J

j A symbol used by engineers to represent the square root of –1. It is an *imaginary number which is distinguished from *real numbers. For example, the solution of $x^2+1=0$ is j and –j. Mathematicians tend to use the symbol i instead of j. *See* COMPLEX NUMBERS.

jacket 1. The outer covering or surrounding of a process vessel or pipe. The jacket is used to contain a heating or cooling medium or used as insulation to prevent heat loss or gain. Water or condensing stream is frequently used as the cooling or heating medium. **2.** The tubular steel support structure placed on the seabed to support the deck of an offshore structure that is used for drilling and for other *topside modules used for oil and gas separation.

jack-up An offshore oil and gas platform that consists of a triangular- or rectangular-shaped structure with moveable legs that enables the platform to stand on the seabed in depths of up to 120 m. They are used mainly in drilling operations for both exploration and for permanent gas installations. The platform can be raised or lowered as required.

Jacobs–Dorr process A wet process used for making phosphoric acid by the reaction of phosphoric acid on phosphate rock. The rock is dissolved in phosphoric acid and calcium sulphate to form a slurry of calcium phosphate. This is then converted to phosphoric acid and calcium sulphate in the exothermic reaction:

$$Ca_3(PO_4)_2+3H_2SO_4 \rightarrow 3CaSO_4+2H_3PO_4$$

Fluorine in the rock is evolved and is required to be scrubbed from the vent gas. The process was developed in the nineteenth century and there have been a number of variations of which the Dorr–Oliver process is still used.

jarosite process A process used to extract iron from the leach liquors of *hydrometallurgical processes. It is named after the mineral and was first used in the processing of zinc sulphate liquors.

jaw crusher A mechanical device used to break coarse raw material such as stone and ore into small pieces. It consists of two jaws, which form a V-shape that has a fixed vertical jaw or anvil and a swinging steel jaw reciprocating on a horizontal plane. The jaws open and close up to 400 times per minute and the material is crushed as it descends under gravity through the opening and closing gap.

JET (Joint European Torus) The largest *tokamak in the world located in Culham, England and is the only operational fusion experiment that is capable of producing fusion energy. It involves a partnership of several European nations and has been investigating the potential for thermonuclear power by nuclear fusion.

The origins of JET extend back to 1970 when the Council of the European Community provided the legal framework for the development of a European fusion device. After construction of the experimental nuclear reactor, which began in 1977, the first JET plasma was achieved in 1983. In 1997, 16 MW of fusion energy was produced for a total power input of 24 MW. The European Fusion Development Agreement (EFDA) was established in 1999 and has responsibility for the future use of JET and defines JET's scientific programme, allowing for the detailed study of nuclear fusion by many scientists and engineers from all over Europe. While JET is effectively a scientific experiment, ITER is a reactor-scale experiment designed to deliver ten times the amount of power that it consumes. DEMO is expected to be the first fusion nuclear power plant to provide electricity to the national power grid.

SEE WEB LINKS

- Official website of EFDA JET programme.

jet fire A fire that results from the ignition of a release of flammable liquid or vapour. It can be the intentional result of *flaring or accidental result such as through the rupture of a natural gas pipeline or a valve leak. The direction of the jet is dependent on the prevailing wind conditions. The hazard through the exposure to thermal radiation is dependent on the rate of release and on the heat of combustion of the fuel involved. A **jet flame** is the combustion of flammable liquid or gas emerging with significant momentum from an orifice or opening.

jet fuel A kerosene-based product of the fractional distillation of crude oil. It comprises various types of hydrocarbons for use as an aviation fuel for turbine engines. The composition of the fuel is governed by strict international regulations and usually has a freezing point of below –40°C, which corresponds to the cold temperatures encountered at high altitudes. *Compare* AVIATION GASOLINE.

jet reactor A type of *bioreactor in which air and a fresh feed solution enter at the base in such a manner as to produce a jet of material that provides the energy necessary to agitate the contents. The air, as bubbles, rises in a tube and disengages at the top. The fermenting solution descends through the annulus for recycle. They are typically used for the industrial production of yeast from whey.

j-factor A dimensionless factor used in heat and mass transfer of fluids with turbulent flow in pipes. It is a function of Reynolds number, geometry, and boundary conditions from which the friction factor can be obtained and agrees well with convective heat transfer correlations or for determining heat transfer coefficients. It was proposed by American chemical engineer Allan P. Colburn (1904–55) and forms part of the *Chilton–Colburn analogy, which is used in heat, momentum, and mass transfer.

jig A vibrating mechanical device used to separate water-suspended particles of differing densities. The separation is based on the differences in the rate of their acceleration.

Joliot-Curie, Irène (1897–1956) A French scientist and daughter of Marie and Pierre Curie. She gained her doctorate at the Sorbonne in 1920 having first served as a nurse during the the First World War. She became Doctor of Science in 1925, having presented a thesis on the alpha rays of polonium. She is noted for her work on natural and artificial radioactivity working together with her husband **Jean Frédéric Joliot-Curie** (1900–58). She shared the Nobel Prize in Chemistry with him in 1935 in recognition of the synthesis of new radioactive elements.

Joule, James Prescott (1818–89) A British physicist who was the owner of a large brewery. Joule carried out much of his scientific work in his own private laboratory achieving a remarkably high standard of accuracy in his work. He stated a law about the heating effect of an electric current in 1840, and thereafter carried out a series of experiments to determine the mechanical equivalent of heat. His first determination of mechanical equivalent of heat was carried out with a calorimeter containing a rotating paddle. Together with Lord *Kelvin, he discovered the *Joule–Thomson effect in which there is a fall in temperature of a gas on expansion due to the attraction between molecules. The SI unit of energy is named after him.

joule (Symbol J) The SI unit of work and energy where one joule is equal to the work done by the force of one newton, in the direction of the force, a distance of one metre. That is 1 joule = 1 Nm or 1 kg m^2 s^{-2}. It is named after the British physicist James Prescott *Joule. The rate of work equal to one joule per second is a called a *watt.

Joule–Kelvin effect *See* JOULE–THOMSON EFFECT.

Joule's laws 1. In a wire of given resistance, the heat developed in a given time is proportional to the square of the current. **2.** The internal energy of a gas at constant temperature is independent of its volume, provided the gas is ideal.

Joule–Thomson effect The cooling that results when a highly compressed gas is allowed to expand adiabatically into a region of low pressure such that no work is done. The cooling effect occurs because as the molecules of the real gas separate during expansion, internal work is done in overcoming the attractive forces between them. A perfect gas, with no attractive forces between the molecules, shows no Joule–Thomson effect. The Joule–Thomson effect is more marked at lower temperatures and was used in the *Linde process for the liquefaction of air. The phenomenon was discovered by James *Joule working with William Thomson (later Lord *Kelvin). Hydrogen is anomalous to the Joule–Thomson effect, by showing a rise in temperature at ambient temperature. This effect continues down to 193 K whereupon it cools under expansion. This is called the inversion temperature. Hydrogen was liquefied by *Dewar in 1898, who cooled the gas below the inversion temperature by liquid air, and then used the principle of the Linde process. Helium, like hydrogen, is also anomalous, with an inversion temperature of 33 K.

JPL chlorinolysis process A process used for the desulphurization of coal by oxidation with chlorine. The reaction converts sulphur to sulphur monochloride. The process was developed by the Jet Propulsion Laboratory at the California Institute of Technology in the US.

K

Kármán *See* VON KÁRMÁN.

Kármán vortex street A phenomenon in which vortices of a moving fluid form as repeating patterns. They are caused by the unsteady separation of flow of a fluid as it passes around an object such as a wire and observed over Reynolds numbers of around 90. It is named after Hungarian-American mathematician and physicist Theodore *von Kármán (1881–1963) and is also known as the **von Kármán vortex street**.

kelvin (Symbol K) The SI unit of thermodynamic temperature. The kelvin temperature scale is equal to the Celsius degree but with zero being absolute zero (0 K). The temperature is expressed in degrees Celsius less 273.15 (i.e. °C = K-273.15). The term 'degrees Kelvin' is no longer used. The unit is named after Lord *Kelvin.

