D

DAC *See* DIGITAL-TO-ANALOGUE CONVERTER.

Dalton, John (1766–1844) A British chemist and physicist noted for his pioneering work on chemistry. From a poor Quaker family, he left his village school at the age of 11 and then taught at there from 12 to 14; from 15 he was a farm labourer. However, he began making scientific studies and even wrote a paper on his own colour-blindness. For 57 years Dalton kept a meteorological diary with over 200,000 observations. He began lecturing in Manchester and by 1800 was secretary of the Manchester Philosophical Society. He measured the rise in temperature of air when compressed and suggested in 1801 that all gases might be liquified by compressing and cooling them. After much work on vapour and gas pressures, he stated his law on partial pressures (*see* DALTON'S LAW) and applying Newton's idea of atoms in gases to his own work, formulated the law of Multiple Proportions in 1804. By 1808 he had a clear theory and published his famous Atomic Theory, which forms the basis of modern chemistry today.

Dalton's atomic theory A theory of chemical combination first postulated in 1803 by British chemist and physicist John Dalton (1766–1844). It includes the postulates that elements are made of individual particles (atoms); that atoms of the same element are identical and that different elements have different types of atoms; that atoms can be neither created nor destroyed; and that so-called 'compound elements' are formed when different elements join together to form molecules. He proposed symbols for the different elements that were later replaced by the present notation for chemical elements.

Dalton's law A law that states that the total pressure of an ideal mixture of gases or vapours is equal to the sum of the partial pressures of its components. The partial pressure is the pressure that each component would exert if it was present alone. The law was formulated by John *Dalton (1766–1844).

Damköhler number A dimensionless number, Da, used to relate the rate of a chemical reaction to certain phenomena that occur in the reaction. There are several types of numbers that are used whose definition depends on whether the chemical reaction is related to momentum transfer or to heat transfer. For example, for an nth *order of reaction, the Damköhler number is:

$$Da = kC_o^{n-1}t$$

where k is the rate constant, C_o is the initial concentration of reactant, and t is the reaction time. It is used to indicate the extent of conversion within continuous flow reactors. In continuous chemical processes, the Damköhler number is defined as the ratio of the chemical rate of reaction to the convective chemical reaction time. A second Damköhler number is defined as the ratio of the chemical reaction rate to the rate of mass transfer:

$$Da_{II} = \frac{kC_o^{n-1}t}{k_g a}$$

where k_g is the mass transfer coefficient and a is the interfacial area. There are two further Damköhler numbers related to heat transfer. They are all named after the German chemist Gerhard Damköhler (1908–44).

damping The gradual reduction or suppression of the oscillatory behaviour of a *process variable such as temperature, pressure, and liquid level in a controlled system or process. Damped harmonic oscillators satisfy the second-order differential equation of the form:

$$\frac{d^2x}{dt^2}+2\varsigma\omega_o\frac{dx}{dt}+\omega_o^2=0$$

where ω_o is the undamped angular frequency and ς is the damping ratio. Critical damping ($\varsigma = 1$) is where response to a change is abrupt, in which there is no overshoot of the set point. Under-damping ($0 < \varsigma < 1$) occurs when there is overshoot, while over-damping ($\varsigma > 1$) occurs when the response is slower than critical damping. An undamped system ($\varsigma = 0$) corresponds to its natural resonant frequency (ω_o).

Danckwerts, Peter Victor (1916–84) A British chemist awarded the George Cross for bomb disposal work in the Second World War. Noted for his application of simple science to complex industrial applications, he was Shell professor in chemical engineering at Cambridge University and executive editor of *Chemical Engineering Science*.

Danckwerts' surface renewal theory A conceptual mass transfer model used to describe the transfer of a substance from a liquid to a gas. It assumes that an element of the surface interface comprises a mosaic of elements of various ages. Each element has a random chance of being replaced by another element from the bulk of the liquid. A feature of the model is that a simple mathematical solution is used for complex cases involving chemical reactions. It was formulated by Peter V. Danckwerts (1916–84).

dangerous substance A chemical substance used or present in the workplace that can cause harm to people due to its physical or chemical properties if not correctly controlled. Such substances include liquids, vapours, gases, and dust in the form of solid particles or fibrous materials that can form an explosive mixture with air. Examples include paints, solvents, reagents, varnishes, flammable gases, such as LPG, dusts and particulates from foodstuffs, machining and sanding operations that can cause harm through fire or explosion. In the UK, the *DSEAR Regulations 2002 of the *HSE (Health and Safety Executive) are intended to protect workers and members of the public from dangerous substances.

Darcy, Henry Philibert Gaspard (1803–58) A French engineer who specialized in fluid hydraulics. In France, he was responsible for many significant hydraulic projects including the construction of a remarkable pressurized water network system in his birth town of Dijon. He developed a way of calculating head loss due to friction, which with further modification by the German mathematician and engineer Julius Weisbach (1806–71) became known as the Darcy–Weisbach equation. The unit of permeability, the darcy, is named after him.

Darcy–Weisbach equation An equation used in fluid mechanics to determine the pressure or head loss due to friction within a straight length of pipe for a flowing fluid:

$$\Delta p_f = f\frac{\rho v^2}{2}\frac{L}{d}$$

or in head form:

$$h_f = f\frac{L}{d}\frac{v^2}{2g}$$

where f is the **Darcy friction factor**, L and d are the pipe length and inside diameter, and v is the average velocity of the fluid. It is also known as the Darcy–Weisbach or **Moody friction factor** whose value depends on the nature of the flow and surface roughness of the pipe. Note that this friction factor is four times greater than the *Fanning friction factor. The value of the friction factor can be obtained from various empirical equations and published charts such as the *Moody diagram.

data Information that is obtained and accumulated from a process or system. It can be in the form of chemical information, measurements, observations, and numerical information used by computers, etc. A **database** is a collection of organized data stored in a computer. The data is available to users and used for various purposes, added to, deleted, or updated as required. The data can include chemical analyses, financial data, process flow information, accumulated history of process information, personnel records, etc. **Data processing** is the sequence of operations that is performed on data to extract information or to achieve some form of order. It usually refers to the use of computers to handle large amounts of data rapidly. **Data mining** is the structured organization of data used to identify relationships within large amounts of computerized data. It is used in various fields of science and engineering, and involves looking for existing or new patterns in data or sequences, as well as forecasting data from patterns within data.

datum A reference or benchmark point from which other measurements are taken. For example, it may be an arbitrary elevation from which other elevations are measured. For fixed offshore installations, the datum is taken as the seabed and not the sea level, which, due to the tide, is variable.

Davis, George Edward (1850–1906) Regarded as the founding father of chemical engineering, he began his career as an apprentice bookbinder. He decided to study chemistry at the Slough Mechanics Institute while working at a local gas works. He spent a year at the Royal School of Mines in London (later Imperial College) before moving to work in the chemical industry around Manchester. Identifying the main features in common to all chemical factories, his *A Handbook of Chemical Engineering* was published in 1901. Working as an alkali inspector, he was responsible for implementing the Alkali Act of 1863 recognizing the importance of air pollution and the need for environmental protection. He also published a series of twelve lectures given in 1888 at Manchester Technical School and helped to define chemical engineering as a distinct discipline.

Deacon, Henry (1822–76) A British chemist and industrialist who founded a major chemical factory in Widnes, Lancashire. He filed a patent for an improved process for the manufacture of sulphuric acid in 1853. He later filed many more patents which included alkali manufacture. In 1870, he invented an improved method for the manufacture of chlorine and hydrochloric acid that used copper chloride as a catalyst. The *Deacon process is named after him.

Deacon process A catalytic process that was once used to convert hydrochloride gas to chlorine gas used in the manufacture of bleaching powder. The bleach was used in the textile and paper industries, and the process was able to reduce the production of hydrochloric acid as a waste product. It involved reacting hydrochloric acid and oxygen in the form of air at a temperature of between 400°C and 450°C in the presence of a copper chloride catalyst:

$$4HCl + O_2 \rightarrow 2Cl_2 + 2H_2O$$

The process was invented by British chemist Henry *Deacon (1822–76) as a way of using the hydrochloric acid from the *Leblanc process. The process was later replaced by an electrolysis process for making chlorine from brine.

deactivation A complete or partial reduction in the reactivity of a substance such as an enzyme or poisoning of a catalyst.

dead band A term used to control a process representing the range through which an input signal can be varied without initiating a response. The dead band is often described as a percentage of the *span.

dead-leg A vertical section of pipe filled with stagnant process liquid that normally has no flow.

dead time The interval of time in a controlled process in which a *process variable begins to change after an input change or stimulus. It is also called a *delay.

de-aeration The removal of air, oxygen, or gas from a substance. This can be achieved by disengagement, by using agents to strip out the gas, by raising the temperature to achieve evaporation or boiling, or by using a reduced pressure.

dealkylation process A catalytic process used for the removal of alkyl groups from molecules. The process is carried out in an atmosphere of hydrogen and is therefore also called **hydrodealkylation**. An example is the formation of benzene from toluene:

$$C_6H_5CH_3 + H_2 \rightarrow C_6H_6 + CH_4$$

Dean number A dimensionless number, Dn, used for flow in curved channels. It is a modified form of the *Reynolds number used to characterize the flow and heat transfer of fluids particularly through helical coils as:

$$Dn = \mathrm{Re}\left(\frac{d}{d_C}\right)^{0.5}$$

where d is the tube's inside diameter and d_C is the diameter of the coil. It is, in effect, the ratio of the centrifugal force to the inertial force of the fluid.

death phase The interval of time that follows the stationary phase in the batch culturing of microorganisms in a bioreactor and where the number of viable cells begins to fall. This is due to complete consumption of available substrate such that the microorganisms then die.

Deborah number A dimensionless number, De, used to classify the rheological behaviour of a fluid, which is able to elastically store energy. It is defined as the ratio of the fluid characteristic time to the process or observed time, where the characteristic time is the stress relaxation time, τ:

$$De = \frac{\tau}{t}$$

Values of De that approach zero indicate liquid behaviour, while values that approach infinity have solid-like behaviour. It was coined by Israeli scientist Markus Reiner (1886–1976) from the Bible (Judges 5:5) as 'The mountains melted from before the Lord . . . '.

debottlenecking An analysis used to identify and find engineering solutions to the limiting part or parts of a process that restrict the way it operates. *See* BOTTLENECK.

de-butanizer A continuously operated distillation column used to remove butane as distillate from a mixed feed of hydrocarbons with the heavier components leaving the bottom of the column. Lighter hydrocarbons may also leave the top of the column with the butane. To ensure that the light hydrocarbons can be boiled and condensed in the liquid phase, the distillation is operated at a gauge pressure of around 10 bar.

decanting The process of separating a liquid from a settled solid suspension or from a heavier immiscible liquid in a vessel known as a **decanter**. This uses either gravity to bring about the separation or centrifugal force such as in a **centrifugal decanter**. The separation of the upper liquid layer can be achieved by careful pouring into a separate vessel or by siphoning of the upper layer. It is also known as **decantation**.

decay The spontaneous transformation of one radioactive nuclide into another radionuclide, or into another energy state of the same nuclide with the emission of one or more particles or protons. The decay of N_o number of nuclides to give N number of nuclides after a period of time t is given by $N = N_o \exp(-\gamma t)$ where γ is known as the **decay constant**.

decay ratio An oscillatory response to a controlled system defined as the ratio of successive peaks and troughs above and below the final steady-state value. *Quarter damping is regarded as the optimal decay ratio in which the magnitude of successive peaks or troughs is one-quarter of those of the preceding peaks or troughs.

DECHEMA An abbreviation for Gesellschaft für Chemische Technik und Biotechnologie, which is the German Society for Chemical Engineering and Biotechnology. Founded in 1926, it is based in Frankfurt and is a non-profit-making organization with over 5,000 members. It aims to support developments in chemical technology, biotechnology, and environmental protection.

SEE WEB LINKS

- Official website of DECHEMA.

deci- (Symbol d) A prefix used in the metric system to denote one-tenth. For example, 0.1 metre is the same as 1.0 decimetre (dm).

decimal reduction time (Symbol D) The time required to reduce the population of viable microbial spores ten-fold in the thermal sterilization process of foods that may be contaminated with harmful spores. Twelve successive reductions is known as a *botulinum cook or a **12-D process**. This is deemed to be sufficient to reduce statistically any potential spores of the highly pathogenic microorganism *Clostridium botulinum* to insignificant levels. This bacterium produces a highly toxic toxin which is destroyed in the cooking process.

decision tree analysis An engineering procedure used in complex multistage decision-making problems that involves planning and organizing decisions. It takes into account how choices are made at earlier stages, the outcomes of possible external events that determine the types of decisions, and events at later stages of that sequence. The decision-making tree represents, in an organized way, the decisions and events that introduce uncertainty, as well as possible outcomes of all those decisions and events. The

nomenclature involves squares that represent decisions. Lines from squares represent options that can be selected. Circles show various circumstances that have uncertain outcomes. Lines from circles denote possible outcomes of that uncontrollable circumstance.

decommissioning The procedure of closing down a chemical process or nuclear facility to a point that permits the release of the property for demolition and site clearance. In nuclear power and reprocessing plants, decommissioning begins by closing down the facility, followed by reducing residual radioactivity to a low level. In nuclear power plants, the process begins with the removal of the nuclear fuel, coolant, and radioactive process waste. The three recognized stages of decommissioning involve safe enclosure, partial removal with safe enclosure, and the complete removal of materials.

decomposition 1. A chemical reaction in which a compound breaks down into more simple compounds or into elements. **2.** The chemical breakdown of organic matter into its constituents by the action of bacteria and other organisms. **3.** The factorization of an integer into other integers that are second- or third-degree (squares or cubes).

decontamination A process that involves the complete removal of hazardous or harmful substances from the surfaces of process pipes, vessels, and equipment. Various cleaning methods are used including acids, rinsing, and the use of steam.

decrepitation A cracking sound produced when certain crystals are heated. This is caused by the loss of water of crystallization during changes in the structure of the crystals.

deep shaft process A biotechnological process used to treat and purify domestic sewage and industrial biodegradable effluents. It consists of a tall vertical loop-type bioreactor with a height of between 30 m and 150 m that is usually installed below ground level. Compressed air is introduced into the downflow leg to drive the circulation of the liquid medium containing microorganisms. As the liquid rises up the upflow section, the hydrostatic pressure decreases, and the bubbles add to the mixing and aeration. This type of bioreactor is used where there is a high oxygen demand such as in the processing of activated sludge. The sludge can therefore have a higher density than conventional *activated sludge systems. It is also known as a **deep shaft airlift fermenter**.

de-ethanizer A continuously operated distillation column used for the removal of ethane as distillate from a mixed feed of light hydrocarbons. Any methane also leaves the top of the column along with the ethane while heavier components leave the bottom. To ensure that the light hydrocarbons can be boiled and condensed in the liquid phase, the distillation is operated at a gauge pressure of around 14 bar.

defined medium A growth medium used for the culture of microorganisms in which the composition and concentration of all the chemicals is known. It is also known as synthetic medium.

deflagration A type of subsonic explosion as a result of a combustion-type chemical reaction in which the *shock wave arrives before the combustion reaction is complete. The flame front advances outwards, whereas the reaction front advances into the unreacted substance. *Compare* DETONATION.

deformation The change in shape of a body due to shrinkage, stretching, or torsion but does not involve breaking up or destruction of the body.

degassing The release of dissolved, absorbed, or adsorbed gases from a liquid or solid. Degassing is often achieved in reduced pressure or vacuum systems.

degradation 1. The reduction of complex molecules into smaller, simpler molecules through natural processes (biogradation) or synthetic processes. **2.** An organic chemical reaction in which a compound is converted into a simpler compound. For example, the action of certain enzymes can bring about the degradation of proteins to amino acids.

degree 1. A division on a *temperature scale. **2.** An angle equal to 1/360th of a circle. **3.** The highest power of a polynomial. For example, the quadratic equation $ax^2+bx+c=0$ has a degree of 2. **4.** The highest power to which a derivative of a differential equation is raised. For example:

$$\left(\frac{d^2y}{dx^2}\right)^4+\left(\frac{dy}{dx}\right)^3=0$$

is a second order differential equation of the fourth degree.

degrees absolute *See* ABSOLUTE.

degrees of freedom The number of independent variables that are needed to describe fully the equilibrium state of a system or process. In defining the thermodynamic equilibrium for a system involving components and phases, the thermodynamic degrees of freedom are the minimum number of variables (temperature, pressure, and composition) that must be stated to define the system completely. In the use of statistics, the degrees of freedom refers to the number of values that can be varied in a calculation determined from the difference between the number of independent values (sample size) and the steps (which is usually one). It is used frequently in linear regression and *analysis of variance calculations, and in some other calculations involving the sum of squares.

dehumidification The process of decreasing the water vapour or humidity of air or a gas through the processes of condensation at a cold surface, diffusion of an absorbing agent, chemical reaction, or heating.

dehydration The process of removing water from a substance. *See* DRYING.

dehydrogenation A chemical reaction involving the removal of hydrogen from a compound. In organic molecules such as straight-chain hydrocarbons or fatty acids, single carbon–carbon bonds are converted into double bonds by the removal of hydrogen atoms.

deionization A process used to purify water by the removal of mineral ions such as the cations calcium, copper, iron, and sodium, and chloride and sulphate anions. The process uses ion exchange resins that exchange the hydrogen and hydroxide ion for dissolved minerals and then form water. Deionized water is used for many purposes such as the cooling water in nuclear reactors. It is also used as an alternative to distilled water in the laboratory. With the absence of ions, deionized water does not conduct electricity.

De Laval, Carl Gustaf Patrik (1845–1913) A Swedish mechanical engineer who worked on the design of steam turbines and machinery used in the dairy industry. After gaining his doctorate in 1867, he invented a number of machines used in the dairy

industry, including a cream separator that involved a spinning container powered by a steam engine. The centrifugal action permitted the lighter cream to separate to the inside with the heavier milk moving to the outside. His most notable achievement was the development of the impulse steam turbine in 1882 that could operate at 42,000 rpm. It was used in many industries through special reduction gearing mechanisms allowing high-speed turbines to drive slow-speed shafts such as propellers for ship propulsion. He was a member of the Royal Swedish Academy of Sciences and was elected to the Swedish parliament. Together with Oscar Lamm (1848–1930), he founded the Alfa Laval company in 1883.

delay A commonly used term instead of *dead time in process control.

del factor The ratio of the number of viable contaminating microorganisms to the initial number in a sterilization process. It is used as a measure of the effectiveness of a sterilization process in which the population of viable microorganisms is reduced due to a combination of both temperature and time.

deliquescence The absorption of moisture from the atmosphere by hygroscopic solids. The extent of the effect produces a concentrated liquid solution of that solid. Examples include sodium chlorate, sodium hydroxide, and calcium chloride.

delivery pressure The pressure of a fluid at the outlet of a pump.

delta (Symbols Δ and δ) As a capital, it represents the difference between two values such as the difference in pressure between two points, Δp. As a lower case, δ commonly represents a partial derivative used in partial differential calculus.

de-methanizer A continuously operated distillation column used in petrochemical refineries to remove methane as distillate from a mixed feed of light hydrocarbons. Any hydrogen will also leave from the top of the column while ethane and other heavier components leave from the bottom. To ensure that the hydrocarbons can be separated in the liquid phase, the distillation process is typically operated at a gauge pressure of around 24 to 28 bar and temperature of –60°C.

demister A device used to remove a fine dispersion of liquid droplets from a gas or vapour. In the processing of natural gas, demisters are often called *scrubbers.

denature 1. To produce an irreversible structural change in a protein or nucleic acid that results in the total or partial biological inactivation. Denaturation can be caused by certain chemicals, high temperature, very low and high pH, ionizing radiation, and UV light. **2.** To add a poisonous or unpleasant smelling substance to ethanol to make it unsuitable for human consumption.

dendrite A crystal that has grown into a tree-like structure.

denitrification A natural process involving a chemical reaction in which nitrates in soil are reduced to molecular nitrogen.

denominator The bottom part of a mathematical fraction. Used in ordinary division operations, it is the number or expression by which the numerator is divided. For example, in the fraction ½, 2 is the denominator and 1 is the numerator. The denominator is the divisor.

dense gas A gas that has a density greater than that of air at the same temperature. A **dense gas cloud** is a release of a gas-and-air mixture that is heavier than the surrounding air. The density of the cloud may be heavier due to its temperature being below ambient.

densitometer An instrument used to measure the density of a substance by measuring the volume for a given mass.

density The mass of a substance per unit volume. The SI units are kg m^{-3}.

dependent variable *See* VARIABLE.

dephlegmator A condenser used in a distillation process in which only part of the vapour is condensed and used as reflux. The rest of the vapour is used as the top product. A dephlegmator is also known as a *partial condenser.

depleted uranium Uranium mostly consisting of the non-fissionable isotope uranium-238, obtained as a *by-product of enriching natural uranium in a nuclear reactor, or obtained from nuclear reprocessing plants. Being radioactive with a *half-life of many thousands of years, it therefore needs to be stored for indefinite periods of time. It has a very high density of 19,000 kg m^{-3} and has found use in various military applications such as coatings for armour-piercing missiles.

deposition *See* CONDENSATION.

depression of freezing point The reduction of the point of freezing of a pure liquid when another substance has been dissolved in it.

