of risks. For example, it is used to manage the exposure to chemicals and ionizing radiation doses in humans working in the nuclear industry. *Compare* ALARP.

alarm An indicator used to alert operators and personnel that there has been a significant deviation from an expected measured *process variable or process condition. The alarm may be audible in the form of a siren, bell, or other noise, or may be a flashing or continuous light signal. Alarms are a feature of control panels where the process is displayed on screens with associated alarms. **Alarm flooding** is a condition in which alarms appear on control panels in *control rooms at a rate which exceeds that which an operator can comprehend or respond to quickly or effectively. It therefore prevents the operator from identifying the cause of the process upset and consequently limits the scope for an effective response.

ALARP An abbreviation for **a**s **l**ow **a**s **r**easonably **p**racticable, it is a management tool used to determine the level to which risks are to be assessed and controlled. It involves a rigorous and systematic assessment of the minimization of risk and the costs in terms of time, money, and effort to achieve it. As a form of good practice requiring judgement between risk and societal benefit, it was developed through the UK parliamentary Health and Safety at Work Act (1974). Outside the UK, similar forms of engineering practice are used and this includes *ALARA (as low as reasonably achievable) in the US for radiation protection.

SEE WEB LINKS

- Official website of the Health and Safety Executive UK offering risk assessment advice.

algorithm A mathematical method or operation that follows a scheme of calculations or steps designed to be repeated such that the result from one calculation forms the basis of the next. The stage-by-stage computation of the liquid and vapour flows and compositions in a distillation process is based on a defined algorithm.

aliquot A portion of a total amount of something. For example, a prepared solution of reactants may be fed to a process in aliquots.

alkali A metal hydroxide that produces hydroxyl (OH-) ions in solution.

alkane A saturated aliphatic hydrocarbon that has the general formula C_nH_{2n+2}. Forming a homologous series, the smallest is methane (CH_4), followed by ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), etc. The smaller alkanes are gases at ambient temperature. Methane is found in oil and gas reservoirs, and in lesser amounts in coal seams. Methane is also the product of the decay of organic material by bacteria and produced from *anaerobic digestion processes. Mixtures of short-chain alkane gases can be separated by distillation, either by condensing the liquids using low temperature or by pressurization, or a combination of the two. They were formerly known as **paraffins** although this name is still used in certain industries such as petroleum refining.

alkene An unsaturated aliphatic hydrocarbon that has the general formula C_nH_{2n}. They comprise one or more carbon–carbon double bonds. They were formerly known as **olefins**. The series starts with ethene (ethylene) with the formula C_2H_4, followed by propene (propylene) C_3H_6, butene (butylene) C_4H_8, etc. Isomerism occurs with the higher alkenes beginning with butane for which there are two isomers: but-1-ene and but-2-ene that differ by the position of the double bond. Alkenes can undergo *polymerization to form thermoplastics such as polyethene (polyethylene).

alkylation A process in which an alkyl group is added to another organic molecule such as by removing a hydrogen atom from an *alkane and adding a methyl group. In the refining of *crude oil, it is used to upgrade petroleum through the alkylation of isobutane with *alkenes (olefins) such as propene, in the presence of either sulphuric or hydrofluoric acid as a *catalyst. The reaction takes place as a two-phase reaction at ambient temperature. The reaction products are a mixture of branched hydrocarbons with a high *octane rating. The octane number of the mixture depends mainly on the kind of alkenes used. Iso-octane has an octane rating of 100 and is the result of reacting isobutane with butene (butylene).

alkyne An unsaturated aliphatic hydrocarbon that has the general formula C_nH_{2n-2}. These are characterized by a triple carbon–carbon bond. Alkynes that feature a single triple bond form a homologous series beginning with ethyne (acetylene) C_2H_2, followed by propyne (propylene) C_3H_5, butyne (butylene) C_4H_6, etc. They were formerly known as acetylenes.

allotropy The existence of different forms of the same element in the same phase, known as **allotropes**. Carbon has the allotropes of graphite, diamond, graphene, and fullerenes. Many other elements exhibit allotropy.

alloy A material that consists of two or more metals, or a metal and a non-metal such as carbon. Pewter is made from tin with lesser amounts of lead along with small amounts of antimony and copper. Steel is made from iron alloys and contains a small amount of carbon.

alpha particle A positively charged particle emitted by various radioactive materials such as uranium during radioactive decay. The particle consists of two neutrons and two protons, and is therefore identical to the nucleus of a helium atom. The result of this *radioactive decay is that the original element is gradually converted into another element with a decreased atomic number and mass. Alpha particle emissions, or **alpha decay** may occur at the same time as *beta decay. It can be stopped by a sheet of paper and is harmful to humans only if the substance emitting the alpha particles is ingested, inhaled, or enters the body through wounds.

alternator Another name for an electromagnetic *generator used to produce alternating current in a power station.

Amagat's law A law that states that for an ideal gas, the total volume occupied by a gaseous mixture is equal to the sum of the pure component volumes:

$$V = V_A + V_B + V_C + \ldots$$

It is named after French physicist Emile Hilaire Amagat (1841–1915).

amalgam 1. An alloy of mercury with another metal, such as silver, used in dentistry. Most metals form an amalgam with mercury with the exception of iron and platinum. **2.** A white mineral consisting of mercury and silver that occurs in deposits of silver and cinnabar, which is a bright-red mineral form of mercuric chloride found near areas of volcanic activity and hot springs.

ambient temperature The temperature of the surrounding atmospheric air. Ambient air temperature can affect the operation of process equipment, instruments, and control. It is sometimes referred to as room temperature.

American Institute of Chemical Engineers (AIChE) A professional society based in the US with a membership of over 43,000 chemical engineers in a hundred countries. Founded in 1908, AIChE was established to provide its members with a focal point to share ideas and grow the discipline. Today it provides its members with technical resources and organizes major conferences, as well as setting accreditation standards for chemical engineering education, and setting guidelines for government agencies.

SEE WEB LINKS

- Official website of the American Institute of Chemical Engineers.

American National Standards Institute (ANSI) An American not-for-profit organization responsible for the accreditation of organizations that write industrial standards. It was founded in 1918.

SEE WEB LINKS

- Official website of the American National Standards Institute.

American Petroleum Institute (API) An American professional trade organization that represents all aspects of the US oil and natural gas industry. It was formed after the First World War (1914–18) as a consortium of oil and gas companies to help the recovery from the war by working together. It was formally established in 1919 as a means of cooperation with the government in all matters of national concern and to develop the wider interests of the petroleum industry. It sets standards and recommends practices, covering

all aspects of the industry, and promoting the use of safe, proven, and sound engineering practices.

SEE WEB LINKS
- Official website of the American Petroleum Institute.

American Society for Testing Materials (ASTM International) An international standards organization that develops and publishes voluntary technical standards for materials, products, systems, and services. Unlike ANSI, it is not a national standards body. It has been responsible for developing and maintaining more than 12,000 standards and the *Annual Book of ASTM Standards* consists of 77 volumes.

SEE WEB LINKS
- Official website of ASTM International.

American Society of Mechanical Engineers (ASME) A professional organization based in the US that provides its members with technical resources focusing on technical, educational, and research matters. It also produces standards such as ASME VIII, which is an accepted code for the design of pressure vessels and heat exchangers covering design, material selection, fabrication, inspection, and testing.

SEE WEB LINKS
- Official website of the American Society of Mechanical Engineers.

AMIChemE Post-nominal letters used after a person's name to indicate that they are an Associate Member of the *Institution of Chemical Engineers.

amine gas treating process A post-combustion process used to remove *acid gases such as carbon dioxide, hydrogen sulphide, and mercaptans from natural gas using an amine chemical solvent to react and form reversible compounds. Carbon dioxide is required to be removed since it reduces the calorific value of natural gas and forms carbonic acid in water which is corrosive as well as having a *global warming potential. The process involves the reversible reaction of the gas with an amine to form an amine salt. Various amines are used including monoethanolamine. The amine solution is sprayed into a large tower and absorbs the hydrogen sulphide as well as carbon dioxide from upflowing gases. A regenerator operating at a higher temperature is used to strip the amine solution of the gases for reuse. *See* GAS SWEETENING.

ammonia-soda process *See* SOLVAY PROCESS.

amorphous A non-crystalline solid form of matter in which the atoms or molecules are arranged at random within a three-dimensional structure. Glass is an example of an amorphous solid. *Compare* CRYSTAL.

amount of substance (Symbol n) A measure of the number of entities present in a substance, such as atoms, molecules, ions, and electrons, etc., expressed in moles. For example, the amount of an element is proportional to the number of atoms present where one mole of that element is equal to $6.022\,1367 \times 10^{23}$ atoms, which is *Avogadro's constant. It is given by:

$$n = \frac{N}{N_A}$$

where N is the number of atoms and N_A is Avogadro's constant. The SI unit is the mole. It is also known as **chemical amount**.

ampere (Symbol A) The SI unit of electric current, it is the constant flow of current that is maintained between two parallel conductors of infinite length and of negligible cross section that produces a force of 2×10^{-7} newtons per metre (Nm^{-1}) between them. It is named after the French physicist and mathematician André Ampère (1775–1836), who made significant discoveries in electricity and magnetism.

ampere-hour A practical unit of electric charge as the quantity that flows in one hour through a conductor carrying a current of one ampere. It is equivalent to 3,600 coulombs.

amplitude The maximum value of varying quantity from its mean or base value. For example, in simple harmonic motion the amplitude of a wave is half the maximum peak-to-peak value.

a.m.u. *See* ATOMIC MASS UNIT.

anaerobic digester A type of bioreactor used for the *anaerobic digestion of organic waste liquids from domestic and industrial sources. The biological process involves the use of bacteria in the near absence of oxygen to produce a mixture of methane and carbon dioxide, known as *biogas. *Continuous stirred-tank reactors are used for the treatment of industrial waste with a continuous inflow and outflow. *Batch processes are used for smaller domestic, community, or farm-scale processes.

anaerobic digestion A biochemical process in which bacteria break down organic matter in the absence of oxygen into a mixture of carbon dioxide and methane known as *biogas. The main stages involve hydrolysis, acidogenesis, acetogenesis, and methanogenesis. An *anaerobic digester can be operated at a steady-state condition through control of temperature for psycrophilic, mesophilic, and thermophilic bacteria, pH, the carbon-to-nitrogen ratio, organic dry matter content, hydraulic retention time, degree of mixing, the availability of nutrients and trace elements, and rate of biogas removal.

analar reagent A high-purity chemical reagent used for chemical analyses with a defined level of purity.

analogue signal An electrical signal used in the control of processes as a current or a voltage representing temperature, pressure, level, etc. The commonly used electrical current signal has a range of 4–20 mA. The voltage range commonly used is 0–5 volts DC.

analogue-to-digital converter (ADC) Electronic hardware used in the control of processes that converts analogue signals such as electrical voltage, current, temperature, and pressure into digital data that a computer can process.

analogy A form of general agreement or similarity between problems, reasoning, methods, or logic. It is used to compare the results from one particular problem to those of another from a known similarity between them.

analysis The detailed examination of something such as a mathematical problem using the theories of calculus, a chemical substance into its constituent parts, the study of a physical process and its function or operation, the economics of a chemical process or business, etc.

a

analysis of variance (ANOVA) One of a number of statistical techniques used to resolve and observe the variance between sets of statistical data into components. These techniques are used to determine whether the difference between samples is explicable as random sampling variation from within the same statistical populations. ANOVA techniques are used in *quality control.

analyte A substance that is being determined in an analytical procedure.

analytical reagent A chemical compound of a known and high purity used in a chemical *analysis.

ancillary equipment Mechanical equipment used to support or assist a primary item of equipment in meeting its functional duties. Pumps, blowers, and heating equipment are all ancillary items of equipment used to support main process plant items.

Andrews, Thomas (1813–85) An Irish scientist noted for his work on gases. He studied chemistry at the University of Glasgow before undertaking further studies in Paris. He then attended Trinity College, Dublin before completing his medical studies in Edinburgh and then returning to Belfast to set up practice as a physician. When Queen's College opened in 1845, he was appointed professor of chemistry, and also the first vice president of the college. During this time, he carried out his most important studies on gases. His three main areas of work concerned thermochemistry, the nature of ozone, and the continuity of liquid and gaseous states of matter. He was offered a knighthood but declined on the grounds of ill health.

Andrussov, Leonid (1896–1988) A chemical engineer born in Riga who is noted for developing a process for the production of hydrogen cyanide based on the oxidation of ammonia and methane over a platinum catalyst.

Andrussov process A catalytic process used for the production of hydrogen cyanide by the reaction of ammonia, methane, and air at a temperature of around 1,000°C using a platinum catalyst:

$$2CH_4 + 3O_2 + 2NH_3 \rightarrow 2HCN + 6H_2O$$

The ammonia in the product gases is removed by gas absorption with sulphuric acid and the hydrogen cyanide is absorbed in water. The hydrogen cyanide is used as the preliminary product for the synthesis of polyamide 66 or nylon, and for polymethyl methacrylate. It is also called **Andrussov oxidation** after the inventor who patented the process in 1930s.

anemometer An instrument used to measure the speed of a gas such as air. It comprises cups or vanes that rotate freely and are linked to a tachometer. **Hot-wire anemometers** feature a heated wire over which the gas or air passes. Since the electrical resistance of certain metals such as tungsten is dependent on temperature, the cooling effect of the gas over the wire changes its resistance from which the velocity is inferred.

aneroid An instrument used to measure barometric or atmospheric pressure. It has metal bellows as a sensing device.

angel's share An amount of Scotch whisky lost by evaporation during the process of maturation in wooden casks. Scotch *whisky is stored for a minimum of three years over which time the level of whisky can drop by as much 2 per cent per year.

angström (Symbol Å) A unit of length equal to 10^{-10} m. It is used to measure the wavelengths of electromagnetic radiations and was formerly used for the measure of intermolecular distances. It has now been replaced by the nanometre (10^{-9} m). It is named after the Swedish astronomer and professor of physics Anders Jonas Angström (1814–74).

angular momentum (moment of momentum) A measure of the momentum of a body caused by its circular motion around an axis of rotation. It is the vector product of the position vector and the tangential component of velocity of an object moving about a centre of rotation. The angular momentum of a mass m of fluid is $mv_\theta r$ where v_θ is the tangential velocity.

angular velocity (Symbol ω) The rate of change of angular displacement with time:

$$\omega = \frac{d\theta}{dt}$$

The rotational speed of shafts for mixers, centrifugal separators, and centrifugal pump impellers are sometimes expressed in radians per second.

annealing A heat treatment process used to relieve internal stresses in ferrous and non-ferrous metals. It involves heating the metal to a specified temperature over a specified period of time to soften it. It is then allowed to cool slowly. The annealed metal is less brittle with reduced internal stress and is therefore easier to work or machine. A similar process is applied to glass.

annular flow A two-phase flow regime of a gas and a liquid in a vertical pipe or tube characterized by a continuous gas core with a wall film of liquid. The flow regime occurs at high gas velocities compared with the liquid. There is often a simultaneous flow of the liquid phase entrained in the gas as a fine dispersion of droplets. In horizontal pipes, the effect of gravity causes the film to become thicker on the bottom of the pipe. As the gas velocity is increased, the film becomes more uniform around the circumference. *See* MULTIPHASE.

annulus The region between two concentric circles. The area of an annulus is equal to $\pi(d_1^2 - d_2^2)/4$ where d_1 and d_2 are the outer and inner radii. An **annular gap** is the clearance between two concentric pipes or tubes. The use of concentric pipes or tubes is found in the nuclear industry as a form of double containment. The central pipe is used to carry a radioactive liquid such as plutonium nitrate and the gap in the annular gap is kept under reduced pressure. In the event of leaks, the radioactive liquid is retained within the annular gap and recovered without release into the environment.

anode A positive electrode in an electrolytic cell. In the process of electrolysis in which electricity is passed through an electrolyte, the electrode attracts electrons from an external circuit. *Compare* CATHODE.

anodize An electrolytic process used to provide a hard, smooth, and corrosion-resistant surface to aluminium and some other metals. The piece for coating is connected to the anode of a DC circuit and is immersed in an acid solution. The flow of current liberates oxygen at the surface which reacts with the aluminium to form aluminium oxide. Chromic, oxalic, and sulphuric acids are commonly used. The anodized surface may typically have a thickness of between 0.005 mm and 0.018 mm.

ANOVA *See* ANALYSIS OF VARIANCE.

a

anoxic reactor A type of anaerobic bioreactor in which oxygen is excluded from the cultured bacteria. **Anoxia** is the absence of molecular oxygen in living tissue cells used to indicate the reduction of the oxygen content of the blood below physiological levels.

antilogarithm (antilog) The inverse function of a *logarithm. That is, a number whose logarithm to a given base is a given number. For example, the antilogarithm of 2 to the base 10 is 100. In natural logarithms, the antilogarithm of x is e^x.

antithixotropic fluids Shear thickening fluids that thicken with time. The viscosity of such fluids increases when a shear stress is applied, as in stirring, and is also dependent on the time that the shear stress has been applied. *Compare* THIXOTROPIC FLUIDS. *See* RHEOPEXY.

Antoine equation An empirical equation used to determine the vapour pressure of a substance as a function of temperature:

$$\log_{10} p = A - \frac{B}{T + C}$$

where p is the vapour pressure, T is the temperature and A, B, and C are empirically determined constants. The pressure is given in mmHg. It is named after C. Antoine who published the equation in 1888.

Antonov's rule An empirical equation used to describe the surface tension between two liquids in equilibrium being equal to the difference between the surface tension of the two liquids when exposed to air.

APCChE (Asian Pacific Confederation of Chemical Engineering) Founded in 1975, it is a not-for-profit organization that brings together various societies, associations, and institutions of chemical engineering in the Asia Pacific region. This covers the thirteen countries of China, Korea, Japan, New Zealand, Thailand, India, Philippines, Indonesia, Singapore, Australia, Malaysia, Taiwan, and Hong Kong. The American Institute of Chemical Engineers and the Institution of Chemical Engineers are corresponding members.

API gravity A measure of the density of petroleum oils used in the US and related to *specific gravity:

$$^{O}API = \frac{141.5}{SG} - 131.5$$

The specific gravity and API gravity refer to the weight per unit volume at 15.6°C (60°F). Most crude oils range between 20 and 45°API.

apparent density The mass per unit volume of a material that includes voids. It is a measure of the bulk of the material. *Compare* SPECIFIC DENSITY.

apparent viscosity (Symbol η) The viscosity of a fluid as a measure of the ratio of the shear stress to shear rate and used for non-Newtonian fluids such as drilling muds.

approximation A mathematical process used to describe roughly the value of a quantity of something that is not exact but is sufficiently close to a known or correct value within acceptable boundaries of error.

aqueous Used to denote solutions in which water is the solvent.

Archimedes of Syracuse (287–212 BC) A Greek mathematician and philosopher credited with the principles of levers, the **Archimedean screw** as a pump, and a method of successive approximations which allowed him to determine the value of π to a good approximation. King Hiero is said to have asked Archimedes to check if a crown was pure gold throughout or contained a cheap alloy. While in a public bath and pondering on how to do this without damage to the crown, Archimedes is supposed to have suddenly thought of the possibility of immersing it in water and checking its density by way of displacement, and to have been so excited that he ran naked through the streets shouting 'Eureka! Eureka! I have found it! I have found it!' He was killed by a soldier in the Roman siege of Syracuse.

Archimedes' principle A principle that states when a body floats it displaces a weight of liquid equal to its own weight. The principle was not stated by Archimedes but is connected to his discoveries in hydrostatics. When a body is partially or totally immersed in a liquid, there is an upthrust on the body equal to the weight of the liquid displaced by the body.

area The extent of a plane figure or surface. The area of a rectangle is the product of the length and base. The area of a circle of diameter d is $\pi d^2 / 4$. The SI unit is m^2.

Argand diagram A graphical way of representing complex numbers in the form $z = x + jy$ in which real and imaginary parts of the complex number are the x and y axes, respectively (see Fig. 2). The modulus is the distance z and the angle of z is the argument. It is named after Swiss mathematician Jean-Robert Argand (1768–1822) and is useful in understanding the stability of controlled processes.

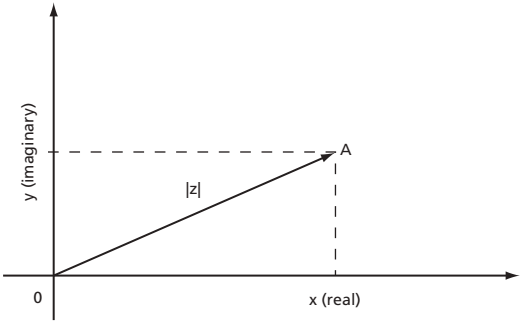

Fig. 2

Arrhenius, Svante August (1859–1927) A Swedish physicist and chemist who did fundamental work on physical chemistry. He worked with *van't Hoff in Amsterdam and proposed a theory of activated molecules and established a connection between rate of reaction and absolute temperature. He also developed a theory for electrolytic dissociation based on van't Hoff's results and stated that any acid, base, or salt dissolved in water is partly split up into positively and negatively charged ions, and that they move in opposite directions on electrolysis. He was awarded a Nobel Prize for Chemistry in 1903.

SEE WEB LINKS

- Official website of the Nobel Prize organization, with a transcript of Arrhenius' lecture of 1903.

Arrhenius equation An equation that represents the effect of temperature on the velocity of a chemical reaction expressed as:

$$\frac{d \ln k}{dT} = \frac{E_a}{RT^2} \text{ or } k = Ae^{\frac{-E_a}{RT}}$$

where k is the *rate constant for the reaction, E_a is the *activation energy, R is the gas constant, T is the absolute temperature and A is frequency factor. An Arrhenius plot of ln$k$ against 1/T gives a straight line of slope –E/R and is valid for a large number of chemical reactions. It is named after Swedish chemist and physicist Svante August *Arrhenius (1859–1927).

aseptic A condition in which all contaminating microorganisms are eliminated, not present, or allowed to reproduce. Substances that provide aseptic conditions are known as antiseptics. **Aseptic processing** involves ensuring sterility and therefore a process that is free from microbial contamination. It is used in the packaging of foods, pharmaceuticals, and medical products. Sterility is achieved using a flash-heating process and the product packaged into aseptic containers. The container is required to be robust and provide a tight seal against outside contamination sources. The container and its contents have the benefit of not requiring refrigeration. *Compare* STERILITY.

ash The non-volatile products and residues that remain after a combustion process. *Electrostatic precipitators are used to remove ash particles from flue gas streams.

ASME *See* AMERICAN SOCIETY OF MECHANICAL ENGINEERS.

aspect ratio The ratio of the height to width or diameter of an item of process plant equipment such as a column or storage tank.

asphyxia A state of unconsciousness as the result of anoxia or *hypoxia and increased carbon dioxide in blood and tissue. *See* SUFFOCATION.

assay An analytical procedure used in the laboratory for assessing a sample of something either qualitatively or quantitatively in terms of an amount of a substance, its composition, or some other entity under investigation. Biochemical assays of samples taken from bioreactors that often feature complex mixtures involve procedures for determining cell content, substrate utilization, and product formation. The complexity of the samples that require various prescribed steps to be followed does not permit conventional forms of chemical analysis such as titration.

association The grouping together of atoms or molecules often in the vapour state or in solution to form conglomerates of high molecular weight. *Compare* DISSOCIATION.

assumption A statement that is used in order to simplify a problem, in reaching a solution, or where the full understanding of the problem is not actually known. Assumptions arise in all forms of chemical engineering. For example, in distillation, liquid and vapour are often assumed as being at equilibrium on a theoretical stage; a reaction mechanism may assume no side reactions; the flow from a vessel may assume no vortex formation or a constant discharge coefficient.

ASTM *See* AMERICAN SOCIETY FOR TESTING MATERIALS.

asymptote A straight line that is closely approached by a curve so that the perpendicular distance between them decreases to zero at an infinite distance from the origin.

ATEX An EU directive that describes the work that may be safely carried out in an explosive atmosphere. The areas or zones in a process plant are classified according to the type of hazards, the location, and size, and the likelihood of an explosion. It is applied to mining operations, offshore processing, petrochemical plants, and flour mills, where potentially explosive atmospheres may exist. The name is derived from the French title for the EU directive *Appareils et systèmes de protection pour les atmosphères explosibles.*

SEE WEB LINKS

- Official website of the Health and Safety Executive, UK, outlining information on ATEX and explosive atmospheres.

atmolysis The separation of a mixture of gases by diffusion through a porous membrane such as hollow fibres. Each gas in the mixture has a different rate of diffusion, allowing them to be separated.

atmosphere A layer of gases of largely oxygen (21 per cent) and nitrogen (79 per cent) surrounding the Earth's surface which comprises the troposphere, stratosphere, and ionosphere and traceable to an altitude of around 800 km. The barometric pressure varies with altitude with *standard atmospheric pressure at sea level being taken to be 101,325 Pa or 1,013 mbar.

atom The smallest particle of an element that can exist and which can take part in a chemical reaction and cannot be chemically divided any further into smaller parts. It is identifiable as that element by its nucleus. The nucleus contains neutrons and protons and is surrounded by a cloud of orbiting electrons. The number of electrons equals the number of protons such that the overall charge is zero.

atom balance A material balance based on the number of atoms of specified elements.

atomic bomb A nuclear weapon whose explosive force is due to the energy released through the process of nuclear fission. It involves bringing together a mass of fissile material sufficient to result in a chain reaction that proceeds explosively. Uranium-235 and plutonium-239 are examples of fissile material used in nuclear weapons. The explosive force of nuclear weapons is quoted in kilotonnes or megatonnes of *TNT equivalents. The atomic bombs that were dropped on Hiroshima (uranium-235 bomb) and Nagasaki (plutonium-239 bomb) had the explosive energy equivalent to 13 and 22 kilotonnes of TNT, respectively.

atomic energy *See* NUCLEAR ENERGY.

atomicity The state of being made up of atoms and is the number of atoms in molecules. For example, carbon dioxide (CO_2) has an atomicity of 3; hexane (C_6H_{14}) has an atomicity of 20, etc.

atomic mass The mass of an isotope of an element expressed in *atomic mass units. It is short for *relative atomic mass.

atomic mass unit (a.m.u.) A unit of mass used to express atomic and molecular weights. It is equal to one twelfth of the mass of an atom of carbon-12 and is equivalent to 1.66×10^{-27} kg.

atomic nucleus *See* NUCLEUS.

a

atomic number The number of protons in an atomic nucleus. The classification of elements is based on the increasing order of atomic number.

atomic pile An early name for a *nuclear reactor that used graphite as the *moderator. *See* WINDSCALE NUCLEAR ACCIDENT.

atomic power An alternative name for *nuclear power.

atomic volume The *relative atomic mass of an element divided by its density.

atomic weight *See* RELATIVE ATOMIC MASS.

atomization The creation of very small droplets of a liquid within a gas. The droplets may range in size from 10 micrometres to 1 millimetre and consequently have a very high surface area, thereby permitting rapid chemical reaction, drying, heat, and mass transfer. Atomization is particularly useful for fuels in combustion processes and for drying or dehydration of liquid products in spray dryers using an *atomizer.

atomizer A device used in the process of atomization to produce very small droplets of a liquid within a gas. Such small droplets can be produced by forcing a liquid through a very small aperture under high pressure or by contacting the liquid with a high-speed rotating plate or disc.

auriferous A rock or ore containing gold.

austenitic stainless steel An alloy of iron that contains at least 8 per cent nickel and 18 per cent chromium. It is noted for its very good corrosion resistance, heat resistance, and creep resistance, and is also non-magnetic. It is used extensively for process pipes and vessels.

autocatalysis A catalyzed chemical reaction in which one of the products is the catalyst for the reaction. The chemical reaction starts slowly as the catalyst is formed and continues rapidly until the point when the reactants are depleted.

autoclave A sealed and heated thick-walled pressure vessel used for the thermal sterilization of biological agents and tinned food products using steam. It is also used for carrying out chemical reactions at elevated temperatures.

autoignition temperature The temperature at which a material ignites in air or some other oxidant at a specified pressure without the aid of a spark or flame. The minimum autoignition temperature is determined by an *ASTM test method. It is also known as the **autonomous ignition temperature**.

automatic control *See* FEEDBACK CONTROL.

autoradiolysis The dissociation of molecules contained within a substance or mixture through *ionizing radiation arising from radioactive materials such as in highly active *nuclear waste.

autothermal A system, process, or reaction that is completely self-sufficient in terms of its energy requirements. Some *exothermic reactions are autothermal. Some *anaerobic digesters are operated in this way in which the methane liberated is used to fuel the process.

average velocity Also known as the *mean velocity, it is the total volumetric flow rate of a fluid per unit flow area. It is a useful parameter particularly where there may be local variations in velocity and hence flow across a flow area due to the effects of turbulence or obstructions in a pipeline, duct, or stack. The SI units are $m\ s^{-1}$.

aviation gasoline A hydrocarbon fuel produced in petrochemical refineries. It is used by aircraft with piston engines. It has a high *octane rating and more closely resembles motor gasoline or petrol than diesel fuel. *See* JET FUEL.