Kelvin, Lord (1824–1907) A Belfast-born Scottish scientist William Thomson, later 1st Baron Kelvin of Largs, who was the son of a gifted teacher. Both he and his brother James matriculated to Glasgow University aged 10 and 12, respectively. William Thomson was elected to the chair of natural philosophy at Glasgow in 1845 aged 22 and held the position for 53 years. His most important work was on thermodynamics, but he is most widely known for his studies of electricity applied to submarine technology. He was knighted in 1866 and made a baron in 1892.

kerosene A combustible liquid hydrocarbon fuel obtained from petroleum in the fractional distillation of oil once gasoline has been removed. It is also known as paraffin. It has a calorific value of around 43.3 kJ kg^{-1} and is used as a fuel for jet engines and domestic uses such as heating and cooking.

kettle reboiler A type of horizontal shell-and-tube type heat exchanger in which liquid to be evaporated is contained on the shell side and condensing steam or a hot liquid used to provide the heat contained on the tube side (see Fig. 24). The shell contains a relatively small bundle of hairpin tubes in a two-pass arrangement in a floating head and tube sheet, and sits in a pool of the boiling liquid, the depth being determined by an overflow weir. A flow of fresh liquid continuously enters from the bottom while vapour leaves from the top of the shell. The condensing steam in the tubes is removed through a trap. Kettle reboilers are typically used with distillation columns to boil up the bottom material and return vapour back into the column for separation.

key component Used in multicomponent distillation, key components are the two main components that are required to be identified in a mixture to be separated. The two key components are the **light key** (LK), which is identified as the lightest component in the *bottoms, and the **heavy key** (HK), which is the heaviest component in the *distillate. They are known as key components since their identification is required to unlock the problem in solving the separation where the difficulty of separation, as measured in terms of the number of trays required for a given reflux ratio, is fixed by the concentration of the key

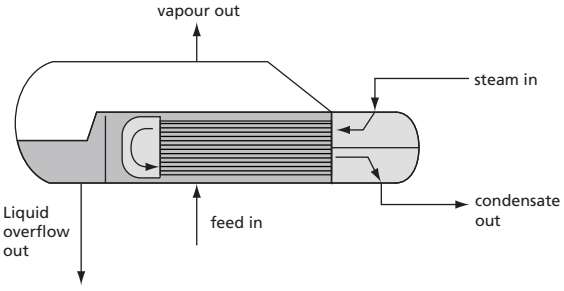

Fig. 24

components in the products. The relative volatilities of the components in a mixture are always determined with respect to the heavy key. Components that are lighter than the light key are termed LLK while those that are heavier than the heavy key are termed HHK.

K-factor A vapour–liquid equilibrium ratio of a substance:

$$K_i = \frac{y_i}{x_i}$$

where x and y are the mole fractions of the substance (i). It is used to describe the complex relationship between pressure, temperature, and equilibrium for vapour- and liquid-phase compositions, and used in multicomponent distillation calculations. For mixtures of substances of similar molecular structure, such as hydrocarbons, the K-factor is dependent on pressure and temperature, and commonly presented as *nomographs known as **K-factor charts,** or *DePriester charts. These present pressure, temperature, and K-factors for various light and heavy hydrocarbons. They are used to determine the *bubble point and *dew points of hydrocarbon mixtures. Given a multicomponent mixture of known composition and total pressure, the bubble point temperature can be found by *trial and error which satisfies the condition. The factors are either used as they stand or are converted to relative volatility values. The bubble point is found from:

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

Similarly, for a given vapour composition, the dew point can be found which satisfies the condition

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

Sensible choices of temperature or pressure can mean that only three values are required.

kiln A type of brick-lined oven used for the hardening, burning, baking, or drying of products such as *calcining lime or firing pottery. The products may be heated in a batch kiln or continuously fed. The kiln may be fixed or stationary, or may be a rotating cylinder through which heated air is fed and used to dry and bake the product. **Kilning** is the processing of materials in a kiln.

kilo- (Symbol k) A prefix used in the metric system to denote a factor of 1,000.

kilogram (Symbol kg) The SI unit of mass, it is equal to the mass of the international platinum-iridium cylinder kept by the International Bureau of Weights and Measures at Sèvres, near Paris.

kilomole (Symbol kmol) The derived SI unit for the amount of a substance that is equal to 1,000 moles.

kilowatt-hour (Symbol kWh) A unit for electrical energy, it is equivalent to the power consumption of 1,000 watts for one hour or 3.6 MJ. It is commonly used as the commercial unit of electrical energy of electricity delivered to consumers.

kinematics The branch of mechanics that is concerned with the motion of bodies considered abstractly and without reference to force or mass. *Compare* DYNAMICS.

kinematic viscosity (Symbol ν) The ratio of the *viscosity of a liquid to its density. It is a useful for quantifying the viscous properties of certain fluids such as hydrocarbon mixtures. The SI units are $m^2 s^{-1}$.

kinetic energy The energy of a body by virtue of its motion:

$$KE = \frac{1}{2}mv^2$$

where m is the mass of the body and v is its velocity. The SI units are kg $m^2 s^{-2}$ or joules.

kinetic parameters The constants in a mathematical model used to describe the speed of a chemical or biochemical reaction. For example, in *Monod kinetics, they are used to describe the rate of growth of microbial cells in which the two kinetic parameters are the *maximum specific growth rate μ_{max} and the saturation constant, Ks.

kinetics 1. The science of the relationship between the motion of bodies and the forces acting upon them. **2.** The study of the rate at which chemical reactions take place under different conditions such as due to temperature, pressure, and the presence of catalysts.

kinetic theory A theory that attempts to understand the properties of liquids and gases. It is based on considering them as a large population of molecules moving freely relative to one another. The temperature of a gas is seen to be a measure of the velocity of its molecules.

Kirchhoff, Gustav Robert (1824–87) A German physicist who founded the science of spectroscopy. He discovered the laws that govern the absorption and emission of radiation and the flow of electricity in electrical networks. In 1859 he presented the law that states that the ratio of the emission and absorption powers of all materials is the same at a given temperature and a given wavelength of radiation produced. He went on to derive the concept of a perfect *black body that can absorb and emit radiation at all wavelengths.

Kirchhoff's law of radiation A law stating that the emissivity of a body is equal to its absorbance at the same temperature. The law was formulated by the German physicist Gustav *Kirchhoff (1824–87).

Kirkbride equation An equation used for the design of distillation columns to determine the ratio of the number of trays above and below the feed point. It is therefore used to determine the location of the feed tray in the column:

$$\ln\frac{N_D}{N_B}=0.206\ln\left[\frac{B}{D}\left(\frac{x_{F(HK)}}{x_{F(LK)}}\right)\left(\frac{x_{B(LK)}}{x_{D(HK)}}\right)^2\right]$$

where N_D is the number of theoretical trays above the feed and N_B is the number below. B refers to the flow at the bottom and D at the top. x is the mole fraction and subscripts F, B, and D refer to the feed, bottom, and top, where LK and HK are the light and heavy *key components. It is named after American chemical engineer Chalmer Gatlin Kirkbride (1906–98).