DePriester charts *Nomographs that present the complex relationships between pressure, temperature, and *K-factor for various light and heavy hydrocarbons. They are used to determine the *bubble point and *dew points of hydrocarbon mixtures and were first published in 1953 as an improvement on earlier charts known as Kellogg charts.

de-propanizer A continuously operated distillation column used to remove propane as distillate from a mixed feed of hydrocarbons with the heavier components leaving the bottom. Lighter hydrocarbons may also leave the top of the column with the propane. To ensure that the light hydrocarbons can be separated by distillation, the distillation column is typically operated at a gauge pressure of around 10 bar.

depth The distance downwards from a reference location or plane. For example, the depth within a liquid is the distance below the surface, while the depth of a mineral ore mine can refer to the horizontal distance to the back of the mine.

derivative 1. A compound that is derived from another compound and retains its general structure. **2.** A function derived from another by the application of differentiation and partial differentiation. A second-order derivative is a derivative of a derivative.

derivative action control A mode of control used to control a process in which the controller output is proportional to the rate of change of the process variable or process error. *See* PID.

derived units An acceptable unit that is defined from base *SI 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. The newton (N) is a derived unit of force where 1 N is equal to 1 kg m s^{-2}. The pascal (Pa) is the derived unit for pressure where 1 Pa is equal to 1 kg m^{-1} s^{-2}. *See* BASE UNIT.

derrick The tall metal tower on an oil or gas drilling platform above a well. It is used for lifting and lowering tubes and tools down into the well.

desalination The removal of salt from seawater used to provide potable water for drinking or irrigation purposes. Desalination is only used where there is a cheap source of energy and where there is a distinct shortage of fresh water. Desalination methods used include reduced pressure evaporation, freezing, reverse osmosis, electrodialysis, and ion exchange.

desalting The process of removing mineral salts from water-containing oil.

desiccation The process of drying and removing the moisture within a material. It involves the use of a drying agent known as a **desiccant**. Desiccants that function by adsorption of moisture include silica gel and activated alumina, while chemical desiccants that function by the reaction with water to form hydrates include calcium chloride and solid sodium hydroxide. A **desiccator** is a container used for drying substances or for keeping them dry and free of moisture. Laboratory desiccators are made of glass and contain a drying agent such as silica gel.

design codes (design standards) Published standards required for equipment and working practices within the chemical and process industries that represent good practice and define the level or standard of design. Developed and evolved over many years and based on tried and tested practices, there are a number of national standards organizations and institutions that provide published standards for design, materials, fabrication, and testing of processes and equipment. These include the British Standards Institute (BSI), the Institute of Petroleum (IP), the American Petroleum Institute (API), the American National Standards Institute (ANSI), the American Society of Mechanical Engineers (ASME), the American Society for Testing and Materials (ASTM), and the American Iron and Steel Institute (AISI). In Europe, there has been a steady move towards harmonization of national standards with the formation of the Euronorm (EN) engineering standards.

design project A distinguishing feature of degree programmes in chemical engineering that are accredited by the *Institution of Chemical Engineers. The design project features near the end of the degree programme and involves the complete design of a chemical process from raw materials through to the production of a product that is defined in terms of an output flow rate and quality. Typically working in teams, students are required to pool their accumulated knowledge in chemical engineering to meet the specifications, which involves the production of a *flowsheet, material balances, and energy balances, with unit operations that typically include mixing, chemical reaction, and separation. It also includes process economics, safety, environmental issues, start-up, *HAZOP, and the preparation of a *P&ID.

desorption The removal of absorbed atoms, molecules, or ions from the surface of a solid material. It is the reverse of absorption and can be achieved by the use of heat.

desublimation *See* SUBLIMATION.

desulphurization A process used to remove sulphur from crude oil and refined petroleum products, and also the removal of hydrogen sulphide from natural gas. It involves a catalytic reaction in the presence of hydrogen. The use of bacteria to remove sulphur from crude oil has also been developed. It is important to remove sulphur as it poisons catalysts and results in harmful sulphur dioxide in the combustion of fuels. Also known as **hydrodesulphurization**, the process involves a high temperature and pressure reaction in the presence of a nickel or alumina catalyst impregnated with molybdenum.

detection limit The ability of an instrument or an analytical technique to detect and measure the lowest quantity of a substance, or some other variable such as temperature or pressure. In analytical work, confidence limits are usually stated for the level of detection.

detonation A supersonic combustion process in which the reaction front advances into unreacted material with a flame front or shock front and reaction products travelling in the same direction. The resulting *blast wave is initially characterized by a very high peak pressure acting over a very short period of time. As the wave travels outwards from the source, the pressure decays. *Compare* DEFLAGRATION.

deuterium (Symbol D) Heavy isotope of hydrogen with a mass about double that of ordinary hydrogen and is sometimes known as heavy hydrogen. A **deuterated compound** is a compound in which some or all of the hydrogen-1 atoms have been replaced by deuterium atoms. Heavy water is water in which the hydrogen atoms are replaced by deuterium oxide (D_2O). It is found naturally in water in very small amounts, and can be separated and concentrated by *fractional distillation or by *electrolytic separation; it is used as a moderator in the nuclear industry due to its ability to reduce the energy of fast-moving neutrons.

deviation The departure from a desired or expected process value. Monitoring departures from expected operating conditions forms the basis of *process control.

devitrification The loss of amphorous structure of glass as a result of crystallization. It is the opposite of *vitrification. It occurs very slowly in nature, which is why glassy rocks are rarely found, having turned to crystalline structures over time.

Dewar, Sir James (1842–1923) A Scottish chemist who was the first to liquify hydrogen in 1898 and later succeeded in solidifying it. He studied the magnetic properties of liquid oxygen and ozone, and the phosphorescence of substances at low temperatures. He invented the *Dewar flask for keeping liquids at very low temperatures.

Dewar flask A container used for storing hot or cold liquids that are able to maintain their temperature independently from their surroundings. The heat loss is kept to a minimum by using a container held within a container separated by a vacuum. The thin walls of the inner container are made of glass (or steel in the case of bigger containers). The inner surface of the glass vessel is silvered to reduce loss through radiation. It was devised around 1872 by Sir James *Dewar, and is also known by its trade name Thermos flask.

dewaxing A process used to remove *wax from processed lube oil to allow it to flow at ambient temperature. Either refrigeration is used to crystallize the wax with the use of solvents to dilute the oil to allow filtration of the wax from the oil; or selective *hydrocracking is used to crack the wax to form light hydrocarbons.

dew point The temperature at which drops of condensate first appear on cooling a condensing vapour. When the *relative humidity of the vapour is 100 per cent, the wet and dry bulb temperatures are the same. When the relative humidity is less than 100 per cent, the wet bulb is less than the dry bulb temperature.

diafiltration A type of *ultrafiltration membrane separation process involving a *semi-permeable membrane to remove salts and microsolutes from a solution. These are small molecules that are separated from larger molecules, which are retained as the *retentate. Unlike *dialysis, which uses osmotic pressure to drive the solutes across the membrane, diafiltration uses an external force such as pressure. The process is typically used to reduce the level of salts in solutions containing proteins, peptides, nucleic acids, and other biomolecules from biochemical processes.

dialysis The separation of molecules in a liquid by differences in their ability to pass through a *semi-permeable membrane using osmotic pressure. Large molecules such as glucose or amino acids in an aqueous solution can be separated by diffusion across the membrane in which they move from an area of high concentration to one of low concentration. Smaller solutes and water are able to pass through the pores of the membrane and retain the larger molecules. The cells of living organisms are semi-permeable. The kidneys in the body are used for the excretion of nitrogenous waste. An artificial kidney also uses dialysis for the same purpose. *Compare* DIAFILTRATION.

diameter (Symbol d) The distance across a circular plane figure at its widest point. The internal diameter of a pipe of uniform cross-sectional area is twice the internal radius of the pipe.

diamond-anvil cell A device used for producing extremely high pressures. Using a screw arrangement, high pressures of up to a megabar (1 Mbar or 10^{11} Pa) can be generated within a small chamber or cell that contains two high-quality diamonds through which samples of materials under investigation can be observed optically. It is used to study the effects of materials under very high isostatic pressures.

diaphragm pump A type of reciprocating pump used to transfer liquids in which a flexible diaphragm is flexed to and fro. The liquid is drawn into a chamber and expelled as the diaphragm flexes. Non-return or *check valves ensure that the liquid flows in the desired direction. The diaphragm provides a barrier between the liquid and the moving mechanical parts of the pump. It is a comparatively low-maintenance sealed pump and useful for transporting liquids where leakage may be a concern. They also have the ability to stall if run against too high a pressure. A **double diaphragm pump** is a variation that has two diaphragms that are flexed to and fro separating a wetted chamber and used where it is essential to fully safeguard against leakage. They are therefore used in the nuclear reprocessing industry, such as in the transfer of radioactive solutions.

diaphragm valve A type of valve in which a flexible membrane is used to restrict the rate of flow. The membrane is usually made from a flexible natural or synthetic rubber. Diaphragm valves are typically used for fluids that contain suspended solids.

diauxic growth The growth of a microorganism that first assimilates a limiting substrate and, on eventual depletion, it metabolically adjusts itself to assimilate another limiting substrate. For example, in the batch culture of yeast, sugar is first assimilated with the

production of carbon dioxide and ethanol. Once the sugar has been depleted, the yeast then has a further period of growth in which the ethanol is used as the limiting substrate. *See* GROWTH CURVE.

Diesel, Rudolph (1858–1913) A German inventor who invented the diesel engine that was first publicly exhibited in 1898. He built a factory and spent the rest of his life perfecting and constructing his engine. While on a night steamer crossing the English Channel to England, he fell overboard and was drowned.

Diesel index An empirical measure of the ignition quality of a diesel fuel defined in terms of the *API gravity and aniline point of the fuel. The higher the number, the better the ignition quality.

differential calculus A branch of mathematics that is concerned with the behaviour of functions at a point and involves the evaluation of the derivative at that point, written as dy/dx or f(x). The derivative gives the slope or gradient of the tangent to the function at x. The overall process of obtaining the derivative is called **differentiation**, and the reverse is called **integration**.

differential distillation A batch distillation process used to separate components in a liquid mixture that does not involve reflux. As the charge is boiled, the first distillate is richest in the more volatile component. As the distillation proceeds, the vaporized product becomes leaner. The distillate can therefore be collected into fractions or cuts of differing purities. *See* WHISKY.

differential equation A mathematical equation expressed as a *derivative of one variable with respect to another. The order of the differential equation is the order of its highest derivative. There are many types of differential equation and each has its own method of solution. The simplest form of differential equation has separable variables enabling each side of the equation to be integrated separately. For example, the rate of change in level, dH/dt, in a vessel of uniform cross-sectional area, A_t, containing a liquid allowed to drain freely through an orifice of cross-sectional area a_o located at the bottom of the tank can be given by the first order differential equation with separable variables:

$$A_t \frac{dH}{dt} + C_d a_o \sqrt{2gH} = 0$$

The *degree of a differential equation is the highest power to which a derivative of a differential equation is raised.

differential pressure The difference in pressure between two points. The difference may be due to frictional pressure resistance of a flowing fluid, blockage, and obstacles, and for some types of flow meters, it can be used to determine flow rate. The differential pressure can be measured using devices such as *manometers. A **differential pressure cell** is widely used to measure the flow rate in pipes in which the differential pressure measured across an orifice is converted to a pneumatic, electrical, or mechanical signal for transmission to a local controller. *See* DP CELL.

differential scanning calorimetry (DSC) A thermal technique used for the analysis of substances in which heat is electrically added or removed to change the temperature, thereby allowing enthalpy changes due to thermal decomposition to be accurately studied.

differentiation A mathematical process used to find the rate at which one variable changes with respect to another. The result of differentiation of a function of y = f(x) is dy/dx or f'(x) and called the *derivative. On a graph of f(x), dy/dx is the slope of the tangent to the curve y = f(x) at that point. In general, the rule for differentiation is that where $y = ax^n$ than

$$\frac{dy}{dx} = anx^{n-1}$$

Tables of standard differentials are used for other forms of equation.

diffuser A widening section of a duct or channel used to carry air or a gas, which is shaped in such a way that its kinetic energy is converted to pressure energy.

diffusion The process of movement in which molecules of one substance move and penetrate other substances. In a mixture of gases, the rate of diffusion of one gas into another is inversely proportional to the square root of its densities (*see* GRAHAM'S LAW). In liquids, the diffusion of a solute through a solvent to produce a solution of uniform concentration is slower. Diffusion in solids occurs much more slowly.

diffusion coefficient, diffusion constant (Symbol D) A proportionality constant between the molar flux as the result of the molecular *diffusion of one substance in a mixture and the driving force. The driving force is a concentration gradient across the mixture. The greater the value, the greater the diffusion of the substance into the other. The use of subscripts such as D_{AB} represents the diffusivity of substance A in substance B. The diffusivity of gases is dependent on temperature, pressure, and the nature of the gas components. The diffusivity of liquids, however, varies appreciably with concentration. For gases, the coefficients are either obtained experimentally or are based on formulae that are based on *kinetic theory. For liquids, empirical correlations are generally used. The SI units are $m^2 s^{-1}$. Typical values for the diffusivity of gases is in the order of $10^{-5} m^2 s^{-1}$ and for liquids in the order of $10^{-9} m^2 s^{-1}$. *See* FICK'S FIRST LAW OF DIFFUSION; FICK'S SECOND LAW.

diffusion flame The combustion of an unmixed fuel in oxygen that results in a laminar flame in which the propagation of the flame is governed by the diffusion of the fuel and oxygen (air). A candle flame is an example of a diffusion flame.

diffusivity Another name for *diffusion coefficient.

digester A vessel used to produce cellulose pulp from wood chips. The wood chips are reacted with chemicals and heated under pressure to remove lignin. The digester is the first step in the process of making paper.

digital signal Used in the computer control of processes, it is a discrete value at which an action is carried out. As a binary signal using the notation of 0 or 1, it is often used to represent on or off.

digital-to-analogue converter (DAC) The electronic hardware used in the control of processes that converts a *digital signal to an analogue signal such as electrical voltage or current.

dilatant A non-Newtonian fluid in which the apparent viscosity increases with shear rate. That is, it thickens when it is being sheared. It can be described by:

$$\tau = k\gamma^n$$

where τ is the shear force, γ is the shear rate, and n has a value greater than unity. Examples include titanium dioxide suspensions, cornflour and sugar suspensions, and cement aggregates.

dilation (dilatation) An increase in volume.

diluent A substance that is added to dilute a solution or mixture; to reduce the strength of a solution by the addition of water or other solvent. Diluents are used to alter the viscosity of a solution in order to meet specifications, such as the addition of naphtha or condensate to heavy oils to meet pipeline specifications for transportation. In solvent extraction, diluents are inert solvents such as kerosene in the *purex process to control the extraction capacity of the organic layer.

dilution The volume of solvent in which a given amount of solute is dissolved.

dilution method A method used to calibrate flow meters. It involves the addition of a concentrated extraneous material whose presence can be quantitatively determined by an analytical technique. The extraneous material may or may not be one that is already present as an impurity and is diluted into the flow of fluid whose flow rate is being measured. Examples are salt in water, ammonia in steam, and chlorine in oxygen. The procedure is to add steadily a known amount of extraneous material to the flowing process fluid over a known period of time. If the addition is made upstream of the meter, the latter can act as a mixing device during the period before samples of the fluid are taken downstream of the meter and then analysed. For the addition of extraneous material added upstream of the meter this can be expressed mathematically as:

$$Q_i C_i + Q_a C_a = C_o (Q_i + Q_a)$$

where Q_i is the flow rate of the process fluid, Q_a is the flow rate of the extraneous material, C_i is the concentration of the extraneous material in the process fluid, C_a is the concentration of the added extraneous material, and C_o is the diluted downstream concentration. This equation can be rearranged to calculate the flow rate of the process fluid as:

$$Q_i = Q_a \left(\frac{C_a - C_o}{C_o - C_i} \right)$$

If the addition of extraneous material is after the meter, then the meter measures Q_i and not Q_i+Q_a.

dilution rate (Symbol *D*) A term used in the continuous operation of a fixed volume vessel supplied with a constant flow stream of material and an equal amount leaving, and defined as the ratio of volumetric flow rate, *Q*, to volume of the vessel, *V*:

$$D = \frac{Q}{V}$$

In the continuous cultivation of microorganisms in a bioreactor containing viable cells, fresh nutrients and limiting substrate promoting growth are supplied while inhibiting metabolic products are withdrawn at the same rate. A material balance for cells, *X*, and limiting substrate, *S*, for an ideally mixed bioreactor is:

$$\frac{dX}{dt} = \mu_S X - DX$$
$$\frac{dS}{dt} = D(S_o - S) - \frac{\mu_S X}{Y_{X/S}}$$

where S_o is the concentration of supplied substrate, μ_S is the growth rate, and $Y_{X/S}$ is the yield coefficient. The SI unit is s^{-1}.

dimensional analysis A method used to check an expression or a solution to a problem used to describe an observable phenomenon. There must be dimensional consistency between the variables and the phenomenon. The relationship of the variables are considered in terms of their dimensions, such as mass, length, time, heat, and temperature, and are regrouped into dimensionless groups. These groups, by virtue that they have no scale of size, mass, or time, can then be used to study the effects of any terms in any situation independent of its application. Dimensionless groups are therefore important in both scale-up and scale-down of processes in chemical engineering.

dimensionless number (or group) A group of variables, which collectively, have no dimensions. They are used to describe observable phenomena such as friction in pipes, the behaviour of fluidized and packed beds, and heat transfer from surfaces. Examples of dimensionless numbers in fluid flow and heat transfer include the *Reynolds number and the *Fourier number, respectively. They are particularly useful for scale-up and scale-down in chemical engineering and can be obtained through *dimensional analysis.

dimensions 1. The size of an area or a body, such as a rectangle or a cylinder that is measured in terms of breadth, height, and diameter. **2.** The product or quotient of the basic physical quantities, raised to the appropriate powers, in a derived physical quantity. The basic physical quantities are mass, length, and time from which derived quantities can be formulated. For example, force is defined as the product of mass [M] and acceleration [LT^{-2}] to give [MLT^{-2}]. Pressure is defined as force per unit area [L^2] to give the derived units of [$ML^{-1}T^{-2}$]. **3.** The number of coordinates needed to define a line, shape, or solid. A rectangular area is two-dimensional and a solid is three-dimensional.

direct-acting controller A type of control device used to control a process in which the output signal from the controller increases with increasing measured (input) value. It has a negative gain. *Compare* REVERSE-ACTING CONTROLLER.

directional solidification A process used to cool a liquid metal or alloy to form a solid casting in which the solidification is allowed to occur progressively along the length of the casting. The process is used to overcome shrinkage problems in alloys, and is also used to remove impurities from the metals in which the impurities collect at the liquid–solid interface. The end piece containing the impurities can then be cut off and removed for recycling.

disc-and-doughnut An arrangement of plates used in distillation and adsorption columns in which alternate discs and rings (doughnuts) are used to allow liquid to cascade

from a disc onto a ring and down onto another disc. This arrangement allows a good contact of descending liquid with ascending vapour, and also has the benefit of a low pressure drop up the column.

disc centrifuge *See* BOWL CENTRIFUGE.

discharge head The *delivery pressure from a pump expressed as a head rather than as a pressure for which the SI unit is metres of the fluid being pumped.

discontinuous phase The phase in a dispersion or emulsion, which is dispersed as particles or droplets in the continuous phase.

dispersion The mixture of one substance dispersed within another as bubbles, drops, or particles. A **dispersed phase** is the dispersion of one phase within another such as suspended gas bubbles, droplets, or solid particles dispersed in a liquid. Fog is the dispersion of water droplets in air, a colloid is a dispersion of suspended particles, and margarine consists of water dispersed in a hydrogenated fat phase. *Compare* CONTINUOUS PHASE. **Dispersed flow** is a two-phase flow of liquid in a vapour or gas in which the liquid is almost entirely entrained as fine droplets.

dissociation A reversible chemical reaction in which ionic compounds break down into smaller particles. For example, in the reversible dissociations of:

$$2HI \Leftrightarrow H_2 + I_2$$

the dissociation constant is constant and is given by:

$$K_d = \frac{[H_2][I_2]}{[HI]^2}$$

The brackets denote the equilibrium concentrations. For gases, this can be expressed in partial pressures.

dissolve The ability to make or become a solution.

distance–velocity lag The *dead time of a signal in a controlled system between the measurement of a variable in a process and making the appropriate controlled adjustment, and seeing some effect due to that adjustment arising solely from the finite speed of the propagation of the signal. For example, it may arise from the measurement of temperature of a flowing fluid in a pipe located downstream some distance from a heat exchanger being controlled. Most in-line chemical analysers such as gas chromatographs take time to return a value once a process sample has been taken and can lead to a dead time.

distillate The liquid or vapour from the top of a *distillation process that is rich in the more volatile component. **Distillate fuel** is a light group of oils extracted by crude oil distillation. They include diesel oil, light heating oil, and heavy gasoils that are used as a feedstock for other petrochemical products. Diesel oil is distilled at between 180°C and 380°C and used in diesel engines.

distillation The separation of liquids by virtue of their difference in boiling points. The process consists of boiling the liquid mixture and condensing and collecting the vapour. It

is used to purify liquids and to separate liquid mixtures into its constituent components. It is the most widely used method for the separation of miscible liquids and takes place in a *distillation column.

distillation column A tall vertical cylindrical vessel used for the process of *distillation. Hot vapour rises up the column, which is brought into intimate contact with cooled liquid descending on stages or trays for a sufficient period of time so as to reach equilibrium between the vapour and the liquid. The vapour rises up from the tray below through perforations in the tray, and the liquid on the tray flows over a weir to the tray below. In this way, the more volatile component increases in concentration progressively up the column. In continuous distillation, fresh feed is admitted at the tray corresponding to the same composition. Below the feed point, the section of column is known as the stripping section, while above is known as the rectifying section. A *reboiler heat exchanger is used to boil the bottom product and produce vapour for the column. A *condenser is used to condense some or all of the vapour from the top of the column. A small portion of liquid is returned to the column as *reflux. The height of the column is an indication of the ease or difficulty of separation. For example, an ethylene splitter in a petrochemical refinery used to separate ethylene from ethane, which have close boiling points, requires many trays and the column is very tall. The width of the column is an indication of the internal vapour and liquid rates. In batch distillation, a charge of feed for separation is fed to the still and allowed to be boiled. The vapour is rich initially in the more volatile component or components. Scotch *whisky distillation uses copper stills and operates as a single equilibrium stage. Multistage rectification is used in small production units where a pure product is required.

distillation train A sequence of distillation columns used to separate components from a multicomponent feed. Each column is required to perform a particular separation of either a pure component or a cut between two components. For example, in the separation of four components ABCD in a mixture in which A is the most volatile and D the least, then the five possible separation sequences requiring three columns are:

Separation	*Column 1*	*Column 2*	*Column 3*
1	A:BCD	B:CD	C:D
2	A:BCD	BC:D	B:C
3	AB:CD	A:B	C:D
4	ABC:D	A:BC	B:C
5	ABC:D	AB:C	A:B

Where it is required to separate a larger number of components, the number of possible separation sequences becomes much larger according to the relationship

$$N = \frac{(2n-2)!}{n!(n-1)!}$$

where N is the number of sequences and n is the number of components:

Components (n)	4	5	6	7	8	9	10
Sequences (N)	5	14	42	132	429	1430	4862

Due to the difficulty in seeking the best train sequence, enumerative or heuristic approaches are used to rapidly identify the best train.

distilled water A form of water that has been purified by the process of distillation such that it is free from dissolved salts and other compounds. *See* DEIONIZATION.

d

distillery A facility or establishment that involves the process of *distillation. Scotch *whisky is produced in a distillery in which malted barley is fermented to alcohol (ethanol) and then distilled to a higher concentration. An industrial distillery uses other grains as the raw material, such as maize or wheat, to produce *neutral spirit that is also used for making gin and vodka.

distributed control system (DCS) A general name for control systems that are used to control processes characterized by multiple controllers distributed throughout the process and connected by networks for the purpose of communication and monitoring data. They are connected to sensors and valve actuators and can use proportional, integral, and derivative control, as well as perform neural network and fuzzy-logic control, and be connected to a *human–machine interface.

distribution coefficient, distribution ratio A coefficient used in solvent extraction to quantify the extent of extraction between phases. It is evaluated as the concentration of the solute in the organic phase divided by the concentration in the aqueous phase. The distribution ratio can be a function of temperature and concentration of chemical species amongst other factors. It is also referred to as the *partition coefficient.

disturbance A change in the expected operating conditions of a process that requires control. The disturbance can be intentional or unintentional, and can be in the form of a step change in a process variable such as temperature, or a ramped change, etc.

