# M

**Mach number** The ratio of the speed of a body or a fluid to the speed of sound in that body or fluid at the same temperature and pressure conditions. Where the speed exceeds the speed of sound (i.e. Mach 1), the speed is supersonic. *Choked flow of air in a pipe or through an aperture occurs at Mach 1. It is named after Austrian physicist and philosopher Ernst Mach (1838–1916).

**macro-** A prefix meaning large. A **macromolecule** is a high molecular weight polymeric molecule such as a protein, carbohydrate, or nucleic acid. Their diameter is typically between $10^{-8}$ and $10^{-6}$ m. Natural and synthetic polymers such as cotton and plastics are also examples of macromolecules. A **macroporous resin** is a type of *ion exchange resin that has an open pore structure capable of absorbing large ions. The rate of absorption of ions and resistance to osmotic shock is better than for gel-type resins, although their overall capacity is lower. Something that is **macroscopic** is large enough to be visible to the naked eye.

**magnex process** A process used to remove minerals from heated pulverized coal by making it magnetic using gaseous iron pentacarbonyl ($Fe(CO_5)$). This deposits a layer of magnetic material on the minerals but not the coal itself. Magnetic separation is then used to remove the minerals.

**Maillard reaction** Also known as non-enzymatic browning, it is the chemical reaction between proteins and reducing sugars during heating which produces colours ranging from brown to red. It is responsible for the colour and flavour in many processed foods. It is named after French chemist Louis Camille Maillard (1878–1936).

**maintenance** The routine action of ensuring that a process facility or item of process equipment is fully serviceable and operable at its original or designed capacity, requirement, and efficiency. It includes a programme of inspection, testing, and servicing. **Scheduled maintenance** is planned and recurring work designed to ensure that a facility or process is serviced before the inconvenience of a breakdown, whereas **unscheduled maintenance** can be a costly inconvenience.

**make-up** The addition of a process material or substance to a process to allow for its gradual loss. The loss, which may or may not be intended, may be due to leakage, through purging, evaporation, or accompanying a product as an impurity. Additional solvent make-up is added to extractive distillation processes, which lose solvent as an impurity to the product. Cooling towers that cool process water for reuse require make-up water for the water lost as vapour.

**malleability** The ability of a material such as gold to be hammered into thin sheets.

**manifold** A pipe or chamber which directs a gas or liquid into a series of smaller pipes or chambers.

**Manning formula** An empirical equation used in open channel flow under the influence of gravity of the form:

$$C = \frac{m^{\frac{1}{6}}}{n}$$

where $C$ is the Manning roughness coefficient and is used in the *Chézy formula, $m$ is the *mean hydraulic depth, and $n$ is a dimensional roughness factor, the magnitude of which depends on the type of surface. It is also known as the **Gauckler–Manning formula** and was first developed by French engineer Philippe G. Gauckler in 1867 and further developed by Irish engineer Robert Manning (1816–97) in 1890.

**manometer** An instrument used to determine the pressure difference between two points, usually by measuring the height difference of liquid in two vertical legs. There are many variations of instrument, and all consist of a vertical leg up which a liquid moves in proportion to the pressure applied.

A **gas-filled manometer** is used to measure the pressure of process gases and consists of a sealed container at some pressure and the other end is attached to a process via a U-tube containing a liquid. The pressure of the process is determined from the levels of manometer liquid in the U-tube and the pressure in the sealed vessel.

A **differential manometer** is used to measure the pressure of a process fluid and measures the difference in pressure between two points in a process, such as the pressure drop across a heat exchanger. An **inverted manometer** is essentially an inverted differential manometer in which the process fluid is used to measure its own pressure. A head of trapped gas (usually air) is used in the device.

**Single leg manometers** replace the U-tube containing a manometer liquid, with a large *sump containing the liquid that extends up one leg when a differential pressure is applied. An **inclined leg manometer** is a variation of the single leg manometer but with the protruding leg from the sump inclined at some angle. This provides a magnification of the movement of the liquid along the leg to an applied pressure and is particularly useful for measuring small pressures.

**manual control** A type of *feedback control used to control a process in which a process operator makes the judgement to adjust a *process variable. The operator receives a signal, usually from a gauge monitoring the temperature, pressure, flow, or level, and manually adjusts a valve. Opening or closing the valve to alter the flow of cooling water, steam, gases, etc., results in changes to the process conditions. The process operator continually monitors the gauges making more adjustments until the required process conditions are met.

**manway** An access port into major process vessels such as reactors, columns, or tanks. It is normally sealed with a lid or covered with an O-ring on a flange and locked with nuts. They are sufficiently wide to enable a person to enter, wearing appropriate *personal protective equipment, to carry out internal inspections, cleaning, and *maintenance, etc.

**Margules' activity coefficient model** A simple thermodynamic model used to describe the excess *Gibbs free energy of a liquid mixture. It uses activity coefficients that are a measure of the deviation from ideality of solubility of a compound in a liquid. *See* RAOULT'S LAW. In the case of a binary mixture, the excess Gibbs free energy is expressed as a power series of the mole fraction in which the constants are regressed with experimental data. The activity coefficients are found by differentiation of the equation. Unlike other

models such as UNIQAC and NRTL, the model has the ability to predict a wide range of reliable thermodynamic values for the coefficients. It is named after Austrian scientist Max Margules (1856–1920) who developed it in 1895.

**Marshall and Swift index** A method of determining the installed equipment cost of a chemical plant. It is based on average cost data from nearly 50 industries involving both process industry and more general industry equipment costs. The cost at any particular time is based on the original cost at some earlier specified time multiplied by a ratio of cost indices for the present to the earlier time of interest. The base year is taken as 1926 with a value of 100. Until April 2012, the index was published in the monthly issues of the magazine **Chemical Engineering*.

**mass** (Symbol m) A measure of the quantity of material. It is defined as the resistance or inertia of a body to acceleration. Newton's laws of motion state that if two bodies of equal mass, $m$, each acquire an acceleration, $a$, then $m_1 a_1 = m_2 a_2$. That is, the mass of one body can be compared to the other. A standard mass is therefore used to compare all other masses. This is a one-kilogram cylinder of platinum-iridium alloy called the international standard of mass.

**mass balance** The analysis of a process in which the total mass of the chemical reactants is correlated with the total mass of the products according to the *law of conservation of mass. Where there is an inequality, there is either an unaccounted loss or accumulation within the process. A mass balance calculation is used in the design stage of a process. It is also used during process operation as a form of inventory or accountancy. It is also known as a *material balance.



**mass fire** A large-scale fire involving many buildings or structures. A forest fire is a mass fire.

**mass flow rate** The flow of materials measured in terms of its mass per unit time. The mass flow rate of a fluid within a pipeline is the product of its density, $\rho$, mean velocity, $v$, and cross-sectional area, $a$, of the pipe. $m = \rho a v$. The *SI units are kg $s^{-1}$.

**mass flux** The rate of mass of a fluid flowing per unit area. It is used to describe the flow of materials through pipes and process equipment such as membranes and filters. In a two-phase system such as a liquid and a gas flowing through a pipe or through an absorption column, the mass fluxes of the different phases are considered and expressed separately. The *SI units are kg $m^{-2}$ $s^{-1}$.

**mass fraction** The proportion of a substance in a mixture expressed as a fraction of the overall mass of the mixture.

**mass loading** (Symbol G and L for gas and liquid, respectively) A measure of the mass flow rate per unit area, and used for the flow of fluids within packed columns to ensure that good mass transfer takes place between a liquid and gas, and that the internal hydraulics of the column provide the required operability. The *SI units are kg $m^{-2}$ $s^{-1}$.

**mass number** The number of neutrons and protons in the atomic nucleus of an atom (i.e. **nucleons**). For example, uranium-238 comprises 92 protons and 146 neutrons.

**mass transfer** The movement of the mass of a component in a system containing two or more components from a region of high concentration to that of a lower concentration. It

forms the basis of many chemical and biological processes such as crystallization, adsorption, liquid–liquid extraction, etc. The movement of mass is either by random molecular motion or by convective forces where mass is transferred from a surface into a moving fluid. The *mass transfer coefficient is a measure of the diffusion rate that relates the mass transfer rate, mass transfer area, and concentration gradient as the *driving force.

**mass transfer coefficient** (Symbol $k_C$) A quantity that characterizes the extent of the movement of mass across a boundary. It is defined as the ratio of the mass flux to the difference between mass fractions on either side of the boundary:

$$k_C = \frac{n}{a\Delta C_A}$$

where $n$ is the mass transfer rate, $a$ is the effective mass transfer area, and $\Delta C_A$ is the driving force concentration difference. It is used to quantify the mass transfer between phases and in mixtures, and is used to design and size separation equipment. Mass transfer coefficients can be obtained from theoretical equations, correlations, and material properties, depending on the material or process being studied. For example, the mass transfer coefficient can be correlated using the Sherwood number (Sh) with the Reynolds number (Re), Grashof (Gr) number, and the Schmidt number (Sc) for various flow regimes such as:

$$Sh = a\,\mathrm{Re}^{b}\,Sc^{c}$$

or for natural convection:

$$Sh = a'\,Gr^{b'}\,Sc^{c'}$$

The coefficients and exponents are determined experimentally.



**material** Any substance or matter (element, compound, or mixture) in any physical state (gas, liquid, or solid). In a process, material may undergo change in its form but the total mass remains constant. Material and mass are therefore not synonymous.

**material balance** The exact accounting of all *material that enters, leaves, accumulates, or is depleted within a given period of operation across an imaginary boundary of a process or part of a process. It is in effect an expression of the *law of conservation of mass in accounting terms. Where the conditions of a process are steady and unvarying with time, the material input flow across the boundary equals the output flow. Depending on whether chemical or physical change occurs, material balances may be conveniently calculated and expressed in either mass or molar terms.

**material safety data sheet (MSDS)** The documented information associated with a supplied chemical for its safe use and handling. The information includes physical data such as melting points, boiling points, flash points, and also includes information of its potential hazards and health effects such as toxicity. It is intended to protect those intending to use or handle the chemical, and includes the necessary *personal protective equipment to be used as well as first-aid information. It is also known as a **product safety data sheet**.

**mathematical model** A mathematic description of a process or system used to understand or predict its behaviour. It can also be used to aid understanding of the influences on a process as well as to control the process or system itself. A model may take the form of a set of differential equations and describe both steady-state behaviour and dynamic behaviour, and may be combined with experimental data for validation purposes or for leading to new theories and hypothesises. *Unstructured models, such as *Monod kinetics, are used to describe the time variation of a component such as accumulation of biomass or depletion

of a limiting substrate in which the environmental changes are ignored. Although mathematically simple, they are frequently useful for design, control, and optimization purposes. Structured models are more complex in nature, and endeavour to describe and predict the influence of the environment on the internal mechanisms of a living organism.

**matrix 1.** A solid substance within which another substance is embedded such as a metal that constitutes the major part of an alloy. **2.** A rock material within which a mineral is embedded. **3.** In algebra, a rectangular array of elements set out in rows and columns used to facilitate the solution to mathematical problems. They can be used to present the coefficients of simultaneous linear equations in which each row corresponds to one equation.

**matte** An impure mixture of metal sulphides such as copper and iron.

**maturation** An aging process used in the production of *whisky following the process of distillation in which the distilled spirit is placed in wooden casks for long periods of time. There is a legal requirement to mature Scotch whisky for a minimum of three years and it is often much longer. During this time flavours from the casks that have been previously used in the wine, sherry, cognac, and port industries are imparted, and include lignin and vanillin from the wood. The aging process also imparts colour. Around 2 per cent is lost each year through evaporation known as the *angel's share.

**maximum allowable working pressure** The maximum pressure at which process equipment can be operated safely at a designated temperature. It applies to vessels and pipes.



**maximum drying rate** The maximum rate at which *moisture can be removed from a substance.

**maximum specific growth rate** (Symbol $\mu_{max}$) The maximum possible rate of growth of a culture of microorganisms in a bioreactor. It is dependent on the temperature, pH, dissolved oxygen, and presence of nutrients. It has dimensions of reciprocal time and commonly has the unit of $h^{-1}$. *See* MONOD KINETICS.

**Maxwell, James Clerk** (1831–79) A Scottish physicist and mathematician noted for his pioneering work on the kinetic theory of gases and electromagnetism. He was known affectionately at school as 'daftie' and at fifteen he had a mathematical paper read to the Royal Society of Edinburgh. He retired in 1865 as professor at Aberdeen and London, but in 1871 he was recalled to be the first professor of experimental physics at Cambridge where he also prepared plans for the Cavendish Laboratory that was named after the Hon. Henry *Cavendish (1731–1810). He also made major contributions to astronomy, colour, and colour-blindness.

**Maxwell–Boltzmann distribution** A mathematical function used in the *kinetic theory of gases. It is derived on the basis of *statistical mechanics and gives the distribution of particle velocities in a gas at a particular temperature.

**MBOED** A unit of volumetric flow in the oil industry as **m**illion **b**arrels of **o**il **e**quivalent per **d**ay. The barrel of oil equivalent (**BOE**) is a unit of energy that is released from the combustion of one *barrel of crude oil. It is used for financial purposes to combine both oil and gas into a single measure.