Avogadro, Amedeo (1776–1856) An Italian chemist and physicist who provided Avogadro's law as a way of calculating molecular weights from vapour densities. He was educated and graduated in ecclesiastical law; however, he had a keen interest in the natural sciences and received private tuition in physics and mathematics. He published his hypothesis, known now as *Avogadro's law, while working as a schoolteacher. He was appointed to the first chair in mathematical physics at Turin University in 1820. The importance of his work was first recognized by the Italian chemist Stanislao Cannizzarro (1826–1910) in 1858, shortly after Avogadro's death.

Avogadro's constant (Symbol N_A) The number of atoms in one mole of a substance. It has the value of $6.022\ 1367(36) \times 10^{23}$ and was formerly known as **Avogadro's number**.

Avogadro's law A law that states that equal volumes of gases at the same temperature and pressure contain the same number of molecules. This was first stated as a hypothesis by the Italian chemist and physicist Amedeo *Avogadro (1776–1856) in 1811. However, this law was not generally accepted until after his death when the Italian chemist Stanislao Cannizzaro was able to explain why there were some exceptions to the hypothesis.

axenic culture A microbial culture in a biological process that involves only one species of microorganism.

axial In the direction of the axis of a pipe, tube, cylinder, or a rotating shaft. A propeller provides a flow of fluid in the direction of the shaft whereas an impeller provides *radial flow of fluid in the direction of the radius.

axial compressor A mechanical device used to move air or a gas at high pressure. The gas to be compressed is drawn through alternate rows of radially mounted rotating and fixed aerofoil blades in which the kinetic energy is converted to pressure energy.

axial dispersion model A mathematic model used in the design of tubular *plug flow reactors. The model is based on the *axial mass transport of material corresponding to an effective or apparent longitudinal diffusivity but with a constant *radial concentration.

axial-flow fan A power-driven mechanical device used to move air or a gas. It consists of a rotating shaft with blades or a propeller in which the flow of air or gas is parallel to the axis of the shaft. It operates with low static pressure and high air flow. *Compare* RADIAL-FLOW FAN.

axis 1. A fixed reference point or line about which a graph or figure is plotted. **2.** A line about which a body rotates such as an impeller in a centrifugal pump.

azeotrope A mixture of two liquids that boils at a constant composition. That is, the composition of the vapour is the same as the composition of the liquid. It is therefore not

a

possible to separate an azeotropic mixture by conventional distillation. Azeotropes occur due to deviations in *Raoult's law leading to either a maximum or minimum in the boiling point-composition diagram. The composition of the azeotrope is dependent on pressure.

azeotropic distillation A method of separating azeotropic mixtures by distillation in which conventional distillation is often not suitable or possible. It is used for mixtures that have a *relative volatility near unity or which form *azeotropes and would otherwise require large numbers of theoretical plates and high reflux ratios *See* SUPERFRACTIONATION. It is therefore necessary to increase the relative volatility, which entails an increase in the non-ideality of the mixture. An *entrainer is therefore added which is fairly volatile and forms an azeotrope, with one or more of the original components, and leaves overhead, allowing one component to leave in a fairly pure state at the bottom. This new azeotrope must be either heterogeneous or readily separable by some other means such as by *liquid–liquid extraction.

The typical layout with heterogeneity (usually on cooling, see Fig. 3) consists of an overhead heterogeneous azeotrope in which there is an entrainer-rich layer that is returned to the column and an A-rich layer that is sent to an entrainer recovery column. The latter produces more azeotrope overhead, which is sent to the common condenser-cooler, and A of the desired purity leaves at the bottom. The A-rich layer is not necessarily the upper layer in the decanter, and an addition of entrainer to the column may have to be made to make up for losses. An example of this system is the use of butyl acetate (entrainer) to remove water (A) from acetic acid (B). Without the entrainer the relative volatility is very low.

Another example is the use of cyclohexane to separate isopropyl alcohol (IPA) and water in which crude IPA is pumped to the first tower or 'dryer' and cyclohexane and water leaves the top of the tower, is condensed, and separates into two layers. Cyclohexane in the top layer is sent as reflux to the tower and the lower water aqueous IPA layer pumped to another tower for part water removal. The amount of cyclohexane in the system is regulated by the level in the reflux drum.

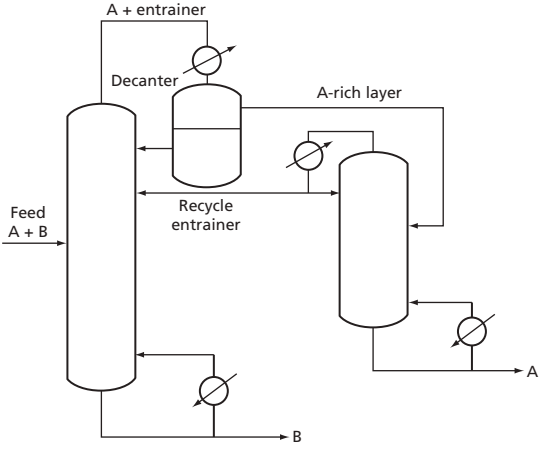

Fig. 3 Azeotropic distillation with heterogeneity

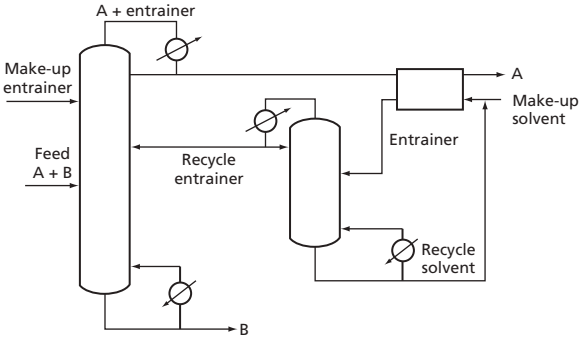

Fig. 4 Azeotropic distillation without heterogeneity

If heterogeneity does not occur, some other means of splitting the A-entrainer azeotrope is required such as liquid–liquid extraction (see Fig. 4).

azeotropic drying The process of removing water from a liquid by the addition of another liquid that forms an *azeotrope with the water. It therefore allows the removal of water at a temperature below the normal boiling point of 100°C.

B

Babbitt metal One of a number of *alloys originally based on tin, copper, and antimony and now includes lead. It is used in bearings for motors and was invented by American inventor Isaac Babbitt (1799–1862).

Babo's law A law that states that the vapour pressure of a solution is reduced in proportion to the amount of solute that is added. It was discovered in 1847 by German chemist Lambert von Babo (1818–99).

backflushing A cleaning process used to dislodge particulate material in a pipe, column, or filter, etc. It involves reversing the flow of fluids to the normal direction of flow.

background radiation A measurable low-intensity *ionizing radiation that is present all around due to the presence of radioisotopes in rocks such as granite, in the soil, and the atmosphere. The radioisotopes in the atmosphere are naturally forming, the result of nuclear fallout, and emissions for nuclear reprocessing, or emanating as waste gases from power stations. The level of background radiation must be taken into consideration when measuring the radiation from a source.

back-mixing The propensity of reacted materials to become mixed with unreacted materials that are fed to stirred vessels or chemical reactors. The design of *continuous stirred-tank reactors (CSTRs) is based on the assumption of instantaneous homogeneity. In reality, the flow of materials short-circuit and leave the vessel or reactor before the expected time, while some reside for longer periods. Back-mixing is a concern in the design of *plug flow reactors, which lead to a departure in ideality.

back-mix reactor *See* CONTINUOUS STIRRED-TANK REACTOR.

back pressure The resistance to a moving fluid to its direction of flow caused by an obstruction, bend, or friction in a pipe or vessel. It is often used to describe the discharge pressure from a pump or compressor. The term often refers to a pressure greater than atmospheric.

backwashing A method used to clean a fixed bed reactor for reuse. Under normal operation, the flow of a fluid is down through the fixed bed that may act as a support but over time may have become fouled or blocked. Backwashing therefore deliberately reverses the flow of the fluid up through the bed causing *fluidization, detaching, suspending, and washing out of undesirable particles. It is often used in *sand filtration and *ion exchange resin beds.

baffle A plate used in an item of equipment to influence the rate or direction of a flow of material. The plate may be flat or curved and used in vessels such as tanks or heat exchangers to increase turbulence or prevent the formation of a vortex. An impingement baffle is

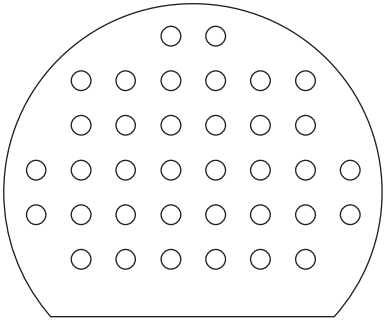

Fig. 5

used to minimize the disturbance of a liquid–liquid interface in a decanter device and can also be used in *shell and tube heat exchangers to reduce the effects of erosion by forcing a vapour stream around the baffle causing any liquid drops to collide with the baffle.

Baffles are often used in shell and tube heat exchangers to direct the fluid stream across the tubes to increase the fluid velocity and increase the rate of heat transfer. The baffle is a circular plate that is similar in size to the tube plate with many holes through which the tubes fit. A segmental baffle allows the shell-side fluid to move under the baffle or over the baffle through the segmental space (see Fig. 5). The **baffle cut** is the segment height removed to form the baffle, expressed as a percentage of the baffle disc diameter. The **baffle spacing** is the distance between the baffles.

Bakelite One of a class of thermosetting resins that are used for making plastic ware and electric insulators. It is named after Belgian-born US inventor L. H. Baekeland (1863–1944).

Baker plot A widely used dimensionless plot representing two-phase flow in pipes (see Fig. 6). Published by O. Baker in 1954 using experimental data for water, various flow

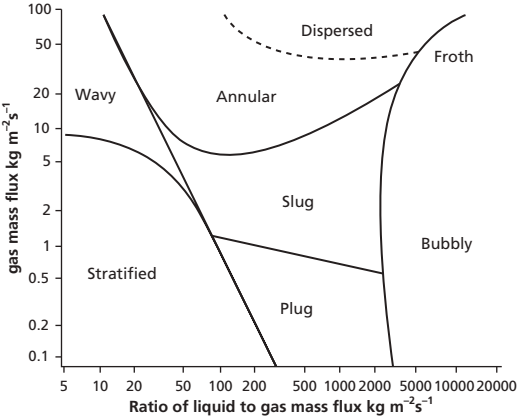

Fig. 6

regimes can be distinguished such as annular, bubbly, froth, plug, slug, stratified, and wavy flow. Corrections are made for two-phase flow mixtures with other densities and viscosities. Improved plots have subsequently been developed by other researchers.

ball mill A mechanical device used to reduce ores to small particles and powder. It consists of a rotating cylindrical chamber mounted on its side containing steel balls and the material to be ground. The slow rotating action of the chamber allows the balls to tumble and cascade over one another thereby crushing the material. They can be operated as a batch or as a continuous operation.

ball valve A type of valve used to control the flow of a fluid in a pipe. It consists of a sphere with a hole through it. When the ball is rotated by 90°, the hole is perpendicular to the pipe axis and the valve is shut preventing flow. With a comparatively low pressure drop, its action is fast and is suitable for dirty and viscous fluids. It is also capable of tight shut-off.

bar A c.g.s. unit of pressure equal to 10^5 newtons per square metre (N m^{-2}) or pascals (Pa). The millibar (mbar) is commonly used by meteorologists (one thousandth of a bar). *Standard atmospheric pressure is 1,013 mbar.

barn (Symbol b) The unit of area defined as 10^{-28} m^2. It is used to express the effective nuclear cross section of atoms or nuclei in the scattering or absorption of particles.

barometer An instrument used to measure atmospheric pressure. Early barometers consist of a tall vertical glass column containing mercury. The top of the column is sealed, while the bottom is open in a reservoir of mercury. The pressure of air on the reservoir balances the vertical column of mercury, from which the pressure can be read directly. *Standard atmospheric pressure (101.325 kPa) corresponds to a height of 760 mmHg. The space above the mercury in the top of the leg is called a *Torricellian vacuum. It is not a true vacuum but is the vapour pressure of the mercury.

barometric leg A tube immersed in liquid that is used to provide a liquid seal for equipment under vacuum. The tube is of sufficient length such that the static pressure exceeds the atmospheric pressure.

barrel A unit of volume used largely in the oil industry. In the US, one barrel is equal to 42 (US) gallons and equivalent to 0.158 98 m^3. One barrel (British) is equal to 36 Imperial gallons and equivalent to 0.163 659 m^3. The abbreviation is *bbl. An oil refinery production and throughput is often quoted in terms of **barrels per calendar day** (BPCD) or **barrels per stream day** (BPSD), which are the average rates based on a 365-day year, or on the number of days per year the refinery was actually operating, respectively.

barrel of oil equivalent (BOE) A measure of the amount of a combustible material which when burnt releases the same amount of energy as the combustion of one *barrel of crude oil. Multiplications of this unit include kilo, million, and billion barrels of oil equivalent (kBOE, MBOE, BBOE). It is also expressed as a rate such as million barrels oil equivalent per day (*MBOED). It is used for financial purposes to combine both oil and gas into a single measure.

Barton, Derek Harold Richard FRS (1918–98) A British chemist noted for his contribution to the pyrolysis of chlorinated hydrocarbons and many other areas of organic chemistry. After gaining his doctorate from Imperial College, London, he held many academic positions and visiting professorships including Regius professor of chemistry at

the University of Glasgow and distinguished professor at Texas A&M University. He was elected Fellow of the Royal Society in 1954 and was awarded the Nobel Prize in Chemistry in 1969. He received many other awards in recognition of his contributions to chemistry, which formed the basis of many industrial processes.

barye A unit of pressure used in the c.g.s. system. It is equal to one dyne per square centimetre and is equivalent to 0.1 pascal.

base 1. A substance that has the tendency to gain protons and form hydroxyl ions in solution. A base is neutralized by an acid to form a salt and water. **2.** Used in mathematics, the base is the number of different symbols used in a numbering system. In the binary system the base is 2, while in the decimal system the base is 10.

BA set An abbreviation for **b**reathing **a**pparatus set and is a form of *personal protective equipment that is worn to supply uncontaminated air through a face mask or mouthpiece. It is used by personnel working in hazardous environments.

base unit A unit that is defined arbitrarily and not related in combination with other units. In the SI system, there are seven base units: kilogram (kg) for mass, metre (m) for length, second (s) for time, kelvin (K) for temperature, mole (mol) for the amount of substance, ampere (A) for electrical current, and candela (cd) for luminous intensity. *Derived units are defined as combinations of base units such the newton (N) which is a unit of force where 1 N is equal to 1 kg m s^{-2}.

basic-oxygen process A process used for the production of high-grade steels that involves a charge of molten pig iron and scrap in a tilting furnace being blown with high-pressure oxygen on the surface through a water-cooled lance. The process has largely replaced the earlier *Bessemer process and *open hearth process.

basis of calculation A statement used at the beginning of a calculation for the quantity of material used entering or leaving a process. The choice of quantity is appropriate for the process and may be expressed in mass or moles. For continuous processes, mass or molar flow rates are used such as kg s^{-1} or kmol h^{-1}, respectively. The total quantities may be used or calculations based on a limiting reactant for a specified product.

basis of design (BOD) A document that is prepared prior to the design and development of a process. It includes the rationale for the design, and includes assumptions and decisions on the options identified for the design as well the codes, standards, and regulations required in the design. The document is used as the basis for the design, development and construction of the process.

basket centrifuge A type of centrifuge used to separate solid particles from liquids. It consists of a perforated bowl or basket that allows the passage of the filtrate and is lined with some form of filter cloth used to retain the solids. It therefore operates as a form of centrifuge filter and operates at relatively low rotational speeds of 1,000 rpm.

BAT An abbreviation for **b**est **a**vailable **t**echniques. It is usually applied to reduce the level of pollution emanating from a process and is considered to be more rigorous than *ALARP.

batch culture A biochemical or biotechnological process such as fermentation in which all the nutrients apart from oxygen are placed in the bioreactor at the start of the operation. The fermentation is inoculated with microorgansims such as yeast or bacteria and the

biological reaction is allowed to proceed until completion whereby a *limiting substrate or nutrient is depleted. It is at this point that the product is usually harvested.

b

batch distillation A type of *distillation process in which the liquids to be separated are placed in a *still. During operation, there is no further addition of liquid for separation. Scotch *whisky is distilled by this technique. Initially, alcohol-rich vapour known as *foreshots is produced and collected before the heart is collected. **Feints**, which are lean in alcohol, are finally recovered. Both the foreshots and feints are returned to the distillation process for the next batch. The process operates at unsteady state and can be described by the *Rayleigh equation.

batch process A process using a fixed quantity of material that is placed within the process equipment and the operation carried out to completion. Described as a *closed system, no material is transferred to or from the system during the time of interest, and can be described using differential material and energy balances. The process may involve several sequential steps but in each the material is kept and processed together. Commonly used for speciality chemicals, pharmaceuticals, and food processing, batch processes include mixing, reaction, and separation. Reactor volumes are generally correspondingly larger than those of continuous processes. The operating costs, including labour costs, are also higher due to materials handling and greater charging and down-times costs. Scotch whisky production is an example of a batch process in which malted barley grain is batch fermented and batch distilled.

batch reactor A vessel within which a controlled chemical or biochemical reaction takes place. They require a charge of reactants, which may be liquid or solid including the use of catalysts. The chemical reaction is allowed to proceed until a required concentration of product has been achieved. The reaction may require heating or cooling depending on the thermodynamics of the reaction. This can be achieved by the circulation of a heat transfer medium through a surrounding jacket or through internal coils and tubes. Once the reaction is complete, the reaction materials are recovered. This type of reactor is considered to be versatile since it can be used for many types of processes.

battery An electric cell used to produce electrical energy. Archaeologists claim that there is evidence from *c.*200 BC Bagdad of batteries being used in early electroplating. Italian physicist Count Alessandro Volta (1745–1827) developed a battery in 1796 that was the first primary source of electrical energy in the form of direct current (DC). His 'voltaic pile' consisted of stacked silver and zinc plates in an acid electrolyte, and could deliver a useful amount of power over a period of several minutes. However, it was not possible to recharge it. French physicist Georges Leclanché (1839–82) developed a carbon-zinc battery in 1866, which was later developed to produce a dry cell battery that is still used today. Rechargeable batteries were first constructed in 1866 by French physicist R. L. Gaston Planté (1834–89) and offered a more convenient electrical source by allowing the electrochemical reaction to be reused and the electrical energy to be replenished. The most common rechargeable battery is the lead-acid battery used in conventional cars.

battery limits The geographical perimeter that surrounds a processing area and includes process equipment, piping, and associated buildings and structures of a process plant. It excludes utilities and process services such as boiler houses and laboratories.

Bayer process A method of making alumina (Al_2O_3) from aluminium ore or bauxite. It involves crushing the bauxite and separating it from the oxides of iron, silica, and titanium that are also contained in the ore. It is then mixed with caustic soda and heated

under pressure. The alumina dissolves in the caustic soda forming a solution of sodium aluminate. After *filtration, crystals of aluminium hydroxide are added to the solution. The alumina precipitates out as crystals and are collected by filtration. The crystals are then dried by heating to around 1,200°C to leave a fine white powder. It was invented in 1887 by Austrian chemist Karl Josef Bayer (1847–1904).

bbl An abbreviation for (US) barrel and is a volumetric unit for crude oil and petroleum products where one barrel is equivalent to 158.978 litres. Also used is **BO** representing **b**arrels of **o**il and **BOPD** as a volumetric measure of flow as **b**arrels of **o**il **p**er **d**ay. The unit of volume originates from the volume of spent whisky barrels that were once used to hold oil in the nineteenth century.

bead mill A mechanical device used for rupturing the cell walls of microorganisms to release their intracellular protein products. Laboratory-scale bead mills consist of a chamber filled with small glass beads and a suspension of the cells requiring rupture. The cell wall and membrane are disrupted by collisions between shear force layers generated by high-speed agitation and grinding action of the beads in the chamber. The vigorous agitation can lead to denaturation of released proteins due to the shear forces and local heating effects.

Becher process A process used for producing synthetic rutile (titanium dioxide) as a titanium concentrate from ilmenite ore. The ore contains largely rutile and the process removes iron oxide impurity by roasting with sulphur at 1,200°C in a rotary kiln. The iron is reduced to metal and removed by magnetic separation along with coal and ash. The reduced ilmenite is washed in water containing ammonium chloride as a catalyst and air blown through to convert metallic iron to a flocculent precipitate of iron oxides. These are then removed. The process was invented by Robert Gordon Becher in the 1960s.

becquerel (Symbol Bq) The SI unit of radioactivity corresponding to one disintegration per second. It is named after Antoine Henri *Becquerel (1852–1908) who discovered radiation.

Becquerel, Antoine Henri (1852–1908) A French physicist who accidently discovered the existence of radioactivity in 1896. By chance, he put away in a drawer some unexposed photographic plates wrapped in black paper. In the drawer there was also a specimen of uranium salt. Later, the plates were found to be fogged and led to the conclusion that the uranium had emitted radiation that was sufficiently powerful to penetrate the wrapping. In 1903 he was awarded the Nobel Prize for physics with Marie and Pierre *Curie. His father (Antoine César) and grandfather (Alexandre Edmond) were also eminent physicists and the three held, one after the other, the position of professor of physics at the Musée d'Histoire Naturelle from 1837 to 1908.

bed volume The total volume that is occupied by the support material in a *fluidized bed or *packed bed, such as by a catalyst.

bell metal An alloy of copper and tin used in casting bells. It often contains some zinc and lead.

Benedict–Webb–Rubin (BWR) equation of state An extended *virial equation of state used to describe the vapour–liquid equilibrium data of various substances in terms of molar density. The equation features eight constants for which published data is available for numerous hydrocarbons. The *Lee–Kesler equation of state is an extended form of the BWR equation of state.

beneficiation One of a number of processes involving the separation of ores into valuable components and waste materials called *gangue. They include crushing, grinding, magnetic separation, froth flotation, etc. The separated or dressed ore is then refined. It is also known as **ore dressing.**

Benfield process A process used for the removal of carbon dioxide, hydrogen sulphide, and other gas components from *acid gas, *syngas, and *natural gas streams by scrubbing with a hot aqueous solution of potassium carbonate.

$$K_2CO_3 + H_2S \rightarrow KHS + KHCO_3$$

The high temperature operation prevents condensation of hydrocarbons. It is named after its inventor H. E. Benfield who developed it in 1952.

Bergius, Friedrich Karl Rudolph (1884–1949) A German chemist noted for the invention of the Bergius process used for the production of synthetic fuels from coal. He gained his PhD at the University of Leipzig and worked for a time with Fritz *Haber and Carl Bosch at the University of Karlsruhe before becoming professor at the University of Hanover. His work on high-temperature, high-pressure processes resulted in the *Bergius process in 1913 for production of synthetic fuels by the hydrogenation of lignite. He was awarded the Nobel Prize for Chemistry together with Carl Bosch in 1931 for his work on high-pressure processes.

Bergius process 1. A process used to make hydrocarbon fuels from coal. It was developed by German chemist Friedrich Karl Rudolph Bergius (1884–1949) as a motor fuel in the First World War. It involves heating coal mixed with tar in the presence of a catalyst at a temperature of 450°C in hydrogen at a pressure of 200 atmospheres. There have subsequently been a number of process improvements particularly with more effective catalysts. **2.** The hydrolysis of cellulose with concentrated hydrochloric acid production of sugar from wood.

Berl saddle A saddle-shaped packing material made from an inert, non-reactive material with good mechanical properties such as ceramic (see Fig. 7). As a packing material used in

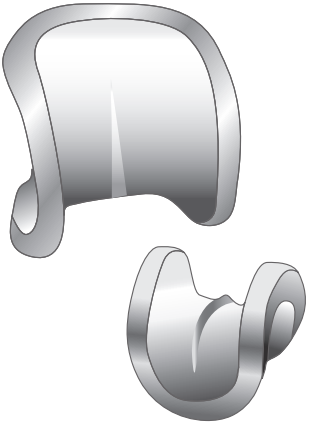

Fig. 7

adsorption towers, it has a good surface-to-volume ratio while allowing gases and liquids to move past easily offering a low pressure drop across a fixed bed of the material.

