G

Galilei, Galileo (1564–1642) An Italian scientist noted for his experiments and studies on gases, dynamics, and temperature measurement. He studied medicine at the University of Pisa aged 17. At the cathedral in Pisa, he timed the swinging lamp with his pulse and found that the oscillations took equal times. This discovery led to the development of the pendulum clock. He became professor of mathematics at Padua and studied dynamics. It is said that he demonstrated from the Leaning Tower of Pisa that bodies of different weights fell with the same acceleration and also that the path of a projectile is a parabola. He also showed that air has weight by weighing a vessel under ordinary conditions and then filling it by means of a pump with compressed air. He carried out experiments on inclined planes to test his theory of falling bodies. He also made the first thermoscope or temperature detector based on the expansion of air with rise in temperature. He was one of the first scientists to make a practical telescope and discovered the four largest moons of Jupiter in 1610, which are known as the Galilean moons. The Galilean telescope has a convex lens for objective and a concave lens for eye-lens and gives an upright image. His hand-made instruments were in demand all over Europe. He was later persecuted by the Church for supporting Copernicus' theory that the sun is the centre of the solar system.

Galileo number A dimensionless number, Ga, used in the study of viscous liquids. It is the relationship between the force due to molecular friction and the force of gravity in a flowing viscous fluid:

$$Ga = \frac{l^3 g \rho^2}{\mu^2}$$

where l is the characteristic dimension of length, g is the gravitational acceleration, and ρ and μ are the density and viscosity of the viscous liquid. Ga is related to the *Grashof number:

$$Gr = \beta \Delta T \; Ga$$

where β is the coefficient of bulk expansion (1/T) and ΔT is the temperature difference. It is used in calculations involving thermal expansion such as in the design of heat exchangers. The Galileo number is also referred to as the **Galilei number** and is named after the Italian scientist Galileo *Galilei (1564–1642).

gallon A British Imperial unit of volume defined as the volume occupied by exactly ten pounds of distilled water of density 0.998 859 grams per millilitre in air of density 0.001 217 grams per millilitre. One gallon is therefore equal to 4.546 09 litres. In the US Customary system, one gallon is equal to 0.832 68 Imperial gallons or 3.785 44 litres. It is the volume occupied by 8.3359 pounds of distilled water and owes its origin to the Winchester or wine gallon.

galvanic cell *See* VOLTAIC CELL.

galvanization A metallurgical process in which zinc is deposited onto steel to provide galvanic protection, abrasion resistance, and resistance to corrosion. The method involves either a hot metal bath in which the steel object is immersed in the molten zinc providing a layer of zinc up to 150 μm thick, or the zinc is electrochemically deposited to form a layer up to 30 μm thick.

gamma radiation An energetic, short-wave *electromagnetic radiation. The waves are emitted as photons by the nuclei of radioactive atoms and have radiation levels that vary in energy between 10^{-15} and 10^{-10} joules corresponding to a wavelength of 10^{-10} to 10^{-14} m, and are highly penetrating. They are stopped by materials with a high density such as lead, concrete, and steel.

gangue The undesired minerals that are associated with ore. Gangue is mostly non-metallic and is separated as tailings. It has little commercial value.

Gantt chart A chart used in project management to provide an easy-to-interpret pictorial representation of the progress of a project. It also shows all the critical activities, which determine the overall timescale of the project. Gantt charts can also be used to monitor the progress of a project by signing off activities as and when they are completed. Major engineering projects may have a hierarchy of Gantt charts that provide a general overview and more detailed analysis of individual parts of the project.

gas A physical state of matter in which the molecules of a substance are free to move and which has neither a definite shape nor volume. An *ideal gas behaves as if the molecules occupy a negligible volume and that the collisions between the molecules are perfectly elastic. A *real gas allows for these deviations from ideal behaviour since the molecules themselves occupy a volume and there is a small amount of attractive force between them.

gas centrifuge process A separation process used to separate radioactive isotopes of uranium in which heavy atoms are separated from the lighter atoms by centrifugal forces. The separation is dependent on the difference in mass between the isotopes being separated. The uranium is prepared as uranium hexafluoride gas (UF_6) in which the lighter uranium-235 is separated from the heavier uranium-238. *See* ENRICHMENT.

gas constant *See* UNIVERSAL GAS CONSTANT.

gas formation volume factor The volume of gas within an underground reservoir at the reservoir conditions of temperature and pressure divided by the volume occupied by the gas at standard conditions of 298 K and 101,325 Pa. The factor is used to convert surface measured volumes to reservoir conditions.

gasification A process used for the production of *fuel gas from liquid or solid hydrocarbons. Examples include the production of *water gas, which is a mixture of carbon dioxide and hydrogen by the reaction of coke or coal with steam. *Producer gas, which is a mixture of carbon monoxide and nitrogen, can be produced from passing air over heated coke or coal. *Synthesis gas, which is a mixture of carbon monoxide and hydrogen, can be produced from liquid petroleum fuels.

gas laws The laws related to the temperature, pressure, and volume of an ideal gas. Boyle's law states that the volume of a fixed mass of gas is inversely proportional to its pressure at constant temperature and was proposed by Robert *Boyle (1627–91) in 1662. Charles's law states that the volume of a given mass of gas is directly proportional to its absolute

temperature at constant pressure and was proposed by Jacques *Charles (1746–1823). The combination of Boyle's law with Charles's law for an ideal gas leads to the universal gas equation $pV = nRT$. The gas laws were established experimentally. However, the laws are only applicable to real gases at low pressures and high temperatures. Equations of state have been developed to predict the actual behaviour of real gases.

gas lift A method for transporting liquids in which compressed gas or air is introduced to the bottom of a long vertical and open leg containing a liquid to be transported. By reducing the overall density in the leg relative to the density of the liquid around the leg, a flow is induced up the leg. At the top of the leg, the liquid and gas are disengaged. It is used to raise oil from wells and also used in *air-lift reactors.

gasohol A liquid fuel comprising a blend of alcohol and gasoline. Ethanol-based gasohol is a blend of typically 10 per cent ethanol and 90 per cent gasoline in which the ethanol is produced from the fermentation of agricultural crops such as maize or sugar cane. Methanol and wood alcohol are also used in other blends. The fuel is used in certain types of combustion engines and noted for its high octane and anti-knock properties.

gas oil An oil refinery distillation stream in which the molecular weights and boiling points are higher than heavy naphtha (205°C). It was once added to city gas supplies to make it burn with a luminous flame, and hence its name. It is used for industrial heating, by off-road diesel vehicles and machinery, as a marine fuel, and as a fuel for rail locomotives.

gas scrubbing *See* SCRUBBING.

gas stripping *See* STRIPPING.

gas sweetening A process used to remove hydrogen sulphide and mercaptans from natural gas. Commonly used in petroleum refineries, the gas treatment uses amine solutions such as monoethanolamine. The process uses an absorber unit and a regenerator. The amine solution flows down the scrubber and absorbs the hydrogen sulphide as well as carbon dioxide from the upflowing gases. The regenerator is used to strip the amine solution of the gases for reuse. It is known as gas sweetening as the foul smell is removed from the gas.

gas turbine An engine that uses internal combustion to convert the chemical energy of a fuel into mechanical energy and electrical energy. It uses air, which is compressed by a rotary compressor driven by the turbine, and fed into a combustion chamber where it is mixed with the fuel, such as kerosene. The air and fuel are burnt under constant pressure conditions. The combustion gases are expanded through the turbine causing the blades on the shaft to rotate. This is then converted to electrical energy. Gas turbines are used in the process industries and on offshore gas platforms for electrical generation.

gas void fraction The fraction of the gas in a multiphase flow system. Knowledge of the gas void fraction is needed in identifying the type of flow regime and flow behaviour of multiphase flow mixture. It is also needed in the calculation of pressure drop and prediction of fluid residence time for pumping requirements and understand the changes in thermal properties along long pipes such as sub-sea pipelines.

Experimentally, the gas void fraction can be measured by quick-closing valves, capacitance, and optical probes, devices based on X-ray and gamma-ray attenuation, and local electrical conductivity. However, different techniques tend to give different values of the

gas void fraction for the same flow. There is, therefore, an inherent uncertainty in the published data on gas void fraction.

gate valve A widely used device that regulates the flow in a pipe. It consists of a vertical moving section across the flow area. They are useful for on–off type flow control operations and provide a low pressure drop when fully open.

Gauckler–Manning formula *See* MANNING FORMULA.

gauge An instrument used to give a reading or a value.

gauge pressure The pressure of a system or fluid measured above the local atmospheric pressure. Atmospheric pressure is a variable quantity and standard atmospheric pressure is taken to be 101 325 $N\,m^{-2}$.

Gaussian distribution *See* NORMAL DISTRIBUTION.

Gay-Lussac, Joseph Louis (1778–1850) A French chemist and physicist noted for his two laws on gases and for his work on alcohol-water mixtures. He was professor of physics at the Sorbonne and later took a chair of chemistry at the Jardin des Plantes. Together with Jean-Baptiste *Biot (1774–1862), he made the first-ever hot-air balloon ascent for scientific purposes in 1804, reaching an altitude of over 6 km. He is also credited with recognizing iodine as a new element and suggested the name iodo, with the codiscovery of boron, and the terms 'pipette' and 'burette'.

Gay-Lussac's law A law stating that if the mass and pressure of a gas are held constant, then gas volume increases linearly as the temperature rises. When gases react, they do so in volumes that bear a simple ratio to one another and to the volume of the product, if it is a gas, temperature and pressure remaining constant. This is sometimes written as $V = kT$ where k is a constant dependent on the type, mass, and pressure of the gas, and T is the absolute temperature. For an ideal gas $k = nR/P$. It is named after *Gay-Lussac (1778–1850) who proposed the law in 1808, which led to *Avogadro's law.