**McCabe–Thiele** A rigorous graphical method used in the analysis of the separation of two heterogeneous liquids by distillation. It is used to determine the number of stages required to bring about a required separation, and is based on a stage-wise approach requiring vapour liquid equilibrium data between the two liquids presented in terms of the more volatile component. The diagram (see Fig. 28) presents the vapour liquid equilibrium data based on the more volatile component as the mole fraction in the vapour phase (y) and the mole fraction in the liquid phase (x). Molar balances over the stripping and rectifying sections of the distillation column provide *operating lines. The step-wise lines represent the vapour liquid equilibrium on each theoretical tray or equilibrium stage and provide an indication of the total number of trays or stages required for a separation. The intercept of the stripping and rectification sections meets the *q-line and represents the condition of the feed to the distillation column. The method assumes a constant molar overflow requiring constant molar heats of vaporization, that for every mole of liquid vaporized a mole of vapour is condensed, that there is no heat of mixing or solution, and that there is no heat transfer to or from the distillation column. The method was developed by American chemical engineers Warren L. McCabe (1899–1982) and Ernest W. Thiele (1895–1993) in 1925, but is now largely obsolete due to the use of computers able to carry out rapid and detailed calculations. Its simple graphical representation makes it a useful teaching tool. *Compare* PONCHON–SAVARIT.

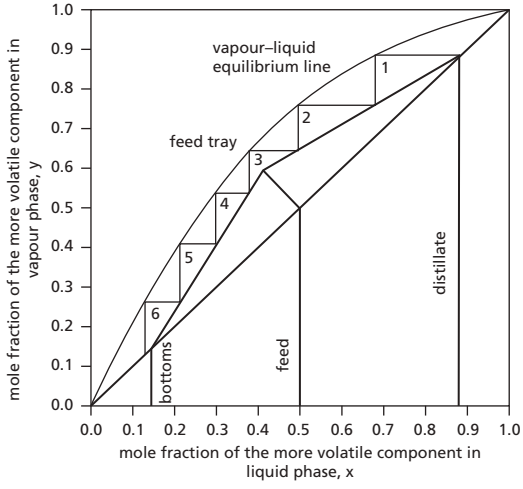



**Fig. 28**

**mean** A representative value of a set of values. The arithmetic mean or average value of a number of values is obtained by summing the values in the set and dividing by the number of values, n. The *geometric mean is obtained by the $1/n^{th}$ power of the product of the values. The harmonic mean is obtained from:

$$H = \frac{n}{\frac{1}{x_1} + \frac{1}{x_2} + \ldots \frac{1}{x_n}}$$

**mean free path** The mean distance between successive elastic collisions of molecules in a gas. According to the *kinetic theory of gases, the mean free path is inversely proportional to the pressure of the gas.

**mean hydraulic depth** The ratio of the flow area to the *wetted perimeter in an open channel used to transport a liquid. It is used in the *Manning formula to determine the *Chézy coefficient needed for determining the rate of flow.

**mean hydraulic diameter** A parameter used in the calculation of fluids flowing in pipes, enclosed channels, and ducts in which the cross-sectional area is not necessarily circular. It is expressed as the ratio of four times the flow area to the *wetted perimeter.

**mean velocity** The average velocity of a fluid in a pipe based on all the local velocities in the cross section. A simple form of calculation is based on the total flow divided by the cross-sectional area. For laminar flow in circular pipes, the mean or average velocity is half the maximum velocity, which occurs along the axis.

**mechanical engineering** A branch of engineering that is concerned with the study and production of mechanical devices, such as machines, tools, and vehicles that are capable of carrying out specific tasks.

**mechanics** The study of the behaviour of bodies under the action of forces. *Statics is the study of forces but without a change in momentum, whereas the study of dynamics concerns changes in momentum. The study of *kinematics deals with the motion of bodies without reference to the forces that affect the motion. Newtonian mechanics is concerned with the bodies in the solid state, whereas *fluid mechanics is concerned with the study of forces on fluids.



**mechanism 1.** A description of the steps that are involved when a chemical reaction takes place. It includes the reactants and describes the steps that result in products as well as any intermediates. **2.** The workings of a mechanical device.

**median** A type of statistical average equal to or exceeded by half the values in a statistical distribution. The medium has the advantage that it is not influenced by extreme values and can be calculated from incomplete data. However, it cannot be used in any other form of mathematical processing. It is useful in quantifying data such as the statistical distribution of particle sizes.

**medium** The aqueous environment containing a dissolved substrate and all the other necessary nutrients in which microorganisms are cultured such as in the process of fermentation. All microorganims require water and a source of carbon, nitrogen, minerals, salts, trace elements, and vitamins. Oxygen is also required for some types of microorganisms. A *defined medium consists of pure compounds in which the composition and concentration of all the chemicals is known. Common media used to culture microorganims as colonies on petri dishes include agar and gelatine.

**mega-** (Symbol M) A prefix used to denote a million, for example one megajoule (1 MJ) is equal to a million joules.

**melt crystallization** A crystallization process used to separate components of a liquid mixture by cooling until a particular component is crystallized as a solid from the liquid phase within a *crystallizer. It involves either a gradual deposition of a crystalline layer on

a chilled surface of a flowing or static melt, or the fast generation of discrete crystals dispersed in the crystallizer.

**melting point** The temperature at which a substance changes state from a solid to a liquid. The transition occurs at a constant temperature and requires the absorption of heat known as the *latent heat of fusion. The melting point of ice at standard atmospheric pressure is 0°C. The melting point temperature is influenced by pressure.

**membrane distillation** A form of distillation process in which a substance is distilled by way of a temperature difference across a *semi-permeable membrane. The pores of the membrane are filled with the substance being distilled, and it is bounded by two liquid phases. *Compare* PERVAPORATION.

**membrane filtration** A form of separation process in which particles are separated from a fluid using a semi-permeable polymeric membrane in which the pore size and construction of membrane permits certain particle types and sizes to pass and retains others. Examples of membrane processes include *dialysis, *microfiltration, *reverse osmosis, and *ultrafiltration.

**membrane permeation flux** The volume of fluid that flows through a *semi-permeable membrane per unit area per unit time. For vapours and gases, the flow is dependent on temperature and pressure. The SI units are $m^3\ m^{-2}\ s^{-1}$.

**membrane separation** A separation process that involves the use of a *semi-permeable membrane that permits the diffusion of one or more selective components to pass. The components able to pass through the membrane are known as the *permeate, while the components unable to pass are known as the *retentate. The membrane is highly porous and the size of the pores can be controlled during its manufacture using an organic polymer evaporating solvent. For example, the pore size selectivity can be used to control the separation of nitrogen molecules from air. The membranes are manufactured as sheets or as hollow fibres and packed into bundles called **modules**.

**Mendeleev, Dmitri Ivanovich** (1834–1907) A Russian chemist noted for the formulation of the periodic table of elements, which was published in 1869. He was appointed professor of chemistry at St Petersburg in 1866.

**meniscus** The curved free surface of a liquid that is separated from a gas in a capillary tube. It can be concave or convex, and is the result of *surface tension.

**Merox process** A catalytic process used in petroleum refineries to remove mercaptans from LPG, propane, butane, naphtha, kerosene, and *jet fuel by oxidation to form hydrocarbon disulphides. An abbreviation of **mer**captan **oxi**dation, the process uses an aqueous solution of sodium hydroxide and a water-soluble catalyst to remove the foul-smelling mercaptans.

**mesh** A way of designating the number of openings in a screen or sieve per linear inch. A mesh of ten has ten openings per inch (100 per square inch). A standard wire size is used so that the area of opening is standardized. The screen or sieve is used to separate solid particles of a particular size.

**MESH equations** A set of equations used for calculating the material, energy, and thermodynamic profiles within a distillation column. They combine material balances, equilibrium conditions, summation conditions, and heat balances, which are required to

be solved simultaneously. Due to the complexity of the computations, computer simulation software uses algorithms based on *Newton-Raphson methods to converge onto solutions. Once the calculations have been solved rigorously for one stage, the next stage is computed. When the traverse of the entire column is completed, a comparison is made of the computed and assumed overall material balance. Another trial is used where there is an unacceptable difference.

**metabolism** The biochemical processes that take place within a living organism and result in the breakdown of large or complex organic molecules into smaller and more simple molecules (catabolism). Metabolism is also accompanied by the release of energy, or the building up of large and complex molecules from small and simple molecules (anabolism), together with the storage of energy. Metabolic processes are usually regulated by enzymes.

**metal** One of a number of chemical elements such as nickel, iron, and copper that are characterized as being lustrous ductile solids at room temperature. They form basic oxides, form positive ions, and are good conductors of heat and electricity. An *alloy, such as steel, contains one or more of these chemical elements.

**metal fatigue** A cumulative effect of repeated applications of applied stress culminating in the failure of a metal. The applied stress is applied on a cyclic basis and does not exceed the ultimate tensile strength. The number of cycles that lead to failure is dependent on factors such as the extent of the applied stress and strain as well as temperature and corrosion.



**metallic bond** A covalent bond between atoms in metals and alloys, in which the valence electrons are free to move through the crystal lattice structure.

**metalline** Resembling or relating to metals.

**metallography** A branch of metallurgy that is concerned with the composition and structures of metals and alloys.

**metalloid** A non-metallic element such as silicon that possesses some of the properties of a *metal.

**metallurgy** The study of the metals. It includes the processes of extraction, refining, alloying, and fabrication of metals as well the study of their properties and structure.

**metal spraying** A process that involves spraying one metal onto another in the molten state.

**metastable** A form of temporary or indefinite stability of chemical and physical equilibria. Metastable phases of matter include the melting of solids, freezing of liquids, condensing of vapours, sublimation of solids, super-cooling and super-heating of liquids. Pure liquids can remain in the liquid state below their freezing point until initiated to crystallize by either applying vibration or seeding.

**metering** The addition of a small quantity of a fluid or solid particles at a constant rate to a process stream used for accurate determination of flow. Positive displacement metering pumps are generally used for dosing or the dispensing of fluids. They operate by trapping a fixed volume of fluid and moving this fluid via gears, pistons, diaphragms, vanes, or other devices such as *peristaltic pumps. They are not particularly sensitive to changes

in discharge and suction conditions, and permit flow regulation by adjusting speed and displacement.

**methanation** A petrochemical process in which carbon monoxide and carbon dioxide are converted to methane using hydrogen gas:

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The reactions are exothermic and carried out in a fixed-bed nickel-based catalytic reactor at a temperature between 370°C and 430°C.

**methane clathrate (methane hydrate)** A solid ice substance in which methane is entrapped within the crystal structure of water. It occurs naturally at the bottom of the ocean floor and in deep sedimentary structures at low ambient temperature and high pressure. It is responsible for oil and gas sub-sea pipeline blockages. Its formation is controlled by the use of additives such as methanol. It is also known as gas hydrate, methane ice, and fire ice.

**method** A defined or systematic way of doing something such as carrying out a chemical analysis.

**metre** (Symbol m) The base *SI unit of length, it is precisely defined as length of the path of light in vacuum during a time interval of 1/2.99 792 458 x $10^8$ second. It was defined by the General Conference on Weights and Measures in 1983 and replaces earlier definitions.



**metric system** A decimal system of units based on the metre, gram, and second for length, mass, and time, respectively. It was originally devised by the French Academy in 1791 that included French mathematicians J. L. *Lagrange and P. S. *Laplace. The system replaced a base twelve system. The SI system is used widely in scientific work and is based on the metric system and uses the kilogram as the SI unit of mass.

**metrology** The study of weights and measures, and the units of measurement.

**Michaelis–Menten kinetics** A general two-parameter enzyme reaction model in which the reaction velocity, $V$, is given by:

$$V = \frac{V_{\max} S}{K_M + S}$$

where $S$ is the substrate concentration, $V_{max}$ is the maximum reaction velocity, and $K_M$ is the Michaelis constant. For simple enzyme reactions, the two parameters, $V$ and $K_M$, can be readily obtained from experimental data by linearizing the equation in a double reciprocal plot of 1/V against 1/S such that the intercept on the y-axis is $1/V_{max}$ and the slope is $K_M/V_{max}$. It is named after German chemist Leonor Michaelis (1875–1949) and Canadian scientist Maud Menten (1879–1960) who proposed the reaction in 1913.

**MIChemE** Post-nominal letters used after someone's name to indicate that they are a *chartered chemical engineer and a member of the *Institution of Chemical Engineers.

**micro-** (Symbol μ) A prefix used to denote $10^{-6}$ of something; for example, one micrometre is equal to $10^{-6}$ m.

**microfiltration** A *membrane filtration separation process used to separate fine particles and molecules. The membrane consists of a polymeric microporous material with a pore size of between 0.1 and 10 micrometres. The filtration separation uses an applied pressure across the membrane as the driving force. It is typically used for the separation of proteins from yeast cells following the process of fermentation, clarification of liquid beverages, separating cream from whey in milk, and the sterilization of liquids by filtering out microorganisms.

**micron** The former name for the unit of length equal to $10^{-6}$ m and is now called the **micrometre**.

**microorganism** A microscopic living organism that is too small to be seen with the naked eye. Microorganisms are simple life forms and usually unicellular. Commonly used microorganisms in industrial processes include bacteria, fungi, and protozoa, and are noted for their rapid rate of reproduction and ability to utilize waste products as substrates such as agricultural waste. They can be cultivated in batch and continuous processes, and on a large scale with high yields. Certain microorganisms can be genetically manipulated through *recombinant DNA technology and other techniques to produce bioproducts such as viral antigens without the need for alternative hazardous processes. They usually produce non-toxic waste products.

**microwave** *Electromagnetic radiation that has a wavelength between $10^{-3}$ m and 0.03 m. Microwaves are used in the drying of materials as well as heating and domestic cooking of foods.