Dittus–Boelter correlation A dimensionless equation used in heat transfer for forced convection. For a fluid with turbulent flow in a pipe of circular cross section:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}$$

where the Nusselt number is given by:

$$\mathrm{Nu} = \frac{hd}{k},$$

*Reynolds number by:

$$\mathrm{Re} = \frac{\rho v d}{\mu},$$

and Prandtl number by:

$$\mathrm{Pr} = \frac{\mu c_p}{k}.$$

The exponent n has a value of 0.4 for the heating of a fluid and 0.33 for the cooling of a fluid. This shows that doubling the forced flow of the fluid does not double the heat transfer coefficient, but raises it by a factor of 1.75 times. *Compare* NATURAL CONVECTION.

divider Used in *flowsheets to represent a process input stream, which is split into two or more output streams that have the same composition with no phase change or reaction taking place. It is also known as a *splitter.

dominant dead time process Used to describe a process being controlled where the *dead time is larger than the *lag time. A **dominant lag process** is used to describe a process being controlled where the lag time is greater than the *dead time. The majority of controlled processes are dominant lag types and includes most temperature, level, flow, and pressure control loops.

dose The exposure to chemicals or ionizing radiation with hazardous effect on the human body. Solid and liquid toxic effects may be presented as LD_0, LD_{10}, or LD_{50}, describing the dose that will produce 0, 10 per cent or 50 per cent chance of fatality, respectively. The values are usually milligrams per kg body weight. Another form of dose is the OEL (Occupation Exposure Limits). The TLV is the *Threshold Limit Value for eight hours per day, while the STEL is the Short Term Exposure time for fifteen minutes. For ionizing radiation, the dose is a measure of the extent to which the human body has been exposed. The **absorbed dose** is the amount of energy per unit mass. The SI unit is the *gray or the rad where 1 rad = 0.01 gray. The **dose rate** is the exposure to ionizing radiation expressed as the ratio of dose with time.

dosing pump A pumping system that is used to supply fluids to a process from time to time. They often form part of a control system such as the need to maintain the pH in a bioreactor with the controlled addition of acids and alkalis. Other dosing examples include chlorine dioxide being added to drinking water and power station water, and chlorine gas for swimming pool disinfection. *Peristaltic pumps are often used for small systems such as laboratory bioreactors, and *diaphragm pumps for larger applications.

double-acting A term used to refer to both sides of a reciprocating pump or engine being used for compression or expansion, respectively.

double block and bleed The use of two block or isolation valves on a length of pipe for the purposes of isolation with a bleed valve between them. It is used to prevent a process fluid from reaching an item of equipment such as a pump requiring maintenance. The pump can therefore be taken out of service without having to drain the entire length of pipe.

double bond *See* CHEMICAL BOND.

Dow, Herbert Henry (1866–1930) A Canadian industrial scientist who founded the Dow Chemical Company in 1897. He is noted for the invention of the *Dow process for extracting bromine using electrolysis to oxidize bromide to bromine. He had a major impact in the breaking of a cartel of European companies in chemical manufacture at the time.

downcomer A duct in an item of process equipment, such as a distillation column or evaporator, used to channel liquid from one location, such as a plate, down to the one below.

Downs process A process used in the extraction of sodium by the electrolysis of a *eutectic mixture of sodium chloride and calcium chloride at 580°C. The **Downs cell** has a central graphite anode and is surrounded by a cylindrical steel anode. Released chlorine is led away through a hood over the anode while molten sodium is formed and collected at the cathode. A small amount of calcium chloride is added, which lowers the melting point and

the sodium chloride is kept molten electrically. Additional sodium chloride is added as it becomes exhausted. The process was invented by J. C. Downs in 1922.

downstream A generic term to mean the stream of material for processing that has already passed through a process. *See* UPSTREAM.

downstream processing A general term for production facilities and unit operations that use process materials derived from another process. They are often in an unchanged state, such as crude oil and natural gas, or products from a fermentation process, and require separation, concentration, reaction, and purification. Downstream processes include petrochemicals, oil refining, biological, pharmaceutical, and fertilizer production facilities. **Downshore processing** are onshore-based processing facilities.

downtime The time that a process or item of equipment is not operating and unavailable for use. It may be out of action due to a fault, failure, or routine *maintenance, such as cleaning and repairs.

Dow process A process used to extract magnesium from seawater. Lime (calcium hydroxide) is used to react with magnesium chloride in the seawater to produce magnesium hydroxide and calcium chloride. The hydroxide is precipitated and filtered. It is then treated with hydrochloric acid, dried, and melted at 710°C. Electrolysis is used to produce the magnesium along with chlorine gas.

DP cell An abbreviation for **d**ifferential **p**ressure cell. A widely used device used to measure the pressure difference between two points, such as a process fluid flowing through a pipeline or across an item of equipment such as a heat exchanger. They are used to measure flow rate, level, or depth of fluids in vessels, and the status of equipment for the presence of fouling, amongst many other uses. By detecting and measuring the pressure difference between two points, such as across an orifice plate, a transducer then converts the signal into an electrical signal. This signal is then used to adjust the rate of flow by sending an appropriate control signal to open or close a valve, for example. *See* DIFFERENTIAL PRESSURE.

drag coefficient (Symbol C_D) The resistance to movement of a particle immersed in a fluid. For a small particle with a particle *Reynolds number (Re_p) less than unity, the drag coefficient predicted by *Stokes's law is:

$$C_D = \frac{24}{\mathrm{Re}_p}$$

drain valve A valve located on process equipment such as vessels and tank, and pipelines to discharge liquids as and when required.

drift The change in the output–input signal relationship of a controlled process over a period of time.

drilling mud A mixture of water and additives used in drilling oil wells to cool the drillbit, remove rock cuttings and transport them up to the surface. It also prevents the well wall from collapsing and maintains sufficient pressure at the bottom of the well to avoid a *blowout.

driving force The difference in physical properties that causes the movement of mass or heat from one place to another. In heat transfer, the driving force is the temperature difference or gradient between two points in which heat flows from a region of high temperature to a region of lower temperature. In mass transfer, the driving force is the difference in concentration of a substance or the partial pressure.

dropwise condensation A type of condensation that occurs at a cold surface that is not wetted by the condensate. *Compare* FILM CONDENSATION.

drum filter A type of filtration device that consists of a horizontal drum covered by a filter cloth. The drum rotates in a bath that is continuously fed with the process solution to be filtered. A vacuum is applied to the inside of the drum and the solid suspension collects on the surface of the rotating drum as a cake as the filtrate is drawn through. The filter cake is removed from the surface by a scraper or knife. Alternatively, a string arrangement is used in which a series of endless belts run around the drum and a separate cylinder. The strings continuously lift off the cake. Drum filters are used in the preparation of certain catalysts.

dry basis 1. A method of representing the moisture content of a substance in which the amount of water is taken as a ratio of the amount of substance. The moisture content of a very wet substance on a dry basis can be above 100 per cent. **2.** In the analysis of gases leaving a process, such as in refining and petrochemical operations, the gases can be defined on a dry basis in which steam is not included in the analysis. *Compare* WET BASIS.

dry bulb temperature A temperature measurement taken from a dry bulb thermometer. Together with the *wet bulb temperature, which uses a soaked wick surrounding the bulb of a thermometer, the humidity of air can be determined.

dryer A device used to reduce the moisture from a solid material. The most common type involves the passing of heated air with a low humidity over the moisture-bearing solid, thereby causing evaporation and removal of the moisture. The drying process is carried out until a desired moisture content is achieved. Other types of batch dryer include the use of desiccant and hygroscopic materials, which absorb the moisture from the air causing a drying effect of the material to be dried. Refrigerated dryers use a reduced temperature form of moisture removal, while membrane dryers use a *semi-permeable membrane to remove moisture.

dry ice Solid carbon dioxide. Instead of melting, it sublimes at –78°C (195 K) at standard pressure. It is used as a refrigerant or cooling agent. It is also used in the preservation of foods such as ice cream and has the advantage that it leaves no residue after sublimation. It is also used in fog machines to produce dramatic fog effects, and in plumbing to freeze water to form a plug in a pipe to allow repairs to be made. It is also used to remove warts by freezing the infected skin, and is also used to attract biting mosquitoes and midges. Dry ice is produced by either carbon dioxide capture or manufacture from another process such as fermentation, and pressurized or refrigerated until it liquefies. When the pressure is reduced causing some of the carbon dioxide to vaporize, there is a lowering of the temperature of the liquid resulting in solidification. The solid carbon dioxide is then compressed into blocks or pellets.

drying The removal of moisture or a liquid from a solid in a process that involves simultaneous heat and mass transfer. The heat is transferred for evaporation by a combination of conduction, convection, and radiation. The moisture may evaporate directly from the

surface of the non-porous solid or be transferred from within the body of a porous solid by *diffusion or capillary flow to the surface.

drying rate The speed at which the moisture content of a material is reduced to a lower moisture content. The drying rate is dependent on the humidity and temperature of the drying vapour as well as the properties of the material such as its porosity. There are many theoretical and empirical methods used to estimate the drying rate. The *constant rate drying period is where the rate of evaporation is constant due to continual surface replacement of moisture from within the materials, while the *falling-rate period is determined by the gas phase mass transfer or rate of heat transfer within the material.

dryness The condition of a substance being dry or having a low quantity of water or liquid. The **dryness fraction** is the amount of moisture in a vapour expressed as the ratio of the mass of moisture in the vapour, to the total mass of the vapour. The dryness fraction of *wet steam ranges from 0 (totally dry) to 1, in which it contains the maximum possible amount of moisture.

dry process *See* WET PROCESS.

dry scrubbing A process used to remove acid gases from flue gases that use sorbent materials such as hydrated lime or soda ash to remove sulphur dioxide and hydrochloric acid gas. They are also used to remove undesirable odours and corrosive gases from wastewater treatment plants, and use activated alumina as the sorbent material to remove hydrogen sulphide as well as mercaptans amongst others. In **spray dryer absorbers**, the flue gases are contacted with a finely atomized alkaline slurry where the acid gases are absorbed and react to form solid salts and are removed.

DSC *See* DISTRIBUTED CONTROL SYSTEM; DIFFERENTIAL SCANNING CALORIMETRY.

DSEAR An abbreviation for **D**angerous **S**ubstances and **E**xplosive **A**tmospheres **R**egulations 2002 of the UK's Health and Safety Executive (HSE). The regulations are intended to protect people from dangerous substances by putting particular duties on employers and self-employed people to protect workers in the workplace as well as members of the public. The regulations require that employers identify the substances that present a risk and put control measures in place to remove the risks or to control them.

SEE WEB LINKS

- Official website of the Health and Safety Executive, DSEAR regulations.

Dubai crude *See* WEST TEXAS INTERMEDIATE.

duct A pipe, tube, or enclosed channel for transporting gases or vapours. They are square, rectangular, triangular, or circular in cross section, and used in air conditioning for transporting heated air and ventilation purposes. The name is derived from the Latin *ductus* meaning both 'leading' and 'aqueduct', formed from *ducere* meaning 'to lead'.

Dulong–Petit law A law proposed by the French physicists Pierre Louis Dulong (1785–1838) and Alexis Thérèse Petit (1791–1820) for the molar heat capacity of a crystal. The law states that the molar heat capacity of a solid element is approximately three times the *universal gas constant, which is about 25 J mol^{-1} K^{-1}. They proposed the law from experimentation before the kinetic theory of gases had been established. The law is only approximate and applies to elements with simple crystal structure.

dump valve *See* BLOWOFF VALVE.

duplex process An early process used in the production of steel in which one furnace begins as another is finished. Iron is converted to steel in a Bessemer furnace in which the molten product is then transferred to an arc furnace to oxidize the impurities. **Duplex** is a group of stainless steels that have near-equal amounts of austenite and ferrite. They are noted for their high strength and resistance to corrosion resistance, and are used for process equipment.

duplex pump A type of reciprocating pump that operates with two pistons or plungers. The pistons operate out of phase in which one pump begins discharging as the other has just finished its stroke and returns to fill. The result is a near-continuous flow. The rate of flow is the product of the frequency of the strokes and the displacement per stroke.

DuPont, Pierre Samuel (1870–1954) An American chemist and industrialist who worked for the E. I. du Pont de Nemours and Company, and becoming its president from 1915 to 1920. He is noted for transforming the American explosives producer into the well-known diversified chemical producer.

Duralumin A trade name class of strong lightweight aluminium alloys containing copper, magnesium, manganese, and occasionally silicon. Their strength and lightness of weight are useful in aircraft fabrication.

dust Dry powders with a particle size of less than 500 micrometres.

dust cloud explosion The rapid combustion of a dispersion of combustible airborne dust particles within a *confined space. Dust can arise from many processes and include materials such as coal, flour, metals, custard powder, and sawdust, and form an explosive suspension in air (oxygen). Within the confined space, the dispersion of particles collectively have a very high surface area to volume ratio. Typical ignition sources include open flames, electrical static discharge, or arcing in process equipment, hot surfaces, and friction.

duty The power requirement for a machine or item of process plant such as a heat exchanger. The duty of a heat exchanger is dependent on the amount of liquid to be heated, cooled, vaporized, or condensed. The duty of a centrifugal pump is dependent on the flow delivered and pressure generated. The SI units for duty are watts or more usually kW or MW.

duty point The maximum possible delivery that can be achieved by a particular centrifugal pump to meet the pressure drop demand of a system (see Fig. 17). It is represented as the crossover point for the pump characteristic curve with the system characteristic on a pressure-flow rate curve. The system characteristic is parabolic since the pressure drop through the pipes is proportional to the square of the rate of flow.

dynamic analysis A method used to control an inherently unstable and dynamic system or process. It involves mathematically describing the system or process in terms of rate equations for materials, energy, and momentum, and determining how the associated variables change with time in order to restore controlled conditions to a disturbance.

dynamic equilibrium *See* EQUILIBRIUM.

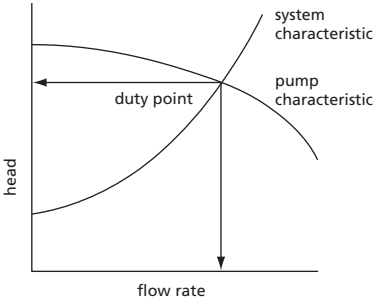

Fig. 17

dynamic error The difference between the actual process parameter and the instrument reading in a controlled process following a *disturbance.

dynamic response The behaviour of the output of a controlled process or item of equipment as a function of the input with respect to time.

dynamics The study of mechanics concerned with the motion of bodies due to the action of forces. *Compare* STATICS.

dynamic similarity A method used to study systems that are geometrically similar such as two stirred tanks, or two piping geometries, in which viscous effects and interfacial phenomena occur, and where the *Reynolds, Weber, and *Froude numbers are the same for both systems. It is useful in the design and interpretation of experimental observations and for the *scale-up of equipment.

dynamic viscosity *See* VISCOSITY.

dynamite A high explosive of nitroglycerine mixed with an inert absorbent, compacted into a cylindrical shape and wrapped in paper. It was invented by the Swedish chemist Alfred *Nobel (1833–96) and was originally formulated from nitroglycerine-absorbed kieselguhr. Once used for military purposes, modern forms of dynamite are used for blasting, mining, and quarrying, and contain sodium or ammonium nitrate with the nitroglycerine soaked into absorbent materials. It is not to be confused with *TNT.

dyne The c.g.s. unit of force. It is the force required to give a mass of one gram an acceleration of 1 cm s^{-2}. 1 dyne = 10^{-5} newton.

E

e The irrational number that has the value of 2.718 281 828 . . . It is calculated from $(1+1/n)^n$ where n tends to infinity. It is used as the base of natural or Naperian logarithms and exponential functions involving e^x.

EA *See* ENVIRONMENT AGENCY.

Eadie–Hofstee plot A graphical method used to obtain a straight line from experimental data from enzyme kinetics (see Fig. 18). It involves forming a plot of V/S versus V in which S is the substrate concentration at which the velocity v is observed. The gradient of the line is equal to $-K_m$ and the intercept on the y-axis is equal to the maximum velocity V. It is named after Canadian biochemist George Sharp Eadie (1895–1976) and B. H. J Hofstee who developed the plot in 1942 and 1959, respectively. *See* MICHAELIS–MENTEN KINETICS.

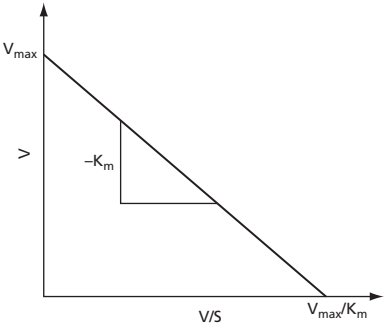

Fig. 18

ECHA An abbreviation for the **E**uropean **C**hemicals **A**gency, which is a regulatory authority within the European Union on the safe use of chemicals. Its aims are to assist chemical manufacturers, importers, and users to comply with legislation and promote the safe use of chemicals. It also provides information on chemicals that are of concern to human health and the environment through authorization, restriction, and labelling of chemicals.

SEE WEB LINKS

- Official website of the European Chemical Agency.

economic pipe diameter The diameter of a pipe that gives the minimum overall cost for any specific rate of flow of a fluid (see Fig. 19). The total costs of a pipe comprise the

capital and operating costs. The capital cost increases with pipe diameter while the operating costs decrease with increasing diameter since the pumping costs to overcome frictional pressure resistance decreases. Where the cost can be related to diameter, the economic pipe diameter can be found mathematically as the turning point by differentiating the total cost with respect to diameter.

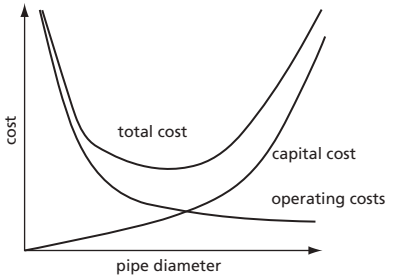

Fig. 19

economic potential The economic viability of a process expressed as the difference between the revenue gained from sales of a manufactured product or products and the cost of the raw materials used. It does not take into consideration capital or operating costs.

economizer A type of *heat exchanger used to raise the efficiency of a steam boiler. It involves first heating the feed water to a steam boiler by the hot flue gases from the boiler. By using some of the heat content of the flue gases, the steam boiler operates more economically since it uses less additional fuel to separately preheat the water feed.

eddy A bulk movement in a stream of fluid which doubles back on itself as a whirlpool or *vortex. *See* TURBULENCE.

EFCE *See* EUROPEAN FEDERATION OF CHEMICAL ENGINEERING.

effectiveness A parameter used to quantify the performance of a heat exchanger, expressed as the ratio of the actual heat transfer in a heat exchanger to the maximum heat that could be transferred by an infinitely long countercurrent single-pass heat exchanger.

effectiveness factor A term used in heterogeneous catalysis defined as the ratio of the actual reaction rate to the reaction rate without diffusion resistance.

efficiency A measure of the effectiveness of a machine or process expressed as a ratio of the energy or power output or delivered to the energy or power supplied. For example, the efficiency of a compressor is the ratio of the energy consumed in isoentropic compression to the actual power consumption.

effluent The liquid or solid waste stream from a process. It can contain contaminated process waste materials such as solvents, acids, alkalis, suspended solids, water from washing operations, and sewage. There is strict legislation governing the release of effluent into

the environment. Effluent treatment plants are therefore designed to treat the effluent from a process to comply with the legislation prior to safe release.

efflux The discharge of a fluid from a pipeline or process vessel. The flow in is called the *influx.

effusion The flow of gases under pressure through small holes such as a gas escaping from a cracked weld on a process vessel. The rate of flow is inversely proportional to the density. *Compare* DIFFUSION.

Einstein, Albert (1879–1955) A German-born mathematical physicist who took Swiss nationality in 1901. He originated the theory of relativity and also explained important results from the quantum theory of energy. He explained the variation of specific heat with temperature and also developed a law of the photoelectric effect. He later produced a complete theory to account for Brownian motion. Einstein resigned his German professorship with the rise of the Nazi regime, and worked first at Oxford University and then in Princeton University. He was awarded the Nobel Prize for Physics in 1921.