Geiger, Hans Wilhelm (1882–1945) A German physicist with an interest in radioactivity and cosmic rays, and who worked with Ernest *Rutherford (1871–1937). He worked in Manchester and then in various centres in Germany. He is noted for the Geiger counter, an instrument he invented for detecting charged particles. Forms of the instrument are sufficiently sensitive to detect beta-particles (electrons) and gamma-radiation.

gel A pliable semi-solid mixture or viscous emulsion that solidifies or sets to a jelly upon cooling. Colloidal suspensions may convert from a gel to a sol by the addition of a solvent, increase in temperature, change in pressure, pH, or some other physical or chemical influence. The conversion may be reversible such as through *drying.

generator A machine used to produce electrical power. Electromagnetic generators are widely used to produce electrical power and are driven by water turbines, steam turbines, internal combustion engines, windmills, or other forms of mechanical energy. In power stations, generators produce alternating current (a.c. current) and are also known as **alternators**.

genetic engineering The general term for the artificial manipulation of the nucleic acids DNA and RNA to produce new, modified species of living cells. It involves the

formation of new combinations of heritable material by the isolation of nucleic acid molecules by whatever means outside the living cell, into a virus or plasmid, and transferred into a host organism in which they do not naturally occur, but in which they are capable of continued propagation. It has been applied to microorganisms such as bacteria and yeast, and plants in which genes for antibiotic resistance can be transferred to the living organism, for example. It is also known as *recombinant DNA technology.

geometrically safe A term used to describe the geometry of an item of process plant used in the nuclear industry to contain fissile material. The geometry is designed in such a way that it is impossible for a nuclear chain reaction to accidently occur since the concentration of fissile material will always fall below that required for a self-perpetuating chain reaction. Examples include toroidal-shaped tanks and tubular-shaped tanks, known as *harp tanks.

geometric mean A type of mean value that is the average value of a set of n numbers, and calculated by multiplying them together, and extracting the nth root of the product. For example, the geometric mean of 10, 20, and 40 is $\sqrt[3]{10\times 20\times 40} = 20$ and is less than the arithmetic mean, which is $(10+20+40)/3 = 23.33$.

geometric similarity Systems that have similar physical dimensions such that their ratio is constant. This is useful in the scale-up of process equipment.

geometric view factors The ratio of thermal radiation leaving a grey surface that is absorbed by another surface, to the total radiation leaving the surface were it to be a *black body. Charts are used for complex surface orientations such as the thermal radiation between adjacent rectangular surfaces in perpendicular or parallel planes.

geothermal energy A natural and renewable source of thermal energy extracted from regions of volcanic activity such as fumaroles, hot springs, and geysers. The heat is extracted by drilling a borehole down into the high-temperature porous rock, which ranges from just below the surface of the Earth in some places, to several kilometres down. Hot water and steam is either brought to the surface and used directly, or water is sent down where it is heated by conduction and returned to the surface. Geothermal energy is used for domestic or district heating, industrial processes, or for power generation in turbogenerators. Countries that use significant amounts of geothermal energy include the US, the Philippines, Iceland, and New Zealand. The district heating system in Reykjavik, Iceland provides heat for 95 per cent of the buildings.

Gibbs, Josiah Willard (1839–1903) An American mathematician and physicist noted for his work on thermodynamics. A professor at Yale University, he developed the theory of chemical thermodynamics and devised the concepts of *Gibbs free energy and *Gibbs' phase rule. He was also a founder of *statistical mechanics and was responsible for the introduction of *vector notation.

Gibbs free energy (Symbol G) A measure of the maximum useful work in a system that can be obtained, defined by:

$$G = H - TS$$

where T is the absolute temperature, H is the enthalpy, and S is the entropy. A quantitative measure as to how near or far a potential reaction is from occurring can be determined from the change in Gibbs free energy ΔG. Negative values of ΔG indicate that change can occur spontaneously whereas positive values indicate that energy is required to be supplied for

the reaction to occur. It is also known as **Gibbs energy** or **Gibbs function** after American physicist Josiah Willard *Gibbs (1839–1903).The Helmholtz free energy is defined as $F = U - TS$ where U is the internal energy. For a reversible isothermal process, the change Helmholtz free energy represents the useful work available. It is named after German physicist and physiologist Hermann von Helmholtz (1821–94).

Gibbs' phase rule A method used to calculate the variance of a heterogeneous equilibrium of a non-reactive system or process, and to establish the number of independent variables. It is calculated from:

$$F = C - \Pi + 2$$

where F is the number of thermodynamic *degrees of freedom, C is the number of components, and Π is the number of phases. Detail of phase equilibria is important in mass transfer and problems are analysed in terms of the phase rule. If insufficient degrees of freedom are fixed, then the problem will be under-specified. If too many are chosen, the problem will be over-specified. For problems involving two components with two phases such as in binary distillation, then $F = 2$. If the pressure is fixed then only one variable remains that can be changed independently, such as temperature. The concentration of the liquid and vapour phases are then fixed. The phase rule does not apply to systems involving chemical reactions. It was deduced by American physicist Josiah Willard *Gibbs (1839–1903). A modified Gibbs' phase rule is used for reacting species:

$$F = \mathrm{n} - \Pi + 2 - r$$

where n is the number of components and r is the number of independent chemical reactions. For example, in a gas reaction involving three components in which only two react (e.g. fuel with air), then there are three independent variables such as T, P, and y_1, which fixes y_2 and y_3.

giga- (Symbol G) A prefix denoting 10^9. For example, the output from a power station may be 1 GW (i.e. 10^9 watts).

Gilliland equation An empirical equation used to estimate the number of stages required in a distillation column. It uses the minimum number of stages as well as minimum and actual reflux ratios in the calculation. It is named after American chemical engineer Edwin Gilliland (1909–73) who was professor of chemical engineering at MIT.

Gilliland–Sherwood correlation A dimensionless equation used to determine the mass transfer in gas absorption and relates the Sherwood number, Reynolds number, and Schmidt number:

$$Sh = 0.023\,\mathrm{Re}^{0.83}\,Sc^{0.44}$$

It was developed in 1934 based on experimental data from wetted wall columns and is valid for Reynolds numbers between 2,000 and 35,000 and Schmidt numbers between 0.6 and 2.5.

global warming potential (GWP) The overall assessment of the effect on the climate by the release of one kilogram of a gas to carbon dioxide, which is used as the reference. A GWP of a so-called greenhouse gas is dependent on its lifetime within the troposphere that surrounds the Earth and the radiative efficiency, which is the amount of infrared radiation that the gas can trap and is dependent on the frequency at which infrared radiation is absorbed. The GWP of carbon dioxide is 1, whereas the GWP of methane is 25. The GWPs

of CFC-11 and CFC-13 are 45 and 640, respectively. Their manufacture and use is no longer permitted. *See* GREENHOUSE EFFECT.

globe valve A device used to regulate the flow of a fluid in a pipe and consists of a flat disc that sits on a fixed ring seat. The disc is movable and allows flow through the valve.

glove box A gas-tight box used to handle either harmful substances or substances that may react with air. The box has a transparent window for viewing and full-length gloves used for the operator to handle the substances inside without direct contact. A *negative pressure is applied to the glove box to ensure that there are no inadvertent leaks or emissions. They are typically used in the nuclear and biomedical industries for handling radioactive substances and biological agents. The glove box can be filled with another gas such as an inert gas to exclude oxygen from the air and used to handle substances that may otherwise react with it. The glove box is therefore maintained at a pressure greater than atmospheric.

glowing combustion The thermal oxidation of solid material with light emission but without a visible flame.

GOLDOX A process that extracts gold from ore by the injection of oxygen into a cyanide solution; the name is an abbreviation of **gold ox**idation.

GOR The ratio of produced gas to produced oil from a well or reservoir. It is an abbreviation of **g**as to **o**il **r**atio.

GOSP An abbreviation for a **g**as **o**il **s**eparation **p**lant.

gradient The slope of a line on a *graph. In Cartesian coordinates, the general equation of a straight line is $y = mx + c$ where m is the gradient or slope and c is the intercept on the y-axis. The gradient at some point on a curve can be found from the derivative dy / dx at that point. The gradient is therefore the tangent to the curve.

Graetz number A dimensionless number, Gz. Used in fluid dynamics, it is used to characterize heat transfer by convection compared with the heat transfer by conduction in ducts as:

$$Gz = \frac{c_p \rho Q}{kL}$$

where c_p is the heat capacity, ρ is the density, Q is the flow rate, k is the thermal conductivity, and L is the length. It is named after German physicist Leo Graetz (1856–1941).

Graham, Thomas (1805–69) A Scottish chemist who was professor of chemistry at Glasgow University in 1830 and later moved to University College London in 1837. He is noted for his law for the diffusion of gases and as founder of the science of colloids based on his work between 1851 and 1861.

Graham's law of diffusion A law that states that the rates of diffusion of gases are inversely proportional to the square root of their densities under the same conditions. This was first proposed by Scottish chemist Thomas *Graham (1805–69) in 1829.

gram (Symbol g) A *fundamental unit of mass equal to one thousandth of a kilogram. It was formerly used within the *c.g.s. system and included units such as the **gram-molecule,** which has now been replaced by the *mole.

granulation A process used in the pharmaceutical industry to prepare powders for the production of tablets. The granulation process involves combining one or more powders to create bonds between the particles of the powder. These are formed by compression or by using a binding agent to produce a tablet with good hardness and a consistent quality. The machines used for granulation are called **granulators** that apply the necessary shear to combine the powders and the binding solution. The fluid-bed granulator uses air to elevate the powders while the binding solution is sprayed onto the particles.

graph A diagram that presents the relationship between numbers or quantities. A graph is normally drawn with coordinate axes at right angles. They are used to display and illustrate the geometric relationship between data. The dependent variable is plotted on the x-axis while the independent variable is plotted on the y-axis.