**Midgley, Thomas** (1889–1944) An American mechanical engineer who developed the petrol anti-knock additive tetraethyl lead and contributed to the production of Freon refrigerants. The son of an inventor, he qualified with a degree in mechanical engineering in 1911. While working for General Motors, he developed the lead additive for which he won an award from the American Chemical Society in recognition of his achievements. However, his health suffered from the effects of working with lead. He later worked on the development of a new type of chemically inert refrigerant to replace earlier refrigerants that were toxic, flammable, and explosive such as ammonia. Dichlorofluoromethane was the first CFC to be developed called Freon and others followed for which he received various awards of recognition. He was president of the American Chemical Society in 1944.

**milli-** (Symbol m) A prefix used to denote $10^{-3}$ such as in millimetre (1 mm = $10^{-3}$ m) or millibar (1 mbar = $10^{-3}$ bar). Standard atmospheric pressure corresponds to 1,013 mbar.

**milling 1.** A mechanical process used to grind grain such as wheat into flour or meal. **2.** A mechanical operation involving cutting, shaping, finishing, or working products manufactured in a mill.

**mineral** A solid substance that occurs in nature characterized by having a definite chemical composition or being made up of several chemical compositions with a distinctive molecular structure. Most minerals are inorganic, although minerals such as coal are organic in origin. Ore is a mineral or aggregate that contains minerals that may be valuable and can be extracted, or contain undesired minerals called *gangue.

**mineral acid** A generic name for organic acids such as nitric, sulphuric, phosphoric, and hydrochloric acids.

**mineral dressing** A series of unit operations used in the mineral processing industries to prepare minerals and ores for extraction. These include crushing, grinding, particle size distribution, and various forms of separation such as flotation.

**mineral oil** A generic name for diesel fuels obtained from petrochemical feed stocks.

**minimal medium** A growth medium for microorganisms in which only the minimum number of nutrients is supplied for the growth of a particular microorganism. *See* MEDIUM.

**minimum reflux ratio** The smallest possible reflux ratio in the operation of a fractional distillation column that can produce top and bottom products of specified compositions. It corresponds to a distillation column with an infinite number of theoretical stages and is therefore a hypothetical quantity.

**mist flow** A type of two-phase gas–liquid flow in which a gas flows with a very high velocity carrying a fine dispersion of the liquid as droplets.

**mitigation** The act of reducing the severity of the consequence of an undesirable event.

**mitosis** The normal process of microbial cell division in which the paired chromosomes duplicate at the beginning of the process, and each of the daughter cells formed has pairs consisting of one original and one new and replicated chromosome. Microorganisms are used as biological catalysts in biotechnological processes such as fermentation.

**mixer 1.** A device used to intimately combine materials. There are various types, the choice of which is dependent on the application. A commonly used mixer consists of a rotating shaft upon which blades are attached. These are either flat or pitched at an angle to provide radial or axial mixing, or a combination of both. Other designs include *static mixers, which are ribbons of metal held within a pipe causing flowing liquids to alter their movement and mix. **2.** A unit operation used in flowsheets to represent process input streams that combine together to provide a single output. It may be a simple vessel with a stirrer. A mixer does not allow a chemical reaction to occur, nor change of phase to take place.

**mixer-settler** A device used in *solvent extraction processes. It consists of a vessel in which two immiscible liquids are dispersed within one another using a *mixer within one section or compartment, and another partitioned section where the two liquids are permitted sufficient time to separate into two layers. Their operation constitutes one theoretical stage. They are therefore often arranged in series and operate with *countercurrent flow.

**mixing** The intimate contact of two or more components and/or phases used to achieve a desired product quality. Mixing is also used to promote mass transfer or enhance the rate of a chemical reaction. *Blending is a type of mixing that involves particulates or powders. Mixing can involve dispersing one phase through another such as sparging gases through liquids, or the use of rotating agitators, impellors, and propellers. *Fluidized beds provide excellent mixing to enhance both heat and mass transfer in which a fluid, such as a gas, is driven up through a bed of particles, such as a catalyst.

**mixing rule** A way of calculating the combined effects of mixtures using pure component parameters. Mixing rules are used for calculating the effects of two or more components for viscosity and density, and used in thermodynamic models such as cubic equations of state.

**mixture** The combination of substances in a process without chemical reaction. It can involve more than one phase such as a solid and a liquid, or an emulsion of liquids. A homogenous mixture has a complete dispersion of components in a single phase, whereas a heterogeneous mixture has distinct phases. Air is a mixture of mainly oxygen and nitrogen.

**mmHg** A unit of pressure used in *manometers and *barometers in which mercury is used as the manometric fluid. *Standard atmospheric pressure (101 325 Pa) is equal to 760 mmHg. A pressure of 1 mmHg is equal to 133 322 Pa.

**MMSCFPD** An abbreviation for **m**illions of **s**tandard **c**ubic **f**eet **p**er **d**ay, which is a volumetric measure of gas flow.

**mode 1.** A type of statistical average. In a discrete set of data, it is a single value. If the data is continuous, the mode is the point of greatest clustering of occurrences. It is used when the most typical value is required. **2.** A type of operation of a controller used to control a process that can either be manual, automatic, or remote. In automatic mode, the controller calculates the output value as the difference between the set point and the measured *process variable. In manual mode, the process operator sets the output, while in remote control, the controller obtains the set point from another controller.

**model** A mathematical representation of a system or process using equations that predict its behaviour. See MATHEMATICAL MODEL.

**moderator** A material, usually graphite, used to slow down fast-moving neutrons in a nuclear reactor in order to allow them to strike fissile material such as uranium-235 and cause a controlled nuclear chain reaction. The rate of neutrons absorption is controlled by lowering the moderator into the reactor. Other moderators include water and *heavy water (deuterium oxide).

**Moh's scale of hardness** A decimal scale of scratch hardness for materials based on ten minerals arranged in order of hardness with 1 being the softest and 10 the most resistant. These are: 1 talc; 2 gypsum; 3 calcite; 4 fluorite; 5 apatite; 6 orthoclase; 7 quartz; 8 topaz; 9 corundum; and 10 diamond. The scale is linear between 1 to 9 although diamond is about ten times harder than corundum. There is a modification to this scale in which the first six minerals are the same, but continues with 7 pure silica glass; 8 quartz; 9 topaz; 10 garnet; 11 fused zircon; 12 corundum; 13 silicon carbide; 14 boron carbide; and 15 diamond. The scale was devised in 1812 by German mineralogist Friedrich Mohs (1773–1839), and is still used today.

**moisture** A liquid, usually in the form of water, that is dispersed through a gas or vapour, or in a solid contained within pores.

**moisture content** The amount of liquid, usually in the form of water, that is contained within a substance. The relationship is expressed either on a **dry basis** as the amount of water per unit mass of substance, or on a **wet basis** as the amount of water per unit mass of substance with water. Both are expressed as a percentage for which the relation between the two is:

$$x_d = \frac{x_w}{100 - x_w}$$

where $x_d$ is the moisture content on a dry basis and $x_w$ is the moisture content on a wet basis. The moisture content measured on a wet basis can exceed 100 per cent.

**molar 1.** The concentration of one mole of a substance dissolved in one litre of solvent. **2.** An amount of a substance. For example, the *molar latent heat is the quantity of heat absorbed or released when an amount of substance changes its physical phase at constant temperature and pressure per mole for which the SI units are J $mol^{-1}$.

**molar density** The number of moles of a substance within the volume occupied by the substance. The SI units are mol $m^{-3}$.

**molar flow rate** The rate of flow of material in a process stream expressed in terms of moles of material. The material is independent of phase and may be expressed as either one component, some, or all of the components in the process stream. The molar flow rate is often presented in a *stream table.

**molar flux** The rate of flow of a fluid expressed as the number of moles per unit area per unit time. It is used for describing the flow of materials in terms of the transport of molecules or particles rather than bulk mass. The SI units are mol $m^{-2}$ $s^{-1}$.

**molar heat capacity** (Symbol $c_m$) The amount of heat required to raise the temperature of one mole of a substance through 1 K. The SI units are J $mol^{-1}$ $K^{-1}$.

**molarity** A measure of the concentration of a substance expressed as moles of solute dissolved in one litre of solvent. For example, a 1 molar solution of sodium chloride contains 58.44 g of NaCl (since its molecular mass is 58.44 g) per litre of solution.

**molar latent heat** The amount of heat absorbed or released when a substance changes its physical phase at constant temperature and pressure per mole. The SI units are J $mol^{-1}$.

**molar volume** The volume occupied by one mole of a substance. It is equal to the product of the *specific volume and molar mass. The SI units are $m^3$ $mol^{-1}$.

**mole** (Symbol mol) The amount of a substance that has many elementary entities as there are atoms in 0.012 kilograms of the isotope carbon-12, and corresponds to the amount of material in *Avogadro's constant or $6.023 \times 10^{23}$. The number of moles of a particular species or element is its mass divided by its molar mass.

**mole balance** A calculation carried out to determine the total amount of substances that flow in and out of a process or system volume that is defined by a boundary. The mole balance does not take into consideration the physical form of the substances, only the number of moles of each substance.

**molecular diameter** A diameter of a molecule in which the molecule is assumed to be spherical. It is usually expressed in *angström unit ($10^{-10}$ m) and is multiplied by a factor depending on the element or compound.

**molecular diffusion** A form of mass transfer in which molecules of a component in a system involving two or more components are transported from a region of high concentration to a lower concentration by random molecular motion. It is independent of any convective forces that may be present. *See* MASS TRANSFER.

**molecular distillation** A vacuum distillation used to separate and purify substances that would otherwise be adversely affected by distillation at a higher temperature. Using pressures of below 0.01 torr, the gaseous phase no longer exerts a significant pressure on

the substance being evaporated. The rate of evaporation is therefore not dependent on the pressure since mass transport is governed by molecular dynamics and not fluid dynamics. Molecular distillation is used for the purification of oils, the manufacture of lubricants from petroleum, and the purification of vitamins.

**molecular formula** A way of expressing a chemical compound using symbols for the atoms. *Compare* EMPIRICAL FORMULA.

**molecularity** The number of molecules or ions involved in a chemical reaction. Unlike the order of a reaction, the molecularity must be a whole number. It cannot be fractional or zero.

**molecular modelling** A computational technique based on theoretical knowledge of molecules to understand their behaviour. The theoretical models typically involve treating atoms as individual particles but can also include the modelling of the electrons of each atom. The interactions of atoms are described as spring-like interactions. The Lennard-Jones potential is often used to describe *van der Waals' forces. While simple calculations can be performed by hand, the complexity of the interactions between molecules requires powerful computers to undertake the necessary number of computations. Molecular modelling is used in the design of pharmaceutical drugs, material science, enzyme catalysis, and other areas of study requiring the understanding of the behaviour of complex molecular systems.

**molecular sieve** An absorbent and inert material such as aluminosilicate or *zeolite used to remove moisture from gases or organic liquids. The absorbent has a high porosity of uniform size in the order of 4 to 5 angströms and adsorptivity at low water vapour pressures.

**molecular weight** *See* RELATIVE MOLECULAR MASS.

**molecule** The smallest part of an element or chemical compound that can exist separately and retain its properties. A molecule of helium consists of a single atom, whereas a molecule of water consists of an aggregation of oxygen and hydrogen held together by valence forces.

**mole fraction** The ratio of the number of moles of a component in a mixture to the total number of moles in the mixture expressed as a fraction. The symbol x is used for the mole fraction of liquids and y is used for vapour. The sum of the mole fractions in the liquid or in the gas phase is equal to unity.

**Mollier chart** The graphical representation of the thermodynamic properties of a pure substance with enthalpy on the y-axis and entropy on the x-axis. Other properties are also included on the chart (see Fig. 29), including pressure and temperature, and the critical point. They are used to visualize thermodynamic cycles such as in power plants, refrigeration, and air conditioning. It is named after German physicist Richard Mollier (1863–1935).

**moment of momentum** *See* ANGULAR MOMENTUM.

**momentum** The quantity given by the mass of a body multiplied by its velocity. Used in the study of dynamics, its quantity is conserved under certain circumstances, and its rate of change gives the amount of force acting on the body.

**momentum balance** A balance in which the sum of all the forces acting on a moving fluid in one direction is equal to the difference between the momentum leaving with the

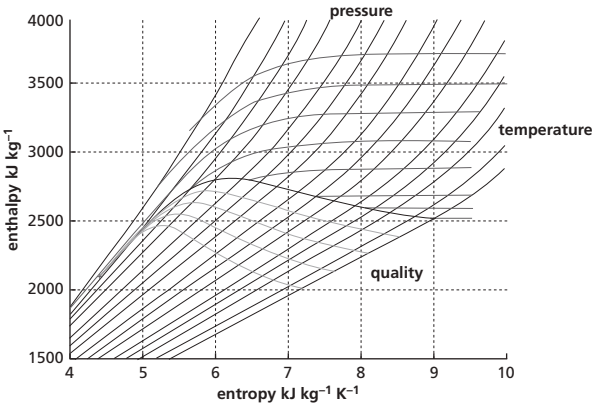



**Fig. 29**

fluid per unit time and that brought in per unit time by the fluid. The momentum flow rate of a fluid stream is the product of the mass flow rate and velocity.

**monatomic molecule** A molecule that consists of one atom such as argon or helium. It is distinct from diatomic molecules that consist of two atoms, or polyatomic molecules than comprise many atoms.



**Mond, Ludwig** (1838–1909) A German-born British chemist noted for the industrialization of several major chemical processes. After studying chemistry under Robert Bunsen (1811–99) at Heidelberg, he worked at various chemical works applying his knowledge to industry. Moving to Britain in 1862, he developed a process to remove sulphur from the waste products from the *Leblanc process. He joined a partnership with John *Brunner in 1873 and established a factory in Cheshire to manufacture soda by the new ammonia process invented by Ernest *Solvay (1838–1922). Mond also developed several other processes including the Mond process for purifying nickel.