Einstein theory of specific heat A theory presented by Albert *Einstein that proposes that the specific heat of solids is a consequence of the vibrations of the atoms in a lattice structure. The theory correctly shows that when the temperature tends towards absolute zero, the specific heat of solids tends to zero.

ejector A type of compressor in which gas or vapour is entrained by injecting a high-velocity jet of gas or vapour. A *steam jet ejector uses live steam as the entraining high-velocity jet in which part of the kinetic energy is converted to pressure energy.

elastic collision An idealized assumption used in the *kinetic theory of gases in which the kinetic energy of atoms before collision is the same as the kinetic energy after collision. Perfect elastic collisions occur unless the kinetic energy is converted into another form of energy. For molecules other than monatomic molecules, the kinetic energy is converted into vibrational energy and rotational energy.

elasticity A fundamental property of certain materials to retain energy during deformation caused by an applied force, with the release of the energy to allow the material to return to its original shape. Certain *non-Newtonian fluids exhibit elasticity. For example, elasticity is seen as the energy that is retained in a fluid once a shear stress is removed causing a reversal of flow.

elastomer A substance or material that has the ability to return to its original shape after an external force has been applied and removed. Natural and synthetic rubber or related rubberoid materials are elastomers.

elbow A short section of curved pipework, usually at 90°.

ELD *See* ENGINEERING LINE DIAGRAM.

electrical resistance *See* RESISTANCE.

electric-arc furnace A type of furnace used to melt metals for the production of alloys such as steel in which the heat generated is in the form of an electric arc. The arc is either formed between an electrode and the metal, known as a direct-arc furnace, or is formed between two electrodes and the heat radiated into the metal, known as an indirect-arc furnace.

electrochemical equivalent (Symbol z) The mass of an element released from a solution of its ions in electrolysis by one coulomb of charge. *See* FARADAY'S LAWS OF ELECTROLYSIS.

electrochemistry A branch of chemistry concerned with chemical reactions that involve electricity. The electrical energy may generate electricity such as in a *fuel cell or *battery, or may initiate a chemical process such as in *electrolysis.

electrode A conductor of electricity through which an electric current enters or leaves an *electrolyte. The *anode is the positive electrode and the *cathode is the negative electrode.

electrodeposition A process involving the deposition of one metal onto another by *electrolysis such as ***electroplating**. An example is the electrodeposition of copper for on-chip wiring of integrated circuits.

electrode potential The potential difference between an electrode and the solution in a *half-cell. This is not able to be measured directly but instead standard electrode potentials $E^{\ominus}$ are defined by measuring the potential relative to a standard hydrogen half-cell using molar solution at 25°C. By convention, the cell is written with the oxidized cell first. Published tables are used that list standard electrode potentials. For example, the standard electrode potential of the half-cell Cu|$CuSO_4$ is 0.34 volt, and the standard electrode potential of the half-cell Ag|$AgNO_3$ is 0.80 volt. The e.m.f. of a cell Cu|$CuSO_4$| $AgNO_3$|Ag is therefore 0.46 volt.

electrolysis The removal of ions from a solution by the passage of electric current in which the solutions are separated in separate chambers by a *semi-permeable membrane. It requires a source of direct current, which is conveyed to the electrolyte by electrodes. The electrode connected to the positive pole is called the *anode; the electrode connected to the negative pole is called the *cathode. The current enters the electrolyte by the anode and leaves by the cathode.

electrolyte An ionic compound which, when molten or in solution, can conduct an electric current with decomposition. Conversely, a non-electrolyte is a compound that will not conduct electric current. Typical electrolytes include acids, bases, and salts, and their solutions, which are also termed electrolytes.

electrolytic cell A device or cell in which *electrolysis occurs. It is sometimes abbreviated and simply called a cell.

electrolytic corrosion A corrosion of metals that occurs as a result of electrochemical activity.

electrolytic refining An electrolytic process used to obtain pure metals. For example, copper can be obtained by using impure copper as the *anode and pure copper as the *cathode. Using a solution of copper sulphate, electricity is passed through the *electrolytic cell resulting in copper being deposited on the cathode. The impurities either remain in solution or are collected as a *sludge.

electrolytic separation A process used to separate isotopes using electrolysis. It was once used to separate deuterium and hydrogen from water since hydrogen is more readily formed at the cathode than deuterium causing an enrichment of the water with deuterium oxide or *heavy water.

SEE WEB LINKS

- Official website of the Norsk Industriarbeider Museum, Vemork (Norwegian Industrial Workers Museum).

electromagnetic radiation A form of energy in the form of electromagnetic waves, which are oscillating electric and magnetic fields at right angles to one another from the point of propagation. It includes radio waves, infrared radiation, visible light, ultraviolet radiation, x-rays, and gamma rays, which travel at the speed of light (2.9979×10^8 m s^{-1}) in a vacuum but slower through materials.

electrometallurgy Processes involving metals and electricity such as the separation of metals from their ores and the plating of metals. *See* ELECTROPLATING.

electron A negatively charged subatomic particle with a mass of about 1/1840 of the mass of a hydrogen atom; together with protons and neutrons in the atomic nuclei it makes up an atom. The electron was identified as being a particle by British physicist Sir Joseph John Thomson FRS (1856–1940) for which he was awarded the Nobel Prize for Physics in 1906, by measuring the angles through which the cathode rays were deflected by known magnetic and electric fields. He succeeded in determining a value for the ratio of charge to mass, which was found to be constant irrespective of the nature of the cathode. The charge was determined around 1910 by American physicist and Nobel laureate for Physics Robert Millikan (1896–1953) to be 1.6×10^{-19} coulombs. The sharing of electrons is the main cause of *chemical bonds.

electro-osmosis The movement of a liquid through a porous material in which an electrical potential has been placed. It is used in dewatering and drying operations, and for materials that are normally difficult to dry such as jelly-like substances. It is used in *fuel cells, where protons move from the anode to the cathode through a proton exchange membrane together with water molecules.

electroplating A process that involves coating one metal with another using *electrodeposition. Within an *electrolytic cell, the item to be coated is made the *cathode, and the other metal used for the plating is made the *anode. The technique is used to provide coatings that provide resistance to corrosion or for decorative purposes.

electrostatic precipitation The process of removing small electrostatically charged particles from a gas stream, such as *ash from combustion processes, using highly charged plates or tubes, and of the opposite polarity. An **electrostatic precipitator** is the apparatus used to bring about the separation in which the charged plates or tubes collect the particles and are cleaned periodically, either by strongly tapping the plates, or by surface cleaning with water. They are typically used to clean the flue gases from coal-fired power stations and can operate effectively at high temperatures and pressures. They are expensive to operate and can tend to be inefficient. They were first commercialized by the American physicist and inventor Frederick Gardner Cottrell (1877–1948) in 1907.

element 1. A substance that is not able to be decomposed into simpler substances by any known chemical process. All the atoms in an element have the same number of protons or electrons but the number of neutrons may vary. All the elements are listed in the *periodic table of which 93 are naturally occurring. **2**. A small part of a system used as the basis for an analysis of an entire system. For example, an element may be a portion of the fluid in a

pipe or vessel upon which a force or energy balance is performed to determine the fluid behaviour within the entire pipe or vessel. **3**. A component of a control device or system.

elementary particle A fundamental particle from which all matter is composed and includes electrons, neutrons, and protons.

elementary reaction A simple form of chemical reaction that takes place in a single step with a single transition state and does not involve intermediates.

elimination reaction A chemical reaction that involves the decomposition of a molecule into two smaller molecules with one being much smaller than the other. An example is the chemical reaction used for synthesizing alkenes and alkynes by removing hydrogen from saturated hydrocarbons.

Ellingham diagram A graphical representation of the dependence of temperature on the stability of compounds, particularly for the reduction of metal oxides and sulphides. The diagram is used to predict the equilibrium temperature between a metal, oxygen, and the metal oxide, and therefore the reduction of an ore to the metal. It is, in effect, a graphical form of the second law of thermodynamics as a plot of the *Gibbs free energy (ΔG) for the oxidation reaction with absolute temperature. The diagram is named after British chemist Harold Johann Thomas Ellingham (1897–1975).

elution A process used to wash components of a mixture through a chromatography column in which absorbed material (absorbate) is removed by washing with a liquid (**eluent**). The **eluate** is the solution consisting of the absorbate dissolved in the eluent.

elutriation The process of separating suspended particles in a liquid by the upward flow of liquid such that the smaller particles with insufficient buoyancy are washed out or **elutriated**. It is used for separating particles into different size fractions.

emergency shutdown (ESD) The rapid and safe shutdown of a process plant or item of equipment due to a serious deviation in plant operation. Critical valves shut to isolate sections of the process. Other valves may be opened to depressurize vessels or rapidly discharge contents of reactors to quench tanks. Emergency shutdowns may occur due to changes in process conditions causing unstable or unsafe operating conditions, a failure in the control system, operator intervention causing unsafe conditions, plant and pipe failure, or some other external event such as an electrical storm.

emissions The discharge of materials into the environment emanating from an industrial or domestic source. It includes solids such as particulates, liquids, gases and vapours, and noise. The exhausts from the internal combustion engine in cars and other vehicles gives emissions of particles, water vapour, and carbon dioxide, and other gases.

emissive power (Symbol E) The rate at which electromagnetic radiation energy is emitted per unit-time, per unit-area of the surface spanning all wavelengths and in all directions. The emissive power is proportional to the absolute temperature to the fourth power, $E_b = \sigma T^4$, where subscript 'b' refers to *black body radiation and σ is the *Stefan–Boltzmann constant with a value of $5.67 \times 10^{-8}\,\mathrm{Wm^{-2}\,K^{-4}}$.

emissivity (Symbol ε) The ratio of the rate of emission of radiant energy from an opaque body due to the temperature, to the rate of emission by the same area from a black body at the same temperature. The emissivity of a *black body therefore has a value of 1.0 while

a perfect reflector of radiant energy has a value of 0. The emissivity is dependent on the material, its surface characteristics, and its temperature.

empirical Derived from or relating to an experiment or observation rather than from established *theory. It can refer to an equation, formula, curve, analysis, or a number.

empirical formula The simplest chemical formula that expresses the composition of a compound by mass. It may not necessarily be the same as the molecular formula. For example, the empirical formula of ethane is CH_3 and, as its relative molecular mass is 30, its molecular formula is C_2H_6.

emulsification The dispersion of two immiscible phases within one another. The emulsification of foods is one of the most complicated unit operations since the nature of the final product varies greatly depending on the method of preparation. The method of addition of components and the rate of addition can significantly affect the emulsion quality. Oil-in-water emulsions can be produced in impeller-agitated vessels operating at high rotational speeds, colloidal mills, or high-pressure valve homogenizers. Continuous processing may be achieved by *in-line mixers, which consist of a high-speed rotor inside a casing, into which the components are pumped and subjected to high shear.

emulsion A colloidal suspension of one liquid dispersed within another. The dispersed phase has droplet sizes usually less than 1 mm. Butter is an example of a water-in-oil emulsion, while mayonnaise is an example of an oil-in-water emulsion. Surfactants or emulsifiers are surface-active agents and used to stabilize emulsions. Detergents possess both hydrophilic and hydrophobic parts to their molecules to behave as emulsifiers. In the offshore oil industry, emulsions form at the interface of water and oil in crude oil gravity separators. Sufficient hold-up time is used to separate the emulsion, or alternatively, surface-active agents are used to encourage separation.

end-of-pipe Used to describe technologies that aim to reduce the emissions of scrubbers, smoke stacks, and catalytic converters on vehicle exhausts that are considered to be pollutants.

endothermic reaction A chemical reaction that absorbs heat from its surroundings in order for the reaction to proceed. Such reactions have a positive enthalpy change and therefore do not occur spontaneously. *Compare* EXOTHERMIC REACTION.

energy The capacity or ability of a system to do work. It may be identified by type as being kinetic, potential, internal, and flow, or by source such as electric, chemical, mechanical, nuclear, biological, solar, etc. Energy can be neither created nor destroyed, but converted from one form to another. It can be stored as *potential energy, nuclear, and chemical energy, whereas *kinetic energy is the energy in the motion of a body defined as the work that is done in bringing the body to rest. The *internal energy is the sum of the potential energy and kinetic energy of the atoms and molecules of the body. Like work, energy has the SI units of joules.

energy balance An accountancy of the energy inputs and output to a process or part of a process, which is separated from the surroundings by an imaginary boundary. All energy forms are included in which the energy input across the boundary must equal the energy output plus any accumulation within the defined boundary. Where the conditions are steady and unvarying with time, the energy input is equal to the energy output. The most important energy forms in most processes are kinetic energy, potential energy, enthalpy, heat, and work. Electric energy is included in electrochemical processes.

Engel process A process invented in the nineteenth century for the production of potassium carbonate from potassium chloride. The process has two steps and first involves the production of soluble salt $MgKH(CO_3)_2.4H_2O$, known as Engel's salt, using carbon dioxide which is passed through a suspension of magnesium carbonate in aqueous chloride. This is followed by its decomposition by hot water and magnesia to form the product and insoluble hydrated magnesium carbonate:

$$3MgCO_3 + 2KCl + CO_2 + 5H_2O \rightarrow 2MgKH(CO_3)_2.4H_2O + MgCl_2$$
$$2MgKH(CO_3)_2.4H_2O + MgO \rightarrow 3MgCO_3.3H_2O + K_2CO_3$$

There were several variations of this process but it was abandoned in the 1930s for economic reasons.

engine A machine used for transforming one form of *energy to another, such as chemical or electrical energy to *kinetic energy or mechanical work. The development of Thomas Newcomen's (1664–1729) steam engine, together with James *Watt's (1736–1819) improvement with a separate condensing chamber, brought about the Industrial Revolution in which steam energy was converted into useful work to operate machinery including the development of the steam locomotive engine.

engineering The study of the design, construction, and operation of mechanical, electrical, and chemical systems, processes, and devices. Derived from the Latin *ingenium* meaning 'invention', the engineering disciplines that we know today originated from military engineering that involved machines of war. Civil engineering was therefore the first engineering discipline to be identified for the design of structures such as bridges, buildings, and roads for civilian and non-military purposes. The establishment of mechanical engineering was also to follow in the early nineteenth century. The discipline of *chemical engineering was developed during the Industrial Revolution through the development of industrial-scale chemical plants outside of the realms of applied chemistry. By 1908, the *American Institute of Chemical Engineers was founded some fourteen years before the *Institution of Chemical Engineers in the UK in 1922. A person who practises engineering is known as an **engineer**. In the UK, a professional *chemical engineer may be qualified as a *chartered chemical engineer or incorporated engineer by the *Institution of Chemical Engineers. An engineer applies the laws of physics and mathematics to solve problems, leading to improvement in the wellbeing of society, while using available resources responsibly, safely, and ethically, and without harm or damage to the environment.

engineering line diagram (ELD) A diagrammatic representation of a process. Also known as an **engineering flow diagram**, it features all process equipment and piping that is required for start-up and shutdown, emergency, and normal operation of the plant. It also includes identification numbers, identifiers for the materials of construction, diameter and insulation requirements, direction of flows, identification of the main process and start-up lines, all instrumentation, control, and interlock facilities, key dimensions and duties of all equipment, operating, and design pressure and temperatures for vessels, equipment elevations, set pressures for relief valves, and drainage requirements.

enhanced oil recovery (EOR) One of a number of methods used to increase the amount of crude oil that can be recovered from an oil reservoir. These include the use of water, gas, chemical, and steam injection into the reservoir. Gas injection is the most commonly used method and involves the use of natural gas, carbon dioxide, or nitrogen to displace the oil. The method is dependent on the temperature and pressure of the reservoir and composition of the oil within it. Carbon dioxide is miscible in light oil and can alter the viscosity and

surface tension of the oil. The use of chemical injection involves dilute alkaline solutions to alter the surface tension and enhance oil recovery. Surfactants are also used. Steam injection also reduces the viscosity of the oil and can also partially vaporize it, aiding recovery.

enrichment The process of raising the amount of a substance in another. In nuclear reprocessing, enrichment involves raising the amount of one radioactive isotope in a mixture of isotopes. The enrichment of uranium-235 from a mixture of uranium-238 involves converting the uranium isotopes into uranium hexafluoride and separating them in a *gas centrifuge process. This involves using an array of centrifuges in which the heavy atoms are separated from the lighter atoms by centrifugal forces. The separation is dependent on the difference in mass between the isotopes being separated.

enthalpy (Symbol H) The thermal energy of a substance or system with respect to an arbitrary reference point. The enthalpy of a substance is the sum of the *internal energy and the flow of energy, which is the product of the pressure and specific volume:

$$H = U + pV$$

The reference point for gases is 273 K and for chemical reactions is 298 K. For foods and refrigerants the reference temperature is 243 K (-40°C).

enthalpy balance A form of energy accountancy for a process in which the stream energies to and from the process are expressed as enthalpies. At steady state, the total enthalpy into a process is equal to the total enthalpy out. Where there is an inequality, there is either a loss or an accumulation of material with an associated loss or increase in enthalpy. An enthalpy balance is used to determine the amount of heat that will be generated in the process or that needs to be removed to ensure that the process operates safely and to specification.

enthalpy-concentration diagram A chart that presents the thermodynamic data for non-ideal mixtures of substances. It is used to calculate the heat of mixing when two pure components are combined to form a non-ideal mixture such as sulphuric acid and water.

entrainer A substance that is added to a homogenous *azeotrope to convert it to a heterogenous azeotrope that can then be readily separated by *distillation. A high concentration is usually needed and is only justified when the improvement in the *relative volatility offsets the extra investment, replacement, and recycle costs involved in the purchase, heating, and pumping of the entrainer. *Azeotropic distillation is useful for separations where the overhead component is present in small amounts. Entrainers should ideally be cheap, readily obtainable, non-corrosive, non-toxic, unreactive, thermally stable, and easily recoverable. As well as being able to form an azeotrope, it is required to have a low latent heat of vaporization. *See* EXTRACTIVE DISTILLATION.

entrainment The capture of bubbles, drops, or particles from one phase to another from which it is being separated.

entrance and exit losses The irreversible energy loss caused when a fluid enters or leaves an opening, such as into or out of a pipe into a vessel. Where there is a sudden enlargement, such as when a pipe enters a larger pipe or vessel, eddies form and there is a permanent energy loss expressible as a head loss as:

$$H_{exit} = \frac{v^2}{2g}\left(1 - \frac{a}{A}\right)^2$$

where v is the velocity in the smaller pipe, a is the cross-sectional area of the smaller pipe, and A is the cross-sectional area of the larger pipe. For a considerable enlargement the head loss tends to:

$$H_{exit} = \frac{v^2}{2g}$$

With a rapid contraction, it has been found experimentally that the permanent head loss can be given by:

$$H_{entrance} = k\frac{v^2}{2g}$$

where for a very large contraction k = 0.5.

entropy (Symbol S) The extent to which energy in a *closed system is unavailable to do useful work. An increase in entropy occurs when the free energy decreases or when the disorder of molecules increases. For a *reversible process, entropy remains constant such as in a friction-free *adiabatic expansion and compression. The change in entropy is defined as:

$$dS = \frac{dQ}{T}$$

where Q is the heat transferred to or from a system, and T is the absolute temperature. However, all real processes are irreversible, which means that in a closed system there is a small increase in entropy.

Entropy can be regarded as a measure of disorder. That is, the higher the value, the higher the level of disorder. A closed system tends towards higher entropy and therefore a higher disorder. For example, two layers of coloured balls in a box shaken will generate a level of randomness and disorder, and will not return to their original state without the intervention of more work in their separation. *See* FIRST LAW OF THERMODYNAMICS.

entry length The distance from the entry plane of a pipe or tube in which a fluid flows that corresponds to 99 per cent of the *centreline velocity of the fully developed velocity profile. That is, the point where fully turbulent or laminar flow has fully formed. The type of flow regime can be determined from the *Reynolds number.

ENVID An abbreviation for **env**ironmental **id**entification, it is a systematic and wide-ranging structured hazard analysis tool used to identify the environmental hazards at an early stage in process design and development. It is conducted like a *HAZID except that it focuses on identifying environmental issues.

Environment Agency (EA) A non-departmental public body that is responsible for the protection of the environment in England and Wales. Its primary role is to protect and improve the environment by being an environmental regulator to protect and regulate activities that can cause harmful pollution. *See* SEPA.

SEE WEB LINKS

- Official website of the UK Environment Agency.

Environmental Protection Agency (EPA) A governmental agency in the US that is responsible for setting standards and monitoring policies for environmental pollutants.

SEE WEB LINKS

- Official website of the US Environmental Protection Agency.

enzyme A protein molecule that catalyzes biochemical reactions. It has a complex molecular structure and its molecular shape or conformation plays an important role in its function as a catalyst. Enzymes as biocatalysts promote biochemical reactions and involve a substrate molecule, which is converted into products. As with all catalysts, enzymes lower the activation energy of the biochemical reaction and increase the rate of reaction. Every type of enzyme is specific to a particular biochemical reaction. For example, maltose and sucrose are disaccharides but are hydrolyzed by different enzymes, with the former by an enzyme called maltase and the latter by invertase. The molecular structure of the enzyme is complex and, being a protein, is formed from long folded chains of amino acids. The substrate undergoing reaction binds to an active site on the enzyme in a *lock and key mechanism to form a short-lived enzyme–substrate complex which dissociates to form the product. Enzyme reactions operate most effectively at a certain optimum temperature and within a narrow pH range. The names of most enzymes end with *–ase*, such as amylase, which is used to break down starches into simple sugars. Enzymes are denatured with excessive temperature, very low or high pH, and certain chemicals.

enzyme inhibition A reduction in the rate of an enzyme-catalyzed biochemical reaction by a substance or inhibitor. **Competitive inhibition** occurs when the conformation of the inhibitor mimics or resembles the substrate and thus prevents the active site from being available to form an enzyme–substrate complex. In **non-competitive inhibition**, the inhibitor binds to the enzyme–substrate complex or part of the enzyme such that the enzyme is unable to catalyze the reaction.

enzyme kinetics The study of the behaviour of enzyme-catalyzed reactions. The rate at which an enzyme-catalyzed reaction proceeds is determined from the disappearance of the substrate or the formation of the product. Simple kinetic models such as *Michaelis–Menten kinetics can often be used to determine the rate of the reaction.