Grashof number A dimensionless number, Gr. It is used in the study of natural convection and represents the ratio of buoyancy forces to viscous forces:

$$Gr = \frac{\rho^2 g \beta l^3 \Delta T}{\mu^2}$$

where ρ is the density, g is the local acceleration due to gravity, β is the volume coefficient of expansion, l is the characteristic length, ΔT is the temperature difference, and μ is the viscosity. The product of the Grashof number and the *Prandtl number characterizes the convective heat transfer. It can be applied to laminar and turbulent regimes and for vertical and horizontal planes and cylinders, such as pipes. An analogous form of the Grashof number used in the study of mass transfer by natural convection is:

$$Gr = \frac{g \Delta \rho L^3}{\rho \upsilon^2}$$

where g is the acceleration due to gravity, Δρ is the density difference between two points, L is the characteristic length, and υ is the kinematic viscosity of the fluid. It is named after German engineer Franz Grashof (1826–93).

gravitational acceleration (Symbol g) The attractive force towards the centre of the Earth that causes an acceleration of a falling body. That is, there is a change in velocity with time. Within a vacuum, the gravitational acceleration is equal to 9.806 65 m s^{-2}. The variation of gravity over the Earth's surface is negligible for most engineering work. *See* GRAVITY.

gravity The force that pulls a body towards the centre of the Earth. According to Newton's second law of motion, the weight of an object is the product of its mass and *gravitational acceleration $F = mg$. It varies with latitude and elevation above sea level. For precise calculations, the *gravitational acceleration is taken to equal to 9.806 65 m s^{-2}.

Suspensions of small particles can be separated from solutions by the force of gravity as in the process of *sedimentation. The process, however, tends to be slow. Centrifugation is a process used to apply a far higher 'gravitational' force to the particles, increasing the rate of separation.

gravity separation A process in which immiscible phases or particles in a liquid separate due to the influence of gravity. In the separation, the more dense phase or particles settle out. It is used in numerous chemical and mining processes.

gray (Symbol Gy) An SI derived unit for the absorbed radiation dose of ionizing radiation defined as the absorption of one joule of ionizing radiation by one kilogram of matter. It is

named after British physicist Louise Harold Gray (1905–65) and replaces the c.g.s. unit of rad where 1 rad = 0.01 Gy.

green chemistry A term used to describe the steady move towards the development of environmentally acceptable chemical processes and products. It was first coined by the US Environmental Protection Agency in the 1990s and focuses on influencing education, research, and industrial practice.

greenhouse effect A phenomenon in which the Earth's atmosphere and surface is steadily heating up. It is caused by the ability of certain gases and particles in the Earth's atmosphere to trap infrared radiation from the sun reflected back from the Earth's surface more effectively than nitrogen and oxygen in air. The principal **greenhouse gases** are water vapour, carbon dioxide, methane, nitrous oxides, chlorofluorocarbons (CFCs), and ozone. Fossil fuel combustion is the main cause of carbon dioxide release, while methane is a by-product of agriculture and landfills. CFCs are even more potent but their use has been reduced in recent times.

The levels of carbon dioxide and other greenhouses gases have been steadily increasing over the past century. It is thought that the level of carbon dioxide is due to industrialization and the burning of fossil fuels has led to the greenhouse effect, contributing to global warming. *See* GLOBAL WARMING POTENTIAL.

grey body A body that does not absorb all the incident thermal radiation and emits radiation that is less than that of a *black body. It has a constant emissivity over all wavelengths and temperatures, and has a value less than 1.0.

grid zone The location in a *fluidized bed in which the fluidizing gas flow is sufficient to form bubbles. The grid zone is located at the bottom of the bed, corresponds to the gas penetrating the bed, and is dependent on the types of grid used.

grinding The process of breaking up particles into more particles or fragments. *Ball mills are typically used, which consist of a slowly rotating vessel on its horizontal axis containing material to be ground and steel or ceramic balls. Due to the cascading and tumbling action of the balls, the material is ground to a smaller particle size distribution.

gross drying rate The loss of moisture from a substance per unit time in a drying process but ignores the change in drying area.

gross economic potential The difference in the economic value of manufactured products and the value of the feed materials. Where this is positive, there is added-value in the process. Where it is zero or negative, there is no economic gain or business value from the process. It does not take into account the cost of equipment or operating costs.

growth curve Used in biochemical engineering to describe and illustrate the evolution of biomass over time. These are plotted to illustrate the change of microbial cell concentration, either as dry weight or total population, over a period of time. Features of the batch cultivation of microorganisms show a lag phase in which the microorganisms adjust to the growth medium, an *exponential growth phase as they rapidly multiply, a **quiescence phase,** and a death phase. A second growth curve may occur, known as **diauxic** or bi-phasic growth in which the microorganisms consume another nutrient, which may be an excreted product from the first phase such as ethanol. *See* LIMITING SUBSTRATE.

growth medium A liquid or a gel used to support the growth of a plant, animal, or microbial cell culture. Also known as a **culture medium**, it contains all the necessary nutrients to sustain growth. An undefined medium, also known as a **complex medium**, contains a rich source of amino acids, nitrogen, vitamins, and trace elements needed for growth, such as yeast extract. It is non-selective in that all species of microorganisms if present would be capable of growth. A defined medium, also known as a **synthetic medium**, has a composition in which all the chemicals used are known. A **minimal medium** contains all the nutrients required for growth except for certain amino acids. They are used to select for or against recombinant DNA microorganisms. *See* SELECTIVE MEDIUM.

guess and check A problem-solving method used to obtain a solution by using conjecture to obtain the answer and then checking that it fits the conditions of the problem. The method is useful when there is no knowledge or information within a problem to reach a solution by alternative means. It is a widely used method and very useful for solving differential equations. *Compare* TRIAL AND ERROR.

guestimate A reasoned estimate that is made to solve a problem with insufficient data or information. It is a corruption of the words 'guess' and 'estimate', and is usually used for solving complex problems as a first trial in an iterative approach used in reaching a solution.

guideword A list of words used in a *HAZOP (hazard and operability) study to identify undesired deviations from the normal operating conditions that may present a hazard. It includes the words *none, more of, less of, part of, more than*, and *other*. In each case the word is applied to the effect of flow, temperature, and pressure.

Guldberg rule A rule stating that the ratio of the normal boiling point to the critical temperature of a substance is equal to a value of 2/3. It was proposed in 1890 by Norwegian chemist Cato Maximilian Guldberg (1836–1902). For simple molecules containing one or two atoms and discounting hydrogen atoms present, the ratio is 0.567, while for other inorganic molecules the ratio is 0.635.

Gurney–Lurie charts Charts used for determining thermal diffusion in materials. First published in 1923 by H. P. Gurney and J. Lurie, they plot the *Fourier number on the x-axis and a dimensionless temperature on the y-axis. The charts can be used to determine the temperature within materials that have a defined geometry such as slabs, cylinders, cubes, and spheres.

H

Haber, Fritz (1868–1934) A German chemist who, working with Carl Bosch (1874–1940), developed the *Haber process in 1908 in which ammonia was synthesized in the catalytic high-temperature, high-pressure reaction of hydrogen and nitrogen. He received the Nobel Prize in Chemistry in 1918 for this work. Being born a Jew, he left Germany in 1933 and worked at the Cavendish Laboratory in Cambridge.

Haber process A major industrial process for the synthesis of ammonia, which is principally used in the manufacture of fertilizers. The process involves passing a mixture of nitrogen and hydrogen at a volumetric ratio of 1:3 under high pressure in the presence of a heated catalyst: $N_2 + 3H_2 \rightarrow 2NH_3$. With a contraction of volume and being exothermic, *Le Chatelier's principle indicates that the yield of ammonia will be increased by pressure and decreased by a rise of temperature. However, a relatively high temperature is used otherwise the reaction is too slow. Most industrial plants vary in operation but, typically, finely divided iron catalysts are used with a temperature of 550°C and pressure of 250 atmospheres. The hydrogen is obtained from the *steam reforming of natural gas. The process was developed by Fritz *Haber (1868–1934) and Carl Bosch (1874–1940) in 1908, and is also known as the **Haber–Bosch process.** *See also* SYNTHESIS GAS.

Hagen, Gotthilf Heinrich Ludwig (1797–1884) A German physicist noted for his contribution to engineering particularly in the field of hydraulics. Qualified in civil engineering and mathematics, he worked as a civil engineer managing various engineering projects before turning to teaching in Berlin. He is credited with independently developing the *Hagen–Poiseuille equation.

Hagen–Poiseuille equation An equation used to determine the rate of flow of a Newtonian fluid with laminar flow expressed as:

$$Q = \frac{\pi}{8\mu}\frac{\Delta p}{L}R^4$$

where μ is the viscosity of the fluid, Δp/L is the pressure drop per unit length of pipe, and R is the pipe inner radius. It is named after G. *Hagen and J. *Poiseuille who independently derived this equation in 1839 and 1840, respectively.

half-cell An electrode immersed in a solution of ions that forms part of a cell. *See* ELECTRODE POTENTIAL.

half-life The time taken for a substance to fall to half of its original value and is independent of the amount of starting material. A reaction that has a constant half-life is a first-order reaction. *Radioactive decay is an example of a first-order reaction. The half-life of a radionuclide is the time for half the nuclei to disintegrate. The time varies between radionuclides ranging from fractions of a second to millions of years. For example, the half-life of beryllium-16 is $2.0x^{-16}$ seconds and tellurium-128 is $7.2x10^{24}$ years. In biological systems,

the half-life is the time taken to naturally excrete half of an absorbed substance from a body or an organ.