Kirpichev number A dimensionless number, *Ki*, used in heat and mass transfer used to relate drying conditions of materials. It is expressed as the ratio of the external to internal heat or mass transfer intensity:

$$Ki_h=\frac{qL}{k-\Delta T}\text{ and }Ki_m=\frac{GL}{D\rho n}$$

where q is the heat flux, L is a characteristic length of the body, k is the thermal conductivity, ΔT is the temperature difference, G is the mass velocity, D is the diffusivity, ρ is the density, and n is the specific mass content. They are named after Russian materials scientist Victor Kirpichev (1845–1913).

k_La The volumetric mass transfer coefficient seen as a measure of the transfer of a gas to a liquid in processes such as fermentation in which oxygen or air is sparged into a liquid containing microorganisms. It is the product of the mass transfer coefficient, k_L, and the interfacial area, a. It is difficult to measure the mass transfer coefficient separately but it is readily measured from gas balances in combination with the interfacial area.

kmol An abbreviation for the SI unit for *kilomole where 1 kmol is equal to a thousand moles (1,000 mol).

knocking The premature explosion of an air–fuel mixture within a piston cylinder of an internal combustion engine. It is due to the over-compression of the mixture and gives a characteristic metallic knocking sound. When the fuel and air mixture is injected into the cylinders of the engine, the mixture is combusted by the use of spark ignition. However, as the flame travels from the sparking plug towards the piston, it compresses the unburnt fuel. Ignition of the unburnt fuel occurs before the flame reaches it, resulting in shock waves that travel up and down the cylinder. The consequence is noise, a loss of power, and damage to the sparking plugs. Knocking is avoided by reducing the compression ratio, although this also results in a loss of efficiency. Antiknocking agents such as tetraethyl lead added to the fuel that increase the octane number and reduce the tendency to detonate are known to cause air pollution and environmental damage, and their use is either much reduced or banned in some countries. New fuels have been designed to have a higher octane number with a higher aromatic content. However, the presence of unburnt aromatics in the atmosphere has an adverse effect on human health.

knockout drum A vessel used to trap droplets of liquid from a gas or vapour stream from a process. They are typically used to remove liquids such as hydrocarbons that would

otherwise damage a vent stack or present a hazard if released into the atmosphere. They are also known as **KO drums** or **KO pots**.

Knudsen diffusion A type of diffusion applied to gases that diffuse through the narrow pores and capillaries of a porous material in which the collisions between the gas molecules and the walls of the pores are appreciable, and consequently influence the rate of diffusion. The movement or motion of gas at low pressure is the result of individual molecular free path motion. **Knudsen flow** occurs where the mean free path is greater than the radius of the aperture by about a factor of ten. It is named after Danish physicist Martin Hans Christian Knudsen (1871–1949).

KO drum *See* KNOCKOUT DRUM.

Kohlrausch's law A law devised by German chemist Friedrich Kohlrausch (1840–1910) that states that the conductivity of a dilute solution is equal to the sum of the independent values. That is, the conductivity of a solution is equal to sum of the molar conductivity of the cations and the molar conductivity of the anions. The law is based on the independent migration of the ions and was deduced experimentally.

koji process A solid substrate fermentation process involving the fermentation of grain and soybeans by the *Aspergillus* fungus. The cooked substrate is inoculated with a culture of the filamentous fungi and grown as a shallow layer in which amylase and protease enzymes break down the substrate to form koji, which is a proteolytic enzyme used for treating flour proteins. It is also the basis of other similar fermentations such as the production of citric acid, and rice fermentations including the rice wine saké.

Kolmogorov, Andrey Nikolaevich (1903–87) A Russian mathematician noted for major contributions in various scientific fields including classical mechanics, probability theory, and fluid mechanics. He studied at the Moscow State University and the Chemistry Technological Institute, graduating in 1929. He became a professor at Moscow University two years later, and went on to become the world's foremost expert in probability theory. In 1935 he became the first chairman of probability theory at the Moscow State University. He was elected to the USSR Academy of Sciences in 1939. He held a number of positions at Moscow State University including head of several departments and served as the dean of the faculty of mechanics and mathematics.

Kolmogorov eddies The smallest size of eddy that can be formed in a fluid. The size of an eddy is dependent on the viscosity of the fluid. In a stirred vessel, the Kolmogorov eddy size also decreases with increasing stirrer speed. Large-sized eddies are unstable and eventually break up to form smaller eddies with the kinetic energy of the initial large eddies being dissipated into the smaller eddies stemming from it. These smaller eddies undergo the same process, giving rise to even smaller eddies. Thus the energy is dissipated to the point that the viscosity of the fluid can effectively dissipate the kinetic energy into internal energy. The theory was first proposed in 1941 by Russian mathematician Andrey Nikolaevich *Kolmogorov (1903–87).

Kopp's rule A generalized rule used to determine the heat capacity of solids. The heat capacity of a solid compound is approximately equal to the sum of the heat capacities of the constituent elements. The rule is used only where experimental values are not available and applies only over a limited temperature range.

Kossovitch number A dimensionless number, Ko, equal to the ratio of the heat energy required for a change in phase to the heat required for heating or cooling:

$$Ko = \frac{\lambda}{c_p \Delta\theta}$$

where λ is the latent heat (of fusion or vaporization), c_p is the specific heat of the body, and $\Delta\theta$ the difference between the phase change temperature point of the material and the temperature of the heating or cooling medium.

Kozeny–Carman equation *See* CARMAN–KOZENY EQUATION.

kraft process A process used for the conversion of wood into wood pulp that was invented by Carl Dahl in 1879. The process is also known as the **sulfate process** and consists of cooking wood in a basic solution of sodium hydroxide, sodium sulphide, and sodium carbonate. The process involves the hydrolysis of lignin to acids and alcohols. Both sodium hydroxide and sodium hydrosulphide (NaSH) are formed by the reaction:

$$Na_2S + H_2O \rightarrow NaOH + NaSH$$

which are active in breaking down the bonds between the lignin and cellulose. The pulping takes place in a continuous digester. Spent cooking liquor known as black liquor contains all the chemicals used in the digestion, and is recovered and concentrated by *multiple effect evaporation before being burnt in a recovery furnace. A fused salt melt known as green liquor is collected at the bottom, which is treated with burned lime to convert sodium carbonate to sodium hydroxide:

$$CaO + H_2O \rightarrow Ca(OH)_2$$
$$Na_2CO_3 \rightarrow Ca(OH)_2 \rightarrow CaCO_3 + 2NaOH$$

The calcium carbonate precipitate is removed by filtration. *Calcination is then used to produce calcium oxide in a lime *kiln:

$$CaCO_3 \rightarrow CaO + CO_2$$

After treatment with calcium oxide the filtrate serves as fresh cooking liquid for the digester. With the small loss of sodium salts in the digestion process, sodium sulphate is added to the recovery furnace as the make-up chemical, hence the alternative name for the process:

$$Na_2SO_4 + 2C \rightarrow Na_2S + 2CO_2$$

Kremser equation An equation used in the calculation of the number of theoretical stages required in the design of an absorption column used for absorption processes such as the drying of natural gas. It is based on the condition that the pressure divided by the product of *Henry's law constant and the ratio of moles liquid to moles vapour is a constant.

Kroll process A process used in the production of certain metals such as titanium by reduction of its chloride with magnesium metal. It was named after William J. Kroll, who invented the process in 1937, replacing the earlier *Hunter process. The process involves reducing refined rutile from its ore at 1,000°C within a *fluidized bed with chlorine gas to

produce titanium tetrachloride ($TiCl_4$). This is then reduced using an excess of liquid magnesium at around 800°C in the reaction:

$$2Mg + TiCl_4 \rightarrow 2MgCl_2 + Ti$$

The titanium is then purified by *leaching and *vacuum distillation. The process is expensive to operate, but the value of titanium metal is far greater than stainless steel and has numerous applications, particularly in the nuclear industry. The process is also used for the commercial production of tantalum, zirconium, and niobium.