Bernoulli, Daniel (1700–82) A Swiss mathematician and physicist noted for his work on fluids. He was one of eleven eminent mathematicians in his family spanning four generations. Born in Groningen in the Netherlands, he was educated at Basel, Switzerland, where his father had been appointed professor of mathematics following the death of Bernoulli's uncle who had previously held the post. Bernoulli gained his master's degree at the age of 16 and his doctorate at 21. He held the position of professor of mathematics at St Petersburg Academy in Russia from the age of 25, but returned to Basel in 1732 to become professor of anatomy and botany at the University of Basel before becoming professor of natural philosophy in 1750. His important work on hydrodynamics demonstrated that pressure in a fluid decreases as the velocity of fluid flow increases, which he published in his book *Hydrodynamica* in 1738. He also made a first statement on the *kinetic theory of gases.

Bernoulli theorem A theorem in which the sum of the pressure-volume, potential, and kinetic energies of an incompressible and non-viscous fluid flowing in a pipe with steady flow with no work or heat transfer is the same anywhere within a system. When expressed in head form, the total head is the sum of the pressure, velocity, and static head. It is applicable only for incompressible and non-viscous fluids. That is:

$$\frac{p_1}{\rho g}+\frac{v_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{v_2^2}{2g}+z_2$$

where p is pressure, ρ is density, g is gravitational acceleration, v is velocity, and z is elevation. It is effectively a statement of the law of the conservation of energy. It was formulated and published in 1738 by Daniel *Bernoulli (1700–82).

Berzelius, Baron Jöns Jacob (1779–1848) A Swedish chemist who discovered several elements including cerium, selenium, lithium, thorium, and vanadium. He invented the present notation of chemical elements and electrochemistry, and worked on the atomic weights of many substances.

Bessel function A type of function denoted by the letter J to represent the solution to a type of differential equation that has independent solutions which can be expressed as infinite series. An example is the harmonic equation:

$$\frac{d^2h}{dr^2}+\omega^2h=0$$

The general solution is $h(\omega r)=AC(\omega r)+BS(\omega r)$ where A and B are constants of integration. The solutions form an infinite series and are listed in tables and plotted. They are used in the study of fluid mechanics and heat transfer, and named after German astronomer Friedrich Wilhelm Bessel (1784–1846).

Bessemer process A process first used for the mass production of steel from pig iron. Named after British engineer Sir Henry Bessemer (1813–98) who in 1856 took a patent on the process; it operates at around 1,250°C in a tilting vessel known as a **Bessemer converter**. The process involves the removal of impurities from iron by oxidation with air blown in at the base through the molten iron. The product is then converted into steel by the addition of spiegeleisen, which is iron containing a high proportion of manganese and carbon. The oxidation process is exothermic and helps to keep the mass molten in which oxides of

silicon and manganese are skimmed off while other oxides are either in the form of gas or solid *slag. The furnace is tilted and the molten steel poured off.

b

best efficiency point The most efficient operation of a centrifugal pump in terms of flow rate and delivery pressure or head. It is usually represented as an identifiable point on the *characteristic curve for a centrifugal pump. The efficiency of the pump is the ratio of the power output (the product of pressure and flow rate) to the power input (electrical energy).

beta decay The spontaneous emission of negatively charged electrons or beta particles by a heavy radioactive element. The radioactive decay results in the original element being gradually converted into another element. For example, the radioactive isotope of lead-210 loses a beta particle to give a radioactive isotope of bismuth-210. Beta decay may occur at the same time as decay of *alpha particles.

beta particle An electron or positron emitted by a radioactive element during radioactive *beta decay or nuclear fission. **Beta radiation** is a stream of beta particles.

BET equation An equation used in the theory of multilayer adsorption of atoms onto a surface. It is based on the assumption that the forces that produce condensation of moisture on a surface are also responsible for the binding energy of multilayer adsorption. It is named after Brunauer, Emmett, and Teller.

Betts process An electrolytic process used for the refining and purification of lead with the associated recovery of silver and gold. The process involves a solution of lead fluorosilicate and hydrofluorosilicic acid as the electrolyte and lead electrodes. Invented by Anson G. Betts in 1901, the process is dependent on cheap forms of electricity. *See* PARKES PROCESS.

billet A small, part-finished piece of metal that is rectangular, circular, or square in shape. Metals such as iron, steel, and plutonium are made into billets for further processing.

billion One thousand million (10^9). In the UK this was formerly one million million (10^{12}) and was changed when the British Treasury started using the term billion in the American sense in the 1960s.

bimetallic strip A metallic strip consisting of two metals that have different thermal expansion coefficients and are firmly joined together. As the strip heats or cools, the strip bends. It is used as a thermal on/off switch in electric circuits.

bimolecular reaction A chemical reaction involving two molecules. The reaction of nitrogen dioxide and carbon monoxide is an example of a bimolecular reaction.

$$NO_2 + CO \rightarrow NO + CO_2$$

binary 1. A system involving two components. A binary separation involves the separation of two components such as ethanol and water by distillation. **2.** A compound or alloy formed from two elements. **3.** A mathematical numbering system involving two symbols (0 and 1) used in digital computers. The numbers represent units, twos, fours, eights, etc. For example, the number 6 in the decimal numbering system is 110 in the binary system (i.e. 4+2+0=6).

binary distillation The separation of two components by the process of distillation. The ease of separation is based on the difference between the boiling points of the two

components. Simple graphical techniques such as *McCabe–Thiele and *Ponchon–Savarit can be used to illustrate the separation for continuous binary distillation processes.

binding site A specific location on the surface of a molecule that can combine with another molecule. An example is the binding site of an enzyme with a substrate. *See* ACTIVE SITE.

Bingham plastic A *non-Newtonian fluid that exhibits a yield stress that must be exceeded for flow to occur. Once the fluid has begun to flow, the rate of shear versus shear stress curve is linear. The applied shear stress is expressed as:

$$\tau = k\dot{\gamma} + \tau_o$$

where τ_o is the *yield stress, k is a constant, and $\dot{\gamma}$ is the *shear rate. Examples include toothpaste, mayonnaise, and drilling muds. It is named after American chemist Eugene Cook Bingham (1878–1945).

biocatalyst A catalyst that is, or derived from, a living organism or cell. Enzymes are biocatalysts and are used to catalyze biochemical reactions.

biochemical engineering The principles of chemical engineering applied to biological systems and includes the synthesis of compounds from biological origins, decomposition of organic material, and the development of technical solutions for biomedical purposes.

biochemical oxygen demand (BOD) The amount of oxygen that is required for the complete oxidation of microbiologically degradable material in water. It is measured by the direct oxygen consumption of materials such as sewage and contaminated water, and represents a measure of the amount of organic pollutants in water. As a form of index used for the degree of organic pollution in water, it is expressed as the amount of oxygen used for biochemical oxidation by a unit volume of water at a given temperature and for a given time. It involves incubating a sample at 25°C for a fixed time (often five days), and the amount of oxygen removed determined by chemical analysis. The result is expressed in milligrams of oxygen per dm^3 of water. The higher the value, the greater the level of pollution. It is also known as the **biological oxygen demand**.

biochemistry A branch of chemistry that is concerned with the chemistry associated with living organisms.

biodiesel A liquid fuel that can be used in the place of, or mixed with, mineral diesel fuel in modified engines. It is made from a variety of plant oil feedstocks such as rapeseed, soya bean oils, and waste cooking oils. It is converted to fatty acid methyl esters (FAME) by a transesterification process involving the chemical reaction with an alcohol such as methanol in the presence of a strong alkali or acid as the catalyst. The FAME product is separated from the glycerol.

bioelement An element that is essential in the molecules of all living organisms. The three main elements are oxygen, carbon, and hydrogen. Sulphur and phosphorus are dominant is most organisms, and calcium in humans. Other elements in lesser amounts include sodium, potassium, magnesium, and copper.

bioengineering A branch of engineering concerned with the application of techniques in the development, design, and manufacture of equipment and devices for use in

biological systems. It includes products to replace lost bodily functions or supplement defective functioning of body parts or organs such as orthopaedic prostheses, artificial limbs, heart valves and pacemakers, artificial livers, hip joints, hearing aids, etc.

bioethanol The most widely used liquid *biofuel. It is produced by the *fermentation of starch or sugars including maize (corn), sugar beet, and sugar cane. Bioethanol is often blended with petrol for use in some specially converted internal combustion engines, or can be used as a pure fuel.

biofilm A layer of growing microorganisms that adheres to a surface. The adhesion by chemical means from the microorganisms involves polysaccharides and glycoproteins. Biofilms are used in sewage filter beds and some forms of cell-immobilization processes. The formation of biofilms causes fouling in industrial water processes and can lead to process blockage.

biofuel A gaseous, liquid, or solid fuel that contains carbon derived from a biological or organic source. There is an increasing interest in the use of biofuels in the quest for alternative sources and forms of energy. Examples include *biogas, *biodiesel derived from plants, and *bioethanol from crops such as maize and sugar beet.

biogas A *biofuel that consists of a mixture of methane and carbon dioxide formed as a result of the decomposition of organic matter by anaerobic digestion. The process uses methanogenic bacteria to produce methane, at a concentration of between 50 per cent and 70 per cent. Biogas can be used directly or mixed with other gases, or by removing the carbon dioxide for use in power engines. Biogas is a major source of energy in underdeveloped countries.

biological agent A microorganism, cell culture, or human endoparasite, whether or not genetically modified, that can cause infection, allergy, toxicity, or otherwise create a hazard to human health.

biological oxygen demand (BOD) *See* BIOCHEMICAL OXYGEN DEMAND.

biomass Any vegetation or biological waste whose energy can be harnessed in a fuel. It includes waste from agricultural and food processing and can be converted to high-energy fuel or other useful chemicals by biotechnological processes.

biomass to liquids (BTL) A combustion reaction used to convert *biomass to liquid fuels. Involving two main steps, the first is the conversion of biomass such as wood into a *synthesis gas consisting of hydrogen and carbon monoxide. The catalytic *Fischer–Tropsch process is used to convert them to synthetic fuels.

biomaterial A biologically naturally occurring, or synthetically produced, substance that is suitable for use in implanted medical devices or as an implant for the replacement of an organ without rejection.

biomolecular engineering The use of chemical engineering principles and practices in the field of biology, and in particular the manipulation of *biomolecules that are used in the pharmaceutical, medicine, food, environment, bioenergy, and agricultural industries. It involves the structural and functional transformation of proteins, carbohydrates, lipids, and nucleic acids along with the detailed knowledge and understanding of biomolecular

mechanisms, thermodynamics, and biochemical reactions kinetics. *See* RECOMBINANT DNA TECHNOLOGY.

biomolecule A molecule that is involved in the maintenance and metabolic processes of living organisms. This includes carbohydrates, proteins, lipids, nucleic acids, and water molecules.

biopolymer A polymer that occurs naturally such as a protein, polysaccharide, and nucleic acid. *See* POLYMER.

bioprocess engineering A specialist branch of (chemical) engineering that involves the design and operation of processes used for the production of biological products such as foods, pharmaceuticals, and biopolymers.

bioreactor A vessel used for biological processing containing the growth of living cells or tissues, either as the product themselves or as biocatalysts in the production of other products. There are many designs of bioreactors. The most common are cylindrical and range in capacity from a few litres to many cubic metres. Small bioreactors are made of glass while large bioreactors are fabricated from stainless steel.

The biological processes contained within the bioreactor may be in the form of a suspension of cells or immobilized, and depending on the living organism, operated aerobically or anaerobically. The mode of operation is batch, fed batch, or continuous. An example of a continuously operated bioreactor is the *chemostat.

Constant agitation within a bioreactor can be maintained with an appropriate stirrer which also aids oxygen transfer in aerobic processes. Low-speed impellers or the use of sparged air up draft tubes are typically used to aid mixing. Since all bioprocesses are exothermic, cooling is required using either an external jacket or, for very large vessels, internal cooling coils.

bioscrubbing The removal of odorous or toxic waste gases from biological processes. Foul-smelling sulphurous odours such as mercaptans, toxic wastes such as cyanide, and microorganisms in aerosol form are removed within a spray column in which the waste gas stream is fed. Within the column, finely sprayed water droplets flow down *countercurrent to the flow up of the waste gas.

biosphere The sphere of life for all living organisms on Earth. It extends several kilometres above the surface of the Earth and down to the bottom of the deepest oceans. On land, it extends only a few metres below ground surface.

biosynthesis The natural formation of complex biochemical products from simple biochemical molecules. An example is the synthesis of proteins from amino acids. It is also known as **anabolism**. The opposite is called **catabolism**.

Biot, Jean-Baptiste (1774–1862) A French professor of mathematics, physics, and astronomy, he made the first balloon ascent ever undertaken for scientific purposes in 1804 together with Joseph Louis *Gay-Lussac (1778–1850). He was particularly interested in the polarization of light and his observations laid the foundations of the polarimetric analysis of sugar. He evolved an experiment using a metal sphere and two metal hemispheres to show that there is no electric charge on the inside of a hollow charged conductor but instead it is all on the outside.

biotechnology A technology that uses biological processes for the development and industrial production of materials for medical and industrial purposes. The technology

b

uses living organisms such as plants, animals, yeast, and bacteria, and uses techniques such as genetic modification and *recombinant DNA technology to improve production or produce new products. Examples include the production of beer, cheese, and wine, the development and production of vaccines, hormones, monoclonal antibodies, and antibiotics, as well as the production of energy and the recycling of waste.

Biot number A dimensionless number, Bi, used in non-steady-state heat transfer or mass transfer that relates the internal resistance to the flow of heat or mass transfer to the resistance of that flow at the surface of a solid body:

$$Bi = \frac{hl}{k}$$

where h is the film coefficient, l is the characteristic dimension as the half thickness of a slab or radius of a sphere or cylinder, and k is the thermal conductivity of the solid. It is named after the French physicist and mathematician Jean-Baptiste *Biot (1774–1862).

Birmingham Wire Gauge (BWG) A form of dimension used for the classification of the wall thickness of pipes and tubing using the units of decimal parts of an inch. It is also known as **Stubs' Wire Gauge**.

Black, Joseph (1728–99) A Scottish doctor and later professor of chemistry at the University of Edinburgh for 33 years. Unusually, he lectured in English rather than Latin, which was the normal practice at the time. His lectures involving many experiments were particularly popular and became a fashionable habit of Edinburgh society. James *Watt was one of his students, to whom he gave both money and ideas for his research. Black's work was largely on specific and latent heats. He distinguished between heat and temperature, found specific heats by the method of mixtures, and obtained the latent heat of water as it froze. He founded the first Chemical Society for his students.

black body Used in heat transfer to describe a body that absorbs all the thermal radiation falling upon it. A black body is noted for having an absorptivity of one and a reflectivity of zero. The emissive power of a black body is dependent on the temperature and proportional to the fourth power of the absolute temperature. **Black body radiation** is the

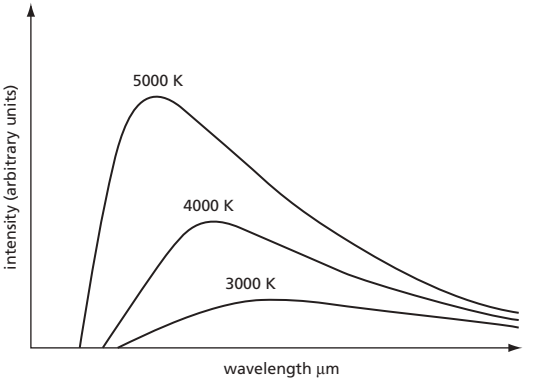

Fig. 8

*electromagnetic radiation that is emitted by a black body, which extends across the range of wavelengths. The intensity of energy rises to a maximum, the wavelength of which is dependent on the temperature (see Fig. 8). The wavelength decreases with increasing temperature. *See* STEFAN–BOLTZMANN CONSTANT.

black box A term used to describe a process or system that is considered only in terms of its inputs and outputs, and with no knowledge or understanding of internal operations. It is typically used to represent complex systems where the precise details or mechanism of the process or system is not known or fully understood. It uses empirical or semi-empirical mathematical models, experimental data, past performance data, and trends to describe or predict behaviour. It gets its name from the opaqueness of not seeing the internal operations. Examples include biological processes involving living organisms and the behaviour of catalysts in heterogeneous chemical reactions.

blanketing A process in which an inert gas such a nitrogen is used to fill the vapour space of a vessel containing a liquid to control its composition. It is used in a wide range of industries including the petroleum, pharmaceutical, and food industries. Carbon dioxide and argon gas are also used although carbon dioxide can tend to be reactive in some cases and argon is a relatively expensive gas.

blanking A method used to block pipelines to intentionally prevent the flow of materials or substances. It is used in maintenance, the closure of redundant pipelines, and process equipment, and usually consists of a plate bolted across the face of a *flange.

blast furnace A smelting furnace used for the continuous production of molten iron from iron ore, from which steel is made. It consists of a steel tower lined with refractory brick into the top of which iron ore, coke, and limestone are charged. Compressed hot air is blasted into the bottom. The chemical reaction of the oxygen in the air and the coke produces carbon monoxide. This then reacts with the iron ore to produce carbon dioxide and iron. The carbon dioxide then reacts with more carbon to produce more carbon monoxide. The limestone combines with the coke ash to form liquid *slag, which absorbs any sulphur in the iron, collects at the bottom of the tower, and floats on the surface of the molten iron. Both the molten iron and slag are periodically and separately tapped off. The hot gases are used as fuel for heating the incoming air. The cast or pig iron is used to produce steel in the *Bessemer process.

blast wave A pressure pulse moving outwards from the site of an explosion. It can be formed by a detonation, a rapid deflagration, or the sudden failure of a piece of process equipment containing a potential energy source that is released at a high rate. The **blast pressure** is the side-on overpressure and can have a destructive effect on buildings and structures.

bleach A disinfectant manufactured from caustic soda dissolved in water and reacted with the chlorine in either a batch or continuous process. The chlorine and caustic soda are made by the electrolysis of salt solutions. Industrial bleach includes calcium hypochlorite, chlorine, and hydrogen peroxide, and is used as a disinfectant and in the paper and textile industries. Domestic household bleach is an aqueous solution of sodium hypochlorite, NaOCl, made from caustic soda, chlorine, and water.

bleed The controlled removal of a small amount of material from a process as a *side stream that prevents an accumulation of undesired materials. It is also known as a **purge**.

blenders A type of mixer used for mixing powders. Powder blenders are broadly classified as vertical or horizontal mixers depending on whether the mixing impeller rotates on a vertical or horizontal axis. Vertical mixers have a movable bowl in which the contents are mixed by mechanical agitation. Paddle agitators are commonly used and the shape of the impeller frequently conforms to the vessel walls. Planetary motion devices are commonly used in vertical mixers in which the agitator revolves in a circle in addition to rotating on its own axis. This ensures that the entire mixer volume receives a beating action and that there are no dead spaces.

blending A process used in oil refining in which two or more hydrocarbon products are mixed together to form a new product with desired and specified properties. The **blending octane number** is a mix of hydrocarbons that provides an octane number greater than for the pure fuel.

BLEVE *See* BOILING LIQUID EXPANDING VAPOUR EXPLOSION.

blinding The blockage of filters in which particles that become entrapped block other particles to the point where the filter becomes blocked, the filter becomes inactive, and no longer able to permit the passage of the flow medium, such as air.

block diagram A diagrammatic representation of a controlled process showing the relationships between the system variables. The controlled process is presented in blocks as functional, non-interacting sections whose inputs and outputs are readily identifiable. The blocks are connected in the same order as they appear in the physical controlled process. The convention includes: lines, which represent signals as flows of information, material, or energy; circular summing junctions, which represent an algebraic summation of the input signals to that point (positive or negative); a branch point, which represents a division of a signal into more than one path without change; rectangles, which represent a modification of the entering signal and describe the dynamic characteristics of the systems that they represent, usually as conversions or transfer functions between the input and output signals.

block flow diagram A schematic representation of an entire process or major part of a process in which unit operations are symbolically represented as blocks in which process material collectively enters for processing and products leave (see Fig. 9). Unlike a *process flow diagram, a block diagram has limited information. No information is provided such as flow compositions or details of process conditions within each unit operation. They are useful at the design stage to present how a complex process fits together. It is also known as a **schematic flow diagram**.

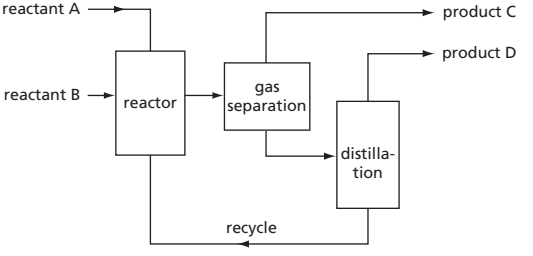

Fig. 9

block valve A type of valve used in a pipeline that provides a tight shut-off. It is typically used for *isolation purposes.

blowdown 1. The removal of oil and gas from a pipeline. **2.** The difference in pressure between that which opens a safety valve and that which closes it. **3.** A technique used to remove periodically accumulated solids in process vessels, boilers in particular, which would otherwise cause problems of deposition on heat transfer surfaces, foaming, and adverse effects on process performance. A **blowdown vessel** is used to receive a large amount of water and precipitated solids removed under boiler pressure.

blower A mechanical device designed to deliver a gas, usually air, with a low gauge pressure of less than 2 bar. The terms *'fan' and 'blower' are often used interchangeably although radial-flow fans are commonly referred to as blowers whereas axial-flow fans are referred to as fans.

blowoff valve A pressure release valve system used to prevent problems associated with fluid surge. It is used on turbocharged engines to prevent compressor surge and is usually vented to atmosphere. It is also known as a **dump valve**.

blowout A term used in offshore oil processing where there is a loss of control pressure of an oil reservoir resulting in an uncontrolled release of fluids to the surface. A **blowout preventor** is a hydraulically or mechanically actuated valve that is located at the wellhead and used to control pressure within the *well.

blue water gas *See* WATER GAS.

BO An abbreviation for **b**arrels of **o**il. It is a volumetric unit of crude oil and other petroleum products equivalent to 42 US gallons or 158.978 litres.

BOD 1. An abbreviation for ***b**iochemical **o**xygen **d**emand or ***b**iological **o**xygen **d**emand. **2.** An abbreviation for the ***b**asis **o**f **d**esign.

Bode plot A type of frequency response diagram used for analysing the frequency response of a system to a disturbance signal. It is the plot of the logarithm of the amplitude ratio with the logarithm of the phase angle measurements.

BOE *See* BARREL OF OIL EQUIVALENT.

boiler A heat exchange device used to raise the temperature or vaporize a liquid. The heat supplied by hot gases from combustion processes or by high-temperature heat transfer liquids such as oils. Many boilers are used to raise steam as a process utility. Steam itself is often used as the heat transfer medium in heat exchanger-type boilers such as *kettle reboilers.

boiler hotwell A container used for hot condensate water that is returned to a boiler and that has been settled out and filtered from impurities. The water is then fed to the boiler feed pump for reuse.

boiling The process of evaporation occurring throughout a liquid that occurs when the vapour pressure of a liquid is equal to the pressure above it. There are various types of boiling including natural convection from a heating surface, nucleate boiling, partial film boiling, and film boiling.

Boiling Liquid Expanding Vapour Explosion (BLEVE) The *explosion that occurs when a pressure vessel with a superheated flammable liquid or a liquefied flammable gas is heated and ruptures. It is the result of the rate of pressure build-up being greater than the rate of pressure relief due to venting. The pressure build-up, together with the reduced structural strength of the vessel caused by the external heating, increases the risk of explosion. At the point of rupture, the pressurized liquid discharges and immediately flashes to a vapour. The rapid rate of vapour expansion causes the explosion in the form of a blast wave. There may also be missile damage. Ignition of the expanding flammable vapour in air can result in a rapid combustion and create a *fireball.

boiling point The transition temperature at which a liquid state to the gaseous state occurs. The temperature corresponds to the point where the saturated vapour pressure of the liquid is equal to the system pressure. In a solution, the presence of a solute raises the boiling point of the solvent. In dilute solutions, the boiling point elevation can be used to determine the relative molecular mass of the solute.

boiling point-composition diagram A diagram that is used to present the relationship between the *boiling point and composition for two components at a given pressure (see Fig. 10). The x-axis ranges from 0 to 100 per cent for one component (i.e 100 per cent to 0 per cent for the other component) with the y-axis representing temperature. The diagram features two curves: the lower curve gives the boiling point temperature for the binary mixture, and the upper curve represents the composition of the vapour for that temperature. For an ideal mixture, the two curves coincide. However, deviations from *Raoult's law may show a maximum or a minimum where the composition of the liquid is the same as the vapour, and illustrates the existence of an *azeotrope.

boiling point elevation The increase in the temperature at which the transition from a liquid to the gaseous state occurs due to the presence of a dissolved substance. It is related to the mole fraction and the molecular weight of the dissolved molecules and ions.

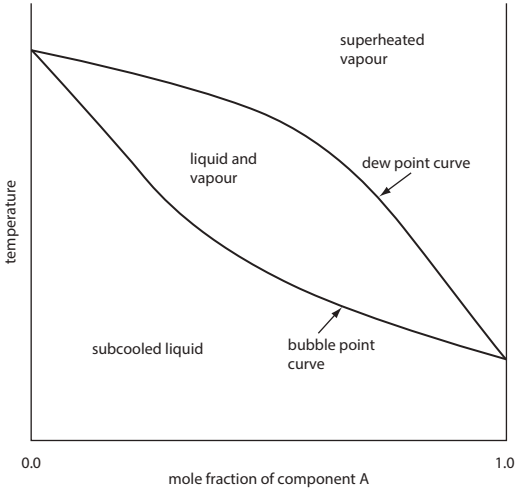

Fig. 10 Boiling point-composition diagram

boil-up ratio The ratio of vapour returned to the bottom of a distillation column to the bottom product removed.

Boltzmann constant (Symbol k) The ratio of the *universal gas constant, R, to *Avogadro's constant, N_A: $k = R/N_A = 1.380\,658 \times 10^{-23}\ JK^{-1}$. It may therefore be seen as the gas constant per molecule. It is named after Austrian physicist Ludwig Eduard Boltzmann (1844–1906).