Hall–Héroult smelting process A continuous electrolytic process used to produce aluminium from alumina. The alumina is dissolved in a bath of sodium aluminium chloride called cryolite that contains alumina fluoride and calcium fluoride. The solution is heated to 950°C in a steel tank with a carbon liner. Carbon anodes are lowered into the solution with the liner being the cathode. Electrolytic action separates the alumina into liquid aluminium, which collects at the cathode, and oxygen at the anode, which combines with the carbon to form carbon dioxide gas. It was invented in 1886 simultaneously and independently by American chemist Charles M. Hall (1863–1914) and French scientist Paul L. T. Héroult (1863–1914).

halogenation A general name for a chemical reaction that involves the introduction of a halogen atom into a compound. The name of the specific reaction is named after the halogen such as bromination, chlorination, and fluorination. The halogenation of aromatics such as benzene involves electrophilic substitution. The halogenation of alkanes involves free radicals and high temperatures.

hammer mill A mechanical device used to shred solid materials such as grains and sugar cane in order to aid extraction of starches and sucrose. It consists of a rotating shaft upon which hinged hammers are fixed. The shaft is contained within a shell through which solid material is fed and emerges from the other end in a shredded form.

hardness The resistance of a material or substance to crushing, indenting, or abrading. Hardness is measured on the *Moh scale of hardness of 1 to 10, representing soft (talc) to very hard (diamond). Hardness is also a measure of the applied force with time.

harp tank A geometrically safe tank used to store radioactive liquids that are capable of fission if the emitting neutron concentration reaches a critical condition. The tanks consist of long slender tubes and join in a manifold at either end much like the strings of a harp. They are used in *nuclear fuel reprocessing.

hastelloy A widely used alloy of nickel, molybdenum, and chromium used for process equipment. It provides good resistance to wet chlorine, hypochlorite bleach, ferric chloride, and nitric acid.

HAZAN An abbreviation for **haz**ard **an**alysis, it is a technique used to assess the probability of a hazard occurring and for determining the subsequent consequences.

hazard A biological, chemical, or physical agent or situation that is reasonably likely, or has the potential, to cause illness or injury to humans, damage to property, damage to the environment, or some combination of these if it is not controlled. The product of the consequence and frequency of that situation occurring, hazards are associated with fire and explosion, pollution, chemical reactions, toxicity, mechanical failure, corrosion, and nuclear radiation. Hazards may arise due to the relaxation of management control, fatigue, carelessness, boredom and complacency, a loss or changes in operational knowledge, ageing and poorly maintained equipment, design modifications, and the abuse of trips. Hazards can be controlled through elimination, control of containment, and the controlled reduction in the likelihood or frequency and effect. They may be reduced through design standards, control of work, inspection, maintenance, safety reviews, control of ignition

sources, use of detection devices, fireproofing, and effective operational and emergency response procedures.

hazard analysis The identification of undesired events that result in a hazard. The analysis seeks to evaluate the likelihood of the undesired events and the harmful consequences of the hazards. A *HAZID and a *HAZOP are both forms of hazard analysis.

hazardous energy Any form of energy in a form that can cause harm to a human. It includes ionizing and thermal radiation, electrical, electromagnetic, mechanical, and chemical energy. A **hazardous substance** is a chemical material which, due to its chemical properties, constitutes a hazard. It may realize its potential through fire, explosion, toxic, or corrosive effects.

HAZID An abbreviation for **haz**ard **id**entification, it is a systematic and wide-ranging structured hazard analysis technique used to identify the potential hazards at an early stage in process design and development. It is applied once details of process materials and flows presented in a *flowsheet have been quantified. HAZID considers both internal and external events such as weather effects, and seeks to broaden the hazard understanding of those involved by encouraging lateral thinking. Whereas *HAZOP is cause-driven, HAZID is consequence-driven. HAZOP can accept a conclusion that an event will not occur, while HAZID assumes that an event will occur and consequently requires a rigorous analysis of the sequence of events for it to occur.

HAZOP An abbreviation for **haz**ard and **op**erability, it is a systematic and structured hazard evaluation technique used to identify the potential failures of equipment or plant systems that may otherwise become hazards and present potential operating problems. The aim is to eliminate or minimize the probability of an incident from occurring and the severity of consequence arising from that incident. It uses a multidisciplinary team-based approach to consider what can go wrong, the causes, consequences, frequency of occurrence, measures for prevention, and justification of the associated costs of prevention. The study uses *guidewords for the possible deviations from an intended design or operation of a process. These include *none, more of, less of, part of, more than*, and *other*, and in each case is applied to the effect of flow, temperature, and pressure. It also includes the effects of impurities, changes in phase and composition, extra phases being present, and activities that can happen, as well as normal operation such as maintenance, purging, access, start-up, shutdown, alternative operation mode, and failure of plant services. The HAZOP team works systematically on a particular point in the process and considers a particular parameter such as flow, pressure, temperature, level, heat, and deviation. The causes and consequences are recorded along with any required action to improve the safety or operability of the process. On completion, the next guideword at the same node is considered until all the nodes with their parameters and deviations have been considered. Finally, the costs of recommended changes to the design or plant are reviewed and justified.

head The pressure of a liquid expressed as the equivalent height that a column of the liquid would exert. The head is related to pressure, p, density, ρ, and gravitational acceleration, g, as:

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

See HYDROSTATIC HEAD.

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

$$C_H = \frac{gH}{N^2 D^2}$$

where H is the head developed, g is the gravitational acceleration, and N and D are the rotational speed and diameter of the impeller.

head end The first process step used in *nuclear fuel reprocessing. It involves all the process stages of mechanical sectioning of fuel elements in preparation for chemical extraction. This includes feeding the fuel elements into a sectioning machine that cuts the fuel element bundles into roughly 5cm-long pieces. The rod pieces then fall into concentrated nitric acid to dissolve the uranium, plutonium, and fission products. The cladding material of the fuel rods is resistant to the acid. *Compare* TAIL END.

header 1. A large tank, reservoir, or hopper used to maintain a gravity feed to a process or to provide a static fluid pressure to a process or item of equipment. It is located above the process and feeds down into the process or equipment under the influence of gravity. **2.** A manifold pipe connected to smaller pipes.

headspace The space above a liquid in a vessel filled with gas or vapour. A space is usually left in sealed liquid storage tanks to allow for safe thermal expansion of the liquid.

health physics A branch of physics that is concerned with the study of the hazards of ionizing radiation and other aspects of atomic physics, and its harmful effects on human life. It has particular application in the protection of industrial workers in the nuclear power and *nuclear fuel reprocessing industries, as well as medical workers and researchers in related fields. It considers monitoring and establishing safe and permissible levels of radiation dosage, the disposal of radioactive contaminated waste, and measures for shielding against radiation exposure. *See* DOSE.

heat A form of thermal energy transferred from one body to another driven by a difference in temperature between the two bodies. The thermal energy of a body in thermodynamic equilibrium with its surroundings involves the internal movement of molecules and atoms. That is, it has internal energy made up of the kinetic and potential energies of the atoms and molecules. When a body changes its temperature, its internal energy changes in which heat is absorbed from the body and work is done simultaneously on the surroundings.

heat balance *See* ENERGY BALANCE.

heat capacity (Symbol C) The amount of heat Q transferred to a substance resulting in a change in temperature ΔT as $C = Q / \Delta T$. The SI units are J K^{-1}.

heat engine A machine used to convert heat into work. The heat is the result of combustion of a fuel. In an internal combustion engine, fuel is burnt inside the engine. A steam turbine is an example of an external combustion engine in which steam is raised outside the engine. Some of the steam's internal energy is then used to do work inside the engine. Heat engines operate as a cycle. The most efficient is the *Carnot cycle. However, this is an idealized cycle and not realized in practice.

heat exchanger A device used to transfer heat from one fluid to another without the two streams coming into contact with one another (see Fig. 23). Temperature is the *driving force for heat transfer to take place in which one of the fluids is either heated or cooled.

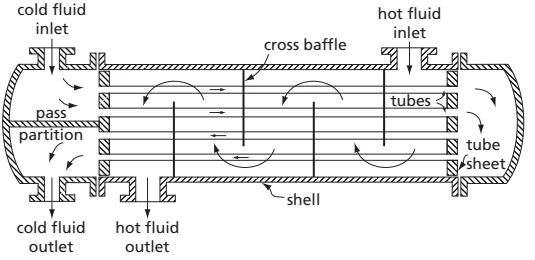


Fig. 23

h

There are many types used in the chemical and process industries. Examples include condensers, kettle reboilers, evaporators, shell and tube heat exchangers, and plate heat exchangers. The choice of heat exchanger depends on the heating or cooling requirement, the thermophysical properties of the fluids, and economics.

heat exchanger network (HEN) A technique based on *pinch analysis to identify the minimum requirements of energy, heat transfer area, and the number of units for a given process at the pinch point. The technique is applied in advance of a detailed design to determine the financial saving through process heat integration in maximizing heat recovery and reducing external utility loads. A network of heat exchangers is optimized through minimization of the total annual cost of energy costs and capital costs.

heat flux The transfer of heat energy from one place to another per unit time per unit cross-sectional area over which heat transfer takes place. Heat transfer calculations are based on the area of heating surface. In the case of tubes or pipes, heat fluxes may be based with reference to either the inside or the outside areas. While the choice is arbitrary, it must be stated as the magnitude of the heat flux is not the same for both. The SI units are $W\,m^{-2}$.

heating medium A fluid used to transport heat. It may be a liquid, a vapour, or a mixture of the two. Oil, water, and steam are often used as the heating media in many processes.

heat loss The unrecoverable dissipation of thermal energy that flows from a body to a place of lower temperature. The amount of heat flow, or loss, is dependent on the temperature difference of the body to the environment at the lower temperature, the exposed area, and the surface heat transfer coefficient. Heat is lost through the walls of pipes that transport hot fluids. The heat loss can be reduced by surrounding the pipe with an insulating material that has a low thermal conductivity. *See* INSULATION.

heat of absorption The heat released when a substance is absorbed into another substance at constant pressure.

heat of adsorption The heat released by a gas when it is adsorbed onto the surface of a solid material at constant temperature.

heat of atomization The heat required to atomize one mole of a substance into atoms.