L

laboratory A building, room, or facility used for carrying out scientific or engineering research experiments or for practical teaching purposes. Routine and specialist analytical testing, *lab-scale process testing, and validation are also carried out in laboratories.

lab-scale The small-scale testing of processes, chemical reactions, mixing, heating, cooling, separation, and other unit operations used in the validation of the design of full-scale process plant or the testing of existing process plant parameters. It involves small quantities of materials with relatively inexpensive equipment tested over short timescales.

lagging Insulation material used to surround process pipes and process vessels to reduce heat transfer. The properties of the insulation material are a low thermal conductivity and effectiveness at minimizing heat transfer, cost, and durability. It should also be corrosion-proof, water and weather-proof. The correct thickness of lagging should be determined based on economics. There is an optimum thickness of lagging for pipes and it is a balance in cost between thickness and surface area which increases with increasing thickness.

lagoon A wide, shallow body of water used for settling and separating fine particles from process liquids. It can also be used for collecting process water and other collected water prior to discharge. The water can also be used as emergency water for fire fighting.

lag phase The initial period of time in a bioreactor after inoculation of microorganims into the nutrient medium in which there is no growth. It is the period of time of apparent inactivity in which the microorganims adjust to their new environment.

Lagrange, Comte Joseph Louis (1736–1813) An Italian-born French mathematician and astronomer noted for his work in mechanics, harmonics, and in the calculus of variations. He also established the theory of differential equations. He succeeded Swiss mathematician and physicist Leonhard Euler (1707–83) as the director of mathematics at the Prussian Academy of Sciences in Berlin, during which time he published his work in *Mécanique Analytique* (1788), that covered every area of pure mathematics.

Lagrange fluid dynamics The study of fluid mechanics in which the movement of small elements in the moving fluid are studied. It is named after Joseph Louis Lagrange (1736–1813). *Compare* EULERIAN FLUID DYNAMICS.

lag time 1. The apparent delay in growth of a microorganism within a bioreactor after inoculation as the living cells adapt and establish themselves to their environment and multiply to appreciate levels. *See* LAG PHASE. **2.** The delay in response of a system or process that is being controlled to a step change disturbance.

laminar flow The streamline flow of a fluid in which a fluid flows without fluctuations or turbulence. The velocities of fluid molecules are in the direction of flow with only minor

movement across the streamlines caused by molecular diffusion. The existence was first demonstrated in 1883 by Osborne *Reynolds, who injected a trace of coloured fluid into a flow of water in a glass pipe. At low flow rates the coloured fluid was observed to remain as discrete filaments along the tube axis, indicating flow in parallel streams. At increased flow rates, oscillations were observed in the filaments, which eventually broke up and dispersed across the tube. There appeared to be a critical point for a particular tube and fluid above which the oscillations occurred. By varying the various parameters Reynolds found that his results could be correlated into terms of a dimensionless number called the *Reynolds number, Re, as:

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

where ρ is the density of the fluid, v is the velocity of the fluid, d is the diameter of the pipe, and μ is the viscosity of the fluid. The critical value of *Re* for the break-up of laminar flow in pipes of circular cross section is about 2,000.

Langmuir, Irving (1881–1957) An American chemist who taught chemistry before becoming a research chemist and later research director for General Electric Company's research laboratory at Schenectady, a post he held for 41 years. He proposed a theory of atomic structure and discovered how to make atomic hydrogen, and invented an atomic hydrogen blowpipe giving an extremely hot flame for welding metals. He developed a high-vacuum pump and electric discharge tubes for radio. He measured the sizes of virus molecules, which he obtained in layers one molecule thick. He is also noted for his work on surface chemistry and the molecular orientation on surfaces, the theory of adsorption catalysis, and the understanding of plasmas. He was awarded a Nobel Prize in Chemistry in 1932.

Langmuir adsorption isotherm An equation expressing the equilibrium fraction, *f*, of an adsorbent homogeneous surface which is covered with a single layer of adsorbed and non-interacting molecules as:

$$f=\frac{ap}{1+ap}$$

where a is an empirical adsorption constant known as the **Langmuir adsorption constant** and p is the equilibrium partial pressure of the adsorbate in the gas phase. Adsorption isotherms are used in the design of gas–solid processes such as solid catalyzed gas phase reactions as in the synthesis of ammonia. It is named after American chemist Irving *Langmuir (1881–1957).

Laplace, Pierre Simon (1749–1827) A French professor of mathematics noted for his contribution to mathematics. Laplace was the son of a farm labourer who owed his education to some rich neighbours. He solved many problems concerning the motion of the solar system. He also worked on surface tension and, with Antoine *Lavoisier (1743–94), did work on the measurement of the heat produced during chemical changes. In 1822 he persuaded the French Academy to carry out experiments to measure the velocity of sound over a distance of eleven miles by firing cannons. The result confirmed his belief that when sound waves pass, the air cools as it expands and heats up as it contracts.

Laplace transform A method of obtaining a solution to a differential equation where the unknown integration constants are obtained using straightforward algebra. It is commonly

used in process control applications since differential equations do not readily enable the relationship between the input and output to be discerned. The Laplace transformation therefore allows a simpler algebraic calculation to be performed. The Laplace transform of a function *f(t)* is therefore multiplied by e^{-st} and the product integrated between zero and infinity. It is denoted by $\mathcal{L}\{f(t)\}$ as:

$$F(s)=\mathcal{L}\{f(t)\}=\int_0^\infty e^{-st}f(t)dt$$

where *s* is a variable whose values are chosen such that the semi-infinite integral converges (i.e. the integration is between 0 and +∞ and is therefore one-sided). For the Laplace transform to exist, the integrand $e^{-st}f(t)$ must converge to zero as *t* approaches infinity.
As an example, the Laplace transform of a unit step function is:

$$\int_0^\infty 1e^{-st}dt=\left[\frac{e^{-st}}{-s}\right]_0^\infty=\frac{1}{s}$$

If *F(s)* is the Laplace transform of *f(t)* then *f(t)* is the inverse Laplace transform of *F(s)*. Thus:

$$f(t)=\mathcal{L}^{-1}\{F(s)\}$$

There is no simple definition of the inverse transform and the solution is found in reverse. Tables of Laplace transforms and their inverse transforms are used.

latent heat (Symbol λ or L) Literally meaning 'hidden heat', it is the quantity of heat absorbed or released when a substance changes its physical phase at constant temperature and pressure. The **latent heat of fusion** is the energy needed to be removed to solidify a liquid, whereas the **latent heat of vaporization** is the energy required to be absorbed to change a liquid to a gas. The *specific latent heat is the heat energy absorbed or released per unit mass at constant temperature, while the *molar latent heat is measured per mole of substance. The SI units are J kg^{-1} or J mol^{-1}, respectively.

lattice The regular and organized arrangement of atoms, ions, or molecules in a stationary structure, such as in a crystal. The arrangement is usually three-dimensional such as in a diamond. However, two-dimensional crystal structures exist such as graphite which has a layer lattice in which the atoms of carbon are chemically bonded in planes, with relatively weak forces between the planes. The **lattice energy** is the energy that is released when one mole of a solid ionic compound is formed from its constituent gaseous ions. It is alternatively defined as the energy required to separate completely the constituent ions of a crystal from each other to an infinite distance. The lattice energy is effectively a measure of the stability of a crystal lattice.