**Mond nickel process** A process invented in 1889 by Ludwig *Mond (1838–1909) for extracting and purifying nickel. The process was developed after Mond noticed that nickel valves in a chemical manufacturing process became corroded by carbon monoxide. He discovered a new compound called nickel carbonyl $Ni(CO)_4$ and that pure nickel could be obtained by reaction with carbon monoxide at 50°C, and that the new compound decomposes on further heating to around 200°C.

**Monel** A type of corrosion-resistant nickel-copper alloy that combines high strength with high ductility. It is used for process equipment in salt and seawater applications.

**monochromatic** Meaning one colour, it is the property of some sources of electromagnetic radiation to emit waves of one frequency (or wavelength). A laser is an example.

**Monod, Jacques Lucien** (1910–76) A French biochemist noted for his work on the study of molecular biology. He studied first in Paris before working at Columbia University having gained a Rockerfeller Fellowship. He gained his PhD from the Sorbonne for his work on bacterial growth. He joined the French Resistance during the Second

World War after which he joined the Pasteur Institut in Paris, becoming its head in 1954 and director in 1971. He was professor of molecular biology at the College de France from 1967. The Monod equation describing the kinetics for molecular growth is named after him.

**Monod kinetics** An *unstructured model used to describe the correlation of substrate concentration with microbial growth kinetics. The model is based on enzymatic *Michaelis–Menten kinetics:

$$\mu_{(S)} = \mu_{MAX} \frac{S}{Ks + S}$$

where $\mu_{MAX}$ is the maximum specific growth rate of the microorganism, $S$ is the substrate concentration, and $Ks$ is the saturation constant and equivalent to the Michaelis–Menten constants. Ks varies with the type of substrate while the maximum specific growth rate is dependent on process conditions such as temperature, pH, and dissolved oxygen. When homogeneous conditions are achieved in the bioreactor and the microorganisms are freely suspended, a relatively low substrate is required to maintain maximal growth. At high substrate concentrations, substrates can inhibit growth for which the Monod kinetic model can be extended accordingly.

**monolayer** A single layer of molecules that are absorbed onto a support, surface, or fluid interface. The layer has a depth of one molecule. *See* LANGMUIR ADSORPTION ISOTHERM.



**monomer** A simple molecule or a compound that joins with others to form a larger molecule such as a dimer, trimer, or a polymer in a repeating form. An example is vinyl chloride monomer, which can be polymerized to form polyvinyl chloride (PVC), used for pipes and tubing.

**Mono pump** A type of *positive displacement pump that consists of a rotating helical worm contained within a casing or stator. A self-priming pump, it is particularly suitable for fluids with high viscosities and solid content such as wastewater, sludge, and slurries. It is widely used in the chemical, oil, and gas industries, as well as food, paper, mining, and mineral processing industries. It can produce high-delivery heads such that *pressure relief valves are required on the delivery line. They were first developed by Mono in 1935.

SEE WEB LINKS

- Official website of Mono Company.

**monosepsis** A biochemical process such as fermentation that involves the culture of a single type or strain of microorganism. A process bioreactor or fermenter is first fully sterilized before being inoculated with a small volume of the required living and viable microorganism. The process is then operated in a monoseptic state by controlling the ports into and out of the bioreactor by filtration and the use of septic seals to avoid microbial contamination by other microorganisms.

**Monte Carlo simulation** A computer-based iterative statistical method that uses sets of random values from a set of ranges or probability distributions to determine a quantitative outcome in complex process simulations. The outcome of the iterations is to build up a distribution of the possible outcomes of the simulation as a frequency distribution or in

graphical form. It was originally developed as a way of simulating random neutron diffusion in fissionable material by workers at the Los Alamos National Laboratory in the 1940s under the secret code name Monte Carlo, which is famous for its casino.

**Montejus** An egg-shaped closed tank used to transport a liquid or slurry by using compressed air. By applying a pressure into the surface of the liquid in the tank, the liquid is forced out by displacement through a dip leg that extends into the liquid. Since the tank does not involve complex and expensive pumps other than a supply of compressed air, it is useful for transporting corrosive liquids such as very concentrated acids. It is also known as an *acid egg on account of its shape and application.

**Moody plot, chart, diagram** A dimensionless representation of friction factor with Reynolds number for a fluid flowing in a pipe. Presented on log-log scales, the diagram includes laminar, transition, and turbulent flow regimes. It also includes the effects of pipe relative roughness as a dimensionless ratio of absolute roughness with internal pipe diameter. The plot was developed in 1942 by American engineer and professor of hydraulics at Princeton, Louis Ferry Moody (1880–1953).

**more volatile component** The component in a heterogeneous mixture that has the highest vapour pressure. It also has the lowest boiling point temperature. In the separation of a mixture of volatile liquids by distillation, the more volatile component rises to the top of the distillation column for separation while the least volatile component is retained at the bottom of the column.



**Morton, Frank** (1906–99) A British chemical engineer after whom a sports day is named. After gaining a degree in chemistry and a PhD in Manchester College of Science and Technology (later UMIST and then Manchester University), he joined the then newly formed department of chemical engineering at the University of Birmingham, before moving to take up head of the department of chemical engineering at the Manchester College of Science and Technology in 1956. He was president of the Institution of Chemical Engineers (1963–64). A very active sportsman, a sports day for UK chemical engineering students and a medal 'for excellence in chemical engineering education' are named after him.

**mothballing** A procedure used to close a process facility for an extended period of time. The facility is shut down and left in a preserved state such that it no longer operates, but may at some future time be successfully operated again if required. All process materials are removed and the process equipment cleaned and shut down thereby preserving the equipment and preventing the effects of corrosion. Mothballing is generally used when a process is no longer economic due to loss of demand for its product. Some nuclear facilities have been mothballed due to political reasons. It is named after mothballs that were once commonly used to deter moths from eating clothes thereby preserving them.

**mother liquor** A term used in crystallization that refers to a highly saturated solution of crystallizable solids from which crystals are nucleated. Once crystallization has taken place, the mother liquor is separated from the crystals by filtration or centrifugation and any residual mother liquor remaining is rapidly washed away to prevent the crystals from redissolving.

**motor** A machine that converts electrical or chemical energy into useful work. Pumps used to transport fluids are driven by electric motors, which convert electrical energy into mechanical energy. A simple form of electric motor uses electric current to power a set of electromagnets on a rotor in the magnetic field of a permanent magnet. An internal combustion engine is also a motor in which fuel is combusted with oxygen in the form of air and converted to useful mechanical energy.

**motor gasoline** *See* PETROLEUM.

**MOV** An abbreviation for **m**otor-**o**perated **v**alve. *See* VALVE.

**MSDS** *See* MATERIAL SAFETY DATA SHEET.

**MTG** An abbreviation for any process used for the conversion of **m**ethanol **t**o **g**asoline.

**MUF** An abbreviation for **m**aterial **u**naccounted **f**or. Used in the accountancy of nuclear material during reprocessing, it is the difference between the actual *inventory and expected amount of nuclear material.

**muffle furnace** A type of electrically heated laboratory furnace used for drying substances or carrying out high-temperature reactions using controlled atmospheres such as the pyrolysis of organic materials. The furnace is insulated and typically operates at temperatures up to 1,200°C.



**Müller–Kühne process** A process used to produce sulphuric acid from calcium sulphate. It uses calcium sulphide to produce lime (CaO) and sulphur dioxide in the so-called **Müller–Kühne reaction**, which takes place in a kiln operated at 1,150°C:

$$CaS + 3CaSO_4 \rightarrow 4CaO + 4SO_2$$

It is named after German chemist inventors W. S. Müller and Hans Kühne (1880–1969) who developed the process in the First World War (1914–18) when Germany was unable to obtain imported supplies of iron pyrites used for making sulphuric acid.

**multicomponent** A mixture having more than two components. The components in a process stream or item of plant equipment may be of the same phase, such as all being gases. *Crude oil is an example of a multicomponent mixture.

**multicomponent distillation** The separation of mixtures containing more than two components in significant amounts. If all of the components are present in small amounts except for two, the mixture can be treated as a binary and the same design principles apply as for binary. Complexity arises from the number of components present. For a given pressure and a particular component composition in the liquid phase, there no longer exists a unique vapour composition and temperature. These depend on the amount and type of the other components present. For hydrocarbons, *K-factors can be used. It is also possible to use vapour pressure data for ideal systems. Calculation methods often depend essentially on an assumed temperature profile that can be used to link vapour and liquid phase compositions for a given column pressure. Checks are made to ensure that the sum of the mole fractions in the liquid and vapour phases are equal unity. The process is repeated until the differences in compositions or flows at product take-off or at the feed point are below an acceptable figure. This assumes equimolar flows in any section.

Together with knowledge of feed condition and reflux ratio, the flow in the column profile can be calculated. Short-cut methods are available for preliminary investigations. The usual ones are the methods of *Fenske, *Underwood, *Erbar–Maddox, and *Smith–Brinkley. Two of the earliest rigorous methods were developed by *Lewis–Matheson and *Thiele–Geddes.

To perform multicomponent distillation calculations requires the introduction of the concept of *key components. These are the components between which the split between components is required and must be present in appreciable amounts in the feed, and effectively all of one will appear in the distillate (light key) and all of the other in the bottoms (heavy key). More correctly, the light key is the lightest component in the bottoms whose composition is to be specified. Some simplified calculations assume that all LLK (lighter than light key) components are absent from the bottoms and all HHK (heavier than heavy key) from the distillate. The key components effectively unlock the problem.

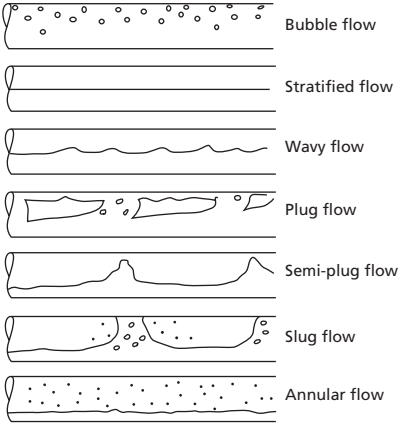
**multipass** The flow of material or energy through a system on more than one occasion. Multipass operations are used to improve process efficiencies. **A multipass heat exchanger** is a heat exchanger device in which one or both fluids pass more than once. They are used when the length of tube for heat transfer is too great to make a single pass operation practical. The heat transfer medium passes through either the *shell side or *tube side transferring heat, and is then returned back for further heat exchange. The temperature profiles are more complex than for single pass operations since some parts of the equipment will be cocurrent and other parts will be countercurrent. For the number of tube passes used, correction factor charts are used to adjust the log mean temperature difference calculations.



**multiphase** Having more than one phase. Material in a process stream or plant equipment may be in combinations of solid, liquid, and gas or vapour phases, including liquid-liquid. It is not dependent on the number of components present. A single component may have more than one phase present such as liquid and its vapour flowing through a pipeline in the form of bubbles (see Fig. 30 for examples of horizontal and vertical pipe flow). The majority of industrial chemical processes are concerned with multiphase flow systems such as power generation, refrigeration, and distillation, and depend on multiphase evaporation and condensation cycles. Desalination, steel-making, paper manufacturing, and food processing all contain critical steps that depend on the nature of multiphase behaviour.

**multiple effect** A number of process units, such as evaporators, operated in series to perform a particular duty. In the case of multiple-effect evaporators, each successive stage has a greater vacuum and operates at correspondingly lower temperature. This enables the heat in the vapour leaving each successive effect to be used to heat the next. There are several arrangements that are commonly used, including feed forward in which the product and vapour both move on to subsequent effects. In backward feed operations, the vapour feeds in the reverse direction starting in the last effect. This requires pumping to overcome the higher pressures. The heating of the feed in the last effect, which has the lowest temperature, requires a lower temperature difference for evaporation. In parallel feed operation, the vapour feeds from one effect to another while fresh feed is fed to each effect independently.

**multistage 1.** A process that involves more than one step. The flow from one stage forms the feed to the next. *See* MULTIPLE EFFECT. **2.** Process equipment such as pumps or compressors in which the flow of material from one stage feeds into the next. It is used to generate high pressure. A multistage compressor may operate with the stages on a common rotating shaft.



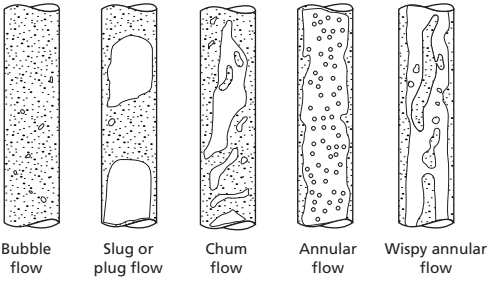




**Fig. 30 Multiphase flow**

**multivariable process control** *See* STATISTICAL PROCESS CONTROL.

**Murphree plate efficiency** A measure of the closeness to equilibrium on a plate or stage within a fractional distillation column. The vapour and liquid on an ideal stage are in equilibrium. However, in practice, this may not be the case. The Murphree plate efficiency is therefore expressed as the ratio of the increase in mole fraction of vapour of a volatile component passing through a plate in a column to the same increase when the vapour is in equilibrium. In effect, more stages are therefore required to bring about a desired separation. For a binary distillation, it is presented as:

$$\eta = \frac{y_n - y_{n-1}}{y^* - y_{n-1}}$$

where the subscripts $n$ and $n–1$ refer to the outlet and inlet vapour streams to a stage, and $y^*$ is the equilibrium vapour concentration. It was proposed in 1925 by Eger V. Murphree (1892–1962).