heat of combustion The heat of reaction for the complete combustion of a mole or unit mass of a fuel in oxygen at the standard state of 25°C and 101.3 kPa. For the combustion of

a hydrocarbon, the carbon is converted to carbon dioxide and the hydrogen is converted to water vapour. For fuels that contain sulphur and nitrogen, the combustion products are sulphur dioxide and nitrogen. It is also known as the **standard enthalpy of combustion**. *See* CALORIFIC VALUE.

heat of condensation The heat released when a substance is converted from a vapour to a liquid and both have the same temperature.

heat of crystallization The heat absorbed when a substance crystallizes in a solution.

heat of evaporation see HEAT OF VAPORIZATION.

heat of formation The energy released or absorbed when the elements at the standard state of 298 K and 101.3 kPa units produce one mole of a compound. The heat of formation may provide evidence of the structure of the compound. Tables of values are available for compounds in the standard state. It is also known as the **standard enthalpy of formation**.

heat of fusion The energy required to melt a substance under isothermal conditions.

heat of mixing The energy required to form a mixture from its components under isothermal conditions.

heat of reaction The energy absorbed or evolved when one mole of product is formed by a chemical reaction at the standard state of 298 K and 101.3 kPa. It can be calculated from the difference in the sum of the *heats of formation of the products and reactants in a reaction carried out in stoichiometric proportion.

heat of solution The energy liberated or absorbed when one mole of a substance is completely dissolved in a solvent.

heat of vaporization The energy required to evaporate a liquid under isothermal conditions; also known as **heat of evaporation**.

heat pump A device used to transfer heat from a cold source to a place or reservoir at a higher temperature by expending mechanical energy, such as in *air conditioning. Unlike a *refrigeration cycle, the heat pump is used to raise the temperature of the reservoir and not to cool it. It operates with an adiabatically compressed gas as the working fluid such that its temperature rises so that heat is given out to the reservoir. The fluid then condenses to a liquid. It is then expanded into an evaporator where it absorbs heat converting it to a vapour again for adiabatic compression.

heat transfer The movement of thermal energy through a body or across a space as a result of the difference in temperature. The three modes of heat transfer are *conduction, *convection, and *radiation. Heat is generated in chemical processes from a number of sources, including *exothermic reactions, mechanical agitation, and adiabatic processes. Heat is removed by cooling water through cooling coils, external cooling jackets, and heat exchangers. Heat may need to be added to *endothermic reactions, which require heat to proceed. For example, high-temperature heat is supplied directly to cracking processes by the combustion of fuel in the form of thermal radiation to heat tubes within which the endothermic reaction takes place, such as in the cracking of dichloroethane to form vinyl chloride monomer and hydrogen chloride.

heat transfer coefficient *See* OVERALL HEAT TRANSFER COEFFICIENT.

heat treatment The process of applying heat to a material to bring about a physical, chemical, or biological change. It is used in the manufacture of glass and metallurgical processes, and can involve heating to very high temperatures as well as chilling to very low temperatures. The heat treatment processes commonly used include *annealing, case hardening, tempering, and quenching. The use of heat and time can modify the grain structure of metals leading to improved strength, machinability, and electrical conductance.

heavy chemicals Bulk chemicals that are manufactured and used in industry in which the production rate is of the order of thousands of tonnes per day. They are often used as the starting materials and feedstocks for other products, such as sulphuric acid that is used in the petroleum, steel, and agrochemical industries. Chemicals produced in large amounts include fertilizers, cement, paints, and plastics. *Compare* FINE CHEMICALS.

heavy key *See* KEY COMPONENTS.

heavy phase The liquid with the higher density in a liquid–liquid extraction process and sits below the *light phase.

heavy water Water in which the hydrogen atoms are replaced by deuterium oxide (D_2O). *Deuterium is a heavier isotope of hydrogen. Heavy water has slightly different properties than H_2O with a melting point of 3.8°C and boiling point of 101.4°C. It is found naturally in water in very small amounts and can be separated and concentrated by *fractional distillation or by *elecrolytic separation. It is used as a moderator in the nuclear industry due to its ability to reduce the energy of fast-moving neutrons.

hecto- (Symbol h) A prefix used to signify one hundred times. For example, a hectolitre (hl) is a unit of volume equal to 100 litres.

height equivalent to a theoretical plate (HETP) The height of packing required in a distillation column or an absorption column that is able to provide the same change in composition in the liquid or vapour phase as one theoretical plate. It can be found from the total height of the packed bed divided by the height of a *theoretical stage. This is a device that has perfect contact between the liquid and vapour phases such that both streams leave in equilibrium. The HETP effectively divides the column into equal portions whereas the *height of a transfer unit (HTU) is a continuous function.

height of a transfer unit (HTU) A dimensionless number used as a measure of the performance of a process separation column or unit such as a distillation column, adsorption column, or cooling water tower. It relates the height of the column or packing that gives the same change in liquid or gas composition as one transfer unit. The height of a transfer unit is therefore calculated from the ratio of the height equivalent to a theoretical plate (HETP) to the number of transfer units (NTU).

Heisler charts A set of graphical plots used to determine the time taken for thermal penetration by heat conduction into a solid body by heating or cooling at its surface. The plots are prepared for standard geometric shapes such as slabs, cylinders, and spheres with the *Fourier number on the x-axis and a dimensionless temperature on the y-axis. The lines represent the reciprocal of the *Biot number. They are named after M. P. Heisler, who compiled them in 1947.

Helmholtz free energy *See* FREE ENERGY.

hemisphere The surface bounded by a sphere and a plane through the centre of the sphere. The ends of cylindrical pressure vessels and columns have domed or hemispherical ends in order to spread the applied stresses.

HEN *See* HEAT EXCHANGER NETWORK.

Henry's law A law that states the effect of change of pressure on the solubility of a gas in a solvent. The law takes the form that the mass of a given gas which saturates a given solvent is directly proportional to the pressure of the gas at equilibrium, provided that the temperature is constant and that the gas does not react chemically with the solvent:

$$p_A = Hx_A$$

where p_A is the partial pressure of component *A*, *H* is Henry's law constant, and x_A is the mole fraction of the component in the solvent. It is used for many gases to describe the relationship between the concentration of a gas dissolved in a liquid and the equilibrium partial pressure. It does not apply to the aqueous behaviour of very soluble gases, and slight inaccuracies also arise because gases do not obey Boyle's law exactly. The SI units for H are pascals per mole fraction. It was formulated in 1803 by English chemist William Henry (1774–1836).

HEPA filter A very efficient type of filter that is able to entrap very small particles. An abbreviation of **h**igh **e**fficiency **p**articulate **a**ir filter, it is required to trap in excess of 99.97 per cent of particles with a diameter of 0.3 microns. HEPA filters are made from high-density mats of glass fibres and used in processes where very clean conditions are required such as the nuclear and pharmaceutical industries.

hermetically sealed A term used to describe something that is fully sealed and without leaks. The compressor on a domestic refrigerator is hermetically sealed. The compressor typically has a steel outer shell that seals the vapour of the refrigerant into the system such that there are no leaks. The packaging of certain foods is hermetically sealed to ensure that no potentially contaminating air can enter and spoil the food.

Herschel–Bulkley fluid A type of fluid that exhibits non-Newtonian behaviour and can be described by a three parameter rheological model as:

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

where τ is the shear stress, τ_o is the yield stress, k is a constant, γ is the shear rate, and n is a power law exponent. Drilling fluids are examples.

hertz (Symbol Hz) The SI unit of frequency where one hertz is equal to one cycle per second. It is named after German physicist Heinrich Rudolf Hertz (1857–94) who discovered radio waves.

Hess's law A law that states that the total heat resulting from a chemical reaction is dependent only on the initial and final states of the reactants and is independent of the reaction route. It is the essential basis of calculations in thermochemistry and has both experimental and theoretical justification. The law is an aspect of the general law of conservation or

the first law of thermodynamics. For example, the chemical route of converting calcium oxide (CaO) to calcium chloride ($CaCl_2$) follows the two routes:

$$\begin{array}{ccccc} CaO(s) & \rightarrow & +2HCl(aq) & \rightarrow & CaCl_2(aq)+H_2O(l) \\ & & \Delta H_1 = -192.5\ kJ & & \\ \downarrow & & & & \uparrow \\ +H_2O(l) & & & & +2HCl(aq) \\ \Delta H_2 = -63\ kJ & & & & \Delta H_4 = -117\ kJ \\ \downarrow & & & & \uparrow \\ Ca(OH)_2(s) & \rightarrow & +H2O(l) & \rightarrow & Ca(OH)_2(aq) \\ & & \Delta H_3 = -12.5\ kJ & & \end{array}$$

$$\Delta H_1 = \Delta H_2 + \Delta H_3 + \Delta H_4$$

h

The law is named after Swiss-Russian chemist Germain Henri Hess (1802–50) who pioneered thermochemistry.

heterogeneous mixture A mixture of two or more different phases. For example, oil and water form a liquid heterogeneous mixture. Solid particles suspended in a liquid is an example of a solid and liquid heterogeneous mixture. A blend of silver and gold filings is an example of a heterogeneous mixture of elements. *Compare* HOMOGENEOUS.

HETP *See* HEIGHT EQUIVALENT TO A THEORETICAL PLATE.

heuristics A procedure based on a *rules of thumb used to provide a shortcut solution to a complex problem rather than an *algorithm. In the case of separating a multicomponent mixture, the rules of thumb are based on a general understanding of the factors that determine distillation cost. This includes the capital costs that comprise the column itself, as well as reboiler and condenser costs, and operating costs mainly associated with the heat flux from the bottom to top of the column. If all separations are equally difficult the whole cost of the train would be minimized if the sum of all the flows from the bottoms and tops of columns were minimized. This is the case if each column produces approximately equal quantities of material from top and bottom. The fewer times that any component in large excess is distilled, the less cost in treating it will be involved. Any arrangement that sets about removing components in large excess early in the train are likely to be favoured. Highly corrosive components should also be removed early as they are likely to cause damage to equipment. For separations of unequal difficulty, it is clearly not favoured to treat a large quantity of material with a difficult separation. It is preferable to delay difficult separations to later in the train when smaller quantities are being dealt with. It is also beneficial not to separate components at all, if separation is not needed. The following heuristics are therefore applied:

1 Remove highly corrosive components first.
2 Favour equimolar splits.
3 Split by widest difference in relative volatility first.
4 Take a single pure component from the top of the column.
5 Remove components in large excess first.
6 Do not separate components that are acceptable as mixed products.