Boltzmann equation An equation used in non-equilibrium statistical mechanics to calculate transport coefficients such as thermal conductivity. The equation describes a distribution function, *f*, which gives a description of the state and how it is changing with position at any time *t*. It has the mathematical form:

$$\frac{\partial f}{\partial t} + a.\left(\frac{\partial f}{\partial v}\right) + v.\left(\frac{\partial f}{\partial r}\right) = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

where v is a velocity vector, a is the acceleration of particles between collisions and r a position vector. It was proposed in 1872 by Austrian physicist Ludwig Eduard Boltzmann (1844–1906).

bomb calorimeter An instrument used to determine the *heat of combustion of a substance. It typically consists of a steel chamber with a non-oxidizable material on the inside, with a tight-fitting screw lid. A known mass of sample of material is burnt in a platinum cup. Insulated platinum leads allow an electric current to be passed through a thin wire to ignite the material. The air in the chamber is replaced with pure oxygen, which is allowed to reach a pressure of around 20 atmospheres. The calorimeter is surrounded by water and once the combustion has begun, the rise in temperature recorded from which the heat of combustion is determined.

bond The linkage between atoms to form molecules. Most bonds involve the exchange or sharing of electrons. *See* CHEMICAL BOND.

Bond number A dimensionless number, Bo, used to characterize the shape of drops of liquid and relates the interactions of gravitational and surface tension forces, σ, in a capillary of diameter *d*:

$$Bo = \frac{(\rho - \rho')gd^2}{\sigma}$$

where ρ is the density of the droplet and ρ' is the density of the surrounding fluid. It is also known as the Eötvös number (Eo) and named after Hungarian physicist Loránd Eötvös (1848–1919).

Bond's Work Index A semi-empirical equation that relates the power consumption required for crushing and grinding solid particles such as rocks and ores into smaller particles. It is named after American mining engineer Fred Chester Bond (1899–1977).

bone seeker A radioactive isotope such as strontium-90 that is preferably deposited in the bones of humans and animals. Chemically, the isotope behaves in the same way as calcium and can actively displace calcium in the bone structure. The substance may enter the body through ingestion, inhalation, and through wounds.

BOPD An abbreviation for **b**arrels of **o**il **p**er **d**ay as a volumetric measure of crude oil produced by an oil well or field. The volume of a barrel is equivalent to 42 US gallons or 159 litres.

borosilicate glass A type of glass that contains a high level of boron. Boron is effective at absorbing neutrons emanating from radioactive isotopes. Borosilicate glass is also resistant to the process of *leaching and is therefore used in various nuclear fuel reprocessing applications such as in the process of *vitrification used to solidify high active liquid wastes.

bottleneck A term used to describe a process or system whose performance or throughput is limited by the action of an item of process plant such as the performance of a pump or volume of a vessel. The term originates from the phenomenon of a liquid pouring freely from a bottle being limited by the restricted area at the bottleneck. A management tool is **debottlenecking** and is used to identify and eliminate such limitations thereby increasing plant production. *See* CRITICAL PATH ANALYSIS.

bottoms The high-boiling liquid removed from the bottom of a *distillation process that is rich in the less volatile component. It is also known as **residue**.

botulinum cook A thermal food process that is used to destroy spores of the pathogenic bacterium *Clostridium botulinum*. It involves heating the food to 121°C and holding the temperature for three minutes which corresponds to twelve successful decimal reductions or 12-D. A decimal reduction is the time required to reduce a population of viable spores ten-fold. A 12-D process therefore corresponds to reducing 1 million million spores to a single surviving spore, which statistically is negligible, thereby rendering the food safe to consume. It is also known as a 12-D process.

boundary condition/value Used in solving differential equations that are used to describe natural phenomena such as the movement of mass or flow of heat or fluids; they are used to define the boundary of the region under consideration. The boundary condition or value is required to be specified for a solution to be reached. The boundary condition may be a physical entity, such as the velocity of a fluid at a surface, or the concentration of components at a fluid interface.

boundary layer The region between a surface or wall and a point in a flowing fluid over it where the velocity is at a maximum. Within this region, the movement of the fluid flow is governed by frictional resistance. By convention the edge of this region is assumed to lie at a point in the flow that has a velocity equal to 99 per cent of the local mainstream velocity. Within the boundary layer, which is laminar in flow, the transfer of heat and mass across it occurs only by molecular diffusion.

boundary slip A *boundary condition used in fluid mechanics. A fluid that flows over a surface of a solid can be assumed to be in the form of layers that are brought to rest at the surface, known as the *no-slip boundary condition. While the assumption is useful in macroscopic treatments and for finding analytical solutions such as the *Hagen–Poiseuille equation, the assumption breaks down when considering fluids at the molecular level. In such cases, a boundary slip condition occurs where the viscosity at the surface is different from the bulk viscosity of the fluid.

bound moisture The liquid that is held by a solid material within capillaries and cavities by physical or chemical adsorption and with a vapour pressure that is less than that of the pure liquid at the same temperature. The *unbound moisture is the moisture that is in excess of the equilibrium moisture content corresponding to saturation humidity.

Bourdon gauge An instrument used to measure gas or vapour pressure. It consists of a tube curved in a circular arc that has an elliptical cross section. One end is fixed while the

other is linked to a mechanical pointer on a calibrated scale. The tendency for the tube to straighten out is measured by a scale calibrated for pressure. It was invented by Eugène Bourdon (1804–88).

BOV *See* BLOWOFF VALVE.

bowl centrifuge A type of continuous centrifuge used to separate liquids carrying suspended particles or droplets of a dispersed phase. It has a set of perforated conical discs that are used to separate the feed liquid into layers. The liquid is fed at the centre of the rotating disc and the suspended particles or heavier dispersion of liquid phase is removed radially.

Boyle, the Hon. Robert (1627–91) An Irish scientist noted for his experimental work on the pressure of gases. The fourteenth child and seventh son of the Earl of Cork, he was sent to Eton at the age of eight and overseas at eleven with a tutor. He settled in England and devoted his life to experimental science. He became an active member of the Invisible Society, which developed into the Royal Society.

Boyle's best-known works include the *Spring of the Air* (1660); he discovered that sound does not pass through a vacuum and established that air has weight. He observed the effect of altitude on pressure and the effect of pressure on the boiling point of liquids. He invented a type of thermometer and carried out many experiments on refraction, colour, electricity, relative densities, and the expansion of water when it freezes. He also defined the term 'element', distinguished between mixtures and compounds, and showed that a compound could have different properties from those of its constituents. He was the first to prepare, collect, and burn hydrogen and one of the first to isolate phosphorus in 1680.

Boyle-Charles's law The combination of *Boyle's law with Charles's law for an *ideal gas as:

$$\frac{p_1V_1}{T_1}=\frac{p_2V_2}{T_2}=nR$$

where R is the gas constant (8.314 J mol^{-1} K^{-1}) and n is the number of moles.

Boyle's law A law that states the relation between gaseous pressure and volume. It states that the volume of a fixed mass of gas is inversely proportional to its pressure at constant temperature. It was proposed in 1662 by Robert *Boyle (1627–91).

brake horsepowe *See* HORSEPOWER.

brass A yellowish alloy that consists of copper and zinc, and occasionally some other metals. The usual ratio is 2:1 copper to zinc. Brass is used for small bore pipes and some pipe fittings such as valves and couplings.

brazing A process used to join metal in which a filler metal is heated to a melting temperature and is then distributed between close-fitting parts to be joined together by capillary action. The filler metal is an alloy and is protected by a flux which is a chemical agent used to prevent oxides from forming while the work piece is heated. It also serves to clean any contamination left on the brazing surfaces.

break-even point A financial measure of the point that a process or business is economically viable. It is measured as the fraction of the production capacity of a process or business where the income is equal to the sum of the variable and fixed costs.

breakpoint chlorination A process used in water treatment in which chlorine is added to water to a point that the required level of chlorination has been satisfied. This corresponds to the amount of chlorine consumed before a freely available chlorine residual is produced. Public water supplies normally chlorinate beyond the breakpoint.

breakthrough 1. The point where an absorbate first appears in the fluid from an absorber. **2.** The maximum concentration of unwanted ions such as calcium ions that are left in a treated liquid in an ion exchange unit. **3.** The point where water or gas injected into an oil or gas reservoir used to maintain reservoir pressure breaks through to another production well.

Brent crude *See* WEST TEXAS INTERMEDIATE.

brewing A *fermentation process used to the production of beer, lager, and whisky. A major component used in beer and Scotch whisky process is barley. The barley is first converted to barley malt by soaking in water until germination. It is then dried in a kiln, followed by milling of the grain, and the starch extracted from the husks. Malting contributes to the flavour and provides the necessary enzymes to produce sugars from the starch. The barley malt is then mixed with water and yeast. When making beer, hops are added to provide bitterness. Mashing is a process involving heating the mixture to around 65°C for about an hour and used to convert starches to sugar; it takes place in a vessel called a mash tun. The mash liquid is known as wort. It is boiled to halt enzyme activity. Fermentation takes place in a washback which is a type of batch fermentation vessel and used to convert the sugar into alcohol. The beer is then filtered, pasteurized to kill any residual yeast, and bottled or canned. For whisky production, the wort is distilled in a *still and the distillate collected, stored, and matured in oak barrels. *See* WHISKY.

Bridgman, Percy Williams (1882–1961) An American physicist who studied the properties of matter under extremely high pressure. A graduate of Harvard, he remained there as professor from 1919 until retirement. He was awarded the Nobel Prize for Physics in 1946. He is also noted for his writings on the philosophy of science and studies of electrical conduction in metals and properties of crystals. He was president of the American Physical Society in 1942.

Brinell hardness number A measure of the hardness of metals and alloys. It involves pressing a small, hardened steel ball into the surface of the metal being tested by a known loading force. The number is the ratio of the mass of the load in kilograms to the area of the depression created by the ball in square millimetres. Typical numbers range from 60 (soft) to 800 (hard). It is named after Swedish metallurgist J. A. Brinell (1849–1925).

Brin process A process that was once used for producing oxygen through the heating of barium oxide in air to form barium peroxide. This was then heated to temperatures in excess of 800°C to produce oxygen:

$$2BaO_2 \rightarrow 2BaO + O_2$$

The reaction was discovered by the French chemists Joseph-Louis *Gay-Lussac (1778–1850) and Louis-Jacques Thénard (1777–1857). The process was particularly inefficient, and a major improvement was developed by Arthur and Leon Brin who found a way of removing the carbon dioxide with sodium hydroxide. The oxygen produced was used to be for limelight before more cost-effective methods of producing oxygen were discovered.

Britannia metal An alloy of tin with between 5 per cent and 10 per cent antimony and small amounts of copper, bismuth, lead, and zinc. It is used in bearings and tableware resembling pewter.

British thermal unit (Btu) The amount of energy required to increase the temperature of one pound of water at around 39.2 degrees *Fahrenheit by one degree Fahrenheit (454 g of water by 0.56°C at around 4°C). It is equal to around 1,056 joules but varies depending on the temperature of the water. As a unit of power, it is expressed as Btu per hour.

British thermal unit per hour An Imperial measure of the rate of release, gain, or flow of energy. In SI, one Btu per hour is equal to 0.293 W.

Brix A scale, expressed in degrees, that measures the percentage by weight of sucrose in water at a given temperature. It represents the concentration of a solution of pure sucrose in water expressed as parts by weight of sucrose per 100 parts by weight of solution.

bronze An alloy of mainly copper with tin and other elements such as phosphorous, manganese, aluminium, or silicon. Unlike *brass, which is an alloy of copper and zinc, and is malleable, bronze is hard and brittle. Being resistant to seawater, it is used in boats and ships for such things as propellers. Bronze is also used for valves, bearings, and other process machinery parts.

broth The aqueous growth medium used to support the growth of a microbiological culture in a *bioreactor. Also known as a **culture medium** or *growth medium, it contains all the necessary nutrients to sustain growth. The broth in a bioreactor is first inoculated with a sample of living microorganism, which then multiply consuming the nutrients. The rate of growth of the microbial cells can be determined by measuring the *turbidity of the broth or taking samples and determining the *cell dry weight.

Brownian motion The small, irregular, and continuous movement of very small particles suspended within a fluid. Particles with a diameter of less than one micrometre (1 μm) have a random movement caused by collisions with other particles. It is named after British botanist Robert Brown (1773–1858) who first noticed the phenomenon while studying pollen particles.

Brunner, Sir John Tomlinson (1842–1919) A British chemical industrialist and parliamentarian who worked in partnership with the German-born chemist Ludwig *Mond (1838–1909) to form the Brunner Mond & Co. Ltd chemical company. The company made alkali using the *Solvay process. He was a 1st Baronet and twice served as a Liberal Member of Parliament for the constituency of Northwich, Cheshire.

BSI An abbreviation for the **B**ritish **S**tandards **I**nstitution. It is responsible for the UK National Standards prefixed by BS as well as publication of standards in the UK prefixed by BS EN.

SEE WEB LINKS

- Official website of BSI, with information about BSI standards.

BTL *See* BIOMASS TO LIQUIDS.

Btu *See* BRITISH THERMAL UNIT.

BTX A mixture of aromatics and includes benzene, toluene, and *xylenes. They are readily separated by distillation.

bubble cap column A *distillation column that is equipped with bubble cap trays, also known as **bubble trays**. These are flat perforated plates with short risers covered with inverted caps over the top. The caps have slots and allow vapour to rise through a liquid on the tray but prevent the liquid from draining back. This type of distillation column was common before the 1960s prior to the introduction of much cheaper *sieve plate column and valve tray designs.

bubble column A tall cylindrical vessel used for liquid-phase reactions using the sparging of a gas at the bottom to form bubbles within the liquid. The bubbles create the necessary turbulence for mixing. The surface area of the bubbles is important for mass transfer. An airlift column is a type of bubble column that has a concentric draft tube in which the bubbles rise outside the draft tube causing a liquid up-flow with the liquid flowing down the inside of the tube.

bubble flow A two-phase flow in which gas or vapour is present as bubbles in the liquid.

bubble point The temperature at which bubbles of vapour first appear on heating a liquid. For single component mixtures the bubble point and the *dew point are the same. For a mixture, the vapour will have a different composition from the liquid. Together with the dew point at different compositions these provide useful data when designing distillation systems. At the bubble point:

$$\sum_{i=1}^{n} y_i = \sum_{i=1}^{n} K_i x_i = 1.0$$

where K_i is the distribution or K-factor and is the ratio of the mole fraction in the vapour phase, y, to the mole fraction in the liquid phase, x, at equilibrium.

bubbling zone The location in a *fluidized bed in which a fluidizing gas is of sufficient pressure and flow to form rising pockets of gas or bubbles. The bubbling zone is where the bubbles grow by coalescence and rise to the bed surface where they break.

bubbly flow A two-phase flow regime in which the gas phase flows as bubbles dispersed in a flowing liquid. This type of flow tends to occur at low gas superficial velocities and high liquid velocities. The bubbles travel with a complex motion, each with a different velocity. The bubbles may coalesce and are generally of non-uniform size. In horizontal pipes, gravity tends to make bubbles accumulate in the upper part of the pipe except at very high liquid velocities when the intensity of the turbulence is enough to disperse the bubbles about the cross section.

Buckingham π theorem A theorem that describes how physically meaningful equations that describe observable phenomena involving n variables can be presented as an equation of $n–m$ dimensionless groups, in which m is the number of fundamental dimensions such as mass, M, length, L, and time, T. The theorem allows the dimensionless groups to be determined from the variables. The **π** theorem was first proved by French mathematician Joseph Bertrand (1822–1900) and is named after American physicist Edgar Buckingham (1867–1940). *See* RAYLEIGH'S DIMENSIONAL ANALYSIS METHOD.

bulk density The gross or apparent density of a material that includes void space. *See* APPARENT DENSITY.

bulk materials Process materials either used or produced in large quantities in a loose bulk form. Examples include ores, coal, grain, wood chip, sugar beet, and sugar cane. They

are delivered to chemical plants by rail wagon, ship, and road tanker, are stored in *hoppers, *silos, or in stockpiles, and transported to the process by conveyor belts and bucket elevators.

bulk temperature The average temperature of a mass of substance or material.

bumping The violent boiling of a liquid caused by superheating such as bubbles of vapour that form at a pressure that is above the pressure of the liquid. Bumping can be prevented from occurring in the laboratory by placing small pieces of porous clay pot in the liquid in order to allow bubbles to form at the pressure of the liquid (i.e. atmospheric pressure for an open container).

bund A containment wall surrounding a storage tank or process vessel designed to contain its contents in the event of accidental leakage, spillage, or catastrophic failure. They are used to contain liquids that may be harmful, polluting, or explosive hazards.

Bunsen burner A type of burner used in laboratories that has a vertical metal tube through which gas is fed. There is a sleeve around a hole near the base used to regulate the amount of air to be mixed with the gas. Adjustment can provide a low-temperature smoky and luminous yellow flame through to an intense high-temperature flame with a blue inner cone. The burner is named after German chemist Robert Wilhelm Bunsen (1811–99).

buoyancy The upthrust on a body immersed in a fluid. The force is equal to the weight of the fluid displaced. *See* ARCHIMEDES' PRINCIPLE.

burn The capability of a material to undergo or cause to undergo combustion.

burn degree The severity of burns to the human body. Burns of the first degree show hyperemia (redness); second-degree burns show vesication (blistering); third-degree burns result in necrosis of the skin and underlying tissues in the form of charring.

burning rate The rate at which a defined mass of a solid or liquid burns and is measured in the direction normal to the surface. The **burning velocity** is the rate at which a combustion wave propagates into unburned gas. For pre-mixed flames the velocity depends only on the temperature, pressure, and composition of the cold gas. *See* FLAME SPEED.

bursting disc (rupture disc) A device used to prevent the unsafe over-pressurization or under-pressurization of a process vessel. In the event of excess internal pressure, the disc will rupture. It consists of a thin disc of corrosion-resistant metal whose thickness is determined by the pressure it is designed to contain. These are widely used in the petrochemical, nuclear, and pharmaceutical industries and are often used in combination with other *safety relief valves.

bushel An Imperial unit of capacity used for liquids and solid substances such as grain. In the UK, this is equal to 8 Imperial gallons. In the US, it is a unit of dry measure and equal to 64 US pints.

butex process *See* PUREX PROCESS.

butterfly valve A type of valve used to control the flow of a fluid in a pipeline; it has a circular body and a rotary motion disc closure member which is pivotally supported by its stem. There are various styles including eccentric and high-performance valves. They offer

a low pressure drop and are suitable for dirty and viscous fluids, however, they are prone to inducing *cavitation and *choked flow.

BWG *See* BIRMINGHAM WIRE GAUGE.

by-product A substance that forms at the same time as the main or desired product during a chemical reaction. It is usually of secondary economic significance to the main product although many industrial by-products have significant economic value and commercial use in their own right. The product from the cracking of oil is petroleum. Many other by-products are also formed that have economic value such as paraffin, lubricating oils, and other distillates. In some cases, the revenues from by-products can exceed the main product, such as, the extraction of gold from porphyry (i.e. a coarse-grained type of igneous rock) deposits. *Compare* CO-PRODUCT.

C

caking The formation of powdered, ground, granular, or crushed solid material into a larger solid mass. This may be desirable as in forming blocks, tablets, and pellets, or undesirable as in the blocking of filters, pipes, drains, and vessels. The moisture content of granular materials such as sugar may affect the propensity to form a cake.

calandria A vertical tube through which heat is exchanged for the purposes of evaporation of a liquid inside. They are used in *evaporators, *thermo-syphon reboilers, and *nuclear reactors. Steam is often used as the heating medium.

calcining (calcination) A high-temperature process used for ores and other granular materials in the presence of air to bring about a thermal decomposition, phase change, or removal of a volatile component. A **calciner** is a high-temperature rotating oven or kiln. Rotating vacuum furnaces are also for calcining.

calculus A branch of mathematics that deals with the differentiation and integration of functions. That is, methods of calculation for solving problems in which an unknown is not able to be expressed as a number or a finite set of numbers, but instead is expressed as a function or system of functions. By treating continuous changes as if they consisted of very small step changes, *differential calculus can be used to find the rate at which something happens such as a particle accelerating as a change in velocity with time. The rate of change, dv/dt in this case, is called the derivative of v with respect to t. If v is a known function of time, t, then the acceleration at any instant can be found through the process of *differentiation. Integral calculus is the reverse mathematical process and is used to find the end result of a known continuous change. It is used to determine the infinitesimal change in a variable over a short period. The overall change is found by a process of summation called *integration. For example, it can be used to find the velocity of a particle, v, that has constant acceleration, a, over a period of time:

$$v = \int_{t_1}^{t_2} a \; dt$$

Integration is also used for finding the area under a curve and volumes, as well as solving problems involving the summation of infinitesimals. The mathematical techniques were developed independently by Sir Isaac *Newton (1642–1727) and Gottfried Leibniz (1646–1716).

calendering A method of producing plastic sheet and film. Plastic that is heated and softened is forced between two heated rollers with a fixed spacing apart. The thick continuous sheet is formed and further rollers reduce the thickness and can emboss the sheet if required. The process is used to produce sheet plastic products such as flooring and tape.

calibration A method of adjusting an instrument so that its reading can be correlated to the actual values that are being measured. Calibration is achieved using methods such as

recognized standards or by experimentation. For example, the calibration of flow meters can be achieved by the *dilution method in which a concentrated extraneous material is added to the flow stream in the vicinity of the flow meter and its diluted effect analysed further downstream from which the actual flow can be determined. For a material balance, the actual flow can be determined and the flow meter calibration completed. Pressure gauges are calibrated against standards and checked periodically for any drift.

A **calibration chart** is a graphical representation of values read from an instrument. It is usually presented on the x-axis and the corrected value or quantity on the y-axis. An instrument should be calibrated with a sufficient number of data points to ensure a proper relationship between the measured and indicated value.

calorie The amount of heat required to raise the temperature of 1 gram of water by 1°C. The calorie has been replaced by the joule as an SI unit, for which the conversion of one calorie (1 cal) is equal to 4.186 joules. The **Calorie** (upper case C) is a largely obsolete unit of energy and confined to defining the energy in foods. It is equal to one kilocalorie (1 kcal) or 4,186 joules.

calorific value The heating value or heat of combustion of a combustible material in oxygen. Determined using a *bomb calorimeter, the calorific value is used as a measure of the energy content of a material such as a hydrocarbon fuel or foodstuff. The calorific values of fuels are usually expressed in joules per unit mass such as MJ kg^{-1}. Hydrocarbon gases such as methane are expressed per unit volume such as MJ m^{-3} with reference to *s.t.p. to allow for temperature and pressure variations.

calorimeter A device used to measure the quantity of heat produced by combustion. It consists of a chamber in which a specimen or sample is placed and is surrounded by an outer chamber containing water. Following combustion of the sample, the temperature change in the outer chamber is measured and the heat produced or transferred is calculated. *See* BOMB CALORIMETER.

candela (Symbol Cd) The SI unit of luminous intensity. It is the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency $540x10^{12}$ hertz that has a radiant intensity in that direction of 1/683 watts per *steradian.

CANDU A type of Canadian heavy-water-moderated pressure tube natural uranium reactor. The name is derived from **Can**adian, **d**euterium (i.e. heavy water) and **u**ranium fuel.

cannibalized The extensive use of components and equipment parts from a redundant process or facility to modify or return to service another plant or item of process equipment.

canning A process of food preservation for long-term storage in which food is sealed in a container and then subjected to an elevated temperature and for a sufficient period of time so as to kill all spoilage and pathogenic microorganisms that may be harmful to human health. Various temperature-time combination exposures have been developed for destroying microorganisms. A 12-D process refers to the necessary time and temperature required to destroy the pathogenic microorganism *Clostridium botulinum* by a million million (10^{12}) times. It uses a steam retort operated at a temperature of at least 121°C for at least three minutes. *See* BOTULINUM COOK.

capacity 1. The working volume of a process vessel. For a liquid, it is less than the total volume as allowance is made for head space or overflow. **2.** The total production rate of a

chemical plant, petroleum refinery, or petroleum production facility. **3.** The amount of electric charge stored in a battery.

capacity coefficient A dimensionless group used in the scale-up of centrifugal pumps:

$$C_Q = \frac{Q}{ND^3}$$

where Q is the flow, and N and D are the rotational speed and diameter of the impeller, respectively.

capacity ratio A parameter used to quantify the performance of a heat exchanger expressed as the ratio of the lower to higher heat capacity rate.

capex An abbreviation of **cap**ital **ex**penditure, it is the finance used to acquire equipment, machinery, and buildings. It tends to refer to significant levels of expenditure. It is also known as **capital spending** or **capital expense**. *Compare* OPEX.

capillary A tube that has a very small internal diameter. In a vertical glass capillary, the elevation of a liquid is due to *surface tension forces. In a porous body, moisture held within capillaries is removed by evaporation at the surface and therefore limits the rate of drying. The rate of evaporation is therefore controlled by the movement of moisture to the surface from within the capillaries, which is dependent on surface tension, pore size, and the density of the liquid.

capillary bound water A thin layer of water that is absorbed on to the walls of a *capillary. This is distinct from *free moisture, which is bound by a free meniscus.

capillary flow The flow of a liquid through the interstices of a porous solid by liquid-solid molecular attraction.

capillary flow number A dimensionless number, Ca, in which the viscous force is related to the surface tension:

$$Ca = \frac{\mu v}{\sigma}$$

where μ is the viscosity, v is the fluid velocity, and σ is the surface tension. It is used in the atomization of fluids and the two-phase flow in beds of solids. It is proportional to the ratio of the *Weber number to the *Reynolds number.

capital cost The total investment that is required for a process or item of equipment to be commercially operable. The capital costs, C, for equipment are often specified as a function of volume or capacity, Q, and can be scaled up using the power law relation:

$$C = \left(\frac{Q_1}{Q_2}\right)^n$$

where n is determined empirically and based on data for equipment of comparable design.

carbon assimilation A process that incorporates carbon from atmospheric carbon dioxide into organic material such as plants through photosynthesis.

carbonation A general name for processes that use carbon dioxide as the reactant and involve dissolving the gas in an aqueous solution. An example is the production of calcium carbonate by passing kiln gases through an aqueous suspension of calcium hydroxide.

carbon capture and storage (CCS) A post-combustion technology that is currently being developed to mitigate the effects of climate change linked to renewable energy systems. It involves extracting carbon dioxide from power plants, factories, and other industrial facilities before being expelled into the atmosphere. The captured carbon dioxide is then injected into a secure underground storage site.

carbon credit An international tradable certificate that shows that an industrial company or corporation has prevented the emission of one tonne of carbon dioxide or another form of greenhouse gas that is equivalent to one tonne of carbon dioxide from entering the atmosphere. Carbon credits are used as a way of mitigating the increase of greenhouse gases by capping the amount of gases that can be emitted. The intention is to encourage industries to seek ways of reducing the amount of emissions into the atmosphere. As commodities with a monetary value, they can be traded between partners and used as a way of lowering a company's *carbon footprint.