EOR *See* ENHANCED OIL RECOVERY.

EPA *See* ENVIRONMENTAL PROTECTION AGENCY.

equation of state A relationship that links the pressure, volume, and temperature of an amount of a substance. It is used to determine thermodynamic properties such as liquid and vapour densities, vapour pressures, fugacities and deviations from ideality, and enthalpies. Various equations of state have been developed to predict the properties of real substances. Commonly used equations of state include the *ideal gas law, *virial equation, *van der Waals' equation, *Peng–Robinson, *Soave-Redlich Kwong, and *Lee–Kesler equations. Cubic equations of state are relatively easy to use and are fitted to experimental data. The van der Waals equation is comparatively poor at predicting state properties. The Lee–Kesler model, which is based on the theory of corresponding states and uses reduced temperature and pressure, covers a wide range of temperatures and pressures.

equilibrium A condition or state in which a balance exists within a system, which may be physical or chemical. A system is in equilibrium if it shows no tendency to change its properties with time. **Static equilibrium** occurs if there is no transfer of energy across the system boundary, whereas **dynamic equilibrium** is when transfer occurs but the net effect of the energy is zero. *Thermodynamic equilibrium occurs when there is no heat or work exchange between a body and its surroundings. *Chemical equilibrium occurs when a chemical reaction takes place in the forwards direction, when reactants form products at exactly the same rate as the reverse reaction of products revert to their original reactant form.

equilibrium constant A reversible process, chemical or physical, in a closed system will eventually reach a state of equilibrium. The equilibrium is dynamic and may be considered as a state at which the rate of the process in one direction exactly balances the rate in the opposite direction. For a chemical reaction, the equilibrium concentrations of the reactants and products will remain constant providing the conditions remain unchanged. For the homogenous system:

$$wA + xB \leftrightarrow yC + zD$$

the ratio of the molar concentrations of products to reactants remains constant at a fixed temperature:

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

where K_C is the equilibrium constant and the square brackets indicate equilibrium concentrations. The relationship is known as the **equilibrium law**. For example, for the *Haber process for the synthesis of ammonia, nitrogen is reacted with hydrogen as:

$$N_2(g) + 3H_2(g) \leftrightarrow 2NH_3(g)$$

The equilibrium constant is expressed as partial pressures as:

$$K_C = \frac{[NH_3]^2}{[N_2][H_2]^3} = \frac{p^2_{NH_3}}{p_{N_2}.p^3_{H_2}}$$

equilibrium distillation *See* FLASH VAPORIZATION.

equilibrium law *See* EQUILIBRIUM CONSTANT.

equilibrium moisture The balance in which the rate of loss of moisture from a system or material is equal to the rate of gain from its surroundings. The **equilibrium moisture content** of a substance is the smallest possible moisture content that can be achieved in the presence of a gas of given pressure, temperature, and humidity. It is also dependent on the nature of the solid and is usually expressed on a dry basis. The *free moisture content is the difference between the *total moisture content and equilibrium moisture content.

equilibrium ratio (Symbol K) The ratio of the mole fraction in the vapour phase of a component in a mixture, *y*, to the mole fraction in the liquid phase, *x*, at equilibrium:

$$K_A = \frac{y_A}{x_A}$$

It is a function of both temperature and pressure. The *relative volatility, α, is less dependent on temperature and pressure than the equilibrium constant where for an ideal mixture of two components, *A* and *B*:

$$\alpha_{AB} = \frac{K_A}{K_B}$$

equimolar counter-diffusion The process of diffusion of one component (A) into another (B) in which their respective molar fluxes are equal but in opposite directions. The diffusivity of A in B is therefore the same as B in A in which the total pressure within the process remains the same throughout. The process of steady-state equimolar counter-diffusion in an ideal gas mixture can be described by *Fick's law for which the concentrations of A and B are expressed in terms of their partial pressures.

equivalent hydraulic diameter An alternative value used in calculations in place of the diameter of a pipe in turbulent flow calculations when the pipe or duct cross-section is not circular. It is equal to four times the flow area divided by the wetted perimeter. It does not apply to laminar flow.

equivalent length A method used to determine the pressure drop across pipe fittings such as valves, bends, elbows, and T-pieces. The equivalent length of a fitting is that length of pipe that would give the same pressure drop as the fitting. Since each size of pipe or fitting requires a different equivalent length for any particular type of fitting, it is usual to express equivalent length as so many pipe diameters, and this number is independent of pipe. For example, if a valve in a pipe of diameter, *d,* is said to have an equivalent length, *n*, pipe diameters, then the pressure drop due to the valve is the same as that offered by a length, *nd*, of the pipe. Values are determined experimentally.

Erbar–Maddox correlation An empirical method used for the design of distillation columns that relates the number of ideal stages for a given separation and reflux ratio to the minimum number at total reflux and the minimum reflux ratio. The minimum reflux ratio corresponds to an infinite number of stages to bring about separation. It is named after American chemical engineers John H. Erbar and Robert N. Maddox.

erg A unit of work in the *c.g.s. system in which one erg is the force when one *dyne of force is exerted upon a body through a distance of 1 cm. This is a very small unit and one joule is preferred in which one erg is equal to 10^{-7} joules.

Ergun equation An equation used to determine the pressure drop per unit length of a fixed bed of particles such as catalyst at incipient gas velocity, v:

$$\frac{-\Delta p}{L} = \frac{150(1-e)^2 \mu v}{\phi e^3 d^2} + \frac{1.75(1-e)\rho v^2}{\phi e^3 d}$$

where $-\Delta p/L$ is the pressure drop over the depth of bed, e is the bed voidage, d is the mean particle diameter, ρ is the fluid density, μ is the fluid viscosity, and φ is the *sphericity. The incipient point of fluidization corresponds with the highest pressure drop at the minimum fluidization velocity. It is named after Turkish-born American chemical engineer Sabri Ergun (1918–2006) who developed the equation in 1952.

erosion The physical removal of material from a surface by mechanisms that exclude chemical attack. The usual phenomenon that causes erosion is impingement by either liquid droplets or entrained solid particles. If there are no corrosive substances present, then in many cases, the most common mechanism for material damage due to erosion is impingement by solid particles. *Compare* CORROSION.

erosion-corrosion The process of metal surface damage and removal due to the combined action of chemical species and mechanical attack. The mechanical damage is by the removal of an otherwise protective film or surface coating by repeated bombardment of either liquid droplets or solid particles. This exposes the reactive metal substrate to chemical attack, and the rate of material damage is frequently many times higher than the base corrosion rate.

error 1. The difference between a measured or indicated value and the expected or true value. The error can be used to control a system or process while **statistical error** can be used as a measure of uncertainty. For example, reading the level of liquid in a vertical glass manometric leg used to measure the pressure in a process may only be possible to the nearest 1 mm. A level of 30 cm should therefore be written as 30 ±0.1 cm, which means a level of

between 29.9 and 30.1 cm. **Random error** is a form of error that can neither be predicted nor accounted. **Systematic error** is due to a fault that requires correcting. For example, a thermometer that reads 10°C less than the actual temperature means that all recorded temperatures are 10°C less than the correct value. **Human error**, blunders, and mistakes can lead to disastrous consequences. **2**. Used in process control of process, the error is the difference between a desired or set point value and the actual and controlled process variable. The control of a process aims to minimize the error. Various forms of process control strategies are used to achieve this. *See* PROCESS CONTROL

ESD *See* EMERGENCY SHUTDOWN.

estimation A solution to a problem that is deemed to be sufficiently close to the right answer and that has involved some rational thought or calculation. It is not a precise value and the level of error may not be known.

ethylene (ethene) A colourless and flammable hydrocarbon with the formula C_2H_4 (m.p. -169°C; b.p. -103.7°C). It is widely used in the chemical industry to produce organic chemicals such as ethanol and ethanal, as well as ethylene dichloride, ethylbenzene, and ethylene oxide. It is polymerized to form polyethylene. Ethylene is made by the cracking of hydrocarbons derived from petroleum and is the simplest form of alkene.

Eulerian fluid dynamics A branch of fluid dynamics that considers the velocity of a fluid at fixed points. It is named after Swiss mathematician and physicist Leonhard Euler (1707–83).

Euler number A dimensionless number, Eu, that represents the relationship between pressure drop due to friction and inertial forces in a moving fluid in a system such as in a pipeline.

$$Eu = \frac{\Delta p}{\rho v^2}$$

where Δp is the pressure drop due to friction, ρ is the density, and v is the velocity. It is named after Swiss mathematician and physicist Leonhard Euler (1707–83).

European Congress of Chemical Engineering (ECCE) A biennial conference on chemical engineering, now held concurrently with the European Congress of Applied Biotechnology (ECAB). The ninth ECCE was held in The Hague, the Netherlands, in April 2013. The ECCE conference series is held under the auspices of the *European Federation of Chemical Engineering (EFCE), an association run jointly by the *Institution of Chemical Engineers, *DECHEMA, and the French Society of Process Engineers.

European Federation of Chemical Engineering (EFCE) A professional organization formed in 1953 representing over 100,000 chemical engineers and scientists from over 30 countries within Europe. It has nineteen working parties in specialist areas covering all areas of chemical engineering.

SEE WEB LINKS

- Official website of the European Federation of Chemical Engineering.

eutectic mixture A mixture of substances having the lowest freezing point of all mixtures of the substances. The **eutectic point** is the lowest temperature at which a solution can exist and that three condensed phases can co-exist (see Fig. 20). Low melting-point

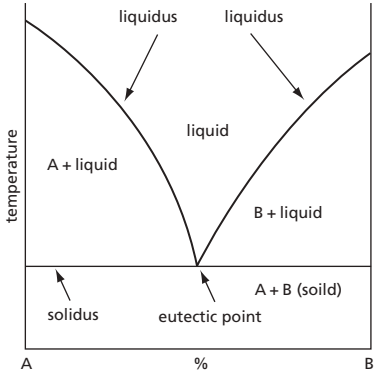

Fig. 20 Eutectic point

alloys are usually eutectic mixtures. For example, the freezing point of pure lead and pure tin are 327°C and 232°C, respectively, whereas a mixture with 62 per cent lead (soft solder) has a **eutectic point** of 183°C.

eutrophication A biological process in which there is excessive algal growth in water due to an excess of nutrients and in particular phosphates and nitrates. The eventual decomposition of the algae depletes the water of available oxygen, resulting in a sterile body of water. While it is a natural process, it is assisted by the release of chemicals into water as a form of *pollution.

evaporation The change of state from a liquid to a vapour at a temperature below the boiling point of the liquid. Evaporation occurs at the surface of the liquid in which the kinetic energy is sufficient to enable it to leave the surface as vapour. The average kinetic energy of the molecules in the liquid is therefore reduced and there is consequently a reduction in temperature resulting in **evaporative cooling**. *See* BOILING.

evaporator A heat exchanger device used to concentrate a solution by boiling. The solution is heated until vapour is released and removed, leaving behind a more concentrated solution. A drying process may then follow evaporation and low pressures may be used for heat-sensitive materials such as milk and other thermally labile foods. Several evaporators or 'effects' can be connected in series as a *cascade process to obtain a desired evaporation with the benefit of good energy utilization. They may be operated as feed-forward or feed-backward. Cold feeds use a backward process because the boiling temperature in the last effect is lower and consequently the required temperature for evaporation is less than that required in the first evaporator. *See* MULTIPLE EFFECT EVAPORATION.

event The occurrence of something happening. It is a term used in *risk analysis and *risk assessment, and used in an evaluation of the probability or likelihood of the event occurring and its consequences. A risk analysis seeks to estimate the risks associated with the event and the risk assessment seeks to make decisions to reduce or mitigate the risks.

excess air A supply of air to a combustion process that exceeds the stoichiometric requirement of oxygen. In practice, a supply of 1.2 times greater than that which is stoichiometrically required is often used to ensure a good level of combustion.

excess flow valve A type of flow valve that permits the flow of a fluid in either direction but prevents excessive flow, in which case, the valve closes automatically.

excess reactants The reactants consumed in a chemical reaction that exceed the stoichiometric proportion. Excess oxygen or *excess air are usually added to a combustion process to ensure good combustion efficiency. The fuel itself is the *limiting reactant. Excess reactants are normally expressed as per cent excess, such as 100 per cent excess, which means that twice as much of one of the reactants is added as is theoretically necessary for complete reaction.

exchange capacity The number of ions that can be retained or exchanged per unit volume by a particular *ion exchange resin within an ion exchange unit. It is generally measured in milliequivalents per gram of resin. The exchange capacity depends on the number of exchange sites and the type of resin.

exergy The maximum amount of useful thermodynamic work that can be extracted from a system in a given surrounding. This can be mechanical work such as running a pumping or lighting a bulb with electrical energy. For example, there is more exergy in an ice cube in a room at ambient temperature than a cup of water in the same room. It applies to kinetic, potential, chemical, nuclear, magnetic, and electric energy. **Exergoeconomics** is the study that combines exergy analysis with process economic evaluation to identify the cost of operating a system in terms of materials in, products out, and the cost of exergy destruction. It is used for the analysis of many processes in terms of the amount of work that can be lost or needs to be applied.

exothermic reaction A chemical reaction that liberates heat. No energy input is required for the reaction to proceed. It has a negative enthalpy change and therefore under the appropriate conditions the reaction will occur spontaneously. Chemical reactors used to contain exothermic reactions therefore require cooling facilities to remove the excess heat that is generated and to maintain a constant temperature. *Compare* ENDOTHERMIC REACTION.

expansion An increase in the volume of a substance for a given mass. This may be due to a decrease in pressure or an increase in temperature of a gas, or due to a swelling effect of moisture in a porous material. When water cools, the density decreases until it reaches 4°C where it has a minimum volume and maximum density. Cooled further and turned to ice, its volume increases and density decreases to below that of liquid water, which is why ice floats and can lead to burst pipes in winter.

expansion bend A loop of pipe placed in a straight run of pipeline to allow for the possible thermal expansion of the pipeline, thereby avoiding the build-up of excess temperature-induced stress. Examples include horseshoe bends and bellows. It is also known as an **expansion joint** or **expansion loop.**

experimental design A statistical procedure used to evaluate the influence of process variables on the outcome from a process. The purpose is to determine the key information such as a process optimization quickly and cheaply. The simplest approach is to adjust one variable at a time, such as changing the temperature, and evaluating the effect before adjusting another variable. Various protocols have been developed in which combinations of all the important variables can be considered simultaneously. The adjustments follow a defined matrix. A simple approach and early method known as response surface methodology (RSM) was developed by British statistician George Edward Pelham Box, FRS, with K. B. Wilson in 1951. It was designed to explore the relationships between several process variables and one or more response variables. It uses two levels (coded as x=-1 and x=1)

for each process variable such as high and low in a full-factorial design. It involves all combinations of all levels of the variables. For example, in a two-level full factorial experimental design with two variables, there are four treatments. In this case, the number of treatments is equal to 2^n. The effects of the two variables and their interactions can be described by the response surface in the form:

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2$$

Other experimental designs have been developed and involve more than two levels, and also involve the use of replicates used to evaluate the statistical error. Fractional factorial experimental designs use part of the full factorial experimental design and cut down the number of trials needed.

explicit A mathematical function that contains no dependent variables. *Compare* IMPLICIT.

explosion A rapid, violent, and uncontrolled release of energy as a result of a chemical or nuclear reaction, which causes a *blast wave or *shock wave. This is a sharp pressure pulse. An explosion is also accompanied by noise, heat, and light. An explosion as the result of a chemical reaction can be due to a deflagration in which the reaction front moves at less than sonic velocity, whereas a detonation is a chemical reaction that is extremely rapid and the reaction front moves into the unreacted material greater than sonic velocity, resulting in considerable blast damage.

explosion limit The highest or lowest concentration of a flammable gas or vapour in air or oxygen that will propagate a flame when ignited.

explosion-proof equipment The equipment in an enclosure that is capable of withstanding an internal explosion of a specified gas or vapour, and of preventing possible ignition of a surrounding flammable atmosphere.

explosion suppression A method, device, or system to effectively extinguish an explosion.

explosive A substance capable of a sudden high-velocity reaction with the generation of high pressure. High-energy explosives generate detonations. An **explosive atmosphere** is a mixture of air and one or more *dangerous substances in the form of gases, vapours, mists, or dusts in which, after ignition has occurred, combustion spreads to the entire unburned mixture. More generally, an **explosive mixture** is a combustible-oxidant mixture that is potentially explosive or capable of propagating flame.

exponent A number or symbol placed as a superscript to a number, expression, or quantity that represents the power to which it is to be raised. That is, the number of times that number, expression, or quantity is to be multiplied by itself. Exponents follow simple laws:

Multiplication: $x^a x^b = x^{a+b}$
Division: $x^a / x^b = x^{a-b}$
Power of a power: $\left(x^a\right)^b = x^{ab}$

Where the exponent is zero, the number or variable is equal to 1, i.e $x^0 = 1$.

exponential decay The decrease in a quantity at a rate that is proportional to its value:

$$\frac{dN}{dt} = -kN$$

For example, the decrease in the viability of contaminating microorganisms during the thermal sterilization of foods in the canning process follow this form of decay where the number of surviving microorganisms after time, t, is:

$$N = N_o e^{-kt}$$

where N_o is the initial number and k is the decay constant. The reciprocal of the decay constant is known as the *time constant. A special case is the radioactive decay of a substance known as the *half-life. This is the time taken for a substance to fall to half of its original value ($N = 0.5N_o$):

$$t_{1/2} = \frac{\ln 2}{k}$$

The half-life of a particular isotope is constant and independent of the amount of starting material.

exponential growth The growth of a microorganism in a culture that is unrestricted in terms of nutrients or substrate such that there is a repetitive doubling. The increase in population is:

$$\frac{dN}{dt} = kN$$

Integrating from an initial population N_o at time t = 0, gives $N = N_o e^{kt}$. In practice, the nutrient or substrate is limiting and the growth curve is not indefinitely exponential but sigmoidal or S-shaped.

exposure The amount of a toxic or harmful substance to which a person is exposed. The exposure may be in the form of ingestion, absorption, or inhalation, and may involve both concentration and time of exposure. It also applies to ionizing and thermal radiation. *See* DOSE.

expression A mathematical variable, function, or combination of constants, variables, or functions.

exsiccant A material capable of drying or being dried. The material is dried in an **exsiccator**. It is applied mainly to paints and varnishes.

extended surface A surface used for heat transfer in which projections are attached, such as fins or pins. These attachments are used to increase the available area of heat transfer on the side that has the lowest surface heat-transfer coefficient.

extensive variable *See* INTENSIVE VARIABLE.

extent of reaction The ratio of the number of moles of a substance consumed or produced in a chemical reaction to its stoichiometric coefficient.

extinguishing agent A substance used to put out a fire by cooling the burning material, inhibiting the chemical reaction, and/or blocking the supply of oxygen. Examples include water, carbon dioxide, foam, and sand.

extract The solvent-rich product stream leaving a *liquid–liquid solvent extraction process. The extract carries an extracted material.

extraction A separation process in which a component is selectively removed by chemical or physical means such as the pressing of seeds to remove oils. Liquid–liquid extraction or *solvent extraction is a separation process in which a component is selectively transferred from one liquid phase to another, such as the extraction of uranium and plutonium from a fission product containing nitric acid solution into a kerosene diluent containing the solvent tri-butyl phosphate.

extractive distillation The separation process used for azeotropic mixtures in which a solvent is added, leaving the bottom of the column carrying one component with it, allowing the other component to leave at the top of the column (see Fig. 21). Extractive distillation is more widely used than *azeotropic distillation since there is a wider choice of agent and there is no need for close matching of volatilities. Azeotropic entrainers must usually boil within 5–20°C of the other components. There is also a lower heat requirement since the solvent is not vaporized. There is also a wider choice of operating conditions. The solvent/feed ratio, for example, is not critical, unlike an entrainer/feed ratio, and there is easier recovery of the agent. Solvents are cheap, readily obtainable, non-corrosive, non-toxic, unreactive, thermally stable, and easily recoverable, as well as being readily miscible, and have a low volatility. The solvent is added a few trays down from the top of the column with the trays above the solvent feed point functioning as a solvent recovery section to remove traces of solvent from the overhead vapour A. The solvent leaves the bottom of the main column together with component B, from which it is usually readily separated in a solvent-recovery column in view of its presumed low volatility. The solvent is recycled to the main column with a make-up stream being provided to allow for any solvent losses. Examples include the separation of paraffins (A) from toluene (B) using phenol, and isobutane (A) from butane (B) using furfural.

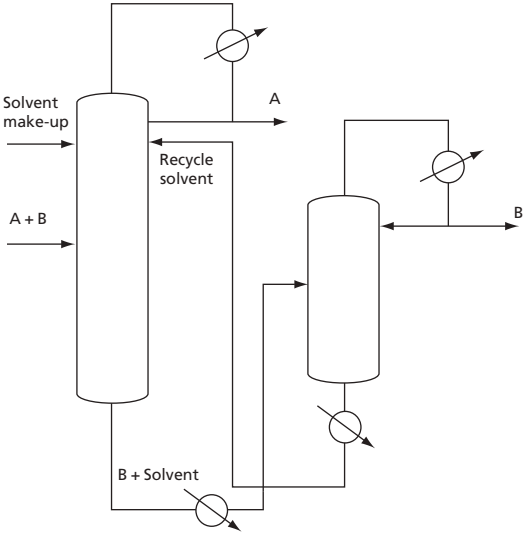

Fig. 21

extractor A device used to selectively remove components from one phase to another, such as a solid or a liquid to another liquid, by leaching or solvent extraction.

extraneous material A substance that may appear intentionally in another substance as an impurity. A method of calibrating flow meters involves the use of a controlled amount of extraneous material that is intentionally added to the process stream either upstream or downstream of the flow meter. A sample is then taken downstream and analysed from which the rate of flow of the process stream is determined, and relevant calibration adjustments made to the flow meter. Examples include the addition of dyes to water, brine to seawater, the addition of radionuclides and oxygen in chlorine.

extrapolation A method of obtaining data that falls outside a range of known data that assumes the estimated data can be obtained by extending the known data.

extrusion A process in which a soft material is forced under pressure through a restricted orifice or opening in a die to produce a continuous flow of material in a desired shape or form. The material is conveyed under pressure using an Archimedes screw. Either a single or twin screw auger is used that is generally powered by an electric motor. Heated *billets of aluminium can be extruded to form sheets, rods, and tubing. Plastics and polymers can also be extruded. The first extruders were developed in 1879 for wire coating. The first hot-melt-extrusion extruders for thermoplastics were developed in Germany in 1935.