**muster area** A designated location where process plant personnel will gather in the event of an emergency. The muster area is required to be clearly defined and located with direct access by all personnel. On offshore installations, the muster area has direct access to survival craft and other life-saving equipment. The area is of a sufficient size to enable all gathered personnel to don *personal protective equipment.

# N

**nano-** (Symbol n) A prefix used to denote a scale of $10^{-9}$. For example, a distance of $10^{-9}$ m or one nanometre (nm) is typically the scale used in the study of molecular structures of macromolecules.

**nanomaterials** A material in which one, two, or three external dimensions range in size from 1 to 100 nm. Nano-sized objects can be classified as **nanoplates** in which one external dimension is at the nanoscale; **nanofibres,** which have two external dimensions at the nanoscale; and **nanoparticles,** which have all three external dimensions at the nanoscale. A **nanotube** is a hollow nanofibre while a **nanorod** is a solid **nanofibre**.

**nanotechnology** The study of materials of the nanometre scale ranging from 1 to 100 nm. Nanotechnology involves the creation and/or manipulation of *nanomaterials, either by scaling up from single groups of atoms, or by refining or reducing bulk materials.

**naphtha** A hydrocarbon distillate mixture obtained from the processing of crude oil in a petroleum refinery. It has a boiling point range of between 150°C to 180°C. Naphtha is used as the feedstock to produce aromatics, by reforming and extracting ethylene and light gases using high-temperature catalytic cracking.

**naphthalene** A white crystalline solid with a melting point of 80.5°C and boiling point of 218°C, once used as mothballs and widely used as the starting material for plasticers, lubricants, resins, and dyes. It was once produced from coal tar as a *by-product of coke production for the steel industry and is now produced as a by-product from petroleum refining as a more pure product. Naphthalene is produced by the process of **hydrodealkylation** from catalytic reformer bottoms or from recycled materials from cracking operations in the presence of hydrogen using chromium and aluminium oxide catalysts at high temperature.

**Natta, Giulio (1903–79)** An Italian chemical engineer noted for his work on polymerization and the development of commercially important polymerization processes. After graduating from the Polytechnic of Milan, he began his career with the study of solids using X-rays and electron diffraction, which he extended to catalysts using the same methods. He was awarded the Nobel Prize in Chemistry in 1963, together with the German chemist Karl Waldemar *Ziegler (1898–1973).

**natural convection** A process by which thermal energy as heat is transported unassisted within a fluid by the movement of the fluid itself. The motion of the fluid is caused by natural means such as the buoyancy effect that manifests itself as the rise of warmer fluid and the fall of the cooler fluid. In contrast, *forced convection is the transport of heat within a fluid by external means such as a pump or a fan.

**natural gas** An odourless and flammable gas consisting largely of methane. It is found in its natural state in particular geologic formations as a product of the decomposition of

organic matter. Natural gas is used as a fuel for domestic heating. Mercaptans and other *stenching agents are added to enable consumers to identify the presence of the gas in the event of leakage.

**natural logarithm** A *logarithm that is to the base e (e = 2.718). It is abbreviated to ln or $\log_e$. All logarithmic functions are the inverse of a power function.

**Navier, Claude-Louis** (1785–1836) A French engineer and physicist who studied at the École Polytechnique and then continued his studies at the École Nationale des Ponts et Chaussées (1804–06). He was admitted to the French Academy of Science in 1824 and became professor at the École Nationale des Ponts et Chaussées in 1830 before taking the position of professor of calculus and mechanics at the École Polytechnique. He directed the construction of bridges at Choisy, Asnières, and Argenteuil, and is noted for his work in fluid mechanics for which the *Navier–Stokes equations are best known.

**Navier–Stokes equations** A set of mathematical expressions used to study the motion of fluids. They are expressed in terms of velocity gradients for a *Newtonian fluid with constant density and gradient. Using Cartesian or rectangular coordinates, the equations represent inertia of the left-hand side and body force, pressure, and viscous terms of the right-hand side:

$$\rho\left(\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=\rho g_x-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v_x}{\partial x^2}+\frac{\partial^2 v_x}{\partial y^2}+\frac{\partial^2 v_x}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial v_y}{\partial t}+v_x\frac{\partial v_y}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=\rho g_y-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v_y}{\partial x^2}+\frac{\partial^2 v_y}{\partial y^2}+\frac{\partial^2 v_y}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial v_z}{\partial t}+v_x\frac{\partial v_z}{\partial x}+v_y\frac{\partial v_y}{\partial y}+v_z\frac{\partial v_z}{\partial z}\right)=\rho g_z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}+\frac{\partial^2 v_z}{\partial z^2}\right)$$

The equations can also be written using cylindrical and spherical coordinates. The solutions to the equations are called velocity fields or flow fields. The equations were developed by Claude-Louis *Navier (1785–1836) in 1822, and developed further by George *Stokes (1819–1903), and find many applications including the study of the flow of fluids in pipes and over surfaces.

**nb** An abbreviation for ***n**ominal **b**ore used for specifying pipe and tube sizes.

**negative pressure** A pressure below atmospheric pressure expressed as a gauge pressure. At sea level using *standard atmospheric pressure, the lowest possible pressure is –101325 $Nm^{-2}$ or –760 mmHg. Negative pressures are used in processes where air is required to be drawn into the process as a way of preventing the release of potentially harmful substances from contaminating personnel or the environment. Fume cupboards operate with a negative pressure.

**Nelson–Farrar cost index** A method of determining the construction cost of a petroleum refinery or a process unit. It is used to compare operating costs over time and involves normalizing cost during that time span and includes changes in productivity costs such as labour and utilities, etc. The purchase cost at any particular time is based on the original cost at some earlier specified time multiplied by a ratio of cost indices for the present to the earlier time of interest. Established in 1926, the original index was given a value of 100 in

1946. The Nelson–Farrar cost index is published in the first issue of each month of *Oil and Gas Journal,* and not considered to be suitable for refineries and process units that are older than five years.

SEE WEB LINKS

- Official website of *Oil and Gas Journal* containing the Nelson–Farrar index.

**net positive suction head (NPSH)** The total head (or pressure) at the suction nozzle side of a centrifugal pump that is required to avoid the potentially destructive phenomenon of *cavitation. To avoid vapour bubble formation at the eye of the impeller, the pressure head must be greater than the head corresponding to the vapour pressure of the liquid. The **available net positive suction head** is a function of the particular system and layout of pipework, whereas the **required net positive suction head** is a function of the pump. The available net positive suction head is required to exceed the required net positive suction head for cavitation to be avoided. Details of the required NPSH for a particular pump are supplied by the pump manufacturer.

**neutral spirit** A commercially produced alcohol (ethanol) obtained through the process of *fermentation of any cereal such as maize and purified through distillation. It is usually produced continuously. It is used for the manufacture of vodka and gin.

**neutron scattering** An analytical technique used to examine the properties of materials at the atomic scale. It involves emitting neutrons from a radioactive source and directed into a substance being tested. The atomic nuclei of the substance are bombarded by neutrons. When a neutron collides with heavy nuclei of the substance, less energy is transferred from the neutron than if it hits light nuclei. The neutrons scattered back to the vicinity of the source are measured by a sensitive radiation counter. Neutron scattering is widely used in the study of materials in many fields of science and engineering such as pharmaceuticals, healthcare, nanotechnology, and IT.



**Newton, Sir Isaac** (1642–1727) An English scientist and politician who made a major contribution to the understanding of many aspects of science and engineering. Although not overly successful at school, he was taken away from school to work on his mother's farm. His uncle, however, noticed his talent in mathematics and had him sent back to school, and eventually on to Trinity College, Cambridge, of which he became Fellow in 1667. He became professor of physics two years later, was a Member of Parliament from 1689, and was Master of the Mint in 1699. He was president of the Royal Society from 1703 until his death. His most productive years were 1665–66, during which he produced a wealth of ideas. He discovered the binomial theorem and the beginnings of differential and integral calculus. He started research on light to show that sunlight was made up of the seven colours of the rainbow, and began ideas of gravity to account for the path of the moon. He proposed a law 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. He also established other laws such as *Newton's law of cooling.

**newton** (Symbol N) The *SI unit of force defined as the force that when applied to a mass of one kilogram, produces in that mass an acceleration of one metre per second per second.

**Newtonian fluid** A classification of fluids in which viscosity is independent of shear stress and time. It is named after Sir Isaac *Newton (1642–1727) who first proposed that an

applied shear stress, $\tau$, is proportional to the deformation of the fluid or velocity gradient (or shear rate), $\gamma$:

$$\mu = \frac{\tau}{\gamma}$$

Examples of Newtonian fluids include water, mercury, treacle, tar, mineral oils, glycerol, sucrose solutions, standard calibration oils (e.g. octane), milk, fruit juices, and honey. Fluids that do not fall into this classification are known as *non-Newtonian fluids.

**Newton number** *See* POWER NUMBER.

**Newton–Raphson** An iterative mathematical method used to find the solution to a mathematic function $y = f(x)$. It involves using an initial approximate value ($x_o$) of a root, and from the gradient of the function a better or improved approximation ($x_1$) can then be obtained using:

$$x_1 = x_o - \frac{f(x_o)}{f'(x_o)}$$

By using the new value, the method is then repeated in order to converge to a solution.

**Newton's law of cooling** An empirical law proposed by Sir Isaac *Newton (1642–1727) that states that for small ranges of temperature, the rate of loss of heat by a body is proportional to the mean difference of temperature between the body and its surroundings. It is valid only for considerable differences in temperature between the body and the surroundings where the heat loss is by forced convection or conduction.

**Newton's laws of motion** *See* LAWS OF MOTION.

**NGL** An abbreviation for **n**atural **g**as **l**iquids that consist predominantly of a mixture of liquefied ethane, propane, normal butane, isobutane, and pentane. With a high calorific value, they are used as petrochemical feedstocks, as domestic heating fuels, refinery blending, and for drying agricultural crops amongst other applications.

**Nichols plot** A type of frequency response diagram used for analysing the frequency response of a controlled system to a disturbance signal. It involves plotting the magnitude and phase-angle measurements with frequency as a parameter. It is similar to the *Nyquist plot and uses Cartesian coordinates in which the real and imaginary parts are plotted on the x and y axes.

**nitrification** The biological conversion of ammonia to nitrate ions by the action of bacteria. The bacteria *nitrosomonas* is able to convert ammonia to nitrate and *nitrobacter* bacteria converts nitrites to nitrates. Nitrification is an important natural part of the nitrogen cycle in soil.

**Nobel, Alfred Bernhard** (1833–96) A Swedish industrial chemist and inventor of dynamite. One of eight children to poor parents, he showed an early interest in explosives. His father was an inventor and having moved to St Petersburg made his fortune making explosives. Now that it was affordable, Alfred first received private tuition and studied chemistry before moving to Paris and then the US. The Nobel family produced armaments for the Crimean War (1853–56) but thereafter filed for bankruptcy. His brother Ludwig

improved the business, while Alfred improved his inventions, including dynamite, and ways in which it could be stabilized. He invented gelignite in 1875. An explosion at his factory in Stockholm killed, amongst others, his younger brother Emil. When his brother Ludwig died in 1888, a French newspaper carried an obituary of Alfred in error condemning him for his invention of dynamite. Having amassed a vast fortune in his lifetime, Alfred left most of his wealth in a trust to fund awards that are known as Nobel Prizes. It is thought that the erroneous obituary convinced him of the need to leave a better legacy after his death.

**noble gases** A group of six monatomic gaseous elements of group 18 in the *periodic table that comprise helium, neon, argon, krypton, xenon, and radon. They differ from other gases in that they have a full set of electrons in their outer shell making them very stable. They were once known as inert gases. However, some of the noble gases can take part in chemical reactions. Apart from helium, all are found in trace amounts in the atmosphere.

**noble metal** A metal that is generally non-reactive to acids and atmospheric oxidizing conditions. Examples include gold and platinum.

**no flux surface** A surface that reflects all the incident thermal radiation. There is no net interchange of radiant heat at the surface.

**nominal bore** *See* NOMINAL PIPE SIZE.

**nominal pipe size (NPS)** A defined set of standard pipe sizes used in the US. Pipes are specified with two non-dimensional numbers for diameter based on the Imperial units of inches, and a schedule describing wall thickness. From the NPS and *schedule number of a pipe, the pipe outside diameter and wall thickness can be obtained from reference tables. These are based on ASME standards. For example, NPS 14 Sch 40 has an outside diameter of 14 inches and a wall thickness of 0.437 inches. The European equivalent to NPS is DN (nominal diameter, *diamètre nominal*, or *Durchmesser nach Norm*), in which sizes are measured in millimetres. The term **nominal bore (nb)** is also used and is equivalent to NPS.

**nomograph (nomogram)** A two-dimensional diagram that uses a parallel coordinate system in which scaled vertical axes are used to evaluate the dependence of two properties such as temperature and pressure on a third property such as the *K-factor. The procedure is to draw a straight line between the left- and right-hand scales, intercepting with a third scale between them. They were once widely used for quick calculations before the advent of the calculator and computer. Nomography was invented in 1884 by French engineer Philbert Maurice d'Ocagne (1862–1938).

**non-combustibility** The property of a material to withstand high temperature without ignition.

**non-competitive inhibition** *See* ENZYME INHIBITION.

**non-destructive testing** A procedure in which materials are tested without damage or destruction. It is used to test and inspect process equipment such as vessels and pipelines for corrosion, damage, material deposits, and blockage without losing integrity. Methods typically used include magnetic particle inspection, ultrasound, X-rays, and gamma rays. It can also be used to determine the presence of fissile material within sealed process equipment and plant.