SEE WEB LINKS

- Official website of Carbon Futures, with an explanation of how carbon trading works.

carbon cycle The series of processes in which carbon is exchanged between organisms and the atmosphere as carbon dioxide, biomass, and carbonates through the processes of photosynthesis, decomposition, and respiration.

carbon fibres The fibres of carbon used to provide strength to a wide variety of lightweight manufactured products such as sports equipment. There are several manufacturing processes: Rayon fibres with a high-modulus are charred around 300°C, carbonized between 1,000°C and 2,000°C, and heat-stretched at 3,000°C. Fibres made from polyacrylonitrile result in a product with lesser mechanical properties but improved yield and follow a similar process. They can also be made from molten coal and heavy petroleum hydrocarbons in which fibres are spun from the liquid in oxygen with heat treatment at 3,000°C.

carbon footprint A representation of the amount of emissions of carbon dioxide from an industrial process or organization. The calculation is based on the amount of energy that has been consumed. The carbon footprint is expressed as either tonnes of carbon per year or tonnes of carbon dioxide per year.

SEE WEB LINKS

- Official website of the Carbon Trust.

carbonization A general name for processes used to produce gases, coke, and smokeless fuels from organic materials such as coal by heat treatment.

carbon offset A method used by industrial organizations to calculate their *carbon footprint and for offsetting their emissions against initiatives that are aimed at reducing the amount of carbon dioxide in the atmosphere. This includes the sequestering of carbon dioxide through the planting and growth of new trees, supporting renewable energy projects such as wind farms, and through buying *carbon credits in the emissions trading market.

A **carbon-neutral process** in one that is completely offset by the amount of carbon dioxide released.

carbon sequestration The process of removing carbon from the atmosphere by capture and long-term storage. In nature, trees, forests, and oceans capture carbon. Captured carbon from millennia is in the sequestered form of oil, gas, and coal located underground in oil and gas reservoirs and coal seams. Modern technologies are now being developed to capture carbon dioxide to reduce the amount of carbon in the atmosphere in order to reduce the *greenhouse effect and control global warming.

carbon tax A tax or surcharge levied on the sale of fossil fuels (i.e. oil, gas, and coal). The level of taxation is based on the carbon content of each fuel. It is designed to discourage the use of fossil fuels and reduce emissions of carbon dioxide into the atmosphere.

carboy A rigid cylindrical container used for storing and transporting process liquids. They vary in capacity and range from around 1 to 60 litres. They are generally made from polypropylene and are suitable for a wide range of liquids. They are often used for collecting waste solvents.

carburization A process used for the surface hardening of steel in which steel is heated in a gaseous, liquid, or solid carburizing medium that allows the absorption of carbon onto its surface. It typically uses temperatures of around 1,700°C and is followed by quenching.

carcinogen A substance or agent that is capable of producing cancer in humans. Chemical substances such as benzene and phenol are known carcinogens. Exposure to *ionizing radiation and *ultraviolet radiation is also known to cause cancer. Asbestos and tobacco particles in the lungs are also known to cause cancer.

Carman–Kozeny equation A semi-empirical relationship used to determine the pressure drop through a *packed bed of solids and permeability of porous media as:

$$\frac{\Delta p}{L} = \frac{180\mu v(1-e)^2}{d_p^2 e^3}$$

where μ is the viscosity, v is the superficial velocity, e is the voidage, and d_p is the diameter of the particles. It is valid only for the laminar flow fluid through the bed up to Reynolds number of about one. It is named after Austrian physicist Josef Kozeny (1889–1967) who proposed the equation in 1927 and Philip Carman who subsequently modified it in 1938 and again in 1956.

Carnot, Nicolas Léonard Sadi (1796–1832) A French physicist who began his career as a military engineer before turning to scientific research. In 1824 he published a book *Reflections on the Motive Power of Fire*, which provided for the first time a general theoretical approach to understanding the conditions under which the efficiency of heat engines could be maximized. The thermodynamic *Carnot cycle eventually led to the concept of *entropy. He died aged 36 from cholera.

Carnot cycle A thermodynamic cycle used in a heat engine and comprises four distinct steps: isothermal expansion, adiabatic expansion, isothermal compression, and then adiabatic compression (see Fig. 11). According to the **Carnot principle**, the efficiency of a heat

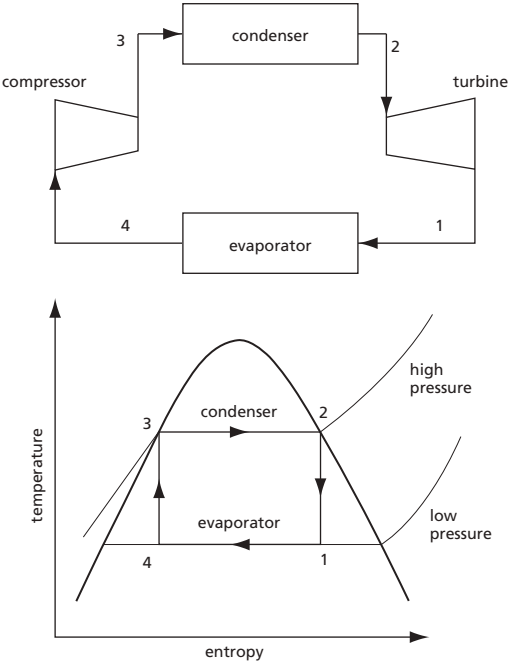

Fig. 11 Carnot steam cycle

engine depends on the temperatures at which it operates. The efficiency is the ratio of the work done, W, to the heat input, q_1

$$\eta = \frac{W}{q_1}$$

where, according to the *first law of thermodynamics, the work done is the difference between the heat in and heat out. The efficiency is therefore:

$$\eta = \frac{T_1 - T_2}{T_1}$$

For maximum efficiency, T_2 should be as small as possible and T_1 should be as high as possible. It was developed by Nicolas *Carnot in 1824.

carrier gas 1. An inert gas such as helium or unreactive gas such as nitrogen used in the chromatographic separation of gases. The carrier gas is the mobile phase and transports the gaseous substances to be separated through a long tube or column containing a packing material known as the stationary phase. The substances have different retention times and are detected as they are eventually eluted from the column. **2.** A gas used in a thermal spraying coating process in which melted or heated materials such as powders are sprayed onto a surface.

cascade control Two or more controllers working together to control a process. The output of the main (or master controller) is used as the *set point for the other (or slave controller). An example is the control of the output temperature of a *CSTR being used as the set point for the cooling jacket temperature. *See* FEEDBACK CONTROL.

cascade process A process that has a series of similar steps or devices having the same function. Each step or device may not provide sufficient chemical, biochemical, or physical change so further devices are therefore required to bring about a measurable or desirable change. For example, in the enrichment of the isotope uranium-235, the separation of uranium-235 from the heavier uranium-238 in the form of uranium hexafluoride (UF_6) gas in a single centrifugal separator is very low. Natural uranium contains 0.7 per cent of the uranium-235 isotope with the remainder being uranium-238. To achieve the sufficient level of enrichment consequently takes place in a cascade process involving many centrifugal separators operated in series in which the enriched gas forms the feed to the next separation.

Another example of a cascade process is where the conversion of a chemical reaction in a *continuous stirred-tank reactor (CSTR) is very low such that the continuous overflow from one can be fed into another reactor for further reaction and conversion. Where there are many CSTRs in series, the operation approximates to that of a *plug flow reactor.

case hardening 1. The formation of a layer in a solid being dried that resists the passage of moisture movement from the interior to the surface. In a food dehydration process, or paint or varnish drying, the surface hardens while much of the interior remains soft. **2.** The process of hardening the surface of steel that is used for tools and specialist purposes. It involves heating the steel in a hydrocarbon or by dipping the red-hot steel into molten sodium cyanide. A layer of nitrides can also be formed by the diffusion of nitrogen.

casing The body surrounding an impeller of a centrifugal pump or compressor.

cast iron A brittle and impure form of iron produced in a blast furnace. It is also known as pig iron and used in the manufacture of steel in a *Bessemer converter.

Castner–Kellner process A process once used to produce chlorine and sodium hydroxide by the electrolysis of sodium chloride solution. The electrolysis took place in a cell with a mercury cathode and graphite anode. The cell consisted of three compartments with a common bed of mercury and solution of sodium chloride above. The cathode was in the central compartment and anodes in the other two. It was invented independently by American industrial chemist Hamilton Young Castner (1858–99), who was working in the UK at the time, and Austrian chemical engineer Karl Kellner (1851–1905). The process was abandoned due to concerns over mercury pollution and replaced by various diaphragm-based electrolytic processes.

CAT An abbreviation for **c**arbon **a**batement **t**echnology. CAT is a group of technologies used to improve the efficiency of power plants with low-carbon alternatives such as biomass. *See* CARBON CAPTURE AND STORAGE.

catalysis The effect of a substance that, without itself undergoing change, aids a chemical change in other substances. The main forms of catalysis are: **homogeneous catalysis**, in which the catalyst is in the same phase as the reactants and products; and **heterogeneous catalysis**, in which the catalyst is in a different phase to the reacting system. A third, mainly biological form is **enzyme catalysis**, in which enzymes catalyze reactions. These are large complex organic molecules and do not form true solutions.

catalyst A substance that alters the rate of a chemical reaction without itself being consumed. While some catalysts are used in small quantities, such as the use of finely divided platinum in the decomposition of hydrogen peroxide, some catalysts are used in relatively large amounts such as in the Friedel–Crafts reaction:

$$C_6H_6 + C_2H_5 \rightarrow C_6H_5C_2H_5 + HCl$$

in which anhydrous aluminium chloride catalyst is required to be at least 30 per cent of the mass of benzene feed to be effective.

catalyst poison A substance that is absorbed more strongly than the reactants at the surface of a solid catalyst such that it prevents the catalyst from functioning. For example, in the ***Haber process**, sulphur compounds that may be present in the hydrogen gas feed can strongly bind on the iron catalyst preventing it from functioning.

catalytic coefficient A constant that relates the rate of reaction in a catalyzed reaction to the concentration of the catalyst. For a catalyzed reaction in which reactants are converted to products, the reaction rate is a function of the reactants. The proportionality or rate constant is dependent on the catalyst and the catalyst concentration. Where several catalysts are present, the overall rate constant is the sum of the products of the catalytic coefficients and catalyst concentrations.

catalytic converter A device used in the exhaust of internal combustion engines of motor vehicles to reduce the amount of harmful gases released into the environment. It consists of a chamber containing catalytic substances through which the exhaust gases flow. The catalyst converts unburnt hydrocarbons, carbon monoxide, and nitrogen oxide gases. Carbon monoxide is formed from the incomplete combustion of hydrocarbon fuel gases, and the nitrogen oxides or *NOx are formed from the high temperature reaction of nitrogen with oxygen in the air. The catalysts used to oxidize the unburnt hydrocarbons and the carbon monoxide, and convert the nitrogen oxides back to nitrogen, include platinum, palladium, and rhodium. Their performance is, however, adversely affected by some chemicals such as tetraethyl lead once widely used in some forms of petrol.

catalytic cracking A process that breaks down complex petroleum hydrocarbon molecules by the action of temperature and pressure in the presence of a catalyst. Zeolites and other minerals are used as the catalyst. Heavy oils can be converted into lighter products such as *LPG. The process takes place in a **catalytic cracker**, which is often abbreviated to the name *cat cracker.

catalytic distillation *See* REACTIVE DISTILLATION.

catalytic hydrocracking A refining process in which hydrogen and catalysts are used at a relatively low temperature and pressure to produce naphtha, diesel fuel, jet fuel, and high-grade fuel oil. *Hydrocracking is used for feedstocks that are particularly difficult to process by catalytic cracking or reforming because they may have a high sulphur content, or contain a high level of polycyclic aromatics or olefins.

catalytic reactor A vessel or item of process plant designed to contain a chemical reaction that requires the use of a catalyst to increase the rate of a reaction. The reactor may be operated batch-wise or continuously, depending on the particular requirements of the reaction, and charged with catalyst. The catalyst may be solid in the form of beads and either packed within tubes or free flowing. It can be either fluidized by the reaction mixtures or stirred to promote good heat and mass transfer.

catalytic reforming A process used to produce aromatic hydrocarbons by reforming straight-chain hydrocarbons in the C_6 to C_8 range from *naphtha or gasoline fractions into compounds containing benzene rings. Hydrogen is produced as a *by-product. The process is carried out at around 500°C and a pressure of 20 atmospheres in the presence of a catalyst. Various catalysts are used such as mixtures of platinum and aluminium oxide. Where platinum is used the process is known as *platforming.

catalytic rich gas process *See* CRG PROCESS.

catastrophic failure The sudden or complete failure of process equipment resulting in the rapid release and loss of process materials such as liquids and gases.

cat cracker An abbreviated form of *catalytic cracker and is a petrochemical refinery unit used to reduce large hydrocarbon molecules into smaller molecules. The conversion takes place at very high temperatures in the order of around 500°C in the presence of a catalyst.

cathode A negative electrode. In the process of *electrolysis in which electricity is passed through an electrolyte, positively charged ions (i.e. cations) are attracted to the cathode. *Compare* ANODE.

cathodic protection A method of preventing the rusting and corrosion of iron by using a reactive metal that makes the cathode of an electrochemical cell. Magnesium alloy bars are used for pipelines and iron structures, while zinc or an aluminium/zinc/indium alloy is used for the jacket legs of offshore platforms where the ions from the bars are formed in preference to the steel structure. It is therefore also known as **sacrificial protection** and the bars are called **sacrificial anodes**. Galvanized iron consists of a layer of zinc, where, like the magnesium ions, zinc ions are formed protecting the iron.

Cauchy number A dimensionless number, Ca, it is a measure of the ratio of the inertial to elastic forces in the compressible flow of fluids. It is the product of the density, ρ, and square of the velocity, v, to the bulk modulus of the fluid, E:

$$Ca = \frac{\rho v^2}{E}$$

causticization A process used for converting a solution of soda (sodium carbonate) with lime (calcium hydroxide) into sodium hydroxide and calcium carbonate as:

$$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$$

The process operates at around 90°C with an excess of lime and the precipitated calcium carbonate separated. Developed in the nineteenth century, the process was used after the *Leblanc process and before the *Castner–Kellner process.

Cavendish, the Hon. Henry (1731–1810) An English scientist and millionaire grandson of the Duke of Devonshire, he devoted his life to scientific investigation. A skilled experimenter, the drawing-room of one of his three London houses was a laboratory, with a forge in the next room and an observatory upstairs. He invented many new methods in both chemistry and physics. He determined many specific heats, the freezing point of mercury, and the relative density of gases. He also discovered the dielectric constant and 'weighed

the Earth'. He was the first to investigate hydrogen, to synthesize water (which until then was thought to be an element), and to analyse air. In 1785 he made nitric acid by sparking nitrogen with oxygen. He also refined many methods such as drying gases for the correction of gas volumes for temperature and pressure. The French scientist Jean-Baptiste *Biot (1774–1862) said that he was: '*le plus riche de tous les savants, et probablement aussi le plus savant de tous les riches*'. The Cavendish Laboratory in Cambridge is his national memorial and contains much of his apparatus.

cavitation The destructive collapse of vapour in a liquid in localized regions of high pressure. Vapour will form in any liquid when the pressure is less than the vapour pressure at the liquid temperature. The possibility of this happening is much greater when the liquid is in motion, particularly in pumps on the suction side where velocities may be high and the pressure correspondingly reduced. Having been formed, the vapour bubbles travel with the liquid and eventually collapse with explosive force giving pressure waves of high intensity. In pumps this collapse, or cavitation, occurs on the impeller blades causing noise, vibration, and erosion of the blades, which then have a typically pitted appearance similar to corrosion. Another sign of cavitation is a rapid decrease in delivered head and efficiency. As a remedy, a throttle valve is placed in the delivery line and when any symptoms of cavitation are noticed the valve is partially closed. This restricts the throughput and hence lowers the velocity. Cavitation is more likely to occur with high-speed pumps and hot liquids. One way of ensuring that cavitation does not occur is to ensure that the available *net positive suction head (NPSH) exceeds the required NPSH.

CCR An abbreviation for **c**entral **c**ontrol **r**oom where process plant information is transmitted, logged, and controlled. The CCR is located in a safe part of the plant and is often protected against fire and explosion.

CCR platforming A **c**ontinuous **c**atalytic **r**egeneration process that uses platinum as the catalyst to convert straight-chain aliphatic hydrocarbons into aromatic hydrocarbons and hydrogen. It is a widely used form of the *platforming process.

CCS *See* CARBON CAPTURE AND STORAGE.

CEFIC An abbreviation for **C**onseil **E**uropéen des **F**édérations de l'**I**ndustrie **C**himique, it is an organization based in Brussels representing around 30,000 chemical companies, which account for about one-fifth of the world's chemical production. Founded in 1959, it comprises corporate, national federation, and business members and has responsibility for logistics, policy, international legislation, research and innovation, and means of public communication on chemical substances and their production. CEFIC is a member of the *International Council of Chemical Associations (ICCA).

SEE WEB LINKS

- Official website of Conseil Européen des Fédérations de l'Industrie Chimique.

cell 1. A simple living organism such as a bacterium or yeast. Bacteria reproduce by binary division whereas yeast cells reproduce through budding. They are used as biocatalysts in biochemical reactions such as fermentation, converting sugars into alcohol and carbon dioxide and used in the food and brewing industries. **2.** A sealed chamber used in the nuclear reprocessing industry in which a process takes place. There is no access by process operators during normal operation. Control of the process is therefore carried out remotely. **3.** A system in which two electrodes are in contact with an electrolyte. In a *voltaic cell, electrochemical energy is produced by a chemical reaction that takes place between two

electrodes made from different metals in an electrolyte consisting of salts or acidic substances. A voltaic cell is also known as a galvanic cell. *See* BATTERY.

cell dry weight A measure of the concentration of microorganisms in a bioreactor. The cell dry weight is obtained by completely drying a small but defined volume of the culture medium and weighing the dried material remaining. The **cell wet weight** can be measured more quickly but not as precisely, and is around four or five times greater than the cell dry weight. Measurement of the *optical density or absorbance of the culture medium is a fast and relatively easy process used to determine the cell density as a direct correlation which typically uses wavelengths between 548nm to 600nm. Most determinations are carried out using *off-line analysis, although absorbance measurements can be carried out *in situ*.

cell homogenizer A device used for the disruption of cell walls and membranes of microorganisms in order to release intercellular material. It involves forcing a volume of the living cells under a very high pressure through a small orifice onto an impact ring. Disruption of the cell wall and membrane occurs due to the high shear forces involved. *See* LYSIS.

cell output rate (COR) The production rate of microorganisms in a continuous stirred-tank bioreactor operating with a fixed volume. A product of the cell concentration and dilution rate, the cell output rate ranges from zero where the bioreactor is operated on a batch basis with no feed of substrate, to a maximum value. Where the rate of fresh substrate is increased further, washout of the microorganisms occurs since the rate of flow out exceeds the rate of growth.

Celsius, Anders (1701–44) A Swedish professor of astronomy who, in 1742, introduced the idea of using 100 divisions between the fixed points of melting ice and boiling water on a mercury thermometer. He called the upper fixed point 0 and the lower fixed point 100. In 1750 Martin Strömer (1707–70), with whom Celsius had worked, inverted the scale.

Celsius scale A temperature scale devised in 1742 by Swedish astronomer Anders *Celsius (1701–44). Celsius used the reference points of the freezing point of water (0°C) and boiling point of water (100°C) divided equally by 100 degrees. The Celsius scale officially replaced the earlier *centigrade scale in 1948. The conversion from degrees Fahrenheit is:

$$^{\circ}C = \frac{5}{9}\left(^{\circ}F - 32\right)$$

Degrees Celsius has the same magnitude as the *kelvin. Note that 0°C is equal to 273.15K.

cement A widely used material in the construction industry which, when mixed with sand and aggregates, is used in the construction of buildings, bridges, and roads. The raw materials in its manufacture are limestone, silica-rich clay, gypsum (used to control the hardening process), and other materials such as sand or slag from a blast furnace used to adjust the mix. They are finely ground and burnt in a kiln at 1,500°C to form clinker. The clinker is formed due to reactions and the evaporation of water, and results in the formation of carbon dioxide. Cement is chemically unstable. When water is added, it cures gradually hardening.

cementation A metallurgical process in which a metallic surface is impregnated with another surface. It involves heating the metal such as steel and dipping it into molten sodium cyanide. It is used to harden the steel. *See* CASE HARDENING.

CEng Post-nominal letters used after someone's name to indicate that the person is a chartered engineer registered with the Engineering Council in the UK. A chartered chemical engineer would additionally include the grade of member or fellow of the Institution of Chemical Engineers with the post-nominal letters MIChemE or FIChemE.

C

centigrade scale A former scale for representing temperature now officially called the *Celsius scale.

centipoise A unit for viscosity in the c.g.s. system and equal to one-hundredth of a *poise. 1 cP is equal to 0.001 Pa s. *See* VISCOSITY.

centistokes A unit of *kinematic viscosity in the c.g.s. system where one cSt is equal to 10^{-6} m^2 s^{-1}.

centreline A reference point along the axis of a tube, pipe, or cylindrical vessel of uniform circular cross section, or along the axis of a rotating shaft.

centrifugal decanter *See* DECANTER.

centrifugal fan A machine used to develop large amounts of air or a gas at low gauge pressure and consists of a rotating shaft with blades or fan. The air is fed axially into the fan and is moved to the periphery by centrifugal force. Variants include forward-curved, backward-curved, and straight-bladed fans. Mechanical efficiencies may be as high as 80 per cent.

centrifugal force A force that acts radially outwards from the centre of a circular path. The opposite is the **centripetal force**, which is the force that acts towards the centre of the circular path.

centrifugal pump A mechanical device used to transport fluids by way of an enclosed impeller rotating at high speed. This commonly used device involves the fluid being fed in at the centre or eye of the impeller and thrown out in a roughly radial direction by centrifugal action. The large increase in kinetic energy that results is converted into pressure energy at the pump outlet by using either an expanding volute chamber or a diffuser. The latter is more efficient but more expensive. There are considerable variations in impeller design, but almost all have blades, which are curved, usually backwards to the direction of rotation. This arrangement provides the most stable flow characteristic. The head developed depends not only on the size and rotational speed of the pump, but also on the volumetric flow rate.

Centrifugal pumps are suitable for handling fluids with a wide range of properties including fluids with suspended solids. They are also capable of operating when the delivery line is blocked. They have low capital and maintenance costs, and easy fabrication in a wide range of corrosion-resistant materials. However, they have an inability to develop high heads unless multiple stages are used. They are also not self-priming. The pump must therefore be full at the point of start-up, which is achieved either manually, or requires ancillary equipment. They have a high efficiency over only a limited range of conditions and are not particularly suitable for highly viscous fluids. They are also prone to *cavitation in which the pressure of the fluid falls below the vapour pressure resulting in the formation of bubbles of vapour which collapse with a violent effect within the pump at a region of high pressure. This results in noise, vibration, and eventually damage to the impeller. It is avoided by ensuring that the available *net positive suction head exceeds the required net positive suction head.

centrifuge A mechanical device consisting of a rotating bowl, basket, or cones or blades, used to separate solid particles from a liquid or a suspension of immiscible droplets in a liquid by virtue of having a difference in density. The particles are usually small and have a similar density to the liquid, such that separation by gravity is too slow or not even possible. By applying a centrifugal force, separation can be achieved more easily. Centrifuges are used in the oil industry to separate droplets of oil from water streams. High-speed centrifuges are used in biotechnological processes such as separating spent yeast cells from fermented beer. *See* CYCLONE SEPARATOR.

CERN An abbreviation for the **C**onseil **E**uropéen pour la **R**echerche **N**ucléaire, which is the European Laboratory for Particle Physics located on the border of France and Switzerland near Geneva. As an intergovernmental research centre founded in 1954, it has been used for research into high-energy particle physics, and is now the home to the Large Hadron Collider. This is a 27-km particle accelerator.

SEE WEB LINKS

- Official information website of CERN, accessible to the public.

cetane number A number used as a measure of diesel fuels that represents the percentage of hexadecane (i.e. cetane) in a mixture with 1-methylnaphthalene that has the same ignition characteristics as a diesel fuel being tested in a standard diesel engine. It is therefore an indication of the ease of self-ignition. The **cetane index** is a number calculated from the average boiling point and the density of a petroleum fraction in the diesel fuel boiling range, which estimates the cetane number of the fraction.

CFC *See* CHLOROFLUOROCARBON.

CFD *See* COMPUTATIONAL FLUID DYNAMICS.

CFM An Imperial volumetric rate of flow of gases and air expressed as **c**ubic **f**eet per **m**inute. It is typically used in the design and specification of ventilation systems.

CFPD An Imperial volumetric measure of gas flow expressed as **c**ubic **f**eet **p**er **d**ay. The flows are usually large and often given as **MMSCFPD** or **m**illions of **s**tandard **c**ubic **f**eet **p**er **d**ay.

c.g.s. system A system of units that uses centimetre, gram, and second as the base units. A great deal of early scientific work was done using the c.g.s. system. Derived units were given names and some are still in use today, such as the *poise for viscosity, *dyne for force, and *erg for energy or work. The c.g.s. system has largely been replaced by *SI units.

chain reaction A self-sustaining chemical reaction or nuclear process. In a *nuclear reactor, the neutron-induced fission of uranium-235 results in the release of neutrons, which in turn cause the fission of further uranium-235 atoms. In chemical chain reactions, free radicals act as intermediates in the overall chemical reaction.

chamber process *See* LEAD CHAMBER PROCESS.

change of phase A change from one physical state to another (i.e. solid, liquid, and gas). The transition is accompanied by a change in energy. While heat is absorbed or evolved, there is no temperature change. Examples include the melting of a solid to a liquid, the freezing of a liquid to a solid, the boiling or evaporation of a liquid to a vapour, the condensation of a vapour to a liquid, and the sublimation of a solid to a vapour.

channel A trough used for the passage or transport of liquids, usually with a free surface. That is, there is a gas or vapour such as air above the surface of the liquid. The cross section of the channel is usually square, trapezoidal, or semi-circular.

C

characteristic curve A diagram presenting the delivered head or pressure, total power consumption, and efficiency against volumetric flow rate for a centrifugal pump. The shape of the curve tends to show a fall or decrease in the delivered head or pressure with increasing volumetric flow rate while the power consumption increases with flow rate. The efficiency of the pump, which is expressed as the ratio of the work delivered by the fluid to the work input to the pump, rises with increasing delivered flow to a maximum known as the *best efficiency point, and then decreases thereafter.

charge The quantity or load of material fed into a process, the quantity contained within a storage vessel, or the amount of fuel fed into a burner.

charge hand A senior process operator whose responsibility is below that of a *foreman.