Lavoisier, Antoine Laurent (1743–94) A French chemist noted for determining the components of water as being oxygen and hydrogen, and establishing that sulphur is not a compound but an element. He also helped to formulate the metric system. Through very careful experimentation he was the first to show that although matter can change its state in a chemical reaction, the total mass remains the same at the end as at the beginning of every chemical change. He was the first to state the conservation of mass. During the French Revolution, he was accused of various crimes and guillotined.

law A description of a principle of nature that covers all circumstances by the wording of the law. There is no ambiguity or exceptions. Eponymous laws are named after their

discoverers such as *Charles's law while others are known by their subject matter such as the *law of conservation of mass.

law of chemical equilibrium *See* EQUILIBRIUM CONSTANT.

law of conservation A law that states that the total quantity of something remains unchanged within a system even though there may be changes taking place within the system such as chemical reactions, changes of states, and other physical, chemical, and biochemical changes. The conservation of mass is a law that states that the total amount of material within a system such as a chemical process remains unchanged. That is, the total amount within the system boundary does not increase nor decline. It forms the basis of a material balance for a process. The conservation of energy is a law that states that the total energy within a system remains unchanged. The Bernoulli theorem is used to show the total energy in a fluid is conserved and takes into consideration pressure-volume, kinetic, and static energies. The total enthalpy of chemical components remains unchanged in spite of any chemical reactions. It forms the basis of an energy balance for a process.

law of universal attraction A law proposed by Sir Isaac *Newton (1642–1727) stating that any two bodies attract each other in proportion to the product of their masses and inversely to the square of their distances apart. To do this, he had to define the meaning of mass, momentum, force, inertia, and to state his three *laws of motion. These ideas appeared to show that the entire universe obeyed simple mechanical laws and remained undisputed until Einstein.

laws of motion Three laws proposed by Sir Isaac *Newton (1642–1727) that state:

First law: Every body continues in its state of rest or of uniform motion in a straight line unless acted on by an impressed force.

Second law: The rate of change of momentum of a body is proportional to the impressed force and takes place in the direction of the force.

Third law: To every action there is a reaction, which is equal and opposite to the action.

layer of protection analysis (LOPA) A form of semi-quantitative *risk analysis used for a process or system that analyses individually the different forms or layers of protection; it is used to reduce or mitigate process risk in terms of reducing the likelihood of the occurrence of an undesirable event or reducing its severity. LOPA is used to determine and understand the *safety integrity level (SIL) and is a widely used technique in the oil and gas industry. It uses various hazard analysis techniques and evaluates the frequency of potential incidents as well as the probability of failure of the layers of protection.

LCA *See* LIFE CYCLE ANALYSIS.

LC_{50} The *lethal concentration of an airborne or waterborne chemical substance that causes the death of half (50 per cent) of a group of exposed test animals in a given time, which is usually four hours. It is used as a measure of the toxicity of a substance and is expressed in micrograms or milligrams per litre, or parts per million of air or water. The lower the value, the more toxic the substance.

LD_{50} The *lethal dose of a chemical substance or other agent that is expected to produce death in 50 per cent of the group of test animals such as mice or rats exposed to one dose. It is often quoted in milligrams per kilogram of body weight. A substance is considered to be highly toxic if the LD_{50} is less than 50 mg per kg of body weight.

leachate The solution that leaves a *leaching process and consists of the solvent containing the leached material as the solute. For example, in the decaffeination of coffee beans using either water or supercritical carbon dioxide, the leachate is the solvent carrying the dissolved caffeine.

leaching A separation process involving the extraction of soluble components of a solid by percolating a solvent through it. The solid carrier material is inert and contains the solute for extraction. The solvent is added to selectively dissolve the solute. The overflow or *leachate consists of the solvent and dissolved solute, while the underflow consists of a slurry with a similar composition to the overflow and also contains the solid carrier. In an ideal leaching equilibrium stage, all the solute is dissolved by the solvent and none of the carrier is dissolved. The efficiency of the leaching process is dependent on the type of equipment used and the properties of the materials used. Examples include the separation of metal from ore using acid, the extraction of caffeine from coffee beans or tea leaves using hot water, and the extraction of sugar from sugar beets using hot water.

lead chamber process A process once used for the large-scale manufacture of sulphuric acid by the oxidation of sulphur dioxide with air using a potassium nitrate catalyst in water. This involved burning iron pyrites, FeS_2, or some other source of sulphur such as zinc sulphide, ZnS, to produce sulphur dioxide which was then oxidized in large lead chambers to sulphuric acid by the action of air, oxides of nitrogen, and water:

$$4FeS_2 + 11O_2 \rightarrow 2Fe_2O_3 + 8SO_3$$
$$SO_3 + H_2O + NO_2 \rightarrow H_2SO_4 + NO$$
$$2NO + O_2 \rightarrow 2NO_2$$

The process was carried out in expensive lead chambers but produced only dilute acid. The process was invented by English physician and industrialist John Roebuck (1718–94) in 1746 and was later replaced by the more economic *contact process in 1876.

leading edge In fluid mechanics, the edge of an aerofoil that first encounters a fluid stream such as air.

least squares method A statistical method of deriving an average value from a set of approximate or inaccurate values by introducing errors as unknown variables and then minimizing the sum of their squares. The method was devised by German mathematician Karl Friedrich Gauss (1777–1855) as a way of best fitting a straight line through a set of plotted data points. *See* REGRESSION ANALYSIS.

Leblanc, Nicolas (1742–1806) A French chemist and physician who invented a process for the manufacture of soda ash (sodium carbonate) from salt (sodium chloride). He began his studies in medicine in Paris to train as a physician. When the French Academy of Sciences offered a prize for the conversion of inexpensive salt to the more highly valued soda ash in 1775, he invented a two-step process. He was awarded the prize for the process that used sea salt and sulphuric acid as the raw materials. The process was successfully developed but was confiscated by the French revolutionary government, which refused to pay him the prize money he had rightfully earned. Napoleon, however, later returned the plant to him in 1802 although not the prize. Unfortunately, Leblanc was not able to afford to run the process and he committed suicide in 1806.

Leblanc process A process used in the nineteenth century for the manufacture of sodium carbonate from salt and superseded an earlier process of manufacturing soda from

the ash of seaweed. The essential features of the Leblanc process were the conversion of sodium chloride to sodium sulphate by the action of heated sulphuric acid:

$$NaCl + H_2SO_4 = Na_2HSO_4 + HCl$$
$$Na_2HSO_4 + NaCl = Na_2SO_4 + HCl$$

The sodium sulphite was then reduced to sulphide and converted to carbonate by double decomposition with calcium carbonate in the form of limestone:

$$Na_2SO_4 + 4C = Na_2S + 4CO$$
$$Na_2S + CaCO_3 = CaS + Na_2CO_3$$

The salt cake was mixed with limestone and powdered coal and heated in a rotary furnace. The product was known as black ash. The sodium carbonate was extracted with water and crystallized from the calcium sulphide by-product. Invented in 1783 by the French chemist Nicolas *Leblanc (1742–1806), this was the first synthetic production of sodium carbonate. The Leblanc process was superseded by the cheaper *Solvay process and is the only method still used for making sodium carbonate.

Le Chatelier, Henry Louis (1850–1936) A French professor of chemistry who investigated the chemistry of silicates, cement, ceramics, and steels. In 1887 he developed the platinum/platinum-rhodium thermocouple, which made possible the accurate measurement of very high temperatures. He worked on electrical conductivity and on specific heats of gases and discovered the effects of temperature and pressure on a system in equilibrium. *See* LE CHATELIER'S PRINCIPLE.

Le Chatelier's principle A law that states that if a system in physical or chemical equilibrium is subjected to a change in temperature, pressure, or concentration, then the system will automatically alter itself so as to reduce the effects of the change. It can be shown that this law must be true if energy is neither created nor destroyed.

Lee–Kesler equation of state An extended form of the *Benedict–Webb–Rubin equation of state used to describe the vapour–liquid equilibrium data of various substances. It expresses the *compressibility factor, z, as a linear function of an *acentric factor.

Lee's disc A device for determining the thermal conductivity of poor conductors in which a thin, cylindrical slice of the substance under study is sandwiched between two copper discs. A heating coil or steam chest is placed on one of these discs and the temperatures of the two copper discs are measured, from which the thermal conductivity of the substance can be determined from the heating profile across the thickness.

Leidenfrost effect A phenomenon in which a liquid in near contact with a surface at a much higher temperature than the liquid's boiling point produces an insulating vapour layer which prevents the liquid from boiling rapidly. It is named after German doctor of medicine and theologian Johann Gottlob Leidenfrost (1715–94).