**non-ferrous metal** A metal or alloy that does not contain iron. Examples include copper, tin, lead, zinc, and aluminium, and their alloys such as brass, which is an alloy of copper and zinc.

**non-Fickian** *See* FICK'S FIRST LAW OF DIFFUSION.

**non-flammable** A substance that is not liable to ignite or burn when exposed to flame. *Compare* INFLAMMABLE.

**non-ideal flow** The flow of fluids that deviates from idealized flow. Idealized flow patterns in chemical reactors include plug flow and mixed flow. However, in reality, there may be appreciable deviation from ideality causing lower process performance. The causes of the deviation may be channelling, by-passing, or stagnant regions. Understanding non-ideal flow is important for *scale-up since the flow varies as the size of equipment increases. It is therefore difficult to predict how the flow changes as size increases. An important measure is the *residence time distribution.

**non-ideal mixture** A mixture of two or more substances in which there is an interaction between the molecules or atoms of the individual components. *Raoult's law applies to ideal mixtures in which the forces between the particles in the mixture are the same as those in the pure liquids. Mixtures that exhibit a positive deviation from Raoult's law have vapour pressures greater than that of an ideal mixture (see Fig. 31). This is caused by the intermolecular forces between the molecules being less than for the pure liquids. Heat is absorbed when the liquids mix. That is, the enthalpy change of mixing is endothermic. An example is ethanol and water, which has a maximum vapour pressure for a mixture containing 95.6 per cent of ethanol by mass. Mixtures that exhibit a negative deviation from Raoult's law have vapour pressures that are less than those of an ideal mixture. This is due to stronger intermolecular forces in the mixture than for the pure liquids. Heat is therefore evolved on mixing. An example is the mixing of nitric acid and water, which react to form hydroxonium ions and nitrate ions.



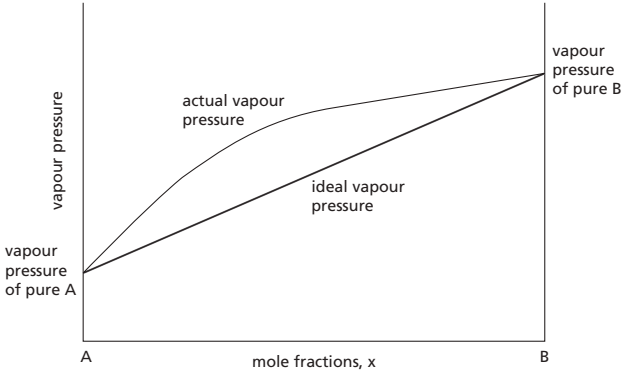



**Fig. 31 Non-ideal mixture (positive deviation)**

**non-Newtonian fluids** Fluids that do not exhibit Newtonian behaviour. That is, the rate of shear is not directly proportional to the shear stress over all values of shear stress.

Instead, the viscosity depends on shear stress and/or time. Non-Newtonian fluids are classified as being time-independent, time-dependent, and viscoelastic. They exhibit characteristics where the apparent viscosity either increases as the rate of shear increases, such as polymer melts, paper pulp, wall paper paste, printing inks, tomato purée, mustard, rubber solutions, protein concentrations, and are known as pseudoplastic, or decreases as the rate of shear increases. Examples of the latter are comparatively rare but include $TiO_2$ suspensions, cornflour/sugar suspensions, cement aggregates, starch solutions, and certain honeys.

With time-dependent fluids, the relation between shear stress and shear rate depends on the time and flow history of the fluid. They can be classified as either thixotropic or antithixotropic (or rheopectic). For thixotropic fluids, the shear stress will decrease with time for a fixed value of shear rate. A simple explanation is that as the liquid is sheared, the structure breaks down. If a cyclic experiment is carried out, a hysteresis loop is formed. Examples include greases, printing inks, jelly, paints, and drilling muds. For antithixotropic (rheopectic) fluids, the shear stress will increase with time for a fixed value of shear rate. Examples include clay suspensions and gypsum suspensions.

Viscoelastic fluids possess the properties of both viscosity and elasticity. Unlike purely viscous fluids where the flow is irreversible, viscoelastic fluids recover part of their deformation. Examples include polymeric solutions, partially hydrolyzed polymer melts such as polyacrylamide, thick soups, crème fraîche, ice cream, and some melted products such as cheese.

**non-polar compound** A chemical compound in which the molecule has no permanent dipole moment. Depending on the relative electro-negativities of the two atoms sharing electrons, there may be partial transfer of electron density from one atom to the other. When the electro-negativities are not equal, electrons are not shared equally and partial ionic charges develop. The greater the difference, the greater the ionic bond. Bonds that are partly ionic are known as polar covalent bonds. Non-polar covalent bonds have an equal share of the bond electrons and arise when the electro-negativities of the two atoms are equal. There are many non-polar substances. Some are completely non-polar while others are considered to be non-polar since they lack any significant polarity. Completely non-polar compounds include nitrogen, oxygen, and chlorine gases, diatomic molecules such $Br_2$, $I_2$, and $F_2$, acetylene, and carbon tetrachloride. They are all perfectly symmetrical in which the dipole moments of any polar bonds is completely annulled by equal and opposite dipole moments from the other bonds. Hydrocarbons such as propane, butane, pentane, hexane, cyclohexane, octane, as well as fats and oils are mostly non-polar.

**non-random two-liquid (NRTL)** A thermodynamic model used in phase equilibria calculations that correlates the activity coefficients of a component in a liquid mixture with its mole fraction. It is based on the hypothesis that the concentration around a molecule is different from the bulk concentration caused by the difference in interaction energy of the central molecule with the molecules of its own kind and that of the molecules of the other kind. The energy difference also introduces a non-randomness at the local molecular level. The model belongs to the local-composition type which includes the Wilson, *UNIQUAC, and *UNIFAC models.

**non-renewable energy** *See* RENEWABLE ENERGY.

**non-return valve** A type of valve used in a pipeline to ensure that the flow of a fluid is in one direction only and therefore prevent the inadvertent change of direction of flow. Also known as a *check valve or *one-way valve, there are various types and designs used for a wide variety of applications. They all consist of a mechanical mechanism that prevents the

reversing of flow such as using a spring-loaded ball that seats and blocks flow in the event of a reversal of pressure. Flexible diaphragms are also used which flex and open in one flow direction but seal in the other. Others consist of a hinged disc that opens freely with flow but seals shut when the flow is reversed.

**normal distribution** A statistical probability density function that is represented as a symmetrically bell-shaped graph in which data is symmetrical with a mean, μ, and standard deviation, σ. It has a near-zero start and rises in a smooth-bell shaped peak of probability in the centre and descends to near-zero at the end. It was also known as the **Gaussian distribution**, named after German mathematician Karl Friedrich Gauss (1777–1855) and was first derived by French mathematician Abraham de Moivre (1667–1754). The probability density function is:

$$\Pr(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

**normal operating conditions** The expected range of conditions used to operate a process or equipment and under which operating influences are usually stated.

**normal solution** A solution having a concentration of one gram equivalent of the solute per litre (1 $dm^3$). It is denoted by N. In comparison, the *molarity of a solution is the number of moles of the solution dissolved per litre of the solution and is denoted by M.

**no-slip boundary condition** A boundary condition assumption used in fluid mechanics that proposes that the velocity of the fluid layer in contact with a surface has the same velocity as the surface. *See* BOUNDARY SLIP.

**notch** A rectangular or triangular cut in a weir over which a liquid flows. They are used in liquid distributors such as within absorption columns and cooling towers.

**NOx** A general term used for nitrogen oxide gases that include nitric oxide (NO), and nitrogen dioxide ($NO_2$), and other oxides of nitrogen. These highly reactive gases have a major role in the formation of ozone. While many NOx gases are colourless and odourless, nitrogen dioxide has a reddish colour. They are formed during the combustion of fossil fuels such as coal as well as the combustion of fuels in motor vehicles.

**nozzle** A device used in spraying or atomizing fluids to form droplets with a high surface area. For example, within a spray dryer used to dry heat-labile liquids such as milk, the nozzle produces a fine spray enabling rapid liquid evaporation to take place.

**nozzle meter** A fluid flow measuring device that consists of a tapered nozzle arrangement within a pipeline. The device is designed to increase the velocity of the fluid with a corresponding decrease in pressure. A measurement of the difference between the upstream and nozzle pressure gives an indication of flow rate. The *coefficient of discharge for high flows is around 0.8 and is therefore better than an *orifice plate meter although it is comparatively more expensive to fabricate.

**NPSH** *See* NET POSITIVE SUCTION HEAD.

**NPV** An abbreviation for **n**et **p**resent **v**alue, representing the cost of a process or product calculated in the present day currency. The premise is that the investment of money today can earn interest and so has a greater present value than money received at some point in

the future. The NPV is therefore determined from the sum of the present values of each individual cash flow starting with the start of the process or product. The annual discounted cash flow is obtained for each year's rate of interest. The greater the NPV, the more economically attractive the process. A negative NPV indicates an economically unviable process. The NPV is dependent on the choice of interest rate used in the calculation.

**NRTL** *See* NON-RANDOM TWO-LIQUID.

**n.t.p.** Normal temperature and pressure of a gas and used for standard conditions of thermodynamic calculations and tabulations. It is defined as 20°C and 1 atmosphere. *Compare* s.t.p.

**NTU** *See* NUMBER OF TRANSFER UNITS.

**nuclear decommissioning** The shutdown and permanent removal from service of nuclear installations such as reactors and reprocessing plants at the end of their commercial life. There are several stages to taking such an installation permanently out of service. *Mothballing involves shutdown and washout to attain a low level of residual radioactivity. The plant may be re-opened at a later date. Removal of nuclear material, decontamination and sealing equipment, dismantling and removing process and ancillary equipment leaves the facility inoperable. The final stage involves removal of major plant such as the reactor, demolishing the buildings, and returning to a green-field site.

**nuclear energy** The energy associated with nuclear reactions. The amount of energy released is considerably greater than that associated with chemical reactions. For example, the amount of energy released from radium, which loses an alpha-particle to form radon, is $4.2 \times 10^{11}$ joules per mole of radium. The possibilities of harnessing nuclear energy changes has been known since the time when *Rutherford brought about the first transmutation of one element to another. This was accomplished by the action of alpha-particles on nitrogen gas to produce the isotope of oxygen-17.

**nuclear fission** A nuclear reaction or a radioactive decay process. In a nuclear reaction, which forms the basis of a nuclear reactor, the exothermic reaction involves the collision of a neutron in which an atomic nucleus is divided into smaller parts together with the release of energy. Nuclear fission was discovered in 1939 by Austrian-born Swedish physicist Lise Meitner (1878–1968), German physicist Otto Hahn (1879–1968), and German chemist Friedrich Wilhelm (Fritz) Strassmann (1902–80). They discovered that the nucleus of uranium-235 could absorb a neutron and then break into two roughly equal parts with mass numbers lying between 72 and 162 and with neutrons also being emitted. During this fission there was also a loss of mass which is converted into energy according to the equation $E = mc^2$ where m is the mass and c is the velocity of light.

**nuclear fuel** A substance capable of nuclear fission for the production of nuclear energy. It can refer to the substance itself or a mixture of substances and assembly of rods. By slowing down fast-moving neutrons that strike the nuclear fuel using a moderator such as graphite, other neutrons are emitted and form a chain reaction generating heat. The most common nuclear fuels are uranium-235 and plutonium-239. The nuclear reaction is contained within a *nuclear reactor.

**nuclear fuel reprocessing** A process developed to separate and recover fissionable plutonium from irradiated nuclear fuel. Originally developed to extract plutonium for nuclear weapons, nuclear reprocessing is used to recover plutonium and uranium for reuse

as fuel in commercial nuclear power stations. Spent uranium fuel contains both fissionable uranium-235 and plutonium-239, and has substantially higher fuel content than natural uranium. It is necessary to separate the uranium and plutonium from the neutron-absorbing fission products, followed by separation of the plutonium from the uranium, and can include enrichment of the uranium. The reprocessing involves a solvent extraction process and based on the fact that both uranium and plutonium nitrate form complexes with tri-butyl phosphate (TBP). The process involves chopping up the spent fuel, which is then charged to dissolvers containing nitric acid. The uranium and plutonium nitrates are extracted from the solution by a solution of TBP in kerosene. Other fission products are retained in the aqueous phase, and then concentrated by evaporation. The uranium and plutonium complexes are backwashed from the kerosene phase into the nitric acid solution. The plutonium is reduced from a valency of 4 to 3 with ferrous sulphate since the valent state of 3 does not form complexes with TBP and can therefore be separated from the uranium. The plutonium is then oxidized back to the 4 state.

There are various variations on this separation. The *purex solvent extraction process is currently used to reprocess spent nuclear fuel to separate plutonium, uranium, and fission products.

**nuclear fusion** *See* FUSION.

**nuclear meltdown** A term loosely used to describe the overheating of a nuclear reactor. A nuclear core melt occurs when the heat that is generated in a nuclear reactor is greater than the ability of the cooling system to remove it, resulting in the nuclear fuel reaching its melting point. A nuclear meltdown may be due to the loss or reduction in the rate of flow of coolant. *See* FUKUSHIMA DAIICHI.

**nuclear power (atomic power)** Electrical or motive power that is produced by a *nuclear reactor.

**nuclear power plant** A thermal power station used to generate electricity through the generation of heat from the controlled process of nuclear fission. The heat from the nuclear fission contained within a nuclear reactor is used to generate steam and converted to electricity using a turbine and alternator.