Charles, Jacques Alexandre César (1746–1823) A French chemist and physicist best known for his discovery of *Charles's law. He made the first hydrogen balloon ascent in 1783, which was sponsored by the Académie des Sciences. He prepared the hydrogen, filled the balloon, and with an assistant, Nicolas-Louis Robert (1760–1820), rose to a height of over 500 m. He also experimented with atmospheric electricity.

Charles's law A law that states the relation between the volume of a gas and its temperature. It states that the volume of a given mass of gas is directly proportional to its absolute temperature at constant pressure. It was proposed by Jacques *Charles (1746–1823) although he never published it. *Gay-Lussac (1778–1850), who had made the discovery in 1802, acknowledged that 'Citizen Charles' had remarked on it fifteen years earlier.

chartered chemical engineer A person who is both academically and professionally qualified in chemical engineering. A chartered chemical engineer has a proven ability to work at a high level without supervision to solve complex engineering problems, develop new or existing technologies through innovation, creativity, and change. He or she may be involved in pioneering or promoting advanced designs and design methods, work on new and more efficient production techniques, marketing and construction concepts, engineering services, and management methods. A chartered chemical engineer is also engaged in technical and commercial leadership. The person is entitled to use the post-nominal letters *CEng after his or her name, and will also be a member of the *Institution of Chemical Engineers.

SEE WEB LINKS
- Official website of the Engineering Council.

chart recorder An electromechanical device used to record data from several inputs using a paper and coloured pens. Strip chart recorders have a long continuous strip of paper that is fed at a constant speed, whereas circular chart recorders have a rotating disc of paper, which requires periodic replacement. Chart recorders were once a common feature of control rooms and used to record the history of process plant operations, but have now been largely superseded by electronic computer capture.

check valve A non-return valve used to control the direction of flow of a fluid such as the entry to and exit from a reciprocating pump. It is designed to close automatically in the

event of reversed flow. The design consists of a flap or ball, which seals the pipe when the pressure caused by flow is in the reverse direction, but lifts or opens when in the required direction.

CHEMECA A major annual international conference of the Australian and New Zealand community of chemical engineers and industrial chemists held under the auspices of *IChemE in Australia, the *Royal Australian Chemical Institute, and the Society of Chemical Engineers New Zealand, the Institution of Chemical Engineers in New Zealand. The 2012 conference took place in Wellington, New Zealand.

SEE WEB LINKS
- Official website for CHEMECA conference 2012.

chem eng An abbreviation or loose term for chemical engineering. A **chem-enger** is a slang term for a student of chemical engineering.

chemical amount *See* AMOUNT OF SUBSTANCE.

Chemical & Engineering News **(C&EN)** A weekly magazine published by the American Chemical Society that provides professional and technical information to chemical engineers. Founded in 1923, it includes topical information on news, research employment information, business and industry news, government and policy, education, and special reports. It is printed and also available online.

SEE WEB LINKS
- Online access to *Chemical & Engineering News*.

chemical bond A mechanism by which atoms are held together to form molecules. There are various types of chemical bond and these include the attraction of opposite charges and the formation of stable configurations through electron-sharing. The main forms of bonds are covalent, ionic, metallic, and hydrogen bonds. Valence governs the number of bonds that an atom can form.

chemical engineering A branch of engineering that deals with the design, construction, and operation of processes and plant that involve physical, chemical, and biological change for the conversion of raw materials into useful products on an industrial scale. The principal operations include mixing, reaction, and separation.

Chemical Engineering **1.** A series of six textbooks co-written and authored by John *Coulson (1910–90) and Jack *Richardson (1920–2011) first published in 1954. **2.** A monthly magazine published in the US covering all aspects of chemical engineering and aimed at professional chemical engineers, academics, and associated professionals in the manufacturing, chemical, and allied industries.

SEE WEB LINKS
- Online access to *Chemical Engineering* magazine.

chemical equation The use of symbols to present a chemical reaction. The equation provides a mathematically balanced number of atoms present in the reaction such that the left-hand side presents the reactants and equals the right-hand side, which presents the products. An example is the combustion of methane in oxygen (reactants) to form carbon dioxide and water (products):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

chemical equilibrium A thermodynamic equilibrium between the reactants and products in a reversible chemical reaction. The balance in a reversible chemical reaction in which two chemical reactions proceed at the same rate but in opposite directions. That is, the rate of the forwards reaction is balanced by the rate of the backwards reaction. For example, in the reaction $wA + xB \leftrightarrow yC + zD$ the reactants *A* and *B* form the products *C* and *D*, which can also return to form *A* and *B*. For the balanced reaction at equilibrium, the *equilibrium constant is the ratio of the molar concentrations of the products to the reactants given by:

$$K_c = \frac{[C]^y[D]^z}{[A]^w[B]^x}$$

The square brackets indicate equilibrium concentrations.

chemical formula The use of symbols to present a chemical compound. The symbols represent atoms. Subscripts are used to represent the number of atoms. An example is sulphuric acid, H_2SO_4, which comprises two atoms of hydrogen, one atom of sulphur, and four of oxygen.

chemical hazard Any chemical substance or chemical process that presents a hazard to humans, property, or the environment, and which may realize its potential through fire, explosion, or toxic or corrosive effects.

chemical industry A major economic manufacturing sector responsible for the development and mass production of chemicals. Early nineteenth-century processes included the mass production of alkalis and, in particular, soda ash, caustic soda, and bleach. By the end of that century, various metals were being extracted from ores in large-scale processes, along with sulphuric and nitric acid, explosives, and fertilizers. The *Haber process in the early twentieth century led to the production of fertilizers and radical changes in agricultural practices through the fixation of nitrogen. After the First World War, the rapid rise of the automotive industry resulted in the demand for petroleum and petroleum products including thermoplastics. The Second World War spurred the development of chemical products such as synthetic rubber, and the decades that followed led to new plastics such as polyester, polyvinylchloride, and polypropylene. The first decades of the twenty-first century are marked by the development of pharmaceutical production and with new and innovative food products.

chemically combined water Moisture that is chemically combined either in the form of hydroxyl ions (OH^-) or in molecular compounds such as hydrates. Chemically combined water is not usually removed from biological materials during drying processes.

chemical oxygen demand (COD) A standard method used for the indirect measurement of the amount of pollution that is not able to be oxidized biologically in a sample of water. The test procedure is based on the chemical decomposition of organic and inorganic contaminants dissolved or suspended in water. The test indicates the amount of water-dissolved oxygen consumed by the contaminants; the higher the chemical oxygen demand, the higher the amount of pollution in the sample. The quantity of oxidant consumed is expressed in terms of its oxygen equivalence and is expressed in mg L^{-1} of oxygen.

chemical plant An industrial factory that processes chemicals on a large or industrial scale. Raw materials undergo chemical, physical, or biological transformation into useful products within process equipment through the processes or *unit operations of mixing, reaction, and separation.

chemical potential (Symbol μ) The change in *Gibbs free energy, G, with respect to the amount, n, of component in a mixture $\partial G/\partial n$ with temperature, pressure, and the amounts of the other components being constant. The components are in equilibrium when their chemical potentials are equal.

chemical process A general term used for the industrial manufacture of useful chemical products from raw materials through chemical, physical, or biochemical transformation. The transformation may involve a single step or many steps within *unit operations such as mixing, reaction, and separation, in either batch or continuous forms of operation. A chemical process can be presented schematically as either a *block flow diagram or as a *process flow diagram. Block flow diagrams use blocks to represent the unit operations with arrows to represent the flows in and out, whereas process flow diagrams provide more detail of the unit operations and include process piping, the main items of equipment, control valves, and operational information such as temperature, pressure, and flows.

chemical reaction The chemical conversion of elements and compounds known as *reactants into other substances or *products that involves the breaking and formation of *chemical bonds. The chemical reaction can be *exothermic with the liberation of heat, or *endothermic in which heat is absorbed during the reaction. Other effects of a chemical reaction can include colour change, the formation of solids such as precipitation, the liberation of gas, light, and sound. All chemical reactions are theoretically reversible although some are deemed to be irreversible since the reverse reaction rate is negligibly small, such as the combustion of fuel in oxygen.

chemical reaction equilibrium The balance in a reversible chemical reaction in which two chemical reactions proceed at the same rate but in opposite directions. For example, in the esterification of fatty acids with an alcohol, an ester and water begin to be formed as products as the concentration of reactants become depleted, eventually reaching a balance point where the products break down and revert back into the reactants. *See* CHEMICAL EQUILIBRIUM.

chemical reactor *See* REACTOR.

chemical substance A material with a definite chemical composition. Elements, compounds, and alloys are chemical substances.

chemical vapour deposition (CVD) A coating process that uses a reactant gas or vapour that decomposes onto the heated surface of a material depositing a solid element or compound. The process takes place in a chamber and the deposition forms coatings that are corrosion resistant and durable. CVD is used to provide coatings in the production of integrated circuits, anti-oxidation coatings of refractory materials, and hard cutting-tool coatings of titanium carbide, and other similar materials.

chemical warfare The use of chemicals as weapons. These include poisons, nerve gases, defoliants, and herbicides; mustard gas was used during the First World War. Their deployment was prohibited by the Geneva Convention in 1925; however, their production is not prohibited. The defoliant Agent Orange was used by the US during the Vietnam War.

chemisorption The force of attraction of gases and vapours by chemical forces to a solid surface of a substance rather than by physical or van der Waals adsorption. It is dependent on the nature of the surface and is restricted to definite sites on the surface.

chemistry The study of chemical elements, the compounds that are formed from elements, and their reactions. There are many specialist fields of chemistry including organic, inorganic, physical, and biochemistry.

chemostat cultivation *See* CONTINUOUS CULTIVATION.

Chernobyl A major nuclear accident that occurred on 26 April 1986 at the Ukrainian nuclear power plant. Following a power output surge, an emergency shutdown was attempted. With an even greater power output surge, the reactor vessel ruptured. A series of explosions then followed, destroying the reactor. With the graphite moderator then exposed, a fire began, with the release of radioactive material into the environment. Many people were killed as the result of exposure to ionizing radiation, and many more were to suffer cancer-related deaths. The disaster had far-reaching implications for nuclear power and safety in the nuclear industry.

Chézy formula A semi-empirical formula that relates the rate of discharge of liquid in an open *channel to its dimensions, slope, and surface roughness as $Q = CA\sqrt{mi}$ where C is the Chézy coefficient, A is the cross-sectional area of the channel, m is the *mean hydraulic diameter, and i is the slope of the channel. The formula was devised by French engineer Antoine Chézy (1718–98) who was responsible for designing a canal system to supply water to Paris. The Chézy coefficient was developed further in 1890 by Irish engineer Robert Manning (1816–97). *See* MANNING FORMULA.

chilling A thermal process in which thermal energy is removed from a substance to reduce the temperature to below ambient but without a phase change. It is widely used in the food industry to reduce the temperature of perishable foods such as meat, fish, and dairy products to extend shelf life by slowing down the microbiological processes of enzymes and microorganisms present.

Chilton, Cecil Hamilton (1918–72) An American chemical engineer who co-edited the *Chemical Engineers' Handbook* with Robert H. Perry (1924–78). He was senior advisor at the Battelle Memorial Institute, Columbus, Ohio. Having completed the 5th edition, he died following heart surgery before its publication in 1973.

Chilton, Thomas Hamilton (1899–1973) An American chemical engineer noted for his pioneering work in chemical engineering practice. A professor of chemical engineering, he studied heat transfer, fluid flow, distillation, and other aspects of chemical engineering, and developed the *Chilton–Colburn analogy. During the Second World War he worked on the Manhattan Project. He was president of the American Institute of Chemical Engineers in 1951.

Chilton–Colburn analogy A widely used analogy from heat, momentum, and mass transfer analogies. Also known as *j-factors, they are used to determine an unknown transfer coefficient when one of the other coefficients is known. It applies to fully developed turbulent flow in pipes, and relates mass and heat transfer coefficients, and friction factors. It was proposed by and named after American chemical engineers Thomas H. *Chilton (1899–1973) and Allan P. Colburn (1904–55).

CHISA An international chemical engineering congress held in the Czech Republic, which began in the Czech city of Brno in 1962. It is aimed at advancing chemical engineering research, development, and practice. The word CHISA originates from the Czech abbreviation for 'Chemical Engineering, Chemical Equipment Design and Automation' and is now a form of trademark for large meetings that have emphasized European collaborations.

chlorination 1. A chemical reaction in which chlorine is added to a compound. **2.** A process for purifying water for drinking or for disinfecting water such as in swimming pools.

chlorofluorocarbon (CFC) A substance, usually an alkane, in which all the hydrogen atoms have been replaced with chlorine and fluorine atoms. Developed for use as refrigerants, aerosol propellants, solvents, and in the manufacture of foam packaging materials, they are chemically inert and unreactive. However, because of these qualities, they are known to diffuse into the upper atmosphere where photochemical reactions result in the reaction with the protective ozone layer of the Earth. Their manufacture and use has therefore been discouraged beginning with the Montreal Protocol in 1987.

choked flow A condition in which a fluid becomes limited in its flow or 'choked' and is not able to be increased further. For a fluid flowing through an orifice or small hole in a pipe, the increase in velocity corresponds to a decrease in pressure, known as the venturi effect. However, a point is reached in which the rate of flow will not result in any further decrease in pressure, thereby limiting flow. The choking of gases occurs when the velocity leaving the orifice approaches sonic velocity i.e. at a Mach number of one. This results in shock waves that restrict flow causing the choking effect. The deliberate choking of gases is sometimes useful for limiting the rate of flow to processes. For liquids, the decrease in pressure below the vapour pressure results in partial flashing and *cavitation, with the formation of vapour effectively limiting flow. It is also known as the **critical flow** and is important in process safety, particularly in terms of the rate of release of material from a vessel or vent when depressurizing.

CHP *See* COMBINED HEAT AND POWER.

Christmas tree An assembly of valves and fittings used to control the pressure and flow in oil and gas wells. It is located on top of the wellhead and provides the controlling mechanism for the isolation of wells. It has many other functions including permitting the injection of chemicals into wells and pressure relief. Playing an essential role in an *emergency shutdown (ESD), a basic form of assembly has several manual gate valves with typically four or five valves being arranged in a crucifix arrangement. The name is derived from its resemblance in both shape and decoration to a Christmas tree.

churn flow A two-phase flow regime in a pipe or tube characterized by the oscillatory transition from a continuous liquid phase to a continuous and predominant gas phase. It occurs when gas bubbles coalesce and liquid becomes entrained in the bubbles. At high gas velocities, **Taylor bubbles** that have been formed in *plug flow break down into an unstable pattern in which there is a churning or oscillatory motion of liquid. Churn flow may be regarded as a breaking-up of plug flow with an occasional bridging across the pipe by the liquid phase. At high gas flow rates, it may be considered as a degenerative form of *annular flow with the direction of the film flow changing and large waves being formed on the interface for which the term **semi-annular flow** is occasionally used.

CIMAH An abbreviation for **C**ontrol of **I**ndustrial **M**ajor **A**ccident **H**azards, which were UK regulations issued in 1984. Since 1999 they have been superseded by the *COMAH regulations.

CIP An abbreviation for: **1. C**old **i**sostatic **p**ressing. **2. C**onstant **i**njection **p**ressure. **3.** ***C**lean-**i**n-**p**lace. **4. C**arbon **i**n **p**ulp.

circulating pump A pump used to circulate a process liquid from, and back to, a process. Circulating pumps can be used as a form of mixing or in the prevention of suspended particles settling.

C

cladding The tight-fitting surrounding material used to contain *nuclear fuel. Its purpose is to protect the fuel against chemically active agents and to prevent the release of fission products into cooling water, particular when the fuel is stored in water prior to reprocessing.

Clapeyron–Clausius equation *See* CLAUSIUS–CLAPEYRON EQUATION.

clarification A general name for processes used to remove suspended matter from a solution. It includes the processes of *filtration, centrifugation, and *sedimentation. *Compare* THICKENING.

clarifier 1. A large tank used to remove suspended matter from a solution under the influence of gravity. It has a continuous input and output flow. **2.** A device used for the removal of suspended particles from a liquid in order to reduce or remove the turbidity. It may be either a filter or a centrifuge.

clarifying agent A soluble component added to a liquid used to remove turbidity. Examples include gelatine and pectinases used to clarify wine and beer.

Claude, Georges (1870–1960) A French chemist and physicist noted for his study of gases at different pressures. He discovered that acetylene is very soluble in acetone and gave rise to a method for storing the gas. His research on rare gases obtained by the *liquefaction of air was developed into the invention of neon signs. Two processes are known by his name: the *Claude process for liquefying gases by a series of processes including cooling by expansion while performing work against a piston; and the *Claude process for the manufacture of ammonia.

Claude process 1. A method used for the liquefaction of gases in which a highly compressed gas is cooled by expansion in an expansion engine. This is followed by further cooling in a heat exchanger, and finally cooled by the *Joule–Thomson effect as it passes through an expansion valve to a lower pressure. The liquid obtained in the last expansion is withdrawn in which the remaining gas is used as the cooling medium in the heat exchanger before it is recompressed and returned to the process. The use of the expansion engine to recover some of the energy used in compressing the gas is a refinement of the earlier *Linde process and also makes the liquefaction process more rapid. **2.** A process for the manufacture of ammonia involving the electrolysis of water to produce hydrogen which is then burnt in air, thus converting oxygen into water and leaving nitrogen. The nitrogen and more hydrogen are then mixed, compressed to 750 bar, and passed over a catalyst at 500°C. It is named after Georges *Claude (1870–1960).

Clausius, Rudolph Julius Emmanuel (1822–88) A German physicist noted for formulating the second law of thermodynamics in 1850 independent of Lord *Kelvin. He introduced the concept of *entropy, and also contributed to electrochemistry and electrodynamics. He held teaching posts in Berlin and Zurich before taking a post at Würzburg in 1869.

Clausius–Clapeyron equation A relationship between the change in saturated vapour pressure and the latent heat of vaporization when there is a change of state:

$$\frac{dp}{dT} = \frac{\lambda}{(V - v)T}$$

where λ is the latent heat of vaporization, p is the saturated vapour pressure, T the absolute temperature, V the specific volume of the vapour at T, and v is the specific volume of the liquid. Assuming that the *ideal gas law applies, then the equation can be written as:

$$\frac{d\ln p}{dT} = \frac{L}{RT^2}$$

The equation can also be used for the transition of a solid to a liquid. The equation is named after German physicist Rudolph *Clausius (1822–88) and French engineer Benoît Paul Émile Clapeyron (1799–1864).

Claus process A two-stage process used for the removal of sulphur from natural gas or crude oil. In the first, hydrogen sulphide is partially oxidized using air to form sulphur dioxide. In the second, the sulphur dioxide is reacted with the hydrogen sulphide in the presence of a catalyst at 300°C to form elemental sulphur and water vapour:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$$
$$SO_2 + 2H_2S \rightarrow 3S + 2H_2O$$

It is named after its inventor, chemist Carl Friedrich Claus, who developed the process in 1883 while working on ways of recovering sulphur from the waste calcium sulphide produced in the *Leblanc process. He originally used iron ore and later bauxite as the catalyst.

Clean Air Act An Act of the UK Parliament introduced in 1956 to reduce the level of air pollution, in particular, by controlling the use of coal as a heating medium in homes. The Act was a major landmark in environmental protection in the UK and was responsible for reducing the level of smoke pollution as well as harmful sulphur dioxide emitted from domestic fireplaces into the environment. The Act was also responsible for the relocation of power stations away from urban areas, and also included an increase in the height of chimneys for more effective dispersion of emissions. The Act was amended in 1993.

In the US, the Clean Air Act was introduced in 1963 as a federal law to control air pollution. The Environmental Protection Agency is responsible for enforcing the regulations and for protecting the public from airborne contaminants that are hazardous to health arising from domestic and industrial sources. There have been subsequent amendments to the Act, particularly to address airborne pollution such as *acid rain and effects of ozone depletion.

SEE WEB LINKS

- Official website of HM Government managed by the National Archives to publish all enacted legislation in the UK.

clean-in-place (CIP) A fully or partly automated technique used to clean and sanitize closed process equipment after use and before reuse. Used throughout the food and biochemical industries, it avoids the time-consuming process of dismantling equipment and manual cleaning, or where cleaning by other means is too difficult due to restricted access. The equipment to be cleaned is equipped with nozzles with supply and return pipes to and from a CIP kitchen. This involves the preparation of the necessary chemicals and wash water, and heat exchangers. The cleaning solution is pumped through the equipment often as a spray through the nozzles. A CIP programme typically involves a pre-rinse with water, circulation with a cleaning solution, an intermediate rinse, disinfection, and a final

rinse with water. Cleaning agents used in the food and drink industry include alkalis such as sodium and potassium hydroxide, sodium carbonate, acids such as nitric acid, phosphoric acid, citric acid, and gluconic acid. Formulated cleaning agents containing chelating agents include EDTA, NTA, phosphates, polyphosphates, phosphonates, as well as surface active agents.

climbing film evaporator *See* RISING FILM EVAPORATOR.

closed loop control A system or process being controlled in which the controlled variable is measured and the result of this measurement is used to manipulate one of the process variables, such as steam flow to a heat exchanger, for example.

closed system A system in which there is no transfer of material across the system boundary. Differential material and energy balances are used to describe closed systems. A batch process takes place in a closed system.

close packing A packing arrangement of spherical particles, such as catalysts, in which there is a minimum amount of space around them. For each spherical particle, there are twelve other particles in contact. The *voidage is the space between the spheres.

cloud point The temperature of a liquid at which dissolved solids precipitate giving a cloudy appearance. It is used in the petrochemical industry to measure the point at which wax forms in diesel fuels. It is used to indicate the point that such liquids will deposit wax onto surfaces causing the blockage of pipes.

coagulation The joining of colloidal particles to form a larger mass of particles. Coagulation occurs when an agent is added to a colloidal solution in which the ions change the ionic strength of the solution, and therefore destabilize the colloid. For example, alum is used to remove proteins in beer and wine which otherwise give cloudiness. Alum and iron (III) sulphate are used as coagulation agents in sewage treatment.

coal equivalent A measure of the energy within a fuel that is equivalent to the energy contained within coal. Although coal itself is variable in composition and calorific value, a standard of one coal equivalent corresponds to 7,000 kilocalories (≈ 29.3 MJ). For examples, 1.0 kg of fuel oil is equal to 1.52 kg coal equivalent; 1.0 m^3 of natural gas is equal to 1.35 coal equivalent; 1 kg of uranium-235 is equal to $27x10^6$ kg coal equivalent.

coalescence The forming together of droplets of liquid that are dispersed within another liquid, such as droplets of oil within water. Coalescence can be improved by adding agents that reduce the surface tension of the droplets. A **coalescer** is a type of separation vessel used to separate emulsions. Baffles and filters are used to cause droplets to coalesce. Electrostatic coalescers use electric fields to cause the coalescence. Coalescers are used in the separation of oil and water, particularly in the offshore and onshore petroleum industries.

coal gas A *fuel gas once produced from the heating of coal in the absence of oxygen. Once used extensively in the nineteenth and early part of the twentieth centuries, coal gas typically contained hydrogen, methane, and a significant amount of toxic carbon monoxide. The *by-products of the production were coke and coal tar, which is a residue containing benzene, naphthalene, and other organic compounds. The availability of *natural gas in the 1970s led to the decline in its use.

cocurrent flow An arrangement in which the flows of two separate process streams are fed into a process in the same direction for the purpose of carrying out heat and mass transfer. It is typically used for heat-sensitive materials and in packed gas absorption columns where the chemical reaction in the liquid phase tends to be rapid. It is generally inefficient as a flow arrangement, since once equilibrium between the process streams has been reached, no further transfer takes place. It is also known as **parallel flow**. *Compare* COUNTERCURRENT FLOW.

coefficient 1. A number or symbol used in an algebraic expression that multiplies an unknown quantity. For example, in the expression $y = ax^2 + bx + c$, a is the coefficient of x^2 and b is the coefficient of x. **2.** A measure of a specified property under specified conditions. For example, the *coefficient of discharge for a discharging vessel through an orifice is the ratio of the actual to theoretical rate of flow and takes into account friction losses, etc.

coefficient of contraction A dimensionless number expressed as the ratio of the minimum flow area or **vena contracta* to the flow area for a fluid discharging through an orifice. It is often difficult to measure directly but can be determined indirectly from the *coefficient of discharge and coefficient of velocity which are more readily measured.

coefficient of discharge A dimensionless number expressed as the ratio of the actual to the theoretical flow rate of a fluid discharging through an opening or restriction. The coefficient is used as an indication of the recovery of energy following through the opening or restriction. Where there is full recovery and no permanent energy loss, the coefficient is equal to 1. For example, for a well-designed *venturi meter the coefficient may be in the order of 0.95 to 0.98 signifying very good energy recovery, whereas an *orifice plate meter may be as low as 0.6 at high flow rates. Orifice plate meters, however, are popular since they are considerably cheaper than venturi meters to fabricate and install.

coefficient of expansion The increase in the physical dimensions of a material due to the effects of temperature. It is expressed as a fraction of the original dimension per degree temperature rise. The coefficient may relate to either linear or cubic expansion.

coefficient of performance (COP) A coefficient used in *air conditioning, *refrigeration, and *heat pump cycles as a measure of the performance of the thermodynamic cycles. In refrigeration, the COP is the ratio of the duty of the condenser to the work input to the compressor, whereas in a heat pump the COP is the total heat output as a ratio of the heat equivalent of work required to produce the heating effect. The difference in COP between a heating and cooling system is due to the heat reservoir of interest being different. For a system where cooling is of interest, the COP is the ratio of the heat removed from the cold reservoir to the input work, whereas for a heating system, the COP is the ratio to input work of the heat removed from the cold reservoir together with the heat added to the hot reservoir by the input work. The COP of a refrigeration system usually varies between 3.0 and 9.0 depending on the refrigerant, head and suction pressure of the compressor, and the superheated conditions.

coefficient of volumetric expansion *See* THERMAL EXPANSION.

coherent units A system of units that are obtained by the multiplication or division of *base units without numerical factors. The SI system is a coherent system. For example, the newton is equal to one kilogram metre per second squared (kg m s^{-2}), while velocity is metres per second (m s^{-1}).

coke A porous material produced from the carbonization of coal in which all the volatile materials have been driven off. It is used in a *blast furnace.