Lessing ring A type of packing material used in packed columns and towers that provides a high surface-to-volume ratio. It consists of a hollow cylinder with an internal structure such as a bar or cross arrangement that provides strength and additional surface area (see Fig. 25). They are made from various materials such as plastic, glass, and ceramic, and are available in various sizes. *See* PACKING.

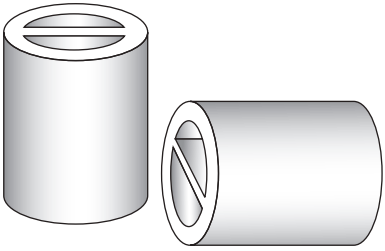

Fig. 25

lethal dose A measure of the toxicity of a chemical substance or ionizing radiation that leads to death. It is usually expressed as the amount of chemical or ionizing radiation per unit body weight. The median lethal dose denoted as *LD_{50} represents the dose that results in the death of half (50 per cent) of the exposed animals within a population within a defined period of time such as within a two-week period. The subscript represents the statistically expected level of mortality. For example, LD_{99} represents a lethal dose leading to the death of 99 per cent of those exposed. The **lethal concentration** is the concentration of an airborne chemical substance over a four-hour period that causes the death of exposed test animals. Where half of test animals in a population die, the lethal concentration is denoted as *LC_{50}.

level alarm An alarm alerting an operator that the level of a substance within a vessel has deviated significantly from the required *set point sufficient to be of concern. A *low-level alarm signifies that a vessel may be nearly empty whereas a high-level alarm may indicate that a vessel is at capacity or near to overflowing.

level control A method of controlling the level of substance such as a liquid contained within a vessel. The level can be controlled either by adjusting a valve on the inlet to the vessel or, if there is a constant flow in, by adjusting a valve on the outlet. A simple form of level control consists of a ballcock in which the position of a float on the surface of the liquid activates the opening and closing of a flow valve.

level gauge An instrument used to indicate the level of a liquid or solid in a tank or process vessel. A simple level gauge consists of a vertical glass or plastic tube attached to the bottom of the tank allowing the liquid to rise to the level in the tank. A *pneumercator is a device that is used to determine the level of a liquid in a tank and consists of a vertical tube through which a gas is gently passed as bubbles through the liquid. The level in the tank is determined from the supplied pressure to overcome hydrostatic pressure.

lever rule A rule that enables the relative amount of two phases in a mixture that are in equilibrium to be found by the construction of a *phase diagram. The lever rule states that $n_1 l_1 = n_2 l_2$ where n_1 and n_2 are the amounts of phase 1 and 2, and l_1 and l_2 are the distances along the horizontal *tie lines of the phase diagram. The lever rule takes its name from the mechanical lever rule relating the moments of two masses about a pivot.

Lewis–Matheson A stage-by-stage calculation used for solving multicomponent distillation problems. The calculation operates from both ends of the column and works towards the middle. The calculations are required to 'mesh' somewhere in the column,

which is usually at a feed stage. For more than one feed a choice of mesh points is made for each component and, if the components vary widely in volatility, the same mesh point cannot be used for all components if serious numerical difficulties are to be avoided. The procedure is subject to large truncation-error build-up where components differ widely in volatility. Arbitrary procedures are also needed for non-distributed components whose concentration in one of the product streams is smaller than the smallest number carried by the computer. The concentrations for these components do not naturally take on non-zero values at the proper point as the calculations proceed through the column.

Lewis number A dimensionless number, Le, used in heat and mass transfer that characterizes a particular substance as the ratio of the *thermal diffusivity, α, to the molecular diffusivity, D:

$$Le = \frac{\alpha}{D}$$

It is named after American chemical engineer Warren K. Lewis (1882–1975). *See* LYKOV NUMBER.

Lewis–Randall rule A thermodynamic rule stating that the fugacity of the species in an ideal solution is proportional to the mole fraction of each species in the liquid phase. It is named after American chemists Gilbert Newton Lewis (1875–1946) and Merle Randall (1888–1950).

LFL *See* LOWER FLAMMABLE LIMIT.

life cycle analysis (LCA) A systematic set of procedures for compiling and examining the inputs and outputs of materials and energy consumed within a process, and the associated environmental impacts directly attributable to the functioning of a product or service throughout its life cycle. It takes a cradle-to-grave approach, starting from the origin of the raw materials from natural resources such as oil wells or extraction from ores, and follows them through transformation into useful products, the use by the consumer, recycling where possible, and eventual disposal. Within each step of the life cycle, waste is created. It is therefore more useful than just concentrating on minimizing waste since problems often lie elsewhere within the life cycle.

The components of a life cycle analysis include the **life cycle inventory**. These involve a complete resource requirement to be identified in terms of materials and energy. The **life cycle impact assessment** characterizes and assesses the effects of the environmental emissions. The **life cycle improvement analysis** is used to quantify the life cycle inventory and import, and is used to assess possible environmental improvements that can be made.

light ends Hydrocarbon fractions in oil refining that have a low boiling point and are easily evaporated. This corresponds to butane or lighter components.

light key *See* KEY COMPONENTS.

light phase The liquid with the lower density in a liquid–liquid extraction separation process and sits above the *heavy phase, which has the higher density.

lignin An organic substance found in the woody parts of plants and is associated with cellulose. It is the raw material used in papermaking such as the sulphite process. In the *kraft process it is cooked with a solution containing sodium hydroxide and sodium sulphide.

limiting factor An environmental variable or a nutrient restriction on the growth of a microorganism in a biotechnological process. While limiting factors may be seen as a form of deficiency, they are useful in bioreactors for the growth of microorganisms where growth may be intentionally limited such that the level of a particular nutrient exceeds the limits of tolerance for the microorganism.

limiting oxygen index The lowest oxygen concentration in an oxygen–nitrogen mixture at which a substance will continue to burn by itself.

limiting reactant A reactant consumed in a chemical reaction that is present in the smallest relative amount to the other reactants, which are not in their stoichiometric proportion. The *excess reactants remain unreacted. For example, in the oxidation of o-xylene to phthalic anhydride:

$$C_8H_{10} + 3O_2 \rightarrow C_8H_4O_3 + 3H_2O$$

three moles of oxygen are required in the reaction for each mole of o-xylene. However, in practice an excess amount of oxygen is added and the o-xylene is therefore the limiting reactant.

limiting substrate A nutrient used in the growth of microorganims in a concentration that restricts or limits the rate of growth. It is intentionally used to control biotechnological processes in which all other essential nutrients are added in excess such that the limiting substrate determines the rate of growth and can lead to the controlled production of a desired bioproduct. In fermentation processes, sugar is used as the limiting substrate to ensure that the yeast cells convert the sugar to alcohol. Where another nutrient is the limiting substrate, other undesirable bioproducts may result or there may be a poor growth of cells.

Linde process 1. An early process used for the *liquefaction of air. It involves first purifying the air by passage over soda lime to remove carbon dioxide, and then drying it. It is then pressurized to around 200 atmospheres, and cooled back to ambient temperature and passed through closely spiralled thin copper tubing surrounded by thicker copper tubing. The air is allowed to expand to about 20 atmospheres and cooled by the *Joule–Thomson effect. The cooled air passes through the annulus between the two tubes thereby cooling further incoming compressed air. The process was developed by German engineer Carl von Linde (1842–1934) and later improved by George *Claude (1870–1960) who made the expansion of the gas doing useful work in an expansion engine. **2.** A process used for the removal of hydrogen sulphide and mercaptans from petroleum fractions by reaction with oxygen in the presence of a metal amino acid chelate in an aqueous solution containing an amine.

linear equation An equation with two variables that gives a straight line when plotted on a graph of the form $y = mx + c$ where m is the gradient and c is the intercept on the y-axis.

linear programming A mathematical technique used to provide an optimal solution to a set of *linear equations. The technique uses a model of a process, which consists of a set of equations and also an *objective function. The objective function may typically represent the economics of the process. The set of linear equations are known as constraint equations and define a region of feasibility that has an infinite number of solutions. The objective function is used to evaluate the optimal solution from these. Linear programming is widely used for process optimization, product supply and distribution, project management, and general resource allocation.