**nuclear reactor** A process in which nuclear energy is produced from a controlled nuclear fission reaction. The reaction takes place in the core and involves fissile materials known as nuclear fuel for which the common nuclear fuels are uranium-235 and plutonium-239. By slowing down fast-moving neutrons using a moderator such as graphite, the neutrons that strike the nuclear fuel results in the emission of other neutrons to form a chain reaction generating heat which is converted into electrical energy through steam turbines. The world's first commercial nuclear power station at Calder Hall in the UK came into operation in 1956. It consisted of four Magnox reactors that were originally capable of generating 60 MW of electrical and thermal power. Named after an abbreviation for the magnesium oxide non-oxidizing cladding of the unenriched (i.e. natural) uranium fuel rods, the reactors were designed as pressurized carbon dioxide-cooled, graphite-moderated reactors. The reactors used boron-steel control rods. The power station was closed in 2003.

There are nearly 500 nuclear reactors in operations around the world and the most widely used is the pressurized water reactor (PWR). These nuclear reactors use water pressurized to around 160 bar to dissipate heat to achieve a high temperature and avoid boiling. The heat is transferred to a secondary system in a steam generator.

**nuclear waste** *See* RADIOACTIVE WASTE.

**nucleon** A proton or a neutron in the nucleus of an atom. The **nucleon number** (*mass number) is the number of nucleons in the atomic nucleus of a nuclide.

**nucleus 1.** The central core of an atom that comprises neutrons and protons. It has a positive charge and is determined by the number of protons. The nucleus is surrounded by electrons of negative charge. Atoms are neutral so the number of electrons around the nucleus must equal the number of protons in the nucleus. The number of neutrons contribute to the atomic mass. It is possible for two or more atoms to exist possessing the same number of protons, the same number of electrons, and the same chemical properties, but different numbers of neutrons, and therefore they have different atomic mass. For example, chlorine-35 and chlorine-37 have the same number of protons (17) and electrons (17), but unequal numbers of neutrons (18 and 20). *See* ISOTOPE. **2.** The spherical part of a living cell that is bounded by a membrane and contains the chromosomes and other essential molecules that determine the growth of the living cell.

**nuclide** An atomic species in which all the atoms have the same atomic number and mass number, such as carbon-14. An isotope refers to a series of different atoms that have the same atomic number but different neutron numbers, such as uranium-235 and uranium-238.

**null hypothesis** Used in statistical probability theory to test the validity of statistical data, it assumes that events occur on a purely random basis.

**number of transfer units (NTU) 1.** A measure of the difficulty of the separation of two components in a liquid–liquid separation. In an equimolar counter diffusion process in which the mole fraction of the more volatile component in a mixture increases from $y_1$ to $y_2$, the NTU is determined from the integral:

$$NTU = \int_{y_1}^{y_2} \frac{dy}{y_i - y}$$

where $y_i$ is the mole fraction of the more volatile component at the interface. The number of transfer units is also used in the cooling tower calculations in which the calculation is based on the differential of the enthalpy of the water. **2.** A parameter used to quantify the performance of a heat exchanger expressed as the ratio of the product of heat transfer area, $A$, and heat transfer coefficient, $U$, to the minimum heat capacity rate, $mc_p$:

$$NTU = \frac{UA}{(mc_p)_{\min}}$$

**numerator** The top part of a mathematical fraction. For example, in the fraction ½, 1 is the numerator and 2 is the denominator. The numerator is the dividend.

**numerical integration** A mathematical procedure used to calculate the approximate value of an integral. It is often used when a function is known only as a set of variables for corresponding values of a variable and not as a general formula that can be integrated. *Simpson's rule and the *trapezium rule are examples of numerical integration. These are used to estimate the area under a curve and involve dividing the area into vertical columns of equal width with each column representing two values for x for which f(x) is known.

**Nusselt number** A dimensionless number, Nu, used in heat transfer calculations characterizing the relation between the convective heat transfer of the boundary layer of a fluid and its thermal conductivity:

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

where h is the surface heat transfer coefficient, d is the thickness of the fluid film, and k is the thermal conductivity. It is named after German engineer Ernst Kraft Wilhelm Nusselt (1882–1957). *Compare* BIOT NUMBER.

**Nyquist plot** A type of frequency response diagram used for analysing the behaviour of a controlled system to a disturbance signal particularly in terms of assessing the stability with feedback. It involves plotting the magnitude and phase angle on a chart with frequency as a parameter. Using polar coordinates, the gain of the transfer function is plotted on the radial coordinate with the phase angle plotted as the angular coordinate. It is named after Swedish engineer Harry Nyquist (1889–1976). *Compare* NICHOLS PLOT.

# O

**objective function** A mathematical equation used to determine the optimal solution to a mathematical problem. Used in *linear programming which consists of a set of *linear equations, the objective function may typically represent the economics of a chemical process. Linear programming is widely used for process optimization in which the objective function may be maximized to represent the greatest economic return, or minimized to reduce resource wastage.

**obligate anaerobe** A bacterium that requires no oxygen for reproduction. The presence of minute traces of oxygen are sufficient to inhibit or kill it. *See* FACULTATIVE ANAEROBE.

**occupational health** The management of personal safety. It deals with the exposure of harmful and hazardous materials, their effect on humans, and seeks ways of reducing risk by comprehensive risk assessments. Exposure can be reduced by containment, distance, reducing the time of exposure, and through the use of *personal protective equipment.

**octane number, rating** A number indicating the resistance of fuels to spontaneous ignition, known as knocking, in spark-ignition engines. The higher the octane number, the greater is the fuel's resistance to spontaneous ignition. The rating is derived from comparison between a fuel and a benchmark blend of iso-octane ($C_8H_{18}$) with normal heptane ($C_7H_{16}$). Higher-octane ratings are more suitable for higher-performance engines whose compression ratios are more likely to make the fuel detonate. *Compare* CETANE NUMBER.

**od** An abbreviation for **o**utside **d**iameter and used for specifying pipes, tubes, and some vessels of circular cross section.

**odourizing** The addition of a substance to another to give a distinctive and strong odour. Pungent-smelling substances such as diethylsulphide and mercaptans are added to odourless natural gas and LPG for the purposes of safety so that leakage can be readily detected. It is also known as *stenching.

**off-gas** A gas that is produced as a *by-product of a chemical or biochemical process, it is often treated before being discharged into the environment. The treatment of off-gases includes the use of filtering, washing columns, venturi washers, and wet filtering. For hot gases, combustion may be used together in pre- or post-filtering and dust retention.

**off-line analysis** The measurement technique that involves withdrawing a sample from the process for its determination. It is used in monitoring a process in which continuous measurement is either not possible or not required. For example, solid, liquid or gas samples can be taken and analyzed using various analytical techniques such as gas or liquid chromatography. These procedures require the discrete processing of samples and it may take many minutes to return a result. **In-line analysis**, on the other hand, involves immediate and direct sensing and reading of process parameters. This form of continuous

process monitoring has the advantage of eliminating errors caused by delays. Examples of in-line analysis probes include thermocouples, pressure gauges, pH probes, and dissolved oxygen probes.

**offset** Used in process control, it is the deviation from a controlled *set point for a process or system at steady state.

**off-sites** Part of a chemical process or petrochemical refinery that supports the actual process or refinery and includes tanks, utilities such as power and steam generation, waste effluent treatment, and flares, etc.

**oil** One of various liquid, viscid, unctuous, usually inflammable, chemically neutral substances that is lighter than and insoluble in water, but soluble in alcohol and ether and classified as non-volatile. Natural plant oils comprise terpenes and simple esters such as essential oils. Animal oils are glycerides of fatty acids. Mineral oils are mixtures of hydrocarbons. Oils have many uses and include fuels, lubricants, soap constituents, varnishes, etc., and are used as the feedstock for the production of many other products.

**oil and gas** Refers to the industry associated with the recovery of liquid and gaseous hydrocarbons from underground deposits as reservoirs found both onshore and offshore around the world. A collection of localized deposits is known as an oil field or gas field. When they are drilled, they are known as oil and gas wells. Oil is mainly used as fuel for transportation purposes, whereas gas is primarily used as fuel for domestic and industrial purposes, and for converting into other chemicals such as plastic. Oil is widely transported in ships. Gas is transported in underground, sub-sea, or overland pipelines covering large distances. Oil from offshore installations is also brought onshore by sub-sea pipelines. *See* FPSO.

**oil gasification** A general name for processes that convert liquid petroleum fractions into gaseous fuels such as through the *cracking of heaving petroleum fractions and reaction of *naphtha with steam in the presence of a *catalyst.

**oil refinery** An industrial process plant where *crude oil is converted into useful products such as naphtha, diesel fuel, kerosene, and LPG. Also known as a *petroleum refinery, the process involves the separation of the crude oil into fractions in the process of fractional distillation. By boiling the crude oil, the light or more volatile components with the lowest boiling point rise towards the top of the column, whereas the heavy fractions with the highest boiling points remain at the bottom. The heavy bottom fractions are then thermally cracked to form more useful light products. All the fractions are then processed further in other parts of the oil refinery, which may typically feature vacuum distillation used to distill the bottoms; *hydrotreating, which is used to remove sulphur from naphtha; *catalytic reforming; *fluid catalytic cracking; *hydrocracking; *visbreaking; *isomerization; *steam reforming; *alkylation; hydrodesulphurization; and the *Claus process used to convert hydrogen sulphide into sulphur, solvent dewaxing, and *water treatment.

**oil shale** An oil-bearing fine-grained carbonaceous sedimentary rock containing an organic matter called kerogen. It is generally uneconomic to extract oil from oil shale unless the cost of extraction falls below the cost of petroleum. A number of recovery methods, such as *fracking, are currently being pioneered in response to threats of declining oil reserves.

**Oldshue–Rushton column** A type of column used for *liquid–liquid extraction that has fitted agitators, horizontal rings with a central opening, and vertical *baffles attached

to the inside of the column wall. The rings divide the column into a series of mixing zones and the vertical baffles enhance mixing. In the centre of each mixing zone is a flat-bladed *Rushton turbine. All the turbines are mounted on a common shaft along the axis of the column. The light phase is fed into the bottom of the column and the heavy phase into the top. These are respectively removed from the top and bottom of the column once extraction is complete.

**olefins** A former name for the class of unsaturated hydrocarbons now known as *alkenes.

**oleum** A fuming liquid of disulphuric acid ($H_2S_2O_7$) produced during the *contact process and used in the sulphonation of organic compounds.

**Olin–Raschig process** *See* RASCHIG PROCESS.

**one-dimensional flow** A simple approach used to determine the flow of a fluid that has a single coordinate x and a velocity in that direction. The flow in a pipe or tube is considered to be one-dimensional.

**one-pot synthesis** A method of synthesizing organic compounds in a single vessel rather than using a series of vessels or stages.

**one-way valve** A type of valve that permits the flow of a fluid in one direction only with no opportunity of reverse flow. *See* CHECK VALVE.

**on/off control** A basic mode of control involving the opening and closing of a valve in response to a measured variable such as temperature. It is a type of *proportional control.

**OPEC** *See* ORGANIZATION OF THE PETROLEUM EXPORTING COUNTRIES.



**open channel** A conduit carrying a liquid with a *free surface. Open channels are used for transporting large volumes of water at low velocities. They are used to transport water from rivers to process plants. The rate of flow is dependent on the slope of the channel, surface roughness, and dimensions. The maximum rate of flow is achieved in an open channel with a trapezoidal cross section. *See* CHANNEL.

**open hearth process** An early method used for the manufacture of steel involving the heating together of scrap, pig iron, and hot metal in a refractory-lined shallow open furnace heated by the burning of *producer gas in air. This causes excess carbon and other impurities to be burnt out. The method was developed to overcome the very high temperatures that are required. Developed in the nineteenth century, it was gradually replaced during the twentieth century with basic oxygen and electric arc furnaces due to its comparatively slow operation.

**open loop control** The manual control of a process or system in which information about a controlled variable is not used to adjust any of the system inputs to compensate for variations in any of the measured process variables. There is therefore no automatic feedback used to adjust the process or system. The term is often used to indicate that uncontrolled process dynamics are being studied.

**open system** A process in which both material and energy are transferred across a defined system boundary. A *continuous process is an example of an open system. *Compare* CLOSED SYSTEM.

**operating conditions** The conditions of temperature and pressure to which a process or item of equipment is subjected. The *normal operating conditions are the expected range of operating conditions used to operate the process or equipment, and under which process operating influences are usually stated.

**operating line** A line used in the graphical determination of the number of theoretical plates or stages in a *multistage process such as distillation. The equation of the operating line is based on the mass balance of the more volatile component and represents the actual vapour–liquid relationship. This is in contrast to the actual equilibrium relationship between the components. *See* MCCABE–THIELE.

**operating manual, instructions** Written information used for the general operation of a process or item of process plant equipment. It includes details of the normal *operating conditions and procedures, start-up, shutdown, *emergency shutdown procedures, sampling, *maintenance, repair, and supervision.

**operator 1.** A trained person who has responsibility for carrying out the day-to-day operation of a process or plant. **2.** An industrial company that is a member of a joint venture and appointed to carry out all the activities and operations for a particular process plant, or for activities such as exploration and drilling for oil. **3.** A mathematical entity used to perform a specific operation such as $\int$ (the integral operator) or $\Delta$ (the differential operator).

**opex** An abbreviation for **op**erational **ex**penditure, it is the on-going cost for operating a process, business, or system. It includes the cost of materials, energy, maintenance, personnel, support services, and utilities. *Compare* CAPEX.