The set of heuristics, however, may not suggest the same decision in each case.

hierarchical control The use of computer control to oversee the control of other computers that are themselves used to control a process.

Higbie's penetration theory A conceptual approach to mass transfer at the interface between a liquid and a gas. The gas–liquid interface is assumed not to be at steady state but is continually being refreshed by liquid from the bulk below. A theory assumes that an element of liquid reaches the interface for a fixed time depending on the hydrodynamic conditions and arrives with a particular concentration. The residence time is assumed to be short enough for the transferred component not to penetrate the element far enough to affect the bulk concentration. It was proposed by R. Higbie in 1935.

highly active waste The radioactive residues remaining after nuclear reprocessing of spent nuclear fuels and which contain a high level of fission products. These are not able to be further processed and are therefore stored in managed environments for very long periods of time. This includes the process of *vitrification in which the waste is converted to a glassy material and stored in containers in geologically stable shafts deep below the surface of the Earth. Over the period of storage, the fission products decay. The rate of decay depends on the *half-life of the fission products.

high-pressure processing (HPP) A non-thermal food-processing technique used to extend shelf life of certain products as well as to create new food textures. Depending on the type of food, it typically uses isostatic pressures in the order of 300 to 800 MPa held for between 1 and 30 minutes. It has the benefit that important food qualities such as flavour, nutrition, and colour are not affected since the covalent bonds of food components including saccharides, vitamins, lipids, and pigments are able to resist the effects of high pressures. Pioneered by Percy *Bridgman, commercial developments began in Japan around 1989. Today many foods worldwide are increasingly being processed by this technique, although the major limitation is the expensive pressure vessels required. It is also known as **ultra-high-pressure processing.**

Hill plot A graphical procedure used to fit experimental enzyme kinetic data to an S-shaped or sigmoidal curve that deviates from *Michaelis–Menten kinetics. It involves plotting log V/(V-v) as a function of the substrate concentration, S, where V is the maximum velocity, and v is the observed velocity. The straight line has a gradient that indicates the number of interacting sites on the enzyme or enzyme complex.

Hinchley, John William (1871–1931) A British chemical engineer and one of the founders of the *Institution of Chemical Engineers. He was the first professor of chemical engineering at Imperial College, London whose aims and ideas for the development of chemical engineering were embodied in his teaching.

histogram A statistical graph that uses the height of a column to represent the number of occurrences or frequency in a particular class of results that arise from an experiment or sample.

Hock process A process used to produce phenol and acetone from cumene (isopropyl benzene). The process first involves using air in the oxidation of cumene liquid to form cumene hydroperoxide:

$$C_6H_5CH(CH_3)_2 + O_2 \rightarrow C_6H_5C(CH_3)OOH$$

It is then followed by a reaction with sulphuric acid or phosphoric acid:

$$C_6H_5C(CH_3)OOH \rightarrow C_6H_5OH + (CH_3)_2CO$$

The process is named after the German Heinrich Hock who invented it in 1942.

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

holding tank A vessel used for temporary storage. The capacity and materials of construction depend on the process fluids being temporarily held. Examples of uses include process water, intermediate chemicals, waste fluids, and sewage.

hold-up The amount of material contained within a process vessel operating continuously. It is applied to liquids and solids such as materials contained within distillation columns and furnaces. **Liquid hold-up** is used in two-phase flow in which the liquid phase is retained in a system at any given time when the gas phase is moving faster than the liquid phase. **No-slip hold-up** is used for two-phase flow in which both liquid and gas phases are moving with the same velocity. The hold-up can be determined by measuring the gas fraction using capacitance probes, optical probes, electrical conductivity measurements, and devices based on x-ray or gamma ray attenuation.

holley-mott A type of *mixer-settler used particularly for solvent recovery in the *nuclear fuel reprocessing industries. With liquids flowing under gravity and with no moving parts, the design allows for the intimate contact of two liquids promoting mass transfer. They are used to separate spent fuels using the *purex process.

hollow fibre membrane A semi-permeable membrane in the form of tubes with inner and outer diameters ranging in the order of 0.5 mm to 1.0 mm. They are used for both liquid and gas separations, depending on the *selectivity of the pores and membrane materials.

hollow fibre bioreactor A type of bioreactor in which *hollow fibre membranes are used to transport fresh nutrients or oxygen to the medium, or to remove products or waste, or to immobilize biocatalysts such as enzymes and mammalian cells. The hollow fibres are porous semi-permeable membranes and packed into bundles within a cylindrical container. The pore size is sufficiently small to retain cells but sufficiently large to permit the passage of nutrients and waste materials. The hollow fibre bioreactor can be operated continuously. Examples include the cultivation of mammalian cells for the production of monoclonal antibodies, the growth of liver cells (hepatocytes), and for small-scale industrial waste treatment.

homogeneous 1. Substances being of the same phase. A **homogeneous catalyst** is a catalyst in the same phase as the reactants and products. *Compare* HETEROGENEOUS MIXTURE. **2.** A mathematical equation that has terms of the same degree. **3.** A differential equation in which a linear combination is set to zero.

homogenization A process in which fine particles or droplets are produced and distributed evenly throughout a continuous liquid phase. It uses a device called a homogenizer, which typically consists of a small nozzle and impact plate through which the liquid is pumped under high pressure. An example is milk in which fat globules are dispersed as fine droplets throughout the aqueous milk phase.

homologous series A series of organic compounds of the same type with each member differing from its preceding member by possessing an additional group in its molecule. Examples include alkanes, alkenes, alkynes, and alcohols. Successive members of a series are called **homologues** in which they show a gradual and regular change in physical properties.

Hooker–Raschig process *See* RASCHIG PROCESS.

hopper A wide container used for powders and particulate materials. It is funnel-shaped leading to a small discharge opening at the bottom.

horsepower (Symbol hp) A British Imperial measure of the rate of doing work. Scottish engineer James *Watt (1736–1819) used the term 'horsepower' to represent the equivalent work that his new steam engine could achieve to replace horses used in coal-mining operations. One horsepower is equivalent to 745.7 watts. The useful work that can be performed by a power device is called **brake horsepower.**

Hortonsphere A spherical pressure vessel used for the storage of compressed volatile gases in a liquid and gaseous state such as hydrocarbons and fuel gases. A trademark name registered by the Chicago Bridge and Iron Company (CBI), it is named in honour of the American bridge designer Horace Ebenezer Horton who founded the company in 1889.

SEE WEB LINKS

- Official website of the Chicago Bridge and Iron Company.

hot gas ignition temperature The lowest temperature required for ignition of a substance by a jet of hot gas.

hot leaching process A process first used in 1860 for the extraction of potash from sylvinite ore based on the differing solubilities of sodium and potassium chloride. The ore, which is a mixture of sodium and potassium chloride, is crushed and mixed with saturated sodium chloride. It is heated to boiling in which the potassium chloride dissolves but the sodium chloride does not. On cooling, the potassium chloride crystallizes and is separated.

hot pressing A process used to create hard and brittle solid materials from a powder, reduce the porosity of metals, and increase the density of ceramic materials. It uses a very high pressure of around 1000 bar and temperature of over 1,000°C depending on the materials. Ceramics and diamond-metal composites are made using this process in which the powder particles pack to form a very dense material. An inert gas such as argon is used to prevent oxidation of the materials.

hot surface ignition temperature The lowest temperature required for ignition of a substance by a hot surface.

hot tapping A technique used to form a connection between pipes or vessels without the need for first emptying or draining the contents. The pipe or vessel can therefore remain in operation at the time of the maintenance or plant modification. It involves temporarily plugging or sealing the pipe to allow the connection to be made.

Hottel charts Graphical charts used to determine the thermal diffusion in materials in the shapes of slabs, cylinders, cubes, and spheres. They plot the *Fourier number on the x-axis and a dimensionless temperature on the y-axis, and are an extension of the

*Gurney–Lurie charts. They are named after American chemical engineer Hoyt C. Hottel (1903–98) who was professor of chemical engineering at MIT.

hot wire anemometer An instrument used to measure the velocity of a gas. It consists of a resistance wire that is electrically heated using a constant current, and works on the principle that a small diameter electric conductor gives off heat in relation to the velocity of gas passing over the wire. The observed temperature of the wire indicates the air flow using an appropriate calibration chart.

hot work A method of carrying out a task in a hazardous area using a tool or item of equipment that can provide a source of ignition, heat, or flame. Examples include welding or the use of a flame or electric arc.

HP An abbreviation for **h**igh **p**ressure. It is often used with reference to a utility or a vent line. For example, an HP air supply.

HPP *See* HIGH-PRESSURE PROCESSING.

HSE An abbreviation for the **H**ealth and **S**afety **E**xecutive. It is the authority responsible for the regulation of most of the risks to health and safety arising from work within the UK.

SEE WEB LINKS

- Official website of the Health and Safety Executive in the UK.