Eyring equation An equation used to describe the kinetics of chemical reactions and relates the reaction rate to temperature in the form:

$$k = \frac{k_B T}{h} e^{\frac{-\Delta G^{\ddagger}}{kT}}$$

where k_B is the Boltzmann constant, T is the absolute temperature, h is the Planck constant, $\Delta G^{\ddagger}$ is Gibbs free energy. The equation is based on the transition state theory and is of a similar form to the *Arrhenius equation. The equation is based on the statistical probability that a chemical reaction will take place once the system has reacted the activated state. There are similar equations used to describe transport phenomena such as viscosity. The Eyring equation is named after Mexican-born American chemist Henry Eyring (1901–81) who derived it.

F

factor 1. A number that can be multiplied by another number. A common factor is a number by which another number is divided exactly. It is also known as a divisor. For example, 12 can be divided by 1, 2, 3, 4, 6, and 12. **2.** An activity that contributes to a particular situation or effect. For example, greenhouse gas emissions are one of the factors that contribute to global warming.

factorial (Symbol !) The product of all the positive whole integers being considered. Note that 0! has a value of 1. For example, 5! is $0 \times 1 \times 2 \times 3 \times 4 \times 5 = 20$.

factorial experimental design A statistical procedure used to study the effects of process variables on a process and their collective effect on an independent variable. It is used when the effect of the combination of the variables is complex and involves the study of the various combinations of the variables. For example, temperature, pressure, and the concentration of reactants can have an effect on the yield of a desired product. By selecting high, medium, and low levels for each variable, the number of separate experiments that would be required to study fully the effects on the product would be $3^3 = 27$. These would be randomly sequenced and possibly repeated in duplicate or triplicate. The test results on yield would then be interpreted by a regression analysis and analysis of variance to determine the influence of each of the variables. Where there are many variables that give too many combinations to be practically considered, a fractional factorial experimental design is used. This allows for a fraction of the full factorial experimental design to be used that can lead to the same outcome, although the level of statistical uncertainty is correspondingly increased. *See* EXPERIMENTAL DESIGN.

factorization The mathematical process of changing an algebraic or numerical expression from a sum of terms into a mathematical product. For example, the equation $2x^2 - 3x - 2 = 0$ can be factorized to $(2x+1)(x-2)$, thereby making it easier to solve for x. Since the product of the two factors is zero, then the solutions are $x = 2$ and $x = -\frac{1}{2}$.

Factory Acts A series of early Acts of Parliament in the UK designed to limit the number of hours worked by women, children, and young people, and to improve working conditions. They were initially aimed at those working in the textile industries and later applied to all industries, in order to protect workers and to compell industry owners to operate lawfully and with accountability. There were a number of Acts passed over the course of the nineteenth century. The Factory Act of 1844, for example, was responsible for reducing the hours of work for children aged between eight and thirteen and stipulated that they must begin after 6 am and end before 9 pm. Women and young persons aged between fourteen and eighteen were to work no more than twelve hours a day. Fines could also be imposed on factory owners. Today, workplace health and safety is governed by the Health and Safety at Work Act 1974. *See* HSE.

facultative anaerobe A living organism, such as certain bacteria and yeast, that can adapt its metabolism to enable it to survive and grow in either the presence or absence

of oxygen. Yeast can grow aerobically producing more cells and carbon dioxide, which is useful in the production of bread, or anaerobically producing carbon dioxide and ethanol as well as more living cells, which is useful in the production of beer, lager, and wine.

Fahrenheit scale A temperature scale invented in 1714 by German physicist and instrument-maker Gabriel Daniel Fahrenheit (1686–1736). Fahrenheit was the first person to make practical thermometers using mercury instead of spirits of wine (alcohol). He calibrated his thermometer between two *fixed points for which he used the eutectic point of salt water as 0°, which was the lowest temperature he could obtain in the laboratory, and the temperature of a healthy human which he originally called 12° and later 96°. He found that on his scale, pure ice melted at 32°F and steam at normal atmospheric pressure was 212°F. The conversion to the *Celsius scale is given by:

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

fail-safe A type of control used in situations such that a malfunction or unsafe condition results in a device, item of equipment, or process safely shutting down. An example is a gas burner where the fuel supply is automatically shut off in the event that the air (oxygen) supply should inadvertently cease. In contrast, a **fail-to-danger** is a fault or failure of a device or item of equipment that renders the plant in a dangerous condition such that a control system is unable to respond to provide the necessary protection.

Falconbridge process A selective leaching process used to extract copper and nickel from a sulphide ore containing nickel, copper, and other precious metals that has been roasted to remove the sulphur known as *matte. The nickel is removed using hydrochloric acid and recovered as nickel chloride crystals. The residue is then leached with sulphuric acid to dissolve the copper.

falling film evaporator A type of tubular heat exchanger in which the feed solution for evaporation falls under the influence of gravity as a film down the walls of the tubular heat exchange surface. The solution separates into liquid and vapour near the bottom of the tube. It is used in concentrating temperature labile solutions such as fruit juices.

falling-rate drying The period of drying in which the rate of change of moisture decreases with time. The falling-rate period follows the *constant-rate drying period. For non-porous solids, the rate of drying changes non-linearly with time and is limited by molecular diffusion of bound water.

fallout The release of radioactive material into the environment either from an accidental release from a nuclear installation such as a power plant, or from a nuclear explosion. The *Windscale nuclear accident in 1957, *Chernobyl in 1986, and *Fukushima Daiichi in 2011 led to wide-scale contamination of the environment. The most harmful isotopes to human health include iodine-131 and strontium-90. Both isotopes are taken up by animals such as grazing cows and transferred to humans through the consumption of milk. Iodine-131 accumulates in the thyroid gland while strontium-90 accumulates in the bones.

fan A mechanical device used to move air, gas, or vapour at low gauge pressure. It consists of blades on a rotating shaft. Fans are classified as being axial or radial, and refer to the direction of flow with respect to the rotation of the fan. The efficiency of a fan is the ratio of the power output to the power input resulting in the flow delivered. *Compare* BLOWER.

Fanning friction factor A dimensionless friction factor used to determine the frictional pressure drop resistance of a moving fluid in a pipe or over a surface. The friction factor is the proportionality constant in which the wall shear stress, τ_w, of a fluid at a surface is proportional to the kinetic energy of the fluid per unit volume

$$\tau_W = f\frac{\rho v^2}{2}$$

where ρ is the density and v is the fluid velocity. It is named after American engineer John Thomas Fanning (1837–1911)

FAR *See* FATAL ACCIDENT RATE.

farad (Symbol F) The SI unit of capacitance and is the capacitance of a capacitor where if it were charged with one coulomb there would be a potential difference of one volt between its plates. The farad is too large for most applications, so it is usually expressed in microfarads (μF).

Faraday's laws of electrolysis Laws that were defined by Michael Faraday (1791–1867) to describe the process of electrolysis. The first law states that the mass of a given element liberated during electrolysis is directly proportional to the magnitude of the steady current consumed during the electrolysis and to the time for which the current passes. The second law states that when the same quantity of electricity is passed through different electrolytes, the masses of the different substances liberated are directly proportional to the masses of the substances that require one mole of electrons (1 faraday) for neutralization. The transfer of 1 mole of electrons corresponds to the passing of approximately 96,500 coulombs of electricity, which is known as the Faraday constant. A coulomb is equivalent to the passage of 1 ampere for 1 second.

fast reactor A type of high-temperature nuclear reactor that has no moderator and uses a liquid metal coolant such as sodium. They are used as either fast breeder reactors in which fissile material such as uranium enriched with plutonium-239 is used as the fuel and is able to produce more plutonium-239 at a rate faster than it uses; or as converter reactors in which *fertile material such as uranium-238 is converted into plutonium-239 by the absorption of a neutron to form uranium-238 and which then decays to plutonium-239. Fertile material is a nuclide that can absorb a neutron to form fissile material.

fatal accident rate (FAR) The number of fatal accidents in a particular industry occurring within a period of 10^8 hours of activity. This is the period of time that corresponds with approximately the working life of a group of a thousand workers. For the chemical industry the FAR is between 4 and 5. For the agricultural industry it is 10, while for the mining and construction industries the FAR is 12 and 64, respectively.

fatigue The failure of materials such as metals under cyclic applications of an applied stress.

fault tree analysis A method used to calculate the probability of an event occurring based on the probabilities or frequencies of its component parts. The fault tree is a diagram used to provide a model of the interactions between the various components in a system to identify how failure may occur and to provide an estimate of the likelihood or frequency of failure. It is used to plan maintenance and to avoid plant and equipment failure.

FCCU *See* FLUIDIZED CATALYTIC CRACKER UNIT.

F-distribution A statistical probability distribution used in the analysis of variance of two samples for statistical significance. It is calculated as the distribution of the ratio of two chi-square distributions and used, for the two samples, to compare and test the equality of the variances of the normally distributed variances.

fed batch bioreactor A type of bioreactor in which microorganisms are cultured in such a way as to overcome growth limitation due to the initial substrate concentration. The substrate is therefore added to the growing cell culture either on a step-wise or continuous basis. A constant flow of substrate can be used to maintain a steady growth rate or exponential growth. Alternatively, the addition can be adjusted to maintain a constant substrate concentration but requires good and rapid measurement of the substrate in the medium.

A substrate-limited fed batch bioreactor uses a continuously supplied substrate with a low concentration. The required amount of substrate supplied can be checked periodically by stopping the supply and monitoring the effect on dissolved oxygen concentration.

FEED *See* FRONT END ENGINEERING DESIGN.

feedback control A closed-loop method of controlling a process in which information about the controlled variable is fed back to the input and compared against a desired value. The difference between the two signals is called the *error or *deviation. The feedback can be accomplished by a human operator as in **manual control**, or by the use of instruments as in **automatic control**. In a **negative feedback control**, the applied counteracting disturbance is motivated by the difference between the desired value and the actual value of the controlled variable. For example, in the manual control of the heating of a liquid in a vessel with steam, an operator periodically measures the temperature of the liquid; if this temperature is below the desired value, the steam flow is increased by opening the valve slightly. In the automatic control of the vessel, a temperature-sensitive device is used to produce a signal, which may be electrical or pneumatic, and is proportional to the measured temperature. This signal is fed to a controller, which compares it with some desired value or set point. Where there is a difference in signals, the controller changes the opening of the steam control valve to adjust the temperature.

feedforward control A method of process control in which a disturbance is detected before it enters the system for which the controller calculates the required counter-acting disturbance. Process disturbances are measured and compensated for without waiting for a change in the controlled variable to indicate that a disturbance has occurred. Feedforward control is useful where the final controlled variable is not able to be measured. The necessary equations are solved by the controller relating all the process variables, such as steam flow, liquid output temperature, etc., which are usually designated as the process model. Perfect models and controllers are rare so a combination of feedback and feedforward control is more desirable.

feed point The location in a process where a stream of material is first introduced. In a distillation column this is located between the rectifying and stripping sections in which the feed is fed onto the **feed plate**.

feed rate The amount of material fed to a process per unit time. The rate may be expressed on a volumetric, mass, or molar basis depending on the process.

feedstock The main raw material used in a process that is converted into a product or products. In a petroleum refinery, the feedstock is crude oil.

feints The final distillate fraction that is collected from a Scotch *whisky *batch distillation once the desired mid-cut composition has been collected. It is lean in alcohol and returned to the next distillation batch.

Fenske equation A shortcut method used to find the minimum number of theoretical trays in a distillation column required for the separation of two *key components. It is calculated from the mole fraction, x, of the key components in the distillate, and in the bottoms where the relative volatility of the key components is reasonably constant. For a binary mixture of components a and b, the minimum number of trays is:

$$N_{\min} + 1 = \frac{\ln\left(\frac{\left(\frac{x_a}{x_b}\right)_D}{\left(\frac{x_b}{x_a}\right)_B}\right)}{\ln \alpha_{ab}}$$

where N_{mn} is the total minimum number of theoretical trays, σ_{ab} is the relative volatility and the subscripts *D* and *B* represent the distillate and bottoms, respectively. The method was proposed in 1932 by American professor of chemical engineering Merrell Robert Fenske (1904–71).

fermentation A biotechnological process that involves the anaerobic respiration of certain microorganisms, in particular yeast. Forming the basis of baking, wine, and beer production, alcoholic fermentation comprises a series of biochemical reactions in which sugars are consumed as a substrate to produce ethanol and carbon dioxide in the reaction:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Industrial applications of fermentation include the production of alcohol and glycerol from yeast, lactic acid, acetone, and butyl alcohol from various bacteria, and citric acid, antibiotics, and vitamins from mould fermentations.

fermenter A vessel used to contain the biochemical process of *fermentation. It is typically made of steel although smaller vessels are made of glass. It can be operated as a batch process, a fed batch process, or continuously. The fermentation process is usually sufficient to create natural turbulence and mixing. However, the extent of mixing can be enhanced using a mechanical stirrer such as an impeller. To avoid a mechanical stirrer, an air-lift or loop fermenter uses an internal or external draft tube up which a small flow of air is admitted to circulate the fermenting medium. In the *whisky industry, the vessel is called a **washback** and is traditionally made of wood.

fertile material A radionuclide that can absorb a neutron to form fissile material. The fissile material used in fast reactors such as uranium-238 is converted into plutonium-239 by the absorption of a neutron to form uranium-238, which then decays to plutonium-239.

FIChemE The post-nominal letters used after someone's name to indicate that he or she is a chartered chemical engineer and a fellow of the Institution of Chemical Engineers. Fellow is the highest category of membership and represents a person with significant leadership and management responsibility within an organization.

Fick, Adolf Eugen (1829–1901) A German physiologist who began his studies in mathematics and physics before pursuing a doctorate and career in medicine. In 1855 he

introduced *Fick's first law of diffusion, which governs the diffusion of a gas across a fluid membrane. In 1870, his law of diffusion led to a method for measuring cardiac output in what is known as the Fick principle.

Fick's first law of diffusion A law concerning the movement of mass by the process of diffusion. The law states that a species diffuses in the direction of decreasing concentration:

$$J = -D\frac{\partial C}{\partial x}$$

where J is the *diffusion flux defined as the amount of substance per unit area per unit time, D is the *diffusion coefficient or diffusivity, C is the concentration, and x is the position. The negative sign shows that the flux is driven in the direction of increasing position. The diffusion coefficient is proportional to the square of the velocity of the diffusing particles, which depends on the temperature, viscosity of the fluid, and the size of the particles, according to the *Stokes–Einstein equation. The SI units for the diffusion coefficients are $m^2\ s^{-1}$. The law was proposed in 1855 by Adolf *Fick (1829–1901) and is analogous to the relationships discovered around the same time by other eminent scientists, such as Darcy's law for fluid flow, Ohm's law for the transport of charge, and *Fourier's law for heat transfer. Diffusion processes that do not follow Fick's laws are known as **non-Fickian**.

Fick's second law A law that predicts how diffusion causes the concentration of a diffusing species to change with time and given by:

$$\frac{\partial \phi}{\partial t} = D\frac{\partial^2 \phi}{\partial x^2}$$

where ϕ is the concentration per volume, and x is the position. The law can be derived from *Fick's first law of diffusion and a mass balance of the diffusing species by assuming that the *diffusion coefficient, D, is constant.

field operator A process plant operator who is based on the chemical plant rather than in the central control room.

film A layer, usually thin, of a gas or liquid on a surface. In convective heat transfer, the heat transfer rate is increased by agitation, reducing the thickness of the film. Boiling and condensation heat transfer is related to the film characteristics. *See* CONVECTIVE MASS TRANSFER.

film badge A lapel badge worn by workers in the nuclear industry and in businesses that use ionizing radiation. It is used to measure and record the accumulative exposure to harmful exposure to beta particles, gamma rays, and X-rays. The badge consists of a photographic film, covered with various metals and thicknesses, which are usually lead and tin.

film boiling A type of liquid boiling in which a layer of vapour is formed on a very hot heat transfer surface causing an insulating effect. The heat transfer from the surface into the bulk of the liquid is due to radiation rather than convection and conduction.

film condensation A type of condensation that occurs on a cold surface that forms a continuous film of liquid condensate. Most *condenser type heat exchangers operate using film condensation. *Compare* DROPWISE CONDENSATION.

film model A mathematical model used to describe the mass transfer between two immiscible liquids in which mass transfer takes place as molecular diffusion through

stationary layers between the interface and the bulk material. The model assumes that the interface is maintained at an equilibrium condition.

filter A device used to remove and separate particles from gases or liquids. The particles may be undesirable such as contaminants in an air stream as in the case of ventilation, or as extraneous material in food processing. The size of the pores or mesh size of a filter determines the size of the particles retained. Filters are classified as roughing, medium efficiency, high efficiency, ultra-high efficiency, and absolute. Strainers are a type of coarse filter. Filter cloths are used to retain particles from liquids and are typically made from cotton, glass, and synthetic woven fibres or mats. *See* FILTER PRESS.

filter cake A layer of particles formed on the surface of a *filter that have compacted to form a solid cake during the process of *filtration.

filter press A device used to carry out the process of *filtration for separating particles from a liquid suspension or *slurry. It consists of a series of filter cloths with a mesh size sufficient to withhold particles, and through which the suspension to be filtered can pass. A *plate and frame filter press consists of alternating plates and frames with a filter cloth between each. The suspension is fed under pressure and the filtrate passes out through channels embedded within the plates. They can be operated as a batch operation or continuously, and are suited for the filtration of large volumes of liquid carrying suspended solids. Once the *filter cake has built up on the filter cloth, the filter press is taken out of service, and the cake removed from the cloth.

filtrate The clear liquid separated from the process of *filtration, leaving behind the suspended particles.

filtration A process in which a suspension of solid particles in a liquid or a gas are separated. The process uses a *filter, which is a material used to entrap the particles. The rate of filtration can be increased by using a vacuum to draw the gas or liquid through, such as in the process of *vacuum filtration, or the use of pressure to force the liquid through the filter, such as *ultrafiltration.

final moisture content The *moisture content of a substance at the point of leaving a *dryer or drying process. The moisture content is expressed on either a *dry basis or *wet basis.

fine chemicals Chemicals produced industrially in relatively small quantities and of high purity, specification, or composition. For example, dyes, pigments, and pharmaceuticals are considered to be fine chemicals.

fines Small particulates ranging in diameter from 1 to over 400 micrometres. They may be carried by gases and accumulate in undesirable places. They can be removed by *filters, centrifugal separators, *cyclones, *electrostatic precipitators, and washing, etc.

finite difference A mathematical approximation method used for solving first- and second-order differential equations. It is based on determining the gradient from two adjacent points separated a finite distance apart. For example, the forward difference for a first order derivative is given by:

$$\frac{d}{dx}f(x_i)=\frac{f(x_{i+1})-f(x_i)}{\Delta x}$$

The approximation therefore requires the difference in value of the function separated by Δx. It is used for complex functions where an analytical solution may not be possible or too cumbersome.

fire The rapid thermal oxidation (combustion) of a fuel source resulting in heat and light emission. There are various types of fire, classified by the type of fuel and associated hazards. In the US, the National Fire Protection Association (NFPA) classifies fires and hazards by types of fuel or combustible in order to facilitate the control and extinguishing of fires: Class A are ordinary combustibles such as wood, cloth, paper, rubber, and certain plastics; Class B are flammable or combustible liquids, flammable gases, greases, and similar materials; Class C is energized electrical equipment; Class D are combustible metals, such as magnesium, titanium, zirconium, sodium, and potassium.

SEE WEB LINKS

- Official website of the National Fire Protection Association in the US.

fireball A phenomenon that occurs as the result of the deflagration of a cloud of combustible vapour but which does not result in a blast wave. The burning cloud may lift off the ground and form into the shape of a mushroom cloud. Combustion rates are extremely high and may exceed one tonne per second.

fire point The lowest temperature at which a flammable liquid gives off sufficient vapour to produce a sustained combustion after removal of the ignition source.

fireproof A condition in which a structure, equipment, wiring, controls, or piping is capable of functioning under the most severe conditions of fire likely to occur at its location. A **fire retardant** is a substance or treatment that reduces the combustibility of a material. It can be used in *personal protective equipment or coated onto process equipment and structures to protect them against severe heat for a limited period of time. **Fire prevention** involves the measures that are needed to prevent an outbreak of fire. **Fire protection** involves the engineering design features and systems that are required to reduce the damaging and harmful effects of a fire.

fire suppression system A method, device, or system used to detect a fire or ignition source, and to extinguish the fire in sufficient time so as to prevent structural damage and/or debilitation of personnel.

fire triangle A way of illustrating the three *factors necessary for the process of combustion which are fuel, oxygen, and heat. All three are needed for combustion to occur. A fire can therefore be prevented or extinguished by removing one of the factors. That is, a fire is not able to occur without sufficient amounts of all three.

first law of thermodynamics A law that is applied to the conservation of energy in which the change in internal energy, ΔU, of a system is equal to the difference in the heat added, Q, to the system, and the work done, W, by the system:

$$\Delta U = Q - W$$

When considering chemical reactions and processes, it is more usual to consider situations where work is done on the system rather than by it.