**optical density** The measure of the reduction in intensity of incident radiation that passes through an absorbent medium. It is largely replaced by absorbance and used to measure the density of materials and media such as the microbial cell concentration in a bioreactor. The optical density or absorbance is often directly correlated with *cell dry weight.

**optimization** A procedure or set of procedures used to find the best compromise or optimal solution to a problem between conflicting requirements. Solved mathematically, it can be used to maximize or minimize a mathematical functional within defined constraints. For example, it can be used to maximize the yield from a chemical reaction or the revenue generated from a process while minimizing the consumption of energy, production of a *by-product, or waste.

**optimum reflux ratio** The reflux ratio used in the operation of a distillation column that corresponds to the minimum cost that combines both operating and fixed costs.

**order of magnitude** A designation used to describe a difference between two numbers with one being ten times greater than that of the other.

**order of reaction** The power to which the concentration of a component in a chemical reaction is raised. It provides an indication of the mechanism of the reaction and is determined experimentally. Most reactions are usually first or second order. In the reaction $A + B \rightarrow products$ the rate may be related to the concentration of component A by $-r_A = k[A]^X$. If X = 1 then the reaction is first order with respect to A and k is the velocity or rate constant. If X = 2 then the reaction is second order with respect to A. If the rate is related to the concentration of component B, then the order of reaction with respect to B is Y. The

overall rate equation is $-r_A = k[A]^X[B]^Y$ and the overall order of the reaction is X+Y. The order of reaction can be fractional. If the rate of a reaction is independent of the concentration of a particular reactant, then the reaction is zero-order with respect to that reactant. The order of reaction cannot be deduced from a balanced chemical reaction equation.

**ordinate** The vertical or y-coordinate in a two-dimensional Cartesian coordinate system such as a *chart or graph. *Compare* ABSCISSA.

**ore** A naturally occurring mineral aggregate from which metal or other valuable constituents can be usefully extracted. Metals may be present in their native form such as gold but most are usually in the form of oxides, sulphides, sulphates, silicates, etc.

**ore dressing** Another name for *mineral dressing and involves the extraction of minerals from ores using crushing, grinding, particle size distribution, and various forms of separation such as flotation. *See* BENEFICIATION.

**ore flotation** A process used to extract potash from an ore known as sylvinite. The ore, which is a mix of sodium and potassium chloride, is crushed and treated using a cationic detergent or a fatty amine. Air is bubbled through a vessel known as a collector, in which, depending on the design, the bubbles attach to either the sodium or potassium chloride crystals, which float to the top and are separated.

**organic chemistry** A branch of chemistry concerned with all aspects of compounds of carbon.

**organic compound** A compound that contains carbon. However, there are some carbon-containing compounds that are inorganic such as carbides and carbonates as well as some oxides of carbon such as carbon monoxide and carbon dioxide, as well as graphite and diamond that are inorganic. The term organic is historical and dates from an age when it was believed that compounds had a connection with living organisms and could be synthesized through alchemy. Organic compounds include all living materials, polymers, rubbers, carbohydrates, fats and oils, vitamins, proteins, peptides, and nucleic acids.

**organic synthesis** A branch of chemical synthesis that is concerned with the formation and methodology of preparation of *organic compounds.

**Organization of the Petroleum Exporting Countries** (**OPEC**) An international intergovernmental organization of member countries that produce oil and gas, which regulates the supply of petroleum for the purpose of ensuring stabilization of world demand and use. It also aims to ensure a fair economic return to producers and for countries investing in the industry. OPEC was formed in 1960 by the five founding member countries of Iran, Iraq, Kuwait, Saudi Arabia, and Venezuela. Others have subsequently joined and the membership is currently twelve member countries. The headquarters is based in Vienna, Austria.

SEE WEB LINKS

- Official website of OPEC.

**orifice** A small opening through which a fluid passes.

**orifice plate meter** A device used to measure the flow rate of a fluid. It consists of a flat plate in which an orifice is drilled. The plate is fitted across the face of flow of a fluid in a pipe

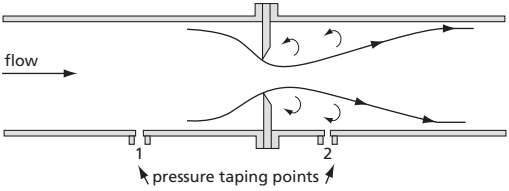



**Fig. 32**

between two flanges (see Fig. 32). The shape of the orifice is usually circular and concentrically aligned with the axis of the pipe although other designs are used and may be offset to below the centreline to enable the passage of fluids carrying suspended solids. The flow of fluid through the orifice results in an increase in velocity and corresponding decrease in pressure. A measurement of the pressure drop provides a measure of the rate of flow. This type of flow meter does not allow for the recovery of energy in the fluid for which there is a high permanent energy loss. This is reflected in the *coefficient of discharge of around 0.6 for high flows.

**Orsat analysis** A measurement of the oxygen, carbon dioxide, and carbon monoxide in a mixture of gases, usually from the exhaust of combustion processes such as boilers, furnaces, fired heaters, and combustion engines. Named after its inventor H. Orsat in 1873, it involves absorption of the gases onto materials contained in pipette tubes. The method has been largely replaced by other techniques.

**osmosis** The movement by diffusion of a fluid or solvent from a low to a more concentrated solution through a *semi-permeable membrane. The movement causes the concentrations on either side of the membrane to equalize. The **osmotic pressure** is the equilibrium pressure difference between the fluids of differing composition on either side of the membrane. It is a function of the solute concentration and is independent of the number of ions or molecules in solution. *Compare* REVERSE OSMOSIS.

**osmotic shock** A method used to extract intracellular materials such as proteins from the cells of yeast and bacteria that have been harvested from a bioreactor. It involves transferring water across the outer membrane of the living cells to build up the **osmotic pressure** inside them, resulting in their eventual disruption. Although it is less energy-intensive than the use of *bead mills for cell disruption, it is relatively inefficient and therefore largely confined to use in laboratory practices.

**Ostwald, Friedrich Wilhelm** (1853–1932) A Latvian-born German physical chemist noted for his work on chemical reactions and electrolytes. Having studied chemistry and physics in Riga, he was appointed professor of chemistry at Riga in 1881. Six years later he accepted the then only chair in physical chemistry in Germany at the University of Leipzig. He retired in 1906 having been appointed as the first German exchange professor to Harvard. He was awarded the Nobel Prize for Chemistry in 1909 for his work on catalysis, chemical equilibria, and reaction velocities.

**Ostwald-de Waele equation** A simplified power law relationship used to describe non-Newtonian fluids as $\tau = a\gamma^n$. Depending on the value of the power index, n, the fluid can be classified as being pseudoplastic ($n < 1$), Newtonian ($n = 1$), or dilatant ($n > 1$). It is named after German chemist Friedrich Wilhelm Ostwald (1853–1932) and British chemist Armand de Waele (1887–1966).

**Ostwald process** A catalytic process used for the production of nitric acid by the oxidation of ammonia with air. The first step involves mixing air as a supply of oxygen and ammonia over a catalyst at a temperature of 700°C:

$$4NH_3 + 5O_2 = 6H_2O + 4NO$$

The gases are then cooled in two towers and the oxidation is completed as:

$$2NO + O_2 = 2NO_2$$
$$3NO_2 + H_2O = 2HNO_3 + NO$$

The NO is in part reoxidized to form more nitric acid in successive repetitions of the process. It is named after German chemist Friedrich Wilhelm *Ostwald (1853–1932).

**Othmer, Donald Frederick** (1904–95) An American professor of chemical engineering who was responsible for cofounding and the editorship of the *Kirk–Othmer Encyclopedia of Chemical Technology*. A graduate of chemical engineering from the University of Nebraska in 1924, he gained his masters and PhD from the University of Michigan in 1927. He joined the department of chemical engineering at the Polytechnic Institute of Brooklyn and became its head in 1937. He became distinguished professor in 1961 and professor emeritus after his retirement, and continued teaching up until his death.

**OUR** *See* OXYGEN UPTAKE RATE.

**output** The quantity of material, energy, or power out of a system. *Compare* INPUT.

**output signal** The output from a controller of a controlled process. In a manually controlled process, the process operator sets the output, whereas in an automatically controlled process, the controller computes the output based on a calculation using the *error signal. The error is the difference between the set point and measured *process variable.

**overall heat transfer coefficient** (Symbol U) Used in heat transfer calculations, it is a measure of the overall transfer of heat through convective and conductive barriers. It is expressed as the *heat flux divided by the difference between the temperature in the bulk of two fluids. Since many types of heat transfer equipment use pipes and tubes, it is necessary to specify the area of heat transfer, where:

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{x}{k} + \frac{1}{h_o}}$$

where $h_i$ and $h_o$ are the inside and outside surface heat transfer coefficients, $x$ is the tube wall thickness, and $k$ is the thermal conductivity of the wall. If the outside area is specified, the overall heat transfer coefficient is based on the outside area and is written as $U_o$, while if the inside area is specified, then the coefficient is denoted by $U_i$. The SI units are W m$^{-2}$ K$^{-1}$.

**overall mass transfer coefficient** (Symbols $K_G$ and $K_L$) Used in mass transfer calculations, it is the mass flux of one fluid to another across an interface divided by the difference between the concentrations of the diffusing component in the bulk of the two fluids. The subscripts refer to the overall mass transfer coefficients in the gas and liquid phases, respectively. The overall mass transfer coefficient is defined as either the liquid- or gas-side since the interfacial composition cannot be determined. The bulk driving force is used.

That is, the composition in the gas phase is assumed to be in equilibrium with the bulk concentration in the liquid phase, or the liquid composition is in equilibrium with the composition of the bulk gas phase. The SI units are $m^2 s^{-1}$. The mass transfer coefficients are dependent on the geometry of the contacting equipment as well as fluid behaviour. Many correlations have been established to determine the coefficients. An example is the use of the *Sherwood number for describing the gas phase in terms of the *Reynolds number and *Schmidt number.

**overall plate efficiency** The ratio of the actual number of plates or trays to the theoretical number that are required in a *distillation column. The actual number of plates or trays that are required is greater than the theoretical number since vapour-liquid equilibrium is not always reached on each plate or tray. *See* MURPHREE PLATE EFFICIENCY.

**overburden** The material in mining processes that lies above the material that is of economic interest. An example is the rock that lies over an ore or a seam of coal. It is also known as waste or spoil. *Compare* TAILINGS.

**overflow** Used in liquid–liquid extraction and leaching processes, it is the flow of less dense material or particulate-carrying liquid, and moves from one stage to another. The underflow is the heavier phase and moves in the opposite direction in countercurrent extraction processes.

**overhead product** The product removed from the top of a distillation column as either liquid, distillate, or vapour. It is also known as the *top product.

**overpressure 1.** The pressure within a process vessel or some other equipment, which exceeds its expected or intended design pressure. **2.** A pulse of pressure that is above atmospheric pressure in the form of a blast wave as the result of an *explosion. The peak positive overpressure is the maximum overpressure that is generated in the explosion. The side-on and reflected overpressures are the pressures experienced by a body placed in the path of the blast wave that offers no obstruction and diffracts the wave, respectively.

**overshoot** A measure of how far a controlled signal responds in a system to a disturbance rising beyond the final steady-state value. The overshoot is the difference between the height of the first peak and the final steady-state value.

**oxidative coupling** A general name given to heterogeneous catalytic processes used for the direct conversion of natural gas, which comprises mainly methane, to ethane, ethylene, and other longer hydrocarbons that have a higher added value, with ethylene being the world's largest commodity chemical. For the production of ethylene, the gas phase reaction $2CH_4 + O_2 \rightarrow C_2H_4 + 2H_2O$ is very exothermic and is therefore carried out at a high temperature. The methane is converted first to ethane and then goes through a process of dehydrogenation to form ethylene.

**oxo process** A high-temperature, high-pressure process used for the production of aldehydes and alkenes from the catalytic reaction between alkanes, carbon monoxide, and hydrogen. The process was invented in Germany in 1938 by O. Roelen, although modified many times since, and is used in the production of fragrances and intermediates for the production of detergents. The name is derived from the German *oxierung* meaning ketonization. It is also known as **oxo synthesis** or **hydroformylation.**

**oxychlorination process** A process used to convert ethylene to ethylene dichloride (1,2-dichloromethane). It involves reacting ethylene, air, and hydrogen chloride in the presence of a catalyst of cupric chloride on potassium chloride. In the production of vinyl chloride monomer, the ethylene dichloride is cracked and the hydrogen chloride recycled.

**oxydesulphurization process 1.** A general name for processes that remove sulphur from coal using oxygen. These use pulverized coal that is heated to a high temperature and pressure in a *fluidized bed. **2.** A process used to remove sulphur from carbon dioxide or natural gas (methane).

**oxygen uptake rate (OUR)** The rate of change of the dissolved oxygen of a nutrient medium used for cultivating microbial cells within a *bioreactor.

**oxyhydrochlorination process** A process developed in the 1920s and used to convert methane into chloromethane that can then be converted in petroleum fuels. It involves mixing the methane with oxygen and hydrochloric acid in the presence of a catalyst:

$$2CH_4 + O_2 + 2HCl \rightarrow 2CH_3Cl + 2H_2O$$

The chloromethane is then converted to petroleum fuel using a *zeolite catalyst. Hydrogen chloride is produced and recycled back to the process.

**ozone** An unstable gas, $O_3$. It is formed naturally in the atmosphere and also by an electric discharge in oxygen. It has a bluish colour and distinctive odour and is used in the purification of air and water.

**ozonolysis** The chemical reaction of alkenes with *ozone to form a group of unstable compounds called ozonides. It was once used to investigate the structure of alkenes by hydrolyzing the ozonide to give aldehydes or ketones.