Colburn j factor (Symbol j_H) A semi-empirical equation used for heat transfer in turbulent flow with *Reynolds numbers ranging from 5,000 to 200,000 inside long tubes and defined as:

$$\left(\frac{h}{c_p G}\right)\left(\frac{c_p \mu}{k}\right)^2\left(\frac{\mu_w}{\mu}\right)^{0.14}$$

and is equal to $0.023\,Re^{-0.2}$. It applies over a range of *Prandtl numbers from 0.6 to 120, but should not be used for Reynolds numbers below 6,000 or for molten metals that have unusually low Prandtl numbers.

cold shot process A technique used to control the temperature in an exothermic reaction in which cold fresh feed is added to the reaction mixture in a *tubular flow reactor or a cascade of *continuous stirred-tank reactors (CSTR). It is used to overcome limitations in conversion due to chemical equilibria. It also avoids the need for a heat exchanger. It is typically used for high-pressure processes such as ammonia synthesis. This reduces the total volume of the reaction vessel since interstage heat exchangers are not required.

cold work A method of carrying out a task in a hazardous area using a tool or item of equipment that does not provide a source of ignition.

Collier, John Gordon (1935–95) A British chemical engineer who was director-general of the Central Electricity Generating Board (CEGB). He began his career at Harwell United Kingdom Atomic Energy Authority (UKAEA), before leaving in 1983 to join the CEGB, but he returned in 1987 to become its chairman. After its breakup he became the first chairman of Nuclear Electric. He was a Fellow of the Royal Society and president of the Institution of Chemical Engineers in 1993. The John Collier Medal is awarded biennially and jointly by the Royal Academy of Engineering, the Royal Society, and the *Institution of Chemical Engineers.

colloid A suspension of particles whose size lies within the range of 1 nm to 1 μm and dispersed within a liquid medium. Hydrophilic colloids consist of thermodynamically stable water-soluble macromolecules such as gelatine and starch. Hydrophobic colloids consist of insoluble particles in a finely divided state suspended in water and are thermodynamically unstable. Colloids often have a kinetic stability due to a surface-charge repulsion effect between particles.

column A tall cylindrical process vessel whose height is considerably greater than its diameter and used for unit operations such as distillation, absorption, and various forms of gas–liquid and liquid–liquid extraction processes. It usually allows liquids to descend under gravity and contact rising gases or vapours, or liquids of lesser density in which there is intimate contact between the two to allow equilibrium to be reached. Some types of columns are empty in which the liquids are sprayed in the form of droplets, while others have internal features such as baffles, plates, or packing materials used to promote the intimate contact between the ascending and descending materials. *See* TOWER.

COMAH An abbreviation for **C**ontrol **o**f **M**ajor **A**ccidents and **H**azards. These UK regulations under the Health and Safety at Work Act require the operator of a process plant or site that contains more than a defined amount of hazardous chemicals to provide a safety case report for the process and its operations, to demonstrate that it can be operated in a

safe and environmentally acceptable manner. The regulations have control of manufacturing sites with major pollution potential and superseded the earlier *CIMAH regulations in 1999.

combined feed ratio The total quantity of a reactant fed to a chemical *reactor expressed as the ratio of the fresh feed to other feeds including any recycled feed.

combined heat and power (CHP) The use of a heat engine or power station to simultaneously generate both electricity and useful heat. The use of low-grade thermal energy such as for municipal district heating is an effective way of raising the overall efficiency of an engine or power station.

combustible A material that is capable of burning under normal conditions. For a material to combust there must be a sufficient supply of oxygen and an ignition source. A **combustible liquid** is a liquid that is capable of combustion, such as a hydrocarbon or alcohol.

combustion The rapid thermal oxidation of a fuel with the production of heat and light. Complete combustion is also known as **stoichiometric combustion**. The products of combustion of a hydrocarbon are water vapour and carbon dioxide. The presence of carbon monoxide indicates incomplete combustion.

comminution The break-up and particle-size reduction of solid materials into smaller particles and fragments by the process of crushing, grinding, pulverization, attrition, impact, or by chemical methods. It is used to break up ores prior to *flotation.

commissioning A final and thorough check of an installed process plant or item of equipment to ensure that it is fully operable as intended. All aspects of the process or equipment are tested individually and collectively. Prior to commissioning, a site acceptance test is carried out. At the end of the working life of a process, the process and its equipment are decommissioned and taken out of service. *See* DECOMMISSIONING.

common logarithms *Logarithms that use base 10.

common rail A type of fuel injection system used in modern automotive diesel engines. The injection nozzles to each cylinder are supplied by a common fuel line. A single pump is used to supply the fuel at a very high pressure of around 1,000 bar. The fuel injection valves open and close automatically and in sequence.

competitive inhibition *See* ENZYME INHIBITION.

complex medium *See* GROWTH MEDIUM.

complex number A number that has a real and an imaginary part of the form $x + jy$ where x and y are real, and $j = \sqrt{-1}$. It can also be written in polar form as $r\cos\theta + jr\sin\theta$ where r is the modulus and θ is the argument. Complex numbers are represented on an *Argand diagram, and are useful in the study of the stability of controlled chemical processes.

component A constituent in a mixture that is defined as a phase or as a chemical species. *See* GIBBS' PHASE RULE.

composition The parts of which something is made up. The chemical composition of a substance is made up of its elements. The composition of an *alloy is made up of *elements

whereas the composition of an ore is made up of elements and compounds. The composition of a flow stream to or from a process, or a chemical reaction itself is made up of the various components involved. *See* PROCESS VARIABLE.

C

compound A substance of uniform composition throughout its bulk and containing two or more elements in a state of chemical combination. Compounds are formed when elements react and are chemically joined. Unlike a *mixture, a compound can only be separated into its components by chemical reaction.

compressed gas A gas or a mixture of gases at a pressure greater than atmospheric pressure. Compressed gases occupy a smaller volume than their uncompressed state and can therefore be conveniently stored and transported. Compressed air is used to power certain types of machines and is also used as *instrument air.

compressibility The fractional reduction in the volume of a substance with applied pressure. The **compressibility factor** is a measure of the compressibility of a gas, z, and used as a multiplier to adapt the *ideal gas law for non-ideal gases:

$$z = \frac{pV}{RT}$$

where p is the pressure, V is the volume, R is the universal gas constant, and T is the absolute temperature.

compressible fluid A fluid in which the density changes with applied pressure. The compressibility of liquids is negligible in comparison with gases and vapours. The **isothermal compressibility** of a gas is the change in volume per unit volume or density for a unit change in applied pressure given as:

$$c = \frac{-1}{V}\left(\frac{\partial V}{\partial p}\right)_T = \frac{-1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_T$$

Isothermal compressibility coefficients are frequently used in oil and gas engineering, transient fluid flow calculations, and in the determination of the physical properties of substances.

compressor A type of machine used to increase the pressure of a gas or vapour by reducing its volume. It is used to compress a gas or vapour in a vessel, to raise its pressure, and for its transport under pressure through pipelines. Compressors are broadly classified as those that are dynamic and those that are positive displacement in design and operation.

Centrifugal compressors are dynamic-type compressors and consist of various types of rotating impeller used to increase the velocity, which is converted to pressure through a diffuser. They are widely used in the chemical, oil, and gas industries. Axial-flow compressors consist of blades or airfoils mounted on the rotating shaft that compresses the flow along the axis of the shaft rather than radially. They are used for generating compressed gases with a high velocity such as in natural gas compression.

Reciprocating compressors are positive displacement-type compressors and consist of a piston attached to a crankshaft to compress gas that is drawn into a cylinder. Many reciprocating compressors are multistaged and can generate high pressures in excess of 2,000 bar. Rotary screw compressors are also positive displacement-type compressors and consist of two meshing rotors. The compressor on a domestic refrigerator is a hermetically sealed compressor used to compress the evaporated refrigerant vapour for condensation, throttling, and recycling back to the evaporator. They commonly consist of a scroll-type compressor although spindle-type compressors are also used.

computational fluid dynamics (CFD) A set of numerical methods and algorithms used to solve and analyse problems involving complex fluid flow behaviour. The problems require many computations that are required to be performed simultaneously using high-speed computers. The problems involve the simulation of the interaction of liquids and gases with surfaces defined by *boundary conditions. The *Navier–Stokes equations are used to define most CFD problems involving a single phase as a liquid or a gas, but not both. For problems involving fluid mechanics, the solvers are based on the finite volume method. For 2-D or 3-D problems, the geometry of interest is first defined as an area or volume and divided into discrete control volumes or cells known as a mesh. The flow into these cells obeys the general laws of conservation for mass, momentum, and energy as algebraic equations. The boundary conditions are specified and in the case of problems involving transient behaviour, the initial conditions are also defined. All the equations are then solved iteratively. The solution is then presented for visual analysis and interpretation. There have been many developments in CFD methodologies and many are available as commercial software packages that can be applied to the study of complex fluid flow systems.

computer-aided design (CAD) The use of computers for the efficient engineering design of process equipment and its layout. This permits prototype designs to be checked, altered, analysed, and tested prior to proceeding to fabrication and construction.

computer control The use of computers to control a process in which analogue signals of measured *process variables such as pressure, temperature, level, etc. are converted to a digital signal that is then manipulated according to a model of the process. The digital output from the computer is then converted back to an analogue signal to make the controlled adjustments to the process. The advantage of computer control is that it is able to process large volumes of data at high speed obtained in real time from around the process compared with traditional analogue controllers.

concentrate 1. The action of intensifying the purity or strength of a material, such as by the action of adding or removing a substance. For example, a solution of salt water can be concentrated by the evaporation of the water. **2.** A product of concentration.

concentration A quantitative measure of the relative amount of a component in a mixture. Concentration is often expressed as a mass and mole fraction. Other forms include volume fraction, molarity, molality, parts per million or billion on either a mass or volume basis, mass per unit volume, mass or weight per unit mass or weight, and activity.

concentrator A device used to increase the concentration of one component dissolved or suspended in another, usually by the removal of the latter. An evaporator is an example of a concentrator in which water as the solvent is removed from a solution of salt, leaving it more concentrated.

concentric Having the same centre.

conceptual process design A work activity performed by engineers at an early stage to evaluate in broad terms the technical feasibility of new and existing processes, as well as process redesigns based on existing feed materials. The work activity examines the thermodynamic feasibility of process routes and the *process variables required, and assesses the broad issues of chemical and process production, which includes information on process costs and material selection. The use of *heuristics and process simulation using computers are useful tools to provide rapid information before committing resources to a more detailed design using tools such as *computer-aided design (CAD).

It is important to define the necessary codes and standards to which a design will adhere. This permits effective communication with other engineering disciplines and equipment vendors, and also allows for appreciation of the full extent of the design. Standards commonly used include British Standards Institution, the *American National Standards Institute, the *American Petroleum Institute, the Deutscher Nornenauschuss, and the International Standards Organization.

conclusion A proposition made at the end of an argument upon what the argument set out to prove. It is based on evidence and facts, and not conjecture.

concurrent *See* COCURRENT.

condensate 1. A liquid obtained from the cooling of a vapour below its saturation temperature, or from a vapour–gas mixture cooled below the *dew point. **2.** A term used to describe liquid drops of light hydrocarbons in *natural gas.

condensation The change in state from a vapour to a liquid or a solid accompanied by the release of energy known as the heat of condensation, which has the same magnitude as the heat of vaporization at the same temperature. Condensation is the opposite of *evaporation. The direct change in state from a vapour to a solid phase is called **deposition.**

A vapour may condense on a cold surface by either *film condensation in which condensate forms a continuous layer of liquid that flows over the surface, or *dropwise condensation in which condensate forms at nucleation sites where droplets tend to coalesce and may form into rivulets that flow under the influence of gravity. Although dropwise condensation is associated with higher transfer coefficients, it is difficult to maintain in practical situations.

condensation reaction A type of chemical reaction in which two molecules combine to form a larger molecule with the elimination of a smaller molecule such as water, hydrogen chloride, or methanol. In a polymerization reaction, similar or different monomers form a long-chain polymer with the release of water molecules, such as in the formation of polyester. The formation of a peptide from two amino acids also involves the elimination of a water molecule.

condensation temperature *See* DEW POINT.

condenser A type of heat exchange used to cool a vapour at constant pressure to a temperature that is sufficiently low as to change the state from a vapour to a liquid, and to carry away the heat from the vapour–liquid mixture. The latent heat is removed using a coolant. The coolant evidently increases in temperature but it is the phase change action that is the important function.

Condensers fall into two classes: those that condense vapour using a coolant separated in a *shell and tube device, and those called **contact condensers** in which coolant and vapour are mixed and leave together in a single stream. They are used with distillation columns to produce reflux to control top temperatures and product quality. They are also used for steam turbines to produce condensate and to maximize the energy from the steam.

conditioner A tank used in mineral flotation into which chemicals are added and allowed sufficient time to absorb on to the particles before flotation.

conduction A mode of *heat transfer in which thermal energy is transmitted through a substance from a region of high temperature to a region of lower temperature. Within gases

and liquids, the thermal energy is by collisions between atoms and molecules to those with lower kinetic energy. The rate of heat transfer for steady-state thermal conduction through a slab is given by *Fourier's law:

$$q = \frac{kA}{x}\Delta T$$

where q is the rate of heat transfer, k is the *thermal conductivity, x is the thickness of material, A is the area perpendicular to the direction of heat flow, and ΔT is the temperature difference along the path of heat transfer.

cone and plate rheometer An instrument used to measure the rheological properties of fluids (see Fig. 12). It consists of a fixed flat surface with a rotating cone above and a sample of the fluid sandwiched between them. The cone just touches the flat surface. The rotational speed and tapered gap defines the shear rate. The torque on the rotating cone that resists the motion defines the characteristic shear rate. The surface can be heated or cooled to determine the rheological properties as a function of temperature.

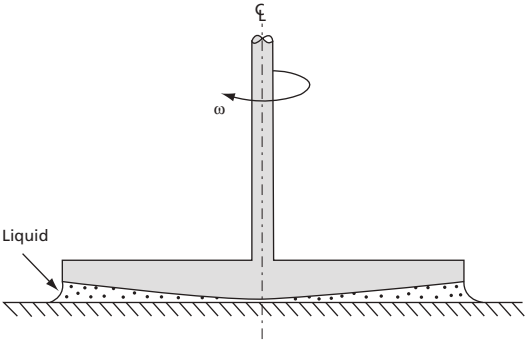

Fig. 12

confined space Any enclosed or partially enclosed space having restricted access and egress that may present itself as a form of trap and be life-threatening.

conflagration A large destructive fire.

conformation The spatial arrangement of atoms in a molecule responsible for its shape. There are many possible arrangements of atoms that can be interconverted by rotation about a single bond in a molecule. The conformation of proteins determines their function as in the case of enzymes as biocatalysts and proteins that have therapeutic properties such as insulin.

constant 1. A quantity that does not vary such as temperature, pressure, or level in a process. **2.** A number used in a mathematical relationship that is multiplied by a variable such as $y = ax$ where a is a constant. **3.** A fundamental constant used in formulae or calculations such as π or g. **4.** A fixed value, c, that is added to an indefinite integral such as:

$$\int x dx = \frac{x^2}{2} + c$$

constant-boiling mixture A mixture of components that boils giving a vapour with the same composition as the liquid. Separation of the components by evaporation or distillation is not possible. The mixture is also known as an *azeotrope.

C

constant molar overflow An assumed condition in which the number of moles of a mixture of volatile liquids evaporating at any point in a system or process, such as on the plate of a distillation column, is equal to the number of moles condensing at the same point. That is, on the plate, the liquid and the vapour flow rates remain constant.

constant rate drying The point in the drying of a solid material in which the rate of evaporation per unit area of the drying surface remains constant. It is dependent on the humidity of the drying air, the mass transfer coefficient, and the velocity of the drying air.

constant variable *See* CONTROLLED VARIABLE.

construction cost The financial expense incurred in the building of process plant and buildings by a contractor for the labour, construction materials, and equipment, as well as services and *utilities. It also includes profits and overheads. It does not include the cost of the site or fees for architects or construction engineers.

contact angle The angle between a solid surface and the surface of a liquid in contact with it. It can be used to determine the *surface tension of a liquid.

contact process A major industrial process used for the manufacture of sulphuric acid. Sulphuric acid is widely used with large quantities involved in the making of rayon, the refining of petroleum, and the manufacture of fertilizers, pharmaceuticals, dyes, and paints. The process involves the exothermic reaction of combining sulphur dioxide and oxygen to produce sodium trioxide, SO_3. The sulphur is produced by roasting ores such as iron pyrites, FeS_2. Excess oxygen is used and the process is controlled at as low a temperature as possible. Platinum catalysts were once used. However, due to their susceptibility to poisoning, especially by arsenious oxide, As_4O_6, finely divided vanadium and vanadium pentoxide catalysts are preferred since these are less susceptible to poisoning although less efficient. The sulphur trioxide is not absorbed in water due to an unmanageable mist of sulphuric acid droplets that is produced, but instead the cooled gases are passed up a tower down which 98 per cent sulphuric acid flows. The water in this acid forms the acid $H_2O + SO_3 = H_2SO_4$. The adsorption can be carried further to produce fuming sulphuric acid or oleum:

$$H_2SO_4 + SO_3 = H_2S_2O_7$$

The process was invented in 1831 in the UK by P. Phillips Jr. and is named after the German *kontaktverfahren* meaning 'catalytic process'. It was once in competition with the *lead chamber process.

containment The prevention of a hazardous material from being released into the environment or beyond a defined boundary. Codes of practice or legislation are often used to define the boundary within which such materials must be contained, such as vessels, chambers, cabinets, glove boxes, nuclear cells, and other similar facilities. Examples include the containment of radioactive process materials and biological substances such as pathogens.

contamination The unwanted or undesirable presence of a substance that may have an undesirable effect such as be infectious or harmful in some way to humans or the environment. It may be in the form of deposition, absorption, or adsorption of radioactive material,

or involve biological and chemical agents such as in food, soil, skins. Bacteria in drinking water, radioactive material in soil, oil in water, or water in oil, are all examples of **contaminants**. *Compare* POLLUTION.

continuity equation An equation that describes the total transport of a conserved quantity moving from one place to another within a pipe, process, or system. It applies to the transport of mass, energy, momentum, and all other natural quantities. Expressed as a simple balance equation, the transport into a system is equal to the transport leaving. There is neither accumulation nor depletion within the system under steady conditions. The conserved quantity is usually defined with reference to a flow area.

continuous cultivation The operation of a *bioreactor that involves the continuous addition of fresh sterile media and its withdrawal at the constant rate. The media contains all the necessary nutrients required to promote biological growth of the microorganisms within the bioreactor. The volume of the bioreactor can be kept constant by an overflow weir arrangement. The *dilution rate is used to characterize the operation which is defined as the ratio of the flow of feed to the volume of the bioreactor. **Chemostat cultivation** involves the continuous feed of substrate in which at least one nutrient is limiting. **Turbidostat cultivation** involves maintaining a constant biomass concentration by varying the dilution rate.

continuous phase A phase such as liquid within which another phase is dispersed such as suspended gas bubbles, droplets, or solid particles. A colloid has two or more phases in which one is dispersed in another. *Compare* DISPERSED PHASE.

continuous process A process in which raw materials are continuously fed and in which processed materials continuously leave at the same rate. As an *open system, both material and energy are transferred across the system boundary. In contrast with a *batch process, the process equipment volumes are smaller and the operating costs lower. Continuous processes are used for high-quality production. Automated control is necessary to ensure that process conditions of flows, temperatures, and pressures are maintained at all times. A **semi-batch process** has certain elements within the continuous process that operate as a batch process, such as the removal of moisture by a molecular sieve, but the overall effect is a continuous production.

continuous stirred-tank reactor (CSTR) A type of idealized chemical reactor vessel used to contain a chemical reaction in which liquid reactants continuously flow into the reactor and products continuously flow out such that there is no accumulation within the reactor. By assuming perfect mixing of the reactants within the reactor by using stirring, the composition of the reaction does not vary with either position or time, and the output composition of the material is therefore assumed to be the same at the composition at all points within the reactor. It is also known as a *back-mix reactor.

continuum A region of material space through which properties such as temperature, density, and composition vary in a mathematically continuous manner.

contractor A company or person that undertakes a contract to provide a service, labour, or materials. A subcontractor is a company or person that is assigned by the contractor to undertake part of the contract. A contract is a legally binding document. Many chemical companies use contractors with specialist expertise to undertake chemical engineering design, construction, and commissioning of chemical plant as well as to undertake plant maintenance and revamp projects.

control charts Graphical tools used in statistical and quality control of a process to represent the state of control. They are used to indicate whether changes are required to be made to control parameters, as well as identify the parameters that require control. They are also used to predict the control of the process. A process that is stable but lies outside desired control limits requires understanding of the causes for control. They are also known as **process-behaviour charts** or **Shewhart charts** after American engineer Walter A. Shewhart (1891–1967) who devised them in the 1920s.

controlled variable A process variable that is not permitted to change unpredictably. It is also known as a **constant variable** as it is not expected to change its value. In process control, the controlled variable, for example, may be the flow of material leaving a heat exchanger that is required to be maintained at a constant temperature, and is achieved by adjusting the flow of the heat transfer medium through the heat exchanger.

controller A device used to regulate a *process variable in a controlled process. The purpose is to receive an input signal of the difference between a measured value and the desired value, and provide an output signal that is then used to control the process. The controller has a reference input or *set point. This is the desired value for the process measurement signal and is transmitted to the controller. The controller measures the difference or **error** between the set point and the measurement signal. The error is manipulated by the controller to provide the **controller output,** which corrects a valve position to reduce the error towards zero. In a *block diagram, the controller is represented by the summing junctions and the control modes block. The main forms of control are proportional, integral, and derivative control. The simplest type is on/off control. To reduce the frequency of switching on and off, which can lead to excessive wear and tear, a neutral zone is used. For example, if temperature is being measured and is rising within the neutral zone, the controller stays on, whereas if the temperature is falling within the neutral zone then the controller stays off. *See* PID CONTROL.

controller tuning The technique of selecting the optimum *controller settings used to control a process. The *Ziegler–Nichols tuning method is a way of selecting the controller settings.

control loop A part of a process control system. *Open loop control involves human operator intervention, whereas *closed loop control is an automated system in which the output signal to the process is compared to a defined *set point.

control mode A type of control action such as *proportional control, *integral control, or *derivative control. *See* PID CONTROL.

control rod A neutron-absorbing rod that is used to control the reactivity variations of a *nuclear reactor. Cadmium and boron are neutron-absorbing materials used for control rods.

control room An operations centre that receives all the process plant information. The information includes details of temperature, pressure, flows, levels in process vessels, and concentrations, etc. and is often presented on an array of computer display screens that represent the process. Process alarms indicate significant deviations from the expected values, and are monitored by process control room operators. The control rooms in hazardous chemical plants are often located a safe distance from the plant itself and are also used as a safe place of refuge. On offshore oil and gas platforms, the control room is shielded and protected from fire and explosion.

control valve A device used to control the rate of flow of a process material through a pipe. It is actuated either electronically or pneumatically in which either a stem or diaphragm changes the position of a plug in a seat either restricting or opening the passage of flow. As the final control element in a control system, it is therefore responsible for changing the value of the manipulated variable to the output signal from the controller. *Pneumatic control valves are either air-to-open or air-to-close. The application depends on safety consideration based on the impact of supplied air failure. An equal percentage valve characteristic is used to describe a type of control valve flow characteristic in which there are equal increments of valve plug movement for the change in flow rate. The change in flow rate with respect to movement is small when the valve plug is near its seat, and high when the valve plug is nearly wide open. A linear control valve characteristic is where the controlled flow is directly proportional to valve travel and is often used with distributive control systems or programmable logic controllers. A quick-opening valve characteristic provides a maximum change in flow rate at low movement of the stem and plug. It is used for on/off control.

control valve actuator A pneumatic or electrically powered device that supplies the force and motion necessary to open or close a *control valve.

convection A mode of heat transfer caused by the movement of currents within a fluid as the result of different localized densities. It is a combination of *conduction within the fluid and energy transport due to fluid motion, which is either by a natural flow of density currents or by a forced fluid flow, known as **natural convection** and **forced convection**, respectively. In natural convection, the movement of fluid is due to gravitational effects in which heated fluid has less density and rises, allowing cooler and denser fluid to descend. This results in a circulating flow. In forced convection, a pump or fan is used to circulate the fluid.

convective mass transfer The mass transfer between one substance or phase and another caused by simultaneous convection and molecular diffusion. It can involve the mass transfer between a fluid in motion and a surface, which may be either a solid or an immiscible liquid. The **convective mass transfer coefficient** relates the molar mass flux of a species to the concentration difference between the boundary surface concentration and the concentration of the diffusing species in a moving fluid. The coefficients k_G and k_L refer to the gas and liquid phases, respectively, and are related to the properties of the fluid, the dynamic characteristics, and the geometry of the system. They are often presented as a product with area through which mass transfer takes place as k_Ga and k_La. In this form, they are useful when considering gas transfer as bubbles, particularly in biological systems for oxygen transfer since oxygen is usually a limiting factor in a *bioreactor.

convergence The approach to a limit of a sequence or series. It is usually the solution of a non-linear problem. Iterative solutions to complex problems solved by computers often seek convergence to a solution. The opposite is **divergence**.

conversion A measure of the completeness of a chemical reaction. It is often presented as the fraction of a particular reactant consumed by the chemical reaction. The **conversion per pass** is a measure of the limiting reactant that is converted in a chemical reactor and recycled for combination with fresh reactant feed. Not all reactions are complete within the reactor, and in many cases, unreacted reactants are separated from products and recycled for further opportunities for reaction.

conversion factor A number used as a multiplication factor to convert a quantity expressed in one set of units to those of another.

converter The reaction vessel used in the *Bessemer process in the production of steel.

conveyor A mechanical device used to transport efficiently large quantities of solid materials from one place to another. It is often used to handle bulky loose materials such as crushed ores, coal, and grain. Used in a wide number of industries, there are many types commonly used. The choice depends on the application such as bottles, pharmaceuticals, foods, packaging, etc. For example, belt conveyors consist of a belt moved by a series of rollers, with the materials resting on the belt.

coolant A fluid used in a process as a heat transfer medium for extracting heat from one place and transferring it to another. Water is widely used as an effective coolant in heat exchangers due to its abundance, low cost, and high heat capacity. In a nuclear reactor, the coolant is used to remove heat from the *core. High-pressure water is used in pressurized water reactors to prevent boiling. Liquid metal-cooled reactors use molten sodium. Mercury has also been used in the past. Gases have been used as coolants; for example, carbon dioxide was used in Magnox and AGR nuclear reactors.

cooler A heat exchange device used for reducing the temperature of a process stream or product but not necessarily with a change in phase.

cool flame A weak luminous hydrocarbon flame of fuel-rich air mixture. It usually has a temperature below 500°C.

cooling jacket An outer cover or surrounding of a process vessel or pipe to contain and transport a heat transfer medium or *coolant in order to reduce the temperature of the process material in the vessel or pipe, or to maintain it at a low temperature. *See* JACKET.

cooling tower A device or structure used to condense steam or reduce the temperature of water used as a cooling medium in a process for reuse. Cooling towers are either natural draught or forced draught in design and operation. Natural-draft cooling towers are large structures that contain packing material with a high specific surface area down which the water to be cooled trickles and cascades, contacting with cool air that is drawn up through the packing by convection. The cooled water collects at the bottom of the tower and is returned to the process for reuse and a make-up of water is added to account for loss by evaporation. Forced-draft cooling towers use fans to pass the cooled air through the packing. Although they have a higher operating cost, they are comparatively smaller and more compact than natural-draught cooling towers. In mechanical-draft cross-flow cooling towers, the air flows horizontally across the downward-flowing water. They therefore have a shorter path for the air to flow and allow a greater flow of air for the same power demand as counter-flow forced-draft cooling towers.

cooling water A supply of water that is used to remove heat from a process that operates at a temperature of less than 100°C. The water, which may be chilled or at ambient temperature, is used as a heat transfer medium or *coolant, and contacted with a hot process stream either by direct contact or directly such as through the walls of a *heat exchanger. After being heated, the water may be reused by removing the heat gained through a *cooling tower, with a make-up to allow for loss from evaporation. Depending on the quantities required and the type of application, the water may be freshwater taken from a river, such

as used in a nuclear power station, or saltwater from the sea although there are associated corrosion issues. The deposition of dissolved salts can also lead to fouling issues.