Fischer–Tropsch process A process used for producing hydrocarbons from carbon monoxide and hydrogen. Named after German chemist Franz Fischer (1852–1932) and

Czech Hans Tropsch (1839–1935), the process was invented to produce motor fuel in Germany during the Second World War. The process involves passing the reactants over a nickel or cobalt catalyst at 200°C. The general reaction is:

$$nCO+(2n+1)H_2 \rightarrow C_nH_{2n+2}+nH_2O$$

The resulting complex mixture of hydrocarbons is then separated into various fractions. The process also results in the formation of alcohols, aldehydes, and ketones.

fissile material A radionuclide of an element that undergoes nuclear fission either spontaneously or through being irradiated by neutrons. Examples include uranium-235 and plutonium-239 used in nuclear reactors. Fissile materials are also used in nuclear weapons.

fission 1. The division of a living cell into new cells as a mode of reproduction. **2.** In a nuclear reaction, fission is the splitting of a heavy atomic nucleus spontaneously or as the result of an impact of another particle with the release of energy, and possibly causing a chain reaction within the mass of the element. Nuclear fission is the process used in nuclear reactors and atomic bombs. **Fission products** are nuclides that are produced by nuclear fission or the radioactive decay of nuclides by fission. Examples include krypton-85, strontium-90, and caesium-137.

fittings Connections and couplings used in pipework and tubing. The type of fittings used depends largely on the wall thickness as well as in part on the properties of the pipes and tubes including welds, flanges, and screw fittings. Fittings include elbows, bends, reducers, and branches.

fixed bed A stationary and immovable layer of particulate material through which a fluid passes. The particulate material may typically be a catalyst, absorbent, or ion exchange resin. *Compare* FLUIDIZED BED.

fixed costs The costs of a process that include the capital cost repayments, scheduled maintenance costs, and overheads such as personnel facilities, administration, laboratory services, etc. The fixed costs of a process are independent of the rate of production. The sum of the fixed and *variable costs is the total cost of the process. *See* PROCESS ECOMONICS.

fixed point A data point that can be accurately located or reproduced to enable it to be used as a reference point. For example, fixed points are used for calibrating temperature scales such as the triple point of water. *See* FAHRENHEIT SCALE.

flaking A process for extracting chemical products as solid flakes from a liquid solution. An internally cooled rotating drum is partially immersed in the liquid; a thin film of product solidifies on the surface, and is removed by a scraper. It is widely used in the food industry.

flame The visible effect of the combustion of gases. A flame may be luminous or non-luminous, and is the result of the burning of soot particles and gaseous products. A **flame front** is the boundary between the burning and unburnt parts of a combustible mixture, such as a vapour and air.

flame proofing A surface treatment or impregnation of wood products, textiles, and other materials with **fire retardant** chemicals. These are flame-inhibiting chemical compounds used to reduce the flammability of a product or a structure over which it has been applied.

flame propagation The spread of a flame from one place to another in a combustible material, especially in a combustible vapour–air mixture.

flame resistant The property of a material that does not conduct a flame or continue to burn when an ignition source is removed.

flame speed The velocity of a propagating flame relative to the observer. The **flame speed rate** is the propagation velocity of a flame over a surface of combustible material.

flame temperature The heat intensity of a flame.

flame trap A device used to prevent a gas flame from entering a pipe or process vessel containing flammable material. It is typically made from a screen, mesh, or metal gauze, and located in the vent pipe to a storage vessel.

flammability limits The maximum and minimum concentration of a combustible gas or vapour in air or oxygen that is capable of propagating a flame at a specified temperature and pressure with the aid of an ignition source such as a spark or open flame. The concentrations are generally expressed as the per cent fuel by volume. Above the *upper flammable limit (UFL), the mixture is too rich to burn, while below the *lower flammable limit (LFL), the lack of oxygen does not allow the fuel to burn. Any concentration between these limits can result in ignition or explosion. For example, the LFL for hydrogen in air is 4 per cent $^{v}/_{v}$ and UFL is 75 per cent $^{v}/_{v}$. Concentrations below or above these limits therefore do not result in ignition or explosion.

The bounds of the flammability envelope expand with increased temperature and pressure. That is, the minimum oxygen level and the LFL decreases and the UFL increases. For example, diesel oil has a very low vapour pressure in which a fuel–air mixture at room temperature is too lean. That is, it is below the lower flammable limit. Once the oil is warmed to above its *flash point it will ignite.

flammable A substance or material that has the ability to support combustion and be capable of burning with a flame. It is easily ignited or highly combustible. The term is more widely used than *inflammable as this is often confused with *incombustible, which means an inability or lack of ability to combust. A **flammable liquid** is a liquid that has the capability of catching fire. In the US, the National Fire Protection Association defines a flammable liquid as a liquid that has a flash point below 100°F (37.8°C) and a vapour pressure not exceeding 40 psia (2.72 bar) at that temperature.

flange A pipe fitting at the end of a length of pipe that consists of flat disc or ring of metal used to attach another length of pipe which has an identical flange. The flanges are bolted together and a gasket is compressed between them. The flanges are attached to the pipe by welding or brazing. A blind flange or blank flange is a flange with no opening and used to close a pipe. Slip-on, weld neck, socket weld, and screwed flanges are types of flange to be found at the end of a length of pipe.

flaring The burning of unwanted gaseous hydrocarbons in a petroleum refinery or on an offshore installation. Once widely used, it is now largely used during the testing of a new well, and when small amounts of unwanted or surplus refinery gas have accumulated, or when there is insufficient pipeline or vessel capacity to transport or store it. A **flare stack** is an installation used to provide the safe disposal of gaseous hydrocarbons produced during the oil refining process. A **flare boom** is used on offshore oil platforms, angled away and extending a safe distance from the deck to permit the safe burning of the gases.

flashback The propagation of a *flame from an ignition source back to a supply of flammable gas or liquid.

flash drum A vessel used for the rapid separation of a mixture into a liquid and vapour by *flash evaporation caused by a sharp drop in pressure. The liquid leaves cooled from the bottom and the vapour from the top at the *saturation temperature of the liquid.

flash drying A rapid form of *drying of particulates using hot gas or air. The particulates either descend through a current of hot gas or air, or are transported pneumatically in which their *moisture content is reduced.

flash evaporation/vaporization The rapid separation of a saturated liquid of a single component into a vapour and a liquid when it passes through a throttling valve to a lower pressure. As a single-stage vapour–liquid separation process, the liquid mixture is partially vaporized by heating and reducing the pressure, allowing the vapour to form at the expense of the liquid adiabatically. The vapour is allowed to reach equilibrium with a residual liquid, and the resulting vapour and liquid phases are separated and removed. It may be operated as either a batch or continuous process. It is also known as **equilibrium distillation**. The process in which both the liquid and vapour are cooled to the saturation temperature of the liquid at the reduced pressure, which forms the basis of vapour compression cycles used for *refrigeration. The flash process is isenthalpic since it involves no work, and is also known as an *adiabatic flash.

flash fire A fire that spreads with considerable rapidity. It occurs when a fuel source such as a flammable vapour and air are mixed in sufficient amounts and ignited. The combustion is rapid and characterized by a rapidly moving flame front with a high temperature. The flame passes through the mixture at less than sonic velocity and with negligible overpressure. *See* FLAME.

flash freezing A rapid freezing technique used for foods in order to retain food quality. Pioneered by American inventor Clarence Birdseye (1886–1956) in 1922, it involves a freezing process that causes the water content to freeze in a very short time, preventing the formation of ice crystals that have a destructive effect on biological cell wall structure. It is used for many foods such as fish, meat, and fruits, and is also known as *quick freezing.

flash point The lowest temperature at which a volatile liquid will produce a sufficient amount of vapour to ignite in air at a given pressure. The rapid combustion occurs in the form of a momentary flash. Flash point data is important for the safe storage and transportation of volatile liquids. *Compare* AUTOIGNITION TEMPERATURE.

Flixborough disaster A major incident that occurred in the UK in 1974. It involved an explosion at the Flixborough Works of Nypro (UK) Limited near Hull, killing 28 people and injuring 36 others, together with extensive damage beyond the factory including 2,000 houses and 200 shops and factories. The incident took place on 1 June 1974 and was the result of a massive leak and subsequent deflagration of cyclohexane gas from a temporary bypass in a chain of six reactors. The reactors were used for the oxidation of cyclohexane to form cyclohexanone and cyclohexanol by the injection of air in the presence of catalyst. The cyclohexane and cyclohexanol were in subsequent stages of the process for conversion to caprolactum, which is a raw material for the production of Nylon 6. At the time, the report from the Court of Enquiry was the most comprehensive inquiry into a disaster in the chemical industry, and was crucial in the development of *Loss Prevention in the UK.

float glass process A process for making sheets of glass and involves molten glass being fed onto a shallow tank containing molten tin. The less dense glass floats on the tin and spreads to form a sheet. The process is carried out in a slightly reducing atmosphere to prevent oxidation of the molten tin. The molten glass starts at around 1,050°C and is cooled to around 650°C before being lifted off the tin.

floating head heat exchanger A type of shell and tube heat exchanger in which the tube sheet assembly is independent and free to move within the shell or within the shell cover. This allows for differential expansion of the tubes. Since the floating tube plate is smaller in diameter than the shell, removal for cleaning and general maintenance is relatively straightforward.

floating production systems (FPS) A floating oil platform that contains all the equipment associated with a fixed installation. They are used in conjunction with sub-sea wellheads to exploit moderate to deep-water oil fields. They are used for small or isolated oil fields or where the water is too deep for a conventional fixed platform. The term is used generally to mean any vessel associated with oil production or oil storage, and includes *FSO, *FSU, and *FPSO.

floating roof The roof of a tank used to store volatile liquids. The roof is allowed to float on the surface thereby reducing the vapour volume and vaporization, and therefore loss of the material by evaporation.

floating, storage, and off-loading unit (FSO or FSU) A floating vessel into which processed oil is pumped from a fixed platform that neither has any storage capacity of its own, nor is connected to a sub-sea pipeline. A **floating, production, storage, and off-loading unit (**FPSO) is a floating oil platform with a storage capacity that is not connected to a sub-sea pipeline. The oil from sub-sea wells is processed and stored aboard the vessel before being off-loaded into shuttle tankers.

flocculation A process that is used to separate particles in a liquid. It is applied to particles in a colloid that aggregate into larger clumps or flocs by weak electrostatic forces. The ability of particles to flocculate relies on a surface charge on the surface of the particles. Reagents or **flocculants** can be added to the liquid to bring the particles together. The clumps are then able to settle under gravity or be filtered more easily. The particles can be dispersed again back into the liquid with agitation. Flocculation is used in the *water treatment industry and for removing yeast from beer at the end of fermentation.

flooding An excessive build-up of liquid in adsorption columns or on the plates of a *distillation column. It is due to high vapour flow rates up the column. In distillation columns this is caused by high heating rates in the reboiler. *Compare* WEEPING. The **flooding point** is a condition in a packed column such as an absorption column which receives a countercurrent flow of gas at the bottom and a liquid descending under gravity from the top where there is insufficient liquid hold-up in the packing for mass transfer to take place effectively. The liquid therefore descends to the bottom of the column without mass transfer. The rate of flow through the packing for effective mass transfer is controlled by the pressure drop across the packing material.

flotation A separation process in which suspended particles in a liquid are carried to the surface by air or gas bubbles attached to them. The air or gas is blown as bubbles through the liquid and the particles are removed from the surface. It is widely used in the mining industries for the separation of minerals, such as copper, lead, and zinc, and *gangue. It

is also used for the separation of oil from oil sands. A **flotation agent** is a surface-active substance added to improve the separation process by promoting the attachment of the particles to the bubbles. Other reagents that may be added can improve the stability of the foam to facilitate the removal of the froth of solids. *See* ORE FLOTATION.

flow The movement of a fluid under the influence of an external force such as gravity or a pump.

flowline A pipeline that carries materials from one place to another. In the offshore industry, a flowline is a pipeline that carries oil on the seabed from a well to a riser. On a *process flow diagram, the flowline is indicated by a line entering and leaving a vessel or unit operation. An arrow indicates the direction of flow.

flow meter A device used to measure the flow of process fluids. Flow meters are broadly classified into those that are intrusive and those that are non-intrusive to the flow of the fluid. Flow meters include differential pressure meters, positive displacement meters, mechanical, acoustic, and electrically heated meters. The measurement of the flow of process fluids is essential not only for safe plant control but also for fiscal monitoring purposes. It is important to select correctly the flow meter for a particular application, which requires a knowledge and comprehension of the nature of the fluid to be measured and an understanding of the operating principles of flow meters.

flow rate The movement of material per unit time. The material may be a gas, liquid, or solid particulates in suspension or combinations of all of these, and expressed on a volumetric, mass, or molar basis. The volumetric flow rate of material moving through a pipe is the product of its average velocity and the cross-sectional area of the pipe.

flow regimes The behaviour of a combined gas and liquid flow through a channel, duct, or pipe can take on an almost infinite number of possible forms. There are many descriptions used to define the possible flow patterns and there is often confusion through the subjective way in which flow patterns are characterized. In general, depending on the conditions of flow of the two phases, one phase may be considered to be the continuous phase while the other is the discontinuous phase. An example is the flow of a mist or fine dispersion of liquid droplets in a gas phase. The smaller the liquid droplet, the higher are the surface tension effects. Distortion of the discontinuous phase causes the shape to become non-spherical. There is a tendency for the liquid phase to wet the wall of the pipe and for the gas phase to congregate at the centre. An exception to this is in evaporators such as in refrigeration where nucleate boiling occurs on the pipe surface resulting in a vapour film or bubbles forming at the surface with a central core of liquid. The flow of fluids through pipes and over surfaces can be broadly described as being:

1 Steady flow in which flow parameters at any given point do not vary with time.
2 Unsteady flow in which flow parameters at any given point vary with time.
3 *Laminar flow in which flow is generally considered to be smooth and streamline.
4 *Turbulent flow in which flow is broken up into eddies and turbulence.
5 Transition flow, which is a condition lying between the laminar and turbulent flow regimes.

Flow regime maps are charts representing the various flow regimes and *flow patterns that are possible for two-phase gas–liquid flow in both horizontal and vertical pipes and tubes. There are many types of flow regime map that have been developed. The simplest form of map involves a plot of superficial velocities or flow rates for the two phases with the most widely used generalized flow regime map for horizontal flow having been developed by

Baker in 1954. More complex maps plot the volume fluxes, mass fluxes, momentum fluxes or similar quantities for both the liquid and gas or vapour flows. The maps are populated with experimental data in which lines are drawn to represent the boundaries between the various distinguishable regimes of flow. These include stratified flow, intermittent flow, annular flow and bubble flow. Maps may also include identification of other regimes including slug, plug, wavy and annular flow. The boundaries between the various flow patterns are due to the regime becoming unstable as it approaches the boundary with the transition to another flow pattern. As with the transition between laminar and turbulent flow in a pipe, the transitions in a flow regime are unpredictable. The boundaries are therefore not distinctive lines but loosely defined transition zones. A limitation of the maps is that they tend to be specific to a particular fluid and pipe.

flowsheet A schematic diagram or representation of a process illustrating the layout of process units and their functions linked together by interconnecting process streams. The development of a flowsheet involves the process of synthesis, analysis, and optimization. The heat and material balances are solved using thermodynamic properties and models. An economic analysis is also completed as well as a safety and environmental impact assessment. The choice of equipment and their interconnectivity are optimized along with the choice of operating parameters such as temperature, pressure, and flows. Steady-state flowsheet computer software packages are frequently used to develop flowsheets.

flue gas A mixture of gases produced as a result of *combustion that emerge from a stack or chimney. The gases contain *smoke, particulates, carbon dioxide, water vapour, unburnt oxygen, nitrogen, etc. An *Orsat analysis is a reliable way to determine the composition of the flue gas and the efficiency of combustion although it has largely been replaced by other techniques.

fluid A substance that offers no resistance to change of shape by an applied force. Liquids, vapours, and gases are fluids while solids are not. However, solid particles may be made to behave as fluids when they are dispersed in liquids, vapour, or gases. *Pneumatic conveying is a technique used to move solid particles such as wheat and catalyst particles and involves mixing the particles in a strong current of air. *See* FLUIDIZED BED.

fluid bed *See* FLUIDIZED BED.

fluidics The use of both the flow and pressure of fluids in pipes to perform sensing and control functions in devices that have no moving parts. Although much slower than electronic devices, they are not influenced by temperature, magnetic fields, and ionizing radiation.

fluidization The process of suspending solid particles in an upward flow of a fluid and is widely used to promote good heat transfer and mass transfer in *fluidized beds. In **particulate fluidization** involving liquids, each particle behaves individually and collides with others remaining a certain distance apart. As the velocity of fluidization is increased, the bed expands. It is used in backwashing of filter beds and ion exchange resin beds. In **aggregated fluidization** involving gases, similar conditions exist up to the point of incipient fluidization. At higher velocities, flow passes through the bed in the form of bubbles and the bed expands due to the volume of the bubbles.

fluidized bed A vessel or chamber in which solid particles are suspended in an upwards flow of a gas (see Fig. 22). The buoyant solid particles therefore behave as though they were in a liquid state. Used extensively in the chemical industry, fluidized beds provide excellent

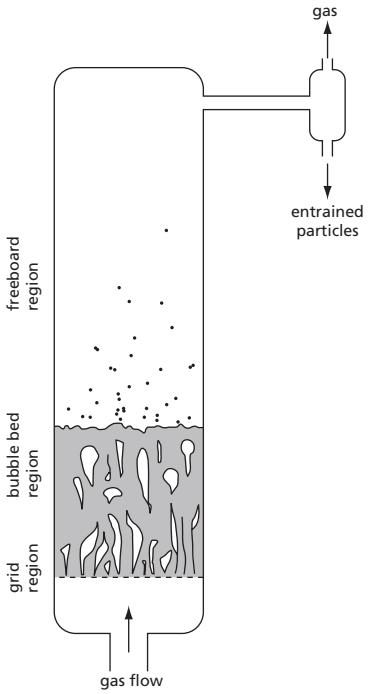

Fig. 22

mixing, heat transfer, and mass transfer characteristics. They are used in catalytic reactions where powdered or pelleted catalysts have a high specific surface area. They are also used in furnaces in which coal is combusted in a hot bed of ash or sand through which air is passed. Fluidization permits lower temperatures to be used thereby avoiding the production of polluting oxides of nitrogen. The behaviour of a fluidized bed depends on the particle size and the fluidizing gas velocity. When fine particles are fluidized at low gas velocities, the bed expands but without the formation of bubbles. At higher velocities, at the so-called bubbling regime, there are three distinct zones in the bed:

- The grid zone is located at the bottom of the bed and corresponds to gas penetrating the bed and is dependent on the types of grid used.
- The bubbling zone is where bubbles grow by coalescence and rise to the bed surface where they break.
- The freeboard zone is where some particles are carried above the bed surface and are elutriated from the system while others are returned back to the bed.

fluidized catalytic cracker unit (FCCU) A unit operation used in petrochemical refineries to convert the heavy components in crude oil into useful products such as fuels for motorized vehicles. They consist of a catalytic reactor front end section in which cracking takes place, reducing long-chain hydrocarbon molecules into smaller short-chain molecules. In the light or back end section, separation takes place where the cracked

molecules are fractionated through a series of columns to produce fuel gas, fuel oil, LPG, diesel, and gas oil.

fluid mechanics A branch of engineering science that concerns the behaviour of fluids when subjected to changes in pressure, the effects of frictional resistance, the flow through pipes, ducts, and restrictions, and the production of power. An understanding of the behaviour of fluids is critical in the cost-effective design and efficient operation of chemical plants, and includes the development and testing of theories devised to explain various phenomena. **Fluid statics** deals with fluids in an equilibrium state of no shear stress, whereas **fluid dynamics** considers fluids in relative motion. Many of the fundamental principles of fluid mechanics were established in the seventeenth and eighteenth centuries by scientists such as *Bernoulli, *Newton, and Euler. Many of today's fluid mechanics problems are complex, nonlinear, three-dimensional, and transient. High-speed and powerful computers are increasingly used to solve complex problems particularly in *computational fluid dynamics (CFD).

fluoridization A process used in the water industry that involves the addition of fluoride to public water supplies for the purposes of reducing the risk of dental decay. It uses a highly soluble fluoride compound whose action in the mouth is to reduce the demineralization of tooth enamel.

SEE WEB LINKS

- Official website of the British Fluoridation Society.

fluorination A chemical reaction that involves the introduction of fluorine atoms to a molecule such as in the production of uranium hexafluoride:

$$UO_2 + 3F_2 \rightarrow UF_6 + O_2$$

The densities of the isotopes of uranium-235 and uranium-238 hexafluoride are appreciably different such that they can then be separated by centrifugation for the purposes of *uranium enrichment.

flux 1. The rate of flow of a substance expressed as the mass or energy per unit cross-sectional area. The SI units are kg m^{-2} s^{-1} or W m^{-2}. **2.** A substance used in soldering to inhibit oxidation. *See* BRAZING. **3.** A substance used in the smelting of metals for the removal of impurities or reaction products as *slag. *See* SMELTING.