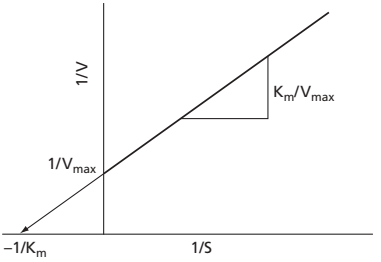

Fig. 26

Lineweaver–Burk plot A double-reciprocal plot used to determine the two constants featured in simple enzyme kinetic equations such as *Michaelis–Menten kinetics, *Monod kinetics, and in similar adsorption isotherm models such as the *Langmuir adsorption isotherm. The constants are determined from the intercept with the y-axis and the gradient (see Fig. 26). It was devised and published in 1934 by American chemist Hans Lineweaver (1907–2009) and American biochemist Dean Burk (1904–1988).

lining An inner surface applied to process equipment to prevent or reduce the occurrence of corrosion, erosion, or the damaging effects of temperature. The surface may be a coating or a shield such as glass, lead, or in the case of furnaces, heat-resistant brick.

Linton–Sherwood correlation A dimensionless equation used to determine the mass transfer in gas absorption:

$$Sh = 0.023\,\mathrm{Re}^{0.83}\,Sc^{0.33}$$

It was developed in 1950 based on experimental data from wetted wall columns and is valid for *Reynolds numbers between 2,000 and 70,000 and *Schmidt numbers between 0.6 and 2,500.

liquation A separation and purification process used for metals from ores. It involves heating to a temperature at which the lower melting metals liquefy and can then be separated by draining. It was once used to separate lead containing silver from copper in the fifteenth century. The lead melts at 327°C whereas copper melts at 1,084°C allowing the silver-rich lead to melt and freely drain away. To avoid oxidation, the liquation furnace operates with a reducing atmosphere.

liquefaction The process of making or becoming liquid. Gases can be liquefied through refrigeration, pressurization, and the *Joule–Thomson effect. *Andrews' work on carbon dioxide showed that to liquefy any gas, it is necessary to cool it below its critical temperature, and then to apply sufficient pressure to induce liquefaction. The liquefied gases occupy a smaller volume than gases for storage, and *multicomponent mixtures can also be readily separated by the process of *distillation. Solid particles can also be made into a fluid-like mass through mechanical vibration.

liquefied natural gas (LNG) Natural gas, largely composed of methane, which has been refrigerated to a liquid. The boiling point of methane at atmospheric pressure is

-161°C. Because of its low critical point, it must be cooled to below this temperature before it can be liquefied by pressure. Once liquefied, it can be stored in well-insulated vessels and can be conveniently transported. It is used as an engine fuel.

liquefied petroleum gas (LPG) A mixture of gaseous petroleum products normally stored and transported as liquid under pressure. The main constituents are propane and butane. LPG has an ignition temperature of 450°C and calorific value or 45.3 MJ kg^{-1}. It is largely used as an engine fuel and has a wide range of other industrial and domestic uses.

liquefied refinery gas A group of gases including ethane, propane, butane, isobutane, and their various derivatives that are produced in petroleum refineries by fractionation. Also known as *still gas, it is kept in the liquid state through compression and/or refrigeration. It is used as a refinery fuel or petrochemical feedstock.

liquid A state of matter between a gas and a solid in which the molecules are free to move with respect to each other, but are held by cohesive forces such that they maintain a definite volume but not a fixed shape. There is still no simple comprehensive theory of the liquid state even though liquids have been studied for many years. *Compare* SOLID; GAS.

liquid distributor A device used to distribute liquid over the top of packing material contained within a packed column. It consists of channels located above the packing through which the liquid flows. The liquid either overflows over small notches and weirs cut in the side of the distributor channel or drains through orifices in the bottom.

liquid–liquid extraction *See* SOLVENT EXTRACTION.

liquidus A boundary line or curve of a *phase diagram between liquid and liquid/solid at equilibrium. Above the line, the substance is liquid.

liquor 1. Liquid as the product of a process used as a wash. **2.** Water used in brewing as the fermented or distilled product. **3.** Water in which food has been boiled. **4.** A solution of a pharmaceutical dissolved in water.

litre (Symbol l) An *SI unit of volume that occupies one cubic decimetre (1 $dm^3 = 10^{-3}\ m^3$). It was previously defined as the volume of one kilogram of pure water under standard conditions of 4°C and standard pressure, which is equivalent to 1.000 028 dm^3.

Little, Arthur Dehon (1863–1935) An American chemist and chemical engineer who founded a major consulting company. He was instrumental in founding chemical engineering at MIT and is credited with coining the term *unit operations. A graduate of chemistry from MIT, he formed a partnership with chemist Roger B. Griffin who was later to die in a laboratory accident in 1893. Working by himself and then closely with MIT and, in particular, with William Hultz Walker, he formed another partnership, Little and Walker, in 1900. After dissolving the company five years later he continued again on his own and established Arthur D. Little in 1909, which is today a leading international management consultancy that covers many industrial sectors. Arthur D. Little taught papermaking at MIT from 1893 to 1916. He was president of the American Chemical Society (1912–14), president of the *American Institute of Chemical Engineers (1919), and president of the Society of Chemical Engineering (1928–29).

lixiviation The process of separating mixtures by dissolving soluble constituents in water. The **lixiviant** is the liquid medium that is used in *hydrometallurgy to extract selectively a

desired metal from the ore or mineral and is used to enable quick and complete leaching. The metal can then be recovered from it in a concentrated form after leaching.

LNG *See* LIQUEFIED NATURAL GAS.

lock and key mechanism A mechanism proposed in 1890 by Emil Fischer (1852–1919) to explain the binding between the active site of an enzyme and a substrate molecule. The active site is seen as the fixed structure (lock) and exactly matches the structure of the substrate (key). An example is the interaction of an enzyme and substrate in which the lock and key mechanism produces an enzyme–substrate complex. The substrate is then converted to products, which no longer fit the active site, releasing the product and liberating the enzyme. Recent X-ray diffraction studies have shown that the active site of an enzyme is more flexible than this simple mechanism would suggest.

lockout-tagout (LOTO) A safety procedure used to disable machinery and process equipment being serviced by disengaging or isolating it from its power source. This is to ensure that it cannot be restarted until associated maintence is completed. It uses a system of locks and tags in which tags on the locked equipment are used to indicate that the equipment cannot be restarted. The procedure involves notifying employees, shutting down and isolating the equipment, locking and tagging, the release of any stored energy, and verification that the equipment has been isolated.

logarithm Any real number can be written as another number raised to a power in the form $y = x^n$ where n is the the logarithm to the base x of y, i.e. $n = \log_x y$. If base 10 is used, the logarithms are called *common logarithms. **Natural logarithms** or (Naperian logarithms) are written to the base $e = 2.718\ 28\ldots$ and written as either $\log_e$ or ln and named after Scottish mathematician John Napier (1550–1617). Logarithms contain two parts: the characteristic is the integer and the mantissa is the decimal. For example, the logarithm to the base e of 10 is 2.302 where 2 is the characteristic and 0.302 is the mantissa. Note that for any base, the logarithm of 1 is zero, the logarithm of 0 is not defined, the logarithm of a number greater than 1 is positive, the logarithm of a number between 0 and 1 is negative, and the logarithm of a negative number cannot be evaluated as a real number. In the past, tables were constructed called Tables of Logarithms. Nowadays, electronic calculators have superseded the use of these tables.