HTU *See* HEIGHT OF A TRANSFER UNIT.

human error *See* ERROR.

human–machine interface Used in control rooms on the display screens, it presents graphically the process and includes vessels, pumps, pipes, etc. together with real-time data, graphs, and trends on temperature, pressure, flow, and levels. The process operator can control the process by adjusting set points, turning on and off pumps, opening valves, etc.

humectants A chemical material that is a wetting or moistening agent and used to provide an environment of moisture. *Compare* DESSICANTS.

humid heat The quantity of heat that is required to raise the temperature by one degree of one unit mass of dry air plus the water vapour that accompanies it. The SI units are kJ kg^{-1} K^{-1}.

humidification The process of adding moisture to air that results in an increase in humidity.

humidity The amount of water contained within a unit volume of dry air. The *absolute humidity is the amount of water in air expressed as the mass of water vapour per unit mass of dry air for a particular temperature and pressure condition. The *relative humidity is the moisture content of air expressed as a percentage, and corresponds to the ratio of the mass of water vapour in a given volume of air at a given temperature and pressure to the maximum quantity of water vapour that can be held in the air at those conditions.

humid volume The volume occupied by one unit mass of dry air together with the water vapour it contains expressed as:

$$V_H = \frac{RT}{p}\left(\frac{1}{29}+\frac{H}{18}\right)$$

where R is the gas constant, T is the absolute temperature, p is the total pressure, H is the absolute humidity, and 29 and 18 are the molecular weights of air and water, respectively. The SI units are $m^3\,kg^{-1}$ of dry air.

Hunter process A process used for the production of titanium metal by the reduction of titanium tetrachloride with sodium metal.

$$TiCl_4 + 4Na \rightarrow Ti + 4NaCl$$

The process takes place in batch reactors in which the reactants are heated in an inert atmosphere to 1,000°C. The salt is leached from the product using dilute hydrochloric acid. Invented by American M. A. Hunter in 1910, the process has been replaced by the *Kroll process.

Huntsman process A process used to purify steel by heating it in a graphite crucible and pouring the melt into a cast-iron mould. It is also known as the *crucible process and was developed by British clockmaker and locksmith Benjamin Huntsman (1704–76). Although not patented, the method was used until eventually superseded by the *Bessemer process.

HVAC An abbreviation for **h**eating **v**entilating and **a**ir **c**onditioning.

HX An abbreviation for **h**eat e**x**changer.

hydrate 1. The combination of certain compounds with water such as ferric chloride and copper sulphate. **2.** A compound consisting of gas molecules such as methane trapped within a cage of water molecules formed at high pressure and cool temperatures. It has the appearance and consistency of wet snow. *See* METHANE CLATHRATE.

hydrated The addition of water to a chemical to form a hydrate.

hydration *See* SOLVATION.

hydraulic fracturing *See* FRACKING.

hydraulic press A device in which forces are transferred by way of pressure in a fluid. A force F_1 is applied over an area a_1 and is transferred to a smaller area a_2 resulting in an increased applied force F_2 such that $F_2 = F_1 \times a_2 / a_1$. Extreme pressures can be obtained using pressure multipliers in which a force applied over a large area is transferred over a very small area thereby intensifying the pressure. This pressure can be intensified further by transfer onto an even smaller area.

hydraulic radius The cross section or area through which a fluid flows divided by the *wetted perimeter:

$$r_H = \frac{A}{P}$$

where A is the area and P is the wetted perimeter. It is used for *open channel flow, and for wide channels and represents the depth of the channel. Note that it is not equal to half the *mean hydraulic diameter.

hydraulic retention time The average period of time that a particular substance or component resides within a reactor or continuously fed vessel. It is also known as the **hydraulic residence time**.

hydraulics The study of the properties of liquids in motion and based on the principles of hydrodynamics and hydrostatics. The principles have been known for millennia with recorded evidence of irrigation canals and dams having been used in Egypt and Mesopotamia (now modern-day Iraq). Italian physicist Evangelista *Torricelli (1609–47) noted in 1644 that the velocity of a flowing liquid is proportional to the square root of the water head. Swiss scientist Daniel *Bernoulli (1700–82) obtained the relation between wall pressure, velocity, and elevation in 1738, using the word 'hydrodynamica' to describe the synthesis between conceptions of hydrostatics and hydraulics. Many other scientists have subsequently developed the subject area using Newtonian dynamics and differential calculus to describe the flow in pipes and channels, leading to many key concepts and the establishment of theorems including vortex motion, fluid resistance, airfoils, meteorological fronts, and statistical approaches to turbulence.

hydrocarbon Chemical compounds that consist of only hydrogen and carbon atoms. They form the main components of petroleum and natural gas and are used as fuel for energy and as the feedstock for producing many useful products such as plastics. There are three main classes based on the types of carbon–carbon bonds. Saturated hydrocarbons contain only single carbon–carbon bonds as alkanes or cycloalkanes. Unsaturated hydrocarbons contain carbon–carbon multiple bonds, such as alkenes and alkynes. Aromatic hydrocarbons are a special class of cyclic compounds and are related to benzene.

hydrochloric acid A strong and widely used acid in the chemical industry. It is largely made as a by-product from the chlorination of both aliphatic and aromatic hydrocarbons. It is also made by dissolving hydrogen chloride gas in water, or by the reaction of sulphuric acid with salt. The greatest use of the acid is in the pickling of steel. Other major uses include the production of chemicals, pharmaceuticals, and in food processing.

hydrocracking A general name given to catalytic processes that involve the hydrogenation of petroleum fractions to produce fractions with a lower molecular weight. Vaporized petroleum feed is mixed with hydrogen at high temperature and pressure and allowed to react with hydrogen in the presence of a catalyst. It includes both fixed-bed and fluidized-bed reactors. There are many variations currently used but the first hydrocracking process was the *Bergius process.

hydrocyclone A type of cyclone device used for the separation of particles suspended in a liquid. It is operated by feeding the liquid suspension tangentially into the top of the device to produce a centrifugal vortex action. This allows the more dense and coarse particles to be separated in the underflow while the smaller particles leave through the overflow. They are used in mineral ore processing, drilling mud separations, and oil–water separations on offshore operations. They have a low *capital cost, are cheap to operate, and have the ability to separate materials based on small differences in particle size.

hydrodealkylation *See* DEALKYLATION.

hydrodesulphurization A catalytic process used for the removal of sulphur from crude oil and refined petroleum products, and hydrogen sulphide from natural gas. The process involves a high temperature and pressure reaction in the presence of a nickel or alumina catalyst impregnated with molybdenum. Sulphur is required to be removed as it poisons catalysts and results in harmful sulphur dioxide in the combustion of fuels.

hydrodynamics The study of the behaviour and interaction of incompressible liquids in motion with reference to their contact with their boundaries. It is used for the study of the behaviour of water in open channel flow, and for liquids in *closed systems.

hydroelectric power Electrical power generated from the flow of water through a water turbine connected to an electrical *generator or **alternator**. The flow and pressure head of water is provided by a dam and channelled through a pipe to the water turbine below. The power generated is a product of the head, mass flow rate, and gravitational acceleration. Hydroelectric power stations produce electricity at peak times and can be used in reverse at other times to return water back into reservoirs for reuse.

hydroformylation A general name for catalytic processes involving high temperature and high pressures to extend the chain length of aliphatic compounds leading to the production of aldehydes and alkenes using carbon monoxide and hydrogen. The process was invented in the 1930s and has been modified many times since and is used in the production of fragrances and intermediates and for the production of detergents. It is also known as **oxo synthesis** or the *oxo process.

hydrogasification An exothermic process that uses hydrogen to gasify coal and produce methane. The hydrogen is provided either by using a methane steam reformer or some other source. Some of the methane is converted to carbon monoxide and hydrogen in the methane steam reformer.

hydrogenation 1. A process involving the heterogeneous reaction of adding hydrogen to molecules containing carbon such as unsaturated animal and vegetable oils. Highly unsaturated vegetable oils can be converted to solid vegetable fats by catalytically hydrogenating some or all of the double bonds in a process known as **hardening**. Margarine is produced from the hydrogenation of unsaturated vegetable oils such as soybean, peanut, or corn to produce the consistency of butter. The product can be churned with milk and artificially coloured to give the appearance or flavour of butter. **2.** Synthetic oil that is made by reacting coal with hydrogen to form synthetic hydrocarbons. *See* FISCHER–TROPSCH PROCESS.

hydroisomerization A general name given to catalytic processes that involve the use of hydrogen to isomerize aromatic hydrocarbons.

hydrometallurgy Processes that involve aqueous solutions used in the extraction and recovery of metals from ores. Leaching is used to treat metallic ores to form a solution of a salt and a metal. Dilute sulphuric acid is the most commonly used agent. The metal is then recovered from the salt solution by precipitation and/or concentration, and uses processes such as carbon adsorption, ion exchange, solvent extraction, and electrolysis. Almost all non-ferrous metals are produced using hydrometallurgy, such as gold, silver, copper, aluminium, nickel, zinc, cobalt, uranium, molybdenum, tungsten, and beryllium. *See* LIXIVIATION.

hydrometer A device used to measure the *density or *specific gravity of a liquid. The device, usually made of glass, floats in the liquid and sinks to an equilibrium depth according

to *Archimedes' principle, leaving a graduated stem unimmersed from which the density or *specific gravity is directly read. It is used in the *whisky, beer, and wine industries, and can provide an indication of the concentration of alcohol after fermentation and in the distillation of spirits.

hydrophilic A substance that has an affinity with water. *Compare* HYDROPHOBIC.

hydrophobic A substance that has little or no affinity with water. *Compare* HYDROPHILIC.

hydroprocessing A general name for a process involving the refining of petrochemicals with hydrogen gas. *See* HYDROCRACKING; HYDROTREATING.

hydropyrolysis A general name given to high-temperature, high-pressure catalytic processes that convert coal into a mixture of liquid and gaseous hydrocarbon products.

hydrorefining A general name given to processes that involve the use of hydrogen for the refining of petroleum mixtures.

hydroskimming A simple form of petrochemical refinery that uses atmospheric distillation to separate crude oil, and also has the capacity for *naphtha reforming and associated treatment processes. A hydroskimming refinery can produce a surplus of desulphurized fuels and gasoline. It is therefore more complex than a *topping refinery.

hydrostatic head The *static pressure of a liquid expressed in head form representing the pressure, p, that would be exerted by a vertical column of the liquid under the influence of gravity:

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

where ρ is the density of the liquid, g is the gravitational acceleration. Although the terms would appear to refer to water, it can be used for the static pressure of any liquid. *See* HEAD.