FMEA (failure modes and effects analysis) A technique or procedure used to analyse the likelihood of failure within a process or system. It involves a process of review in assessing and quantifying risks; identifying those that are of the greatest concern to the overall process or system, and preventing problems before they arise, saving both time and money. The 'failure modes' are problems that need to be identified and the 'effects analysis' are the consequences of the problems, which may include loss of plant function, equipment damage, plant shutdown, injury, release of materials to the environment, etc.

foam An aggregation of gas or vapour bubbles that remains as a stable suspension. The liquid is the continuous phase and exists as bubble films. Foaming is often a problem with fermentation processes where it forms on the surface of the broth. The existence of foam can be controlled by the addition of chemicals such as glycol, which interrupts the stability of the foam. A **foam breaker** is a mechanical device used to break up the formation of foam. Foam breakers are sometimes used in fermentation vessels in which foaming may occur and otherwise overflow. They usually consist of high-speed spinning discs and are positioned in a region above a potentially foaming liquid.

foot A unit of length used in *f.p.s. engineering units. It has a length equal to 12 inches and one third of a yard. In science and engineering, the foot as a measure of length, and other foot-related units such as the foot-pound-force, has been replaced by SI units, where one foot is equal to 0.3048 m.

force (Symbol F) A physical agent that brings about a change in momentum. For a body of mass, m, travelling with a velocity, v, the momentum is mv. The agent that brings about a change in momentum is therefore:

$$F = \frac{d(mv)}{dt} = m\frac{dv}{dt}$$

The force is therefore directly proportional to the product of mass and acceleration of a body. That is $F = ma$. The SI unit is the newton (N).

forced convection The process by which heat is transported within a fluid by the movement of the fluid with the assistance of a fan, pump, or blower. *Compare* NATURAL CONVECTION.

forced vortex A rotating fluid due to the action of a rotating impeller or stirrer that creates a vortex. *Compare* FREE VORTEX.

foreman A senior or experienced process operator in a factory or chemical plant who has responsibility for a team of operators.

foreshots The first distillate fraction taken from a Scotch whisky *batch distillation. It has a high alcohol content and contains many volatile components not suitable for Scotch *whisky, some of which may be harmful. It is therefore recovered and redistilled. After the heart is then recovered, which is used for Scotch whisky, the *feints are finally recovered, which are lean in alcohol and also returned to the next distillation batch.

formula 1. A statement in algebraic form representing a mathematical relationship of variables. An *empirical formula is based on experimental results and not necessarily on the laws of physics. **2.** The use of symbols to present a chemical compound in which the symbols represent elements. Subscripts are used to represent the number of atoms. For example, the molecular formula for ethanol is C_2H_5OH, which is a molecular compound that has two carbon atoms, six hydrogen atoms, and one oxygen atom. *See* CHEMICAL FORMULA.

forward-curved fan A centrifugal or radial-flow fan that has blades on a rotating shaft such that they are arranged with the leading edge on the outer periphery.

forward mixing The propensity of part of a flowing fluid to accelerate through a system such as a pipe, vessel, or reactor, and to reach the exit point having effectively short-circuited the rest of the fluid. Forward mixing leads to reduced reactor efficiencies where some of the reactants that are expected to undergo a chemical reaction pass through unreacted. It is therefore a form of departure from ideality where the flow of fluids leave before the expected time. Conversely, some reactants will reside for longer periods, known as *back-mixing.

fossil fuel A naturally occurring organic hydrocarbon fuel formed millions of years ago from the decomposition of fossilized remains of plants, trees, and aquatic life to form coal, oil, and natural gas found in rock strata. With a high carbon and hydrogen content, they

are energy-rich having captured the energy of the sun in prehistoric times. Fossil fuels are extracted from the ground and used for *power generation in power stations, as fuel for motorized vehicles, and for domestic heating. In power stations, the fuel is combusted to produce heat, which is used to produce steam from water that supplies steam turbines to drive a generator. Coal is the most widely used fossil fuel. Both coal and wood were burned in the earliest power stations. In 1920, crushed coal was first used thereby improving combustion efficiency. However, limited economical coal supplies and pollution concerns have led to a recent decline in its use. Oil and gas are also used as fuel in power stations. Natural gas, which is largely methane, produces less airborne pollution than either coal or gas. Natural gas provides a significant proportion of the UK's electricity and is combusted directly in a *gas turbine. As a finite and non-renewable energy source, fossil fuels produce carbon dioxide through combustion and are attributed to causing *pollution and the *greenhouse effect.

fouling A deposition of solid material on a surface causing resistance to heat and mass transfer. The material may be process materials, precipitates, and particulates that build up on the surface of heat exchangers, packing supports, and distillation trays, etc. Pipe scale, lime, carbon, gums, and other chemical deposits can restrict the passage of flow, reducing heat transfer, and increasing pressure drops. Extreme fouling can cause blockages or plugging. Periodically, the process equipment must be taken out of service and cleaned. A **fouling factor** is a number used in heat transfer calculations where fouling is likely to be an issue on a surface causing resistance to heat transfer. Scale, dirt, and other deposits may accumulate on the heat transfer surface resulting in additional resistance to heat flow. Fouling factors are usually specified to provide a margin of safety.

Fourier, Jean Baptiste Joseph (1768–1830) A French physicist and mathematician noted for his work in heat transfer and his work leading to the Fourier series. He made a notable contribution to the French Revolution and as a result was rewarded with a position at the École Normale Superiéure in 1795 and then a chair at the École Polytechnique. He accompanied Napoleon Bonaparte to Egypt in 1798 and was appointed to senior positions there before becoming cut off by the British fleet. Later returning to France, Fourier carried out his work on heat propagation. The Fourier transform and *Fourier's law are named in honour of him. He is also credited with the discovery of the *greenhouse effect.

Fourier number A dimensionless number, Fo, used in unsteady-state heat and mass transfer calculations that characterize the connection between the rate of change of temperature, the physical properties, and the dimensions of the body defined as:

$$Fo = \frac{\alpha t}{l^2}$$

where α is the thermal diffusivity, t is time, and l is the length through which conduction takes place. The Fourier number is used together with the *Biot number to solve unsteady-state heat transfer problems. In the case where the Biot number is less than 0.1, the time can be calculated from:

$$t = \frac{mc_p}{hA} \ln \frac{T_o - T_\infty}{T - T_\infty}$$

where T_o is the initial temperature and T is the temperature at the centre of the body. The analogous form of the Fourier number used for mass transfer is given by:

$$Fo = \frac{Dt}{l^2}$$

where D is the diffusivity. The Fourier number is named after the French physicist and mathematician Jean Baptiste Joseph *Fourier (1768–1830).

Fourier's law A relationship that states that the steady-state rate of heat transfer by conduction is proportional to the cross-sectional area perpendicular to the direction of flow and to the *temperature gradient of the path of conduction:

$$Q = -kA\frac{\partial T}{\partial L}$$

where k is the *thermal conductivity, A is the area, T is the temperature, and L is the distance through which heat flows. The negative sign signifies that heat flow occurs from hot to cold.

FPS *See* FLOATING PRODUCTION SYSTEMS.

f.p.s. engineering units A non-decimal British system of units based on the foot, pound, and second, formerly used in engineering. It also uses the thermodynamic Rankine scale (°R) for temperature. The gravitational unit of force is called the pound force (lb_f) and is defined as the standard gravitational field that exerts a force of one pound on a mass of one avoirdupois pound. The standard gravitational acceleration (g) is 32.174 ft s^{-2}. The system has now been replaced by *SI units.

FPSO *See* FLOATING, STORAGE, AND OFF-LOADING UNIT.

fracking An informal name for **hydraulic fracturing,** which is a method used to release and recover oil and natural gas from rock in natural underground reservoirs by fracturing the rock using a pressurized fluid. By injecting a fluid such as water, oil, or gas at high pressures into channels within the reservoir rock, new channels are created by fracturing the rock thereby increasing the release and recovery of the fossil fuels. A proppant such as sand is also used, which is intended to fill the cracks and prevent collapse of cracks. There is some concern that fracking results in noticeable seismic activity and that drinking water supplies from underground aquifers may become contaminated with oil.

fractional crystallization A process used to produce pure crystals that involves dissolving crystals in a small amount of a hot solvent and cooling the solution to produce crystals. The process is repeated until a required purity of crystal has been obtained.

fractionation The process of separating a mixture of components into distinct components or groups (fractions) of components having different properties such as size, boiling point, etc. It is applied to solids, liquids, isotopes, and particles in suspension. **Fractional distillation** is used to separate mixtures of liquids with different boiling points such as the separation of hydrocarbons in crude oil in a fractionating column or **pipestill**. The crude oil is heated to around 350°C until it vaporizes and enters the fractionating column. The vapour rises through perforated trays in the column condensing back down into distinct liquids. Light fractions such as kerosene and naphtha collect near the top while heavier fractions such as lubricants and waxes collect near the bottom.

Frasch process A production method used to recover sulphur from underground deposits. Named after German-born US chemist Hermann Frasch (1851–1914), it uses three concentric pipes in which superheated steam is passed down the outer pipe to melt

the sulphur. Compressed air is fed down the inner pipe to force the molten sulphur up the middle pipe while steam in the outer pipe keeps the sulphur molten.

freeboard zone The location in a *fluidized bed of solid particles in which the fluidizing gas is sufficient to form bubbles within the particles. The freeboard zone is where some particles are carried above the bed surface and are elutriated from the system while others are returned back to the bed.

free convection The movement of a fluid caused by localized differences in density due to differences in temperature. The heated fluid due to a hot surface is less dense than the cooler and more dense fluid, and therefore rises, creating natural circulating currents. *Compare* FORCED CONVECTION.

free energy A measure of a system's ability to do work. The *Gibbs free energy provides an indication of the conditions under which a chemical reaction will occur and is given by $G = H - TS$ where G is the energy liberated or absorbed in the reaction process at constant temperature, T, and pressure, H is the enthalpy, and S is the entropy. Changes in Gibbs free energy, ΔG, are useful for indicating the conditions under which a reaction will occur. Negative values of ΔG indicate that the reaction will proceed spontaneously to equilibrium, while positive values indicate that the reaction will only occur if sufficient energy is supplied to force it away from equilibrium. The **Helmholtz free energy** is given by $F = U - TS$ where U is the internal energy. For reversible isothermal processes, the change in the Helmholtz free energy represents the useful work available. It is named after German physicist and physiologist Hermann von Helmholtz (1821–94).

free moisture content The moisture in a substance that is not held by hygroscopic forces and is the difference between the *total moisture content and the *equilibrium moisture content. It therefore indicates the excess mass of water that is removed prior to reaching equilibrium. It can be removed by mechanical methods such as by applying centrifugal force or pressing. It is sometimes defined as the moisture above the equilibrium moisture content and can also include *unbound moisture.

free surface The interface of a stationary liquid with a vapour or gas above.

free vortex A freely rotating liquid as it drains from an orifice at the bottom of a tank. It occurs with non-viscous liquids in which the tangential velocity is proportional to the inverse of the distance from the axis. The streamlines move freely in horizontal concentric circles with no variation of the total energy across them. *Compare* FORCED VORTEX.

freeze crystallization A process used to produce crystals in which heat is removed from a solution to form crystals of the solvent rather than of the solute. The product can be either melted crystals, as in water desalination, or the concentrated solution, as in the concentration of coffee extracts.

freeze drying A process used to remove a solvent by sublimation from the frozen state. The process is used to preserve or extend the shelf-life of heat-sensitive materials by removing the water (i.e the solvent) by rapid freezing and subsequent drying in a vacuum. Frozen water sublimes directly to the gas phase reducing the moisture content. The porous structure of the material is maintained by carefully applying heat. It is also known as *lyophilization or **cryodesiccation**. A **freeze dryer** is a device used to remove the moisture of a body in which a vacuum is maintained. In freezing foods, the vacuum is maintained such that the water is frozen in the product and the moisture is removed by

sublimation of the ice to water vapour. Freezer dryers are used for drying heat labile foods and pharmaceutical products that would otherwise be damaged if higher temperatures were to be used.

freezing point The temperature at which a liquid turns to the solid state. The freezing point can be depressed by adding a solute.

frequency A statistical number of occurrences within a defined interval. Used in a *risk analysis, it is the number of occurrences of an *event happening per unit time.

frequency response An analysis used in process control to determine the output signal as the result of a disturbance in a system. It involves both the magnitude and phase angle of the output signal as a function of frequency in comparison with the input signal. The magnitude is typically measured in decibels and the phase angle is measured in radians. The frequency response of a system can be analysed by plotting the magnitude and phase on a chart. The three commonly used frequency response diagrams are the *Bode plot, the *Nyquist plot, and the *Nichols plot.

Freundlich adsorption isotherm An empirical adsorption isotherm proposed in 1909 by German–American physical chemist Herbert Max Finlay Freundlich (1880–1941) that relates the quantity of gas molecules adsorbed onto a surface at a constant temperature of the form:

$$\theta = kp^{\frac{1}{n}}$$

where θ is the measure of the sites occupied per unit area of surface measured as the ratio of the mass of adsorbate to the mass of adsorbent, p is the equilibrium pressure of the adsorbate, and k and n are empirical constants for a particular temperature. When 1/n approaches zero, the adsorption becomes independent of pressure. The isotherm is often applied to the adsorption from liquid solutions and is useful when considering the performance of heterogeneous catalysis.

frictional head The head required by a system involving a flowing fluid to overcome the resistance in pipes and associated fittings. The frictional head, h, is related to frictional pressure as:

$$h = \frac{p}{\rho g}$$

where ρ is the density of the fluid and g is the acceleration due to gravity.

friction factor A dimensionless number used in fluid flow calculations that accounts for the permanent energy loss as a fluid moves over a surface. It is related to shear stress at a surface and kinetic energy of the fluid per unit volume as:

$$\tau = f\frac{\rho v^2}{2}$$

Proposed by John Thomas Fanning (1837–1911), the Fanning friction factor for laminar flow in pipes and tubes is related to *Reynolds number as:

$$f = \frac{16}{\mathrm{Re}}$$

For turbulent flow, numerous correlations exist for both smooth and rough-walled pipes. A number of charts have been prepared such as those by Moody, and by Stanton and Pannell, in which friction factor is correlated against Reynolds number for differing pipe surface roughness. It is important to note that this Fanning friction factor has a value of one-quarter of the Darcy friction factor.

Friedel–Crafts reactions Catalyzed chemical reactions that involve the alkylation and acylation reaction of aromatics. An example is the production of toluene from benzene using chloromethane in the presence of aluminium chloride catalyst.

$$C_6H_6 + CH_3Cl \rightarrow C_6H_5CH_3 + HCl$$

The reactions are named after French chemist Charles Friedel (1832–99) and American chemist James Craft (1839–1917).

front end engineering design (FEED) A conceptual study used for the development and analysis of process engineering projects. It defines the processing objectives and examines the various technical options.

froth A dispersion of a high fraction of gas or vapour in a liquid that readily separates at the surface of the liquid as bubbles that then disintegrate without forming a *foam.

froth flotation A process used to separate ore and *gangue using small bubbles of air or another gas generated inside a tank containing particles of the ore and gangue. Water is treated with a water-active agent (detergent), which allows either but not both materials to adhere to the bubbles. The bubbles rise and are skimmed from the surface.

Froude number A widely used dimensionless number, Fr, that represents the influence of gravity in the power relationship for fluid systems such as pumping, mixing in unbaffled tanks and reactors, and in determining the extent of fluidization of particles in a fluidized bed. For a fluidized bed it is expressed as:

$$Fr = \frac{v^2 d_p}{g}$$

where v is the minimum fluid velocity calculated over the entire cross-section of the bed, d_p is the particle diameter (or diameter corresponding to the surface mean diameter), and g is the gravitational acceleration. Since the viscosity of gases is low, the velocity is high and aggregative fluidization occurs for Fr greater than a value of 1. Particulate fluidization occurs for Fr less than 1. For stirred tanks it is expressed as:

$$Fr = \frac{N^2 D}{g}$$

where D is the diameter of the impeller and N is the rotational speed in rps. It is named after British engineer William Froude (1810–79) who developed laws for the resistance of the hulls of ships in water and in predicting their stability.

FSO (or FSU) *See* FLOATING, STORAGE, AND OFF-LOADING UNIT.

fuel 1. A substance that has a calorific value and is used for producing thermal energy by combustion. Examples include coal, oil, natural gas, wood, and *biofuels. Their controlled combustion is used to release the energy as heat, and conversion to mechanical motion in automotive vehicles, and conversion to electricity in power stations. Primary fuels are

those obtained directly from nature such as methane, whereas secondary fuels are derived from primary fuels, such as coke. *See* COMBUSTION. **2.** A nuclear fuel is a substance capable of nuclear fission for the production of nuclear energy such as certain isotopes of uranium and plutonium. *See* NUCLEAR FUEL.

fuel cell An electrochemical device in which the energy of a chemical reaction is converted directly into a low-voltage, direct current electrical energy. The simplest fuel cell involves the oxidation of hydrogen to form water. Hydrogen gas is used as the fuel and fed to the porous anode, and oxygen is fed to the porous cathode. The two electrodes are separated by a hot alkaline electrolyte such as potassium hydroxide. The electrodes are porous to allow the two gases to react with the electrolyte. At the anode the hydrogen reacts with the hydroxide ions in the electrolyte to form water and the release of two electrons per hydrogen molecule. At the cathode, the oxygen reacts with the water to take up the electrons and form hydroxide ions. The flow of electrons from the anode to the cathode is via an external circuit as an electrical current:

$$\text{Anode}: H_2 + OH^- \rightarrow 2H_2O + 2e^-$$

$$\text{Cathode}: 1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

The overall fuel cell reaction of $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ is, in effect, the spontaneous cold combustion of hydrogen. However, unlike the combustion process, hydrogen and oxygen must be kept separate. Little heat is liberated in the fuel cell and instead the free energy is released directly as electrical energy. Fuel cells are therefore more efficient than combustion processes. However, fuel cells are more bulky than heat engines and require a continuous supply of gaseous fuels.

fuel element *See* FUEL ROD.

fuel gas A mixture of methane and hydrogen produced in petrochemical refineries. It is used as a fuel in gas turbines and furnaces such as for cracking, etc.

fuel rod A *nuclear fuel used in a nuclear reactor that has been compressed into pellets and sealed into metal tubes. There are various designs of rod depending on the type of nuclear reactor. The pellet is formed from an enriched form of the easily fissionable material such as the isotope of uranium-235, which has been converted to uranium dioxide powder. The powder is calcined, compressed into pellets, and loaded into the tubes. The rods used in nuclear reactors are made into an assembly called a **fuel element**. At the end of the life of the fuel rod in the nuclear reactor, once fissile impurities have built up, the rod is removed, and the unused fuel is recovered and reprocessed for reuse. This involves cutting the rod and recovering the fissile material inside. *See* NUCLEAR REPROCESSING.

fuel tank inerting A method used to prevent fire and explosion in tanks and vessels that contain flammable liquids by the use of inert or non-combustible gases such as nitrogen. The addition of the inert gas is used to exclude air and prevent otherwise flammable vapour and air mixtures from building up. *See* INERTING.

fugacity A thermodynamic function that represents a pseudo-pressure in place of the partial pressure of a real gas or gas mixture. The **fugacity coefficient** for gases is the ratio of the fugacity to the partial pressure. It is therefore equal to 1.0 for an ideal gas. For liquids, the fugacity is the mole fraction of the constituent multiplied by the fugacity of the pure substance at the temperature and pressure of the solution.

fugitive emissions The uncontrolled release of air pollutants from a process other than those via stacks and vents. Fugitive emission are often due to leaks, evaporation, and accidental releases.

Fukushima Daiichi A nuclear disaster that occurred at the Fukushima nuclear power plant in Japan following a major earthquake and tsunami on 11 March 2011. It led to a series of equipment failures resulting in a nuclear meltdown, explosion, and the release of radioactive material into the environment. The tsunami was responsible for breaking the connection to one of the boiling water reactors to the power grid, causing the reactors to overheat. The earthquake and flooding prevented a controlled shutdown. Seawater was used in an attempt to cool the reactors before some electrical power was eventually restored to cool the reactors. It was the biggest nuclear accident since *Chernobyl in 1986.

fully developed flow The point above a surface in which fluid flows in such a way that it has attained its final form and remains unchanged thereafter. The fluid in contact with a surface, such as in a pipe wall, is retarded to the point that it is theoretically brought to rest. Above the surface it increases in velocity to the point that it has reached the mean velocity of the bulk flow. *See* BOUNDARY LAYER.

fume A cloud or dispersion of very small airborne particles or droplets that generally have a diameter less than one micrometre (1 μm). The particles are caused by a chemical reaction, by the condensation of vapour, emitted through the process of calcination, through volatilization of liquids, by distillation, and sublimation. They are sufficiently small that they are visible as a cloud.

function A mathematical formula or algorithm that expresses an output value for a given input. For the form of notation $y = f(x)$, then y is a function of x in which x is the input or independent variable and y is the output or dependent variable. If x is known, then y can be determined.

fundamental constants Parameters that do not change such as the *universal gas constant, *Avogadro's constant, the Planck constant, and the speed of light. They are also known as *universal constants.

fundamental dimensions The primary dimensions used in a system of units. These are mass, length, and time denoted M, L, and T. It is convenient to include temperature (θ) and electrical charge (Q), although they are not strictly fundamental dimensions. Fundamental dimensions are used in *dimensional analysis.

fundamental units An independent set of units of measurement that forms the basis of a basis of units. In the *SI unit system (Système International d'Unités), there are seven fundamental units: kilogram, metre, second, kelvin, mole, ampere, and candela. Derived units are also acceptable in the SI system and include the units for pressure as newtons per square metre (Nm^{-2}) with base units $kgm^{-1}s^{-1}$. The pascal (Pa) is also acceptable. In British Imperial units, the units are foot, pound, second. Many process instruments are still to be found with these units. *See* F.P.S. ENGINEERING UNITS.

furnace A device used for the controlled combustion of fuel with air for the heating of solids, liquids, or gases. Furnaces operate at high temperatures and are used for melting metals, cracking hydrocarbons, and promoting strongly endothermic reactions.

fusel oil A liquid by-product arising from the fermentation of yeast and separated by distillation. It comprises a mixture of high molecular weight alcohols and also contains esters and fatty acids. It is sold and used by the paints, perfumes, and plastics industries.

fusion 1. The process of changing from the solid state to liquid state, as in melting, by the application and absorption of heat. The latent heat of fusion is the quantity of heat required to change a mass of solid to a liquid. The latent heat of fusion of changing ice to water is 333 kJ kg^{-1}. **2.** The combining of atomic nuclei of lighter elements to form nuclei of a heavier element.

fuzzy logic A form of logic used in the computer control of a process that allows for a degree of impression. In contrast to using truth values of 'true' or 'false', fuzzy logic uses terms such as 'fairly true' or 'more or less true'. These are then represented numerically within the range of 0 to 1 depending on the level of truth.

F-value The time in minutes required to bring about an acceptable level of sterilization of foods in a thermal treatment process such as canning. The F-value often has a subscript, which denotes the temperature at which it applied. For example, F_{121} is the time in minutes at 121°C.