COP *See* COEFFICIENT OF PERFORMANCE.

copper A valuable metal noted for its high electrical conductivity, malleability, suitability as an alloy with other metals, and resistance to corrosion. It is extracted from various ores by crushing and ball milling, followed by *flotation separation to raise the copper content, and remove unwanted minerals. Smelting with sulphur then produces copper and iron sulphide. This is melted in a reverbatory furnace in which air (oxygen) is added to produce sulphur dioxide, iron, and copper. The copper is then electrolytically refined to produce commercial copper. Copper has many uses in the process industry in addition to electrical wiring. It is also used for small bore pipes and for copper stills in the *whisky industry.

co-product A substance formed at the same time as the main or desired product during a chemical reaction that has equal or comparable economic significance. In the mining and extraction of ores, many of the elements recovered are of similar economic significance to one another. *Compare* BY-PRODUCT.

copyright The exclusive legal right to produce copies and to control a published literary work granted by law for a specified period.

COR *See* CELL OUTPUT RATE.

core The part of a *nuclear reactor where the fission chain reaction takes place. A **core meltdown** is the uncontrolled reaction within a nuclear reactor in which the core cooling fails, leading to the nuclear fuel heating up due to *radioactive decay of the fission products to the point that the fuel melts. The cooling system may fail due to a major leakage in the nuclear reactor cooling circuit with the simultaneous failure of the emergency cooling system. *See* CHERNOBYL.

Coriolis flow meter A non-invasive type of flow meter used to measure the mass flow of a fluid through a pipeline. It is based on the Coriolis effect and involves diversionary loops of pipe through which the fluid passes. As the fluid moves through the loop, the fluid momentum changes and rotates, exerting a force on the loop causing it to twist and vibrate. The extent of the twisting and vibration effect gives an indication of the rate of mass flow. It is named after French physicist Gaspard de Coriolis (1742–1843) who first used the term for describing the movement of fluids in rotating systems.

corollary *See* THEOREM.

correlation coefficient (Symbol R) A statistical number that represents the linear relationship between two variables or groups of variables (X and Y). The correlation has a value between -1 and +1. A positive value represents a positive linear relationship, whereas a negative value represents a negative relationship. A value of 0 represents no relationship between the variables. It is calculated from:

$$R = \frac{n\sum XY - \left(\sum X\right)\left(\sum Y\right)}{\sqrt{\left(n\sum X^2 - \left(\sum X\right)^2\right)\left(n\sum Y^2 - \left(\sum Y\right)^2\right)}}$$

where n is the number of values. The correlation coefficient requires that the relationship between the two variables is linear. Where this is known not to be the case, then the correlation coefficient is not useful.

corresponding states A condition in which fluids are compared at temperatures and pressures that are fractions of their corresponding critical properties. That is:

$$T_r = \frac{T}{T_c}; p_r = \frac{p}{p_c}$$

where the subscript *r* refers to the reduced state and subscript *c* refers to the critical state. In practice, the law of corresponding states is valid only near the critical point since all substances deviate from the law. Within groups of similar substances that have a similar form of intermolecular interaction, the deviations are often relatively small such that the properties of otherwise little-studied substances can be determined with confidence based on corresponding states.

corrosion The unwanted wastage of metallic materials due to reaction with the environment. The effect includes the loss of strength of material, a change in appearance, change in surface heat transfer and fluid flow properties, contamination, seizure, electrical contact failure, leakage, and general surface damage. Corrosion rates are determined to a large extent by the chemical nature of the process stream and its pressure and temperature; due account must be taken of the flow conditions, and how they interact with the ongoing chemical processes. The electrochemical corrosion process of *rusting involves the oxidation of iron to form a hydrated iron oxide that occurs in the presence of both water and oxygen, and is particularly damaging to process equipment and support structures. *Compare* EROSION. In some cases, the corrosive action of the environment can be reduced through the use of chemicals known as **corrosion inhibitors**. Cathodic corrosion inhibitors include oxygen scavengers such as sodium sulphite used in enclosed systems such as boilers, and ions such as Ca^{2+}, Mg^{2+}, HCO_3^-, and Zn^{2+}, which form insoluble precipitates at the cathodic (alkaline) surface. Anodic corrosion inhibitors are used to encourage oxidized passive films of surfaces using an oxidizing agent such as chromates (Cr^{VI}).

COSHH An abbreviation for **C**ontrol **o**f **S**ubstances **H**azardous to **H**ealth. These are regulations used in the UK for the safe use of chemicals. Originally established in 1988, there have been subsequent amendments. Where chemicals are used, such as in a laboratory, a COSHH assessment must first be completed to identify the controls required for their safe usage.

cost estimation A method of determining the capital cost of process plant and equipment. There are four recognized ways this is done: 1. *Rules of thumb provide approximations to the order of magnitude of cost. They are useful as a rough guide but are prone to major error. 2. The use of cost curves provide estimates based on similar process plants or equipment, and may involve *scale-up factors. 3. Multiplication factors can be applied to different types of equipment, such as heat exchangers and pumps etc., that might be involved in a process. 4. Definitive estimates require the use of detailed materials and equipment, the direct and indirect costs. Although time-consuming due to the level of detail involved, it is the most accurate method.

Couette flow A type of flow in which a fluid is sandwiched between two parallel plates, one of which is stationary and the other is moving at some constant velocity. For a Newtonian fluid, the velocity gradient is linear between the plates. It is named after French physicist Maurice Marie Alfred Couette (1858–1943).

Couette rheometer An instrument used to measure the rheological properties of fluids. It consists of a cup within which fits a cylindrical bob (see Fig. 13). A sample of the

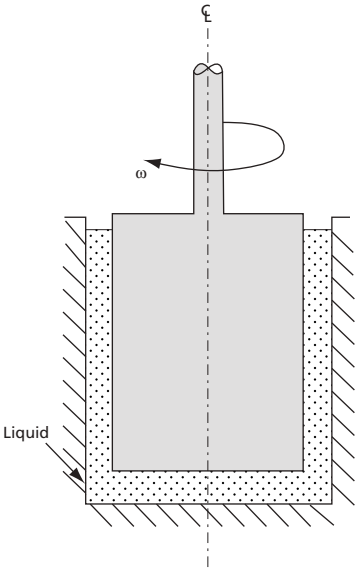

Fig. 13

fluid being tested is sandwiched between them. Either the cup is held and the bob rotated or, more rarely, the bob is held and the cup rotated. The rotational speed and distance between cup and bob define the shear rate. The torque to resist the motion defines the characteristic shear rate. The cup can be heated or cooled to determine the rheological properties as a function of temperature.

coulomb (Symbol C) The SI unit of electric charge and is equal to the charge transferred by a current of one ampere in one second. It is named after the French physicist Charles-Augustin de Coulomb (1736–1806).

Coulson, John Metcalfe (1910–90) A British chemical engineer and academic who co-authored a series of six textbooks, *Chemical Engineering*, with Jack *Richardson, that were first published in 1954. A twin to his brother Charles, who was a noted chemist, John Coulson gained his first degree from Cambridge and his PhD in chemical engineering from Imperial College, London. He was the first head of chemical engineering at the University of Newcastle where he remained until his retirement.

countercurrent flow The flow of two fluids in contact with each other or separated by a surface but flowing in opposite directions. In a distillation or adsorption column, the flow of liquid descends while the flow of vapour ascends, meeting in intimate contact. In a heat exchanger, the two fluids travelling in opposite directions are not in direct contact with each other, but exchange heat from one to the other through the tube walls. This arrangement is more efficient than *cocurrent flow, in which the flows are in same direction.

covalent bond A type of chemical bond that involves the electrostatic attraction between a pair of atoms through the sharing of electrons and the positive nuclei. This bond was discovered by American chemist Gilbert Newton Lewis FRS (1875–1946).

C

Cowles process A process used for the production of aluminium alloys from aluminium ores (bauxite). The ores are reacted with carbon in the form of charcoal in an electric furnace, together with the metal used to form the alloy, which is usually copper. Another metal is required in the process, since without it, the product would result in the formation of aluminium carbide. The process is named after its American inventors, the Cowles brothers: Alfred H. Cowles (1858–1929) and Eugene H. Cowles (1855–92).

CPA *See* CRITICAL PATH ANALYSIS.

cracker The chemical reactor in which the catalytic cracking of high molecular weight hydrocarbons to small molecules takes place. It is also known as a *cat cracker.

cracking A process in which high molecular weight hydrocarbons are broken down into lower molecular weight products by the effect of high temperature in the presence of an alumina-silica catalyst. The process is used to produce gases such as methane, ethane, propylene, and propane that are the subsequent raw materials used for the manufacture of a wide range of products including of plastics, detergents, textiles, and agricultural chemicals. *Thermal cracking uses high temperatures and pressures to break the molecular bonds to form smaller molecules. *Catalytic cracking uses a catalyst to assist in the breakdown of the molecules. In a *fluidized bed catalytic cracker, the catalyst is present as a bed of very fine particles which is agitated by the vaporized hydrocarbons as they pass up through the bed.

creep The continuous deformation of the structure of a solid material that is held under constant stress but below the *yield point. It is usually observed in metals that are held at elevated temperatures but may also occur over long periods at ambient temperatures. Horizontally supported pipelines at fixed points may eventually be seen to bow under their own weight.

CRG process (catalytic rich gas process) A catalytic process used to produce *fuel gas from *naphtha, which is a light petroleum distillate. The naphtha is reacted with steam over a nickel-based catalyst at a temperature of up to 650°C and pressure of 70 bar to produce a gas mixture that is rich in methane. Other gases in the product include carbon dioxide, carbon monoxide, and trace amounts of hydrocarbons. The process was superseded in the UK by the discovery of North Sea gas.

cricondenbar The maximum pressure at which two phases, such as a liquid and vapour, can coexist. A gas cannot be formed above this pressure irrespective of the temperature.

cricondentherm The maximum temperature above which liquid cannot be formed irrespective of the pressure.

critical damping *See* DAMPING.

critical dilution rate The highest possible dilution rate at which steady state is able to be attained within a constant volume *bioreactor such as a fermenter with continuous inflow and outflow. The dilution rate is the ratio of the flow of fresh feed to the volume of broth containing a viable population of microbial cells. At the critical dilution rate, the rate

of microbial growth is insufficient to replenish the cells being washed out. Above the critical dilution rate, all the cells are eventually washed out.

critical dissolved oxygen concentration The lowest possible concentration of oxygen in a *bioreactor or biological system below which oxygen becomes the limiting substrate for growth. Under normal operating conditions, the level of oxygen supplied must be sufficient to ensure that the microorganisms are able to function metabolically. A dissolved oxygen electrode is used to monitor the level of dissolved oxygen in the medium to ensure that sufficient oxygen is being supplied, which is usually in the form of sparged bubbles of air or oxygen.

critical flow *See* CHOKED FLOW.

criticality accident An accident occurring in the nuclear industry resulting in the release of dangerous levels of gamma and neutron radiation, and energy from uncontrolled *nuclear fission reactions.

critical mass The smallest amount of a fissile material required to sustain a nuclear fission chain reaction. In a *nuclear reactor, the chain reaction is controlled in order to produce thermal energy, which raises steam used to produce electricity. The fissionable material of an *atomic bomb is divided into portions, each less than the combined critical mass. When they are brought together at the moment of detonation, their combined mass exceeds the critical mass.

critical moisture content The moisture of a solid material at the point when the *constant rate drying period changes to the *falling-rate drying period. It is also used to represent the point between the *bound moisture and *unbound moisture content.

critical path analysis (CPA) A management tool used to manage complex projects. It uses all the necessary information about the project as individual activities and their inter-relationship, and the time required to complete them. The mathematical analysis allows the project manager to identify the critical path, which determines those activities that must be completed and the time taken to reach a target date. It was originally devised in the US as a visual planning technique to manage large-scale military projects and has been adapted to other project management applications, in particular engineering and construction projects.

critical point The temperature and pressure of a substance at equilibrium when two phases become identical and form a single phase. The **critical state** is the condition in which the density of both the liquid and vapour phases of a substance are the same as occurs at the critical point.

critical pressure The minimum pressure required to liquefy a substance at its *critical temperature.

critical properties The properties of substances at their *critical point. Critical properties include critical temperature, critical pressure, critical volume, and compressibility factors. They are used to determine the properties of liquids and gases.

critical temperature The temperature above which a gas cannot be liquefied by pressure alone.

critical velocity The velocity above which the flow of a fluid no longer continues to be streamline but becomes turbulent.

critical volume The volume occupied by one mole of a substance at its *critical temperature and *critical pressure, known as the critical state. The SI units are $m^3\ mol^{-1}$.

C

CRO An abbreviation for **c**ontrol **r**oom **o**perator, this is a person who forms part of a team based primarily in the control room of a process plant. The CRO is responsible for monitoring the screens and displays that present real-time data of the process, as well as taking appropriate action when process variables deviate beyond the expected limits. This is normally brought to the attention of the CRO by flashing displays and audible alarms.

cross-current separation A stage-wise liquid–liquid separation technique in which fresh solvent is added to each stage that progressively removes the solute (see Fig. 14). The number of stages and the amount of solvent needed is determined by a material balance at each stage. Experimental data is required to determine the effectiveness of each separation stage.

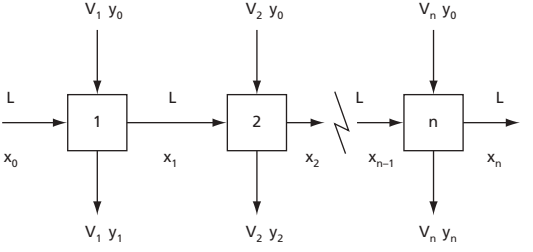

Fig. 14

crossflow filter A type of continuously operated filter configured such that the feed slurry flows across the face of the filter so as to prevent the build-up of solid material on the filter surface, but allows some of the liquid to pass through the filter.

crossflow plate A plate or tray used in a distillation column in which liquid flows enter from one side and flow across and out of the other (see Fig. 15). In a *distillation column the liquid is retained on the plate and prevented from descending through the perforations by the rate of upflow of vapour, bubble caps, or valve seals. A weir is used to control the depth on the plate over which the liquid descends to the plate below via the downcomer.

cross-sectional area The area of pipe or process vessel cut perpendicular to its axis. The cross-sectional area is the area through which material passes. For a circular cross section, the area related to diameter by $a = \frac{\pi d^2}{4}$. The volume of the pipe or vessel, V, is the cross-sectional area multiplied by the length $V = al$. The average velocity, v, of the movement of a fluid through a pipe is the volumetric flow, Q, divided by the cross-sectional area $v = \frac{Q}{a}$.

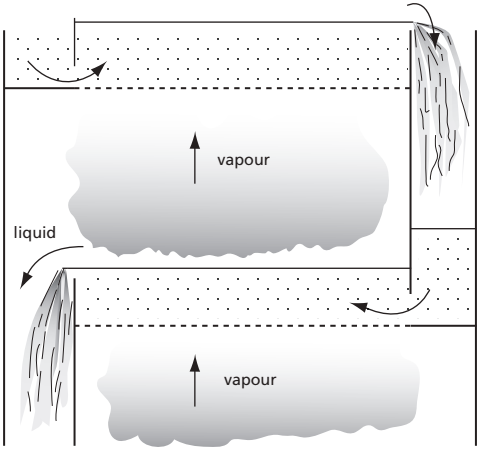

Fig. 15

crucible process An early process used to purify steel by heating steel in a graphite crucible and pouring the melt into a cast-iron mould. It is also known as the *Huntsman process. The method was used until it was superseded by the *Bessemer process.

CRUD A term used in the nuclear reprocessing industry to describe unidentified materials; it is an abbreviation of **c**orrosive **r**adioactive **u**ndetermined **d**eposit. It is usually used in the description of precipitation processes involving fission products.

crude distillation The separation or *fractionation of *crude oil into separate components or groups of components known as fractions in an distillation column called a

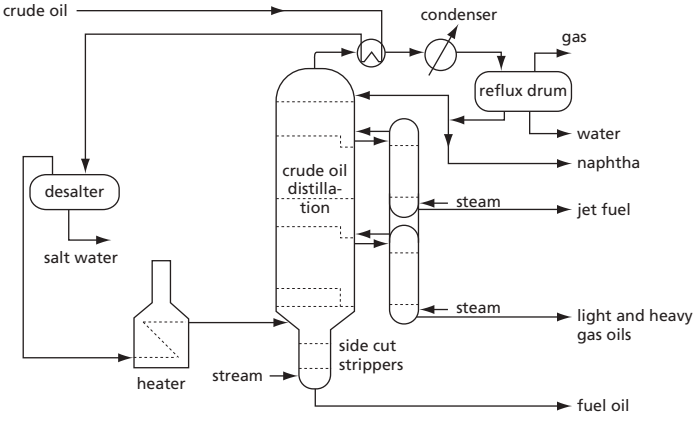

Fig. 16

fractionator operating at atmospheric pressure (see Fig. 16). It is the first step in the petrochemical refinery process in which the crude oil is first desalted and heated to around 370°C in a furnace. It is then separated into fractions according to their boiling points such as butanes, unstabilized naphtha, heavy naphtha, kerosene, and topped crude. This allows subsequent processing units to have *feedstocks that meet particular specifications. *Vacuum distillation is used to separate the heavier portion of the crude oil into fractions that would require higher temperatures to vaporize it at atmospheric pressure and cause *cracking to occur. The fractionator consists of a tall cylindrical column containing perforated trays upon which liquid sits and is in intimate contact with vapour rising up the column through the perforations. Unlike conventional distillation, the column does not feature a *reboiler. Instead, steam is introduced below the bottom tray to strip out any remaining gas oil and to reduce the partial pressure of the hydrocarbons. Reflux at the top of the column is provided by condensing the overhead vapour and returning a portion to the top. Side cut strippers are used to withdraw a liquid sidestream, which contains lower boiling point components, known as light ends. Steam is added and the vapour vented back into a higher position in the column.

crude oil A viscous black liquid composed of a mixture of hydrocarbons formed over millions of years through the gradual decay of buried aquatic animal and vegetable matter. It collects in vast underground pockets in sedimentary rock at depths ranging from a few metres to several kilometres. It is brought to the surface by drilling and pumping operations. It is then refined into useful products in *petroleum refineries.

crude unit A petrochemical refinery processing unit in which initial crude oil distillation takes place to make the first *cut. Lighter hydrocarbon products are further refined in a *catalytic cracker or *reforming unit. Heavier hydrocarbon products are further distilled by *vacuum distillation.

crusher A mechanical device used to reduce large quantities of coarse rock, ore, or other solid bulk material to smaller and more manageable sizes for further processing such as extraction. The main types of crusher include *jaw crushers, gyratory, and smooth-roll crushers that operate by compressing the material. Toothed-roll crushers tear the material apart as well as crushing it.

cryodesiccation *See* FREEZE DRYING.

cryogenic process A very low-temperature process used for separating substances, such as nitrogen and oxygen in air, that are gases at normal ambient conditions. Foods can also be preserved at very low temperatures using solid carbon dioxide or liquid nitrogen.

cryogenic pump A vacuum pump used to produce very low pressures of 10^{-6} Pa by the condensation of gases onto the surface kept at low temperatures using liquid hydrogen or liquid helium. It is possible to reduce the pressure further to 10^{-13} Pa with the combined used of a diffusion pump.

crystal A pure and homogenous solid form of matter in which the atoms, molecules, or ions are arranged in a regular and orderly three-dimensional array or lattice. A crystal structure is formed by the regular arrangement of atoms, molecules, or ions in which they have the same angle between their faces. However, depending on the conditions, different faces can grow at different rates, leading to slightly irregular-appearing shapes. *Compare* AMORPHOUS.

crystal bar process *See* VAN ARKEL–DE BOER PROCESS.

crystallization The process of forming crystalline substances from vapour, solutions, or melts. For example, snowflakes are formed from water vapour, ice is formed from water, and alum crystals from a saturated solution. A crystal may form from molecules, atoms, or ions by coming together randomly to form a cluster. An embryo is formed when sufficient particles have come together to form a solid phase. If *supersaturation is sufficient, the embryo may grow into a nucleus, which if it gains more particles, will grow into a crystal. The crystallization of petroleum fraction contaminants is used to remove wax and other semi-solid substances from heavier fractions. The removal of wax from lubricating oils involves mixing the oil with solvents and then cooling to a temperature of around -20°C to cause the wax to crystallize. This is then separated.

crystallizer A vessel used to contain and bring about the process of *crystallization. This involves nucleation and crystal growth within a supersaturated solution.

crystalloid A substance dissolved in a solvent that can pass through a *semi-permeable membrane.

CSTR *See* CONTINUOUS STIRRED-TANK REACTOR.

culture medium *See* BROTH.

cumene process A process used for the production of phenol from benzene. The process, developed in the 1940s, involves reacting benzene and propene (propylene) vapour over a phosphoric acid catalyst at high temperature and pressure to produce cumene (isopropyl benzene):

$$C_6H_6 + CH_3CH:CH_2 \rightarrow C_6H_5CH(CH_3)_2$$

The cumene is then oxidized in air and reacted with dilute acid to yield phenol.

cupellation process A process used to separate lead and other base metals from noble metals such as gold and silver by blowing hot air over the surface of the molten metal held in a shallow refractory dish known as a cupel. The lead oxidizes to lead monoxide, floats to the surface, and is then removed.

cupola furnace A brick-lined furnace known as a cupola used for the conversion of pig iron into iron castings. It involves charging the furnace with coke and igniting it. Air is forced up beneath a charge of heated material to raise the temperature required to bring about the conversion. The molten iron picks up carbon as it descends under gravity and is collected at the bottom.

Curie, Marie (née Marja Sklodowska 1867–1934) A Polish-born scientist noted for her work on ionizing radiation. Taught by her father, she was not accepted by Warsaw University but at the age of 24 she instead went to study in Paris. There she married Pierre Curie (1859–1906) four years later. Together they discovered radium and polonium. They extracted less than a gram of radium from eight tonnes of pitchblende, which was noted for its high *radioactivity. In 1903, together with Henri *Becquerel, the Curies received the Nobel Prize for Physics. However, Pierre was killed in a street accident three years later. She took his place as professor of physics at the Sorbonne, and in 1911 she was awarded the Nobel Prize for Chemistry, becoming the only woman to receive two Nobel prizes, and for different sciences.

curie (Symbol Ci) A former non-SI unit of radioactivity named after Marie *Curie. It was originally defined as the volume of radon gas in equilibrium with 1 g of radium-226. It is now associated with the quantity of a radioactive isotope that decays at a rate of 3.7×10^{10} disintegrations per second. The *becquerel (symbol Bq) is the SI-derived unit of radioactivity where one Bq is equal to one disintegration per second. The millicurie (mCi) and microcurie (μCi) are also used.

curing A process used for hardening polymers by causing the cross-linking of polymer chains. The curing process can involve the use of heat, ultraviolet radiation, and chemical additives. The curing process of rubber is known as *vulcanization.

customary units A system of measurement used in the US. These are largely similar to the British Imperial units.

cut A division in separating distilled products of differing compositions or purities from a distillation process based on composition or temperature. In the continuous fractionation of *crude oil, the *naphtha cut, which contains a number of different hydrocarbon compounds, has a boiling point range of around 35°C to 200°C. In the batch distillation of *whisky, the differential compositions of alcohol are termed the *foreshots and **feints** whose composition is determined by *specific gravity.

CVD *See* CHEMICAL VAPOUR DEPOSITION.

cyanide process A process used to extract gold from crushed rock. It involves dissolving the rock in aqueous sodium or potassium cyanide in the presence of air. The gold is converted to aurocyanide, which is then reduced back to gold with zinc in the following reactions:

$$4Au + 8KCN + 2H_2O + O_2 \rightarrow 4KAu(CN)_2 + 4KOH$$
$$2KAu(CN)_2 + Zn \rightarrow 2Au + K_2Zn(CN)_4$$

The process is also known as **cyanidation**.

cycle A series or sequence of periodic changes in which a system moves away and returns to its expected or normal condition or position. *See* THERMODYNAMIC CYCLES.

cyclic system *See* SYSTEM.

cyclone separator A device used to separate particles from air or a gas stream. Particles in sizes that typically range from 5 to 200 μm enter the separator with a high velocity, and are swirled around the circular chamber as a vortex under centrifugal action, and descend to the bottom of the separator for collection. The separated particle-free air or gas leaves the top of the separator. Cyclone separators are commonly used after a spray drying process to collect the dried product.

cylinder A geometric shape that has a uniform circular cross section and length. The length is greater or equal to the diameter. Examples of cylindrical vessels include drums and tanks, and may be either vertically or horizontally positioned along their axis. Columns are also cylindrical and mounted vertically, whereas gravity separators such as those used to separate oil, gas, and water on offshore platforms, are mounted horizontally.

Czochralski process A process used for growing single crystals. It involves melting a material in a crucible. A single crystal of the material is lowered onto the surface and drawn slowly upwards producing a cylindrical crystal known as a boule. The process is used to grow single crystals that have a high value, such as crystals of silicon and germanium used in the semi-conductor industry, and pure metals, such as platinum, silver, and gold, and synthetic gemstones. It is named after the Polish chemist Jan Czochalski (1885–1953) who invented the process in 1916.