logarithmic mean temperature difference A temperature driving force applied to the heat transfer between fluids with constant heat capacities. It is applied to fluids that transfer heat in countercurrent directions and is determined from the difference in the temperature difference in fluid temperatures at either end of the heat exchanger divided by the natural logarithm of the ratio of the same two temperature differences:

$$\Delta T_{lm} = \frac{(T_3 - T_2) - (T_4 - T_1)}{\ln\left(\dfrac{(T_3 - T_2)}{(T_4 - T_1)}\right)}$$

It should not be used where the *overall heat transfer coefficient varies appreciably, with *multipass heat exchangers, nor where heat is generated such as on one side of the heat transfer surface as in an exothermic reaction in a water-cooled reactor (see Fig. 27).

logarithmic scale A scale of measurement in which an increase or decrease of one unit represents a tenfold increase or decrease of that measurement: pH measurement is an example of a logarithmic scale. Data that follows a logarithmic relationship can be plotted

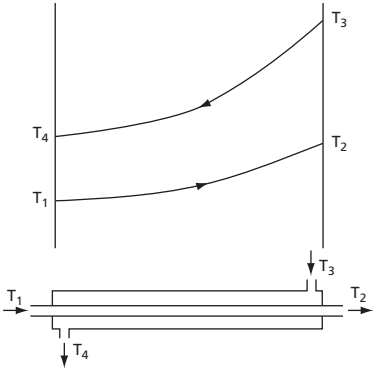

Fig. 27 Log mean temperature difference

on special graph paper with a logarithmic scale. Alternatively, the relationship can be linearized. For example, the Fanning friction factor for turbulent flow in smooth pipes is related to *Reynolds number as $f = a\mathrm{Re}^{-b}$. This can be represented as a linear relationship on a plot of *ln f* versus *ln Re*. This is a straight line, therefore $\ln f = \ln a - b\ \ln \mathrm{Re}$ which enables the gradient *b* to be determined.

log phase A period of time in which microbial cells grow at a constant maximum rate, unrestricted in terms of nutrients or substrate such that there is a repetitive doubling of cells. After inoculation of a bioreactor with living cells, there is an initial *lag phase in which the cells adjust to their new environment. There is then an *acceleration phase until the cells begin to grow at their maximum rate. The increase in population is then expressed as:

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

Integrating from an initial population N_o at time t = 0, gives $t = \frac{1}{k}\ln\left(\frac{N}{N_o}\right)$. It can also be expressed as $N = N_o e^{kt}$ and alternatively is known as the *exponential phase.

loop reactor A type of chemical reactor that has an external loop from the main body of the reactor through which a portion of the reacting material flows. Used for liquid-phase reactions, it operates as a form of gas lift in which gas is admitted into the bottom and rises as bubbles. After disengagement of the bubbles, the reacting materials descend into the bottom of the reactor via the external loop. This type of reactor does not require mechanical mixing to achieve good gas–liquid dispersions. There are, however, difficulties in controlling the rate of mass transfer and the consumption of energy.

LOPA *See* LAYER OF PROTECTION ANALYSIS.

loss The amount of material, energy, power, or pressure lost during a process. An increase in loss is usually synonymous with a reduction in efficiency.

loss prevention A comprehensive and systematic approach to the study of safety, the prevention of accidents, and the minimization of their effects on people, processes, and equipment. Derived from an insurance term for the financial loss incurred due to

an accident, it considers the cost of replacing damaged plant, third-party claims, loss of production and sales. The whole system is examined in detail in order to ensure process efficiency and safety can be achieved within reasonable economic limitations. Within process design, safety and loss prevention considers the identification and assessment of the hazards, their control such as containment of flammable and toxic materials, the control of the process through the provision of control systems, alarms, trips, and operating practices, and the limitation of damage and injury through pressure relief, plant layout, and provision of fire-fighting equipment.

lost time incident (LTI) A work-related incident that involves an injury or illness where an employee of an organization or a contractor is unable to return to work as a result of their injury.

LOTO *See* LOCKOUT-TAGOUT.

low and vacuum pressure safety valve (LVPSV) An automatic system that relieves the pressure on a gas in a vessel or pipeline. It is used for small, negative or positive pressure differences near to atmospheric pressure.

lower flammable limit (LFL) The lowest concentration of a flammable vapour or gas mixed with an oxidant such that it will propagate flame at a specified temperature and pressure. *Compare* UPPER LIMIT OF FLAMMABILITY. *See* FLAMMABILITY LIMITS.

low-level alarm *See* LEVEL ALARM.

low pressure safety valve (LPSV) An automatic valve system that relieves pressure on a gas. It is used for small differences between the pressure in a vessel and atmospheric pressure.

LP An abbreviation for **l**ow **p**ressure. It is often used with reference to a utility or a vent line, for example, an LP air supply.

LPG *See* LIQUEFIED PETROLEUM GAS.

LPSV *See* LOW PRESSURE SAFETY VALVE.

LTI *See* LOST TIME INCIDENT.

lubrication The use of substances to reduce the frictional forces between two surfaces. Lubrication is required in the smooth running of machinery such as pumps, gears, and bearings to prevent wearing and overheating. Most lubricants are based on hydrocarbons. Additives are often added to control the viscosity and prevent oxidation. Greases are used to seal against moisture and dirt and other particulates and are often used on vertical surfaces. A **lubricating oil** is a fraction of crude oil distillation at around 300°C to 370°C that is used for motor oil and other lubricants designed to reduce the friction in machinery. Impurities are removed that affect the viscosity before adding additives that enable the lubes to be used in various circumstances such as at low temperatures.

lumen (Symbol lm) An *SI derived unit of luminous flux equal to the flux emitted in a solid angle of one steradian by a point source having a uniform intensity of one candela.

Lurgi process A coal gasification process that was originally developed in Germany. It is used for the gasification of poor-quality coal, and uses high temperature and pressure in the presence of steam and oxygen. The gas produced is mainly hydrogen and carbon dioxide, which is then mixed with steam and passed over a catalyst to convert the carbon monoxide and steam into carbon dioxide and hydrogen by the *water-gas shift reaction.

lute A U-shaped loop in a pipe or tube in which a liquid is trapped and used to provide a seal for gas flow. For example, the pipe from a gravity-fed reflux from the condenser of a distillation column contains a lute. The distillation column has a higher pressure than the condenser and the lute prevents vapour entering from the wrong direction. The depth of the lute is determined from hydrostatics and is greater than the maximum vapour pressure difference between the column and the condenser outlet.

lux (Symbol lx) An*SI derived unit of illumination equal to a luminous flux of one *lumen per square metre.

LVPSV *See* LOW AND VACUUM PRESSURE SAFETY VALVE.

Lykov number (Luikov number) A dimensionless number, Lu, that combines heat and mass transfer as the ratio of mass diffusivity, D, to thermal diffusivity, α:

$$Lu = \frac{D}{\alpha}$$

See LEWIS NUMBER.

lyophilization The removal of moisture from a material such as a biological substance in which the properties are preserved by freezing under vacuum. It is used at temperatures of around –80°C, followed by drying in a vacuum. The moisture is removed by *sublimation. It is used for the long-term preservation of microbial cultures and protein samples. *See* FREEZE DRYING.

lyophobic A term used to mean lacking an affinity for a solvent. Where water is the solvent, the term hydrophobic is used. The opposite is **lyophilic**, or in the case of water being the solvent, hydrophilic.

lysis The process of rupturing the cell wall and membranes (if present) of microorganisms by physical, chemical, or biochemical means to release the contents of the cells. Presses and liquid shear such as *bead mills provide physical disruption to the cells, whereas chemical agents, including detergents such as Triton X, remove the lipid molecules thereby causing disruption of cell membranes. The enzyme lysozyme, obtained from hen egg white, dissolves the cell wall causing disruption. It is, however, expensive and rarely used for large-scale extraction processes. The processes are often used in combination.