hydrostatic pressure The *static pressure of a liquid equivalent to the pressure that would be exerted by a vertical column of the liquid under the influence of gravity. The term can be applied to any liquid although in general most applications of hydrostatics involve water in reservoirs and dams.

hydrostatics The study of the behaviour of liquids under the action of forces and pressure when the liquid is stationary. It includes the study of liquids in storage tanks, vessels, reservoirs, and dams.

hydrostatic testing A form of pressure testing of vessels and piping or any other item of process plant equipment that is required to operate above atmospheric pressure. It involves filling the equipment with water to exert a *hydrostatic pressure. It is a safe method as water is virtually incompressible and by using colouring, leaks can also be easily detected.

hydrotreating A general name given to catalytic refining processes that involve the use of hydrogen. They are used to remove various components such as organic sulphur, nitrogen, metal, and oxygen compounds.

hygro- A prefix indicating humidity and moisture.

hygrometer An instrument used to measure the *humidity in the atmosphere. A **wet and dry bulb hygrometer** uses two thermometers to measure the *dry bulb temperature and *wet bulb temperature from which the humidity can be determined. In a *dew point hygrometer, the temperature of a polished surface is reduced to the point that moisture condenses to water. Other types of hygrometers use an organic material such as a fibre that expands and contracts due to the humidity, or use a change in electrical resistance of a *hygroscopic material to provide an indication of the humidity.

hygroscopic A material that gains or loses moisture depending on the product and the humidity and temperature of the surroundings. Biological products are hygroscopic. *See* ABSORPTION.

hypergolic Ability of a substances to ignite spontaneously when mixed with an oxidizer.

hypothesis A suggested explanation or argument to explain a phenomenon as the basis for either further verification or accepted as fact. It may be a theory or law that has the status of not being incontrovertible or universally true. There are some hypotheses in which there is no doubt such as *Avogadro's hypothesis but for which the label 'hypothesis' remains. *Compare* THEORY.

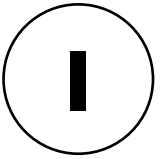
hypotonic The exertion of less osmotic pull than the medium on the other side of a *semi-permeable membrane. The material therefore has a lower concentration and loses less water during osmosis.

hypoxia A deficiency in the body when blood fails to deliver the necessary level of oxygen to tissues and organs. It can be caused by a lack of oxygen in the atmosphere due to displacement or exhaustion, particularly by the release of gases in confined spaces, or due to carbon monoxide poisoning, which inhibits the ability of haemoglobin in the blood to release the oxygen bound to it. The symptoms include headaches, tiredness, and shortness of breath, to loss of consciousness and death. Cyanosis, a blue discolouration of the skin and in particular the lips, show this in severe cases.

hypsometer An instrument used to determine elevation above sea level by measuring the change in the boiling point of water. Water and liquids generally boil at progressively lower temperatures as pressure decreases. Since atmospheric pressure decreases with altitude, the decrease in boiling point temperature is therefore an indicator of the atmospheric pressure and therefore elevation. It can also be used to calibrate thermometers.

hysteresis A lagging effect from an expected value due to a resistance such as friction. For example, in the control of processes, hysteresis is where there is a change in signal before a move in a valve.

HYSYS An abbreviation for **Hy**protech **Sys**tems, it is process-modelling software developed by AspenTech. It is used for steady-state and dynamic simulation of processes, process design, process performance monitoring, and process optimization across a wide range of industries and processes.



i A symbol used to represent $\sqrt{-1}$. It is an *imaginary number, which is distinguished from *real numbers. Engineers tend to use the symbol j instead of i. *See* COMPLEX NUMBERS.

IBC *See* INTERMEDIATE BULK CONTAINER.

ice point A freezing point of water under standard atmospheric pressure conditions in which water and ice are in equilibrium. It was once used as the *fixed point for 0°C. The kelvin and International Practical Temperature Scale has sixteen fixed points with temperatures including the triple of water.

IChemE *See* INSTITUTION OF CHEMICAL ENGINEERS.

id 1. An abbreviation for **i**nternal **d**iameter and used for specifying pipes, tubes, and some vessels of circular cross section. **2.** An abbreviation for equipment **id**entification used on flowsheets. Equipment such as a process vessel may have a specific code and number.

ideal crystal The shape of an individual crystal that has a perfectly regular lattice and has no deformations, irregularities, or imperfections.

ideal gas An idealized gas consisting of elastic and non-interacting molecules in which the effective volume occupied by the molecules is zero and obeys the **ideal gas law** $pV = nRT$ where p is the pressure, V is the volume, n is the number of moles, R is the universal gas constant, 8.314 J mol^{-1} K^{-1}, and T is the absolute temperature. Gases with a low density and far from their *critical point can be approximated as being ideal in which a gas occupies 22.4 litres per mole at 1 atmosphere and 273 K. *Compare* REAL GAS.

ideal mixture A mixture of two or more substances that form a solution in which there is no interaction between the molecules or atoms of the individual components. The total volume of the mixture is the sum of the partial volumes. *Compare* NON-IDEAL MIXTURE.

ideal solution A solution that conforms to *Raoult's law over a range of temperatures and compositions, and which shows no attractive forces between the components.

ideal stage *See* THEORETICAL STAGE.

IGPM An abbreviation for an Imperial unit of volumetric flow rate as **I**mperial **g**allons **p**er **m**inute and is used in the oil industry.

ignition The process of causing a substance to combust. Initiation of combustion is evidenced by a glow, a flame, or explosion. A substance will burn when the rate of heat gain due to oxidation exceeds the rate of heat loss. The **ignition delay** is the time to ignition

from the instant reactants are mixed or exposed to a heat source. The **ignition energy** is the quantity of heat or electrical energy that must be absorbed by a substance to ignite. The **ignition temperature** is the lowest temperature at which a substance can sustain combustion in air or oxygen at a specified pressure. *See* COMBUSTION.

imaginary number The part of a *complex number that is a multiple of $\sqrt{-1}$, which is denoted as j. For example, $\sqrt{-5} = j\sqrt{5}$.

immiscibility The property of fluids to form distinct and separate phases under all relative proportions. For example, oil and water are immiscible in which oil floats on water due to its lesser density. Immiscible fluids are used in liquid–liquid extraction processes in which a solute is transferred from one phase to the other by contacting the two fluids. This often requires a large interfacial surface which can be achieved by stirrers, *pulsed columns, and in *mixer-settlers.

immobilized cell bioreactor A type of fixed bed or fluidized bed reactor in which living microbial cells or enzymes are held statically such that their movement is restricted. Depending on the characteristics of the cells or enzymes, they may be immobilized in the form of aggregates such as pellets, or adhere to porous structures such as diatomaceous earth, glass, dextran, and gelatine, or be entrapped within beads such as calcium alginate. The advantage of immobilization is that high oxygen transfer rates can be achieved and the cells can be protected from high shear forces. Cell washout can also be avoided.

impact The ultimate effect of the occurrence of an undesirable and hazardous event. It may result in loss of life, injury, property damage, destruction of equipment or process plant, economic loss, or environmental damage. The impact is evaluated in a *risk assessment.

impact pressure A measure of the pressure of a flowing gas or liquid that is brought to rest onto a surface. A *Pitot tube flow meter measures the difference in the impact pressure and the static pressure of a fluid from which the rate of flow of the fluid is deduced.

impeller A series of blades attached to a shaft used to provide radial current of a fluid when rotated. It is used in *centrifugal pumps and for mixing purposes. **Radial-flow impellers** discharge the fluid in a horizontal (radial) direction to the vessel wall. If suitable baffles are provided, this device produces strong top-to-bottom currents. If the vessel is unbaffled, then swirling and vortexing may result. **Axial-flow impellers** create a flow parallel in the direction of the axis of the shaft. These devices produce more flow per unit power supplied than radial impellers, and are generally used in flow controlled operations. As with radials, swirling and vortexing may develop without the use of baffles. *Compare* PROPELLER.

Imperial units A British non-metric system of weights and measures. The system includes the ounce, pound, stone, inch, foot, yard, mile, acre, pint, quart, gallon, etc. It has largely been replaced by *SI units for scientific and engineering applications although there is still some usage.

impingement separator A device used to separate particles or droplets in a gas stream. The gas is diverted around an obstruction such as a *baffle so that the particles or droplets hit the baffle, coalesce on the surface, and drain away without re-entrainment. *Demisters are examples of impingement separators.

implicit function A mathematical function that contains two or more variables that have not been solved explicitly. For example, in the equation $x^2 + y^2 - 2 = 0$ the variables x and y are not dependent on each other where x is an implicit function of y and y is an implicit function of x.

implosion The inward collapse of a vessel as a result of evacuation. Steam trapped inside a closed vessel that has insufficient wall strength will implode when the steam cools and condenses.

impulse 1. A quantity used to measure the total change in momentum of a body produced by a force acting on the body for a very short time. **2.** In process control, it is a disturbance to a process that occurs over a very short period of time.

incandescence The emission of light by a substance due to its high temperature. For a substance to emit white light, it is required to be heated to above 700°C. Examples include electric heaters and stoves, and the white-hot filament of a light bulb of an incandescent lamp. British chemist Humphry Davy (1778–1829) demonstrated in 1802 that a strip of metal heated to a temperature using electricity can emit light. To overcome the oxidization of the metal British chemist and physicist Joseph Wilson Swan (1828–1914) invented an electric lamp using a filament of carbonized paper in 1860 but was unable to produce a sufficient vacuum. American inventor Thomas Alva Edison (1847–1931) produced the first practical incandescent light bulb two decades later.

incineration The process of combusting materials. An **incinerator** is a type of furnace used to incinerate waste organic materials to the point that only ash remains. It is often the case that combustion of toxic wastes such as halogenated hydrocarbons, herbicides, and pesticides are best treated by incineration, otherwise they would persist within the environment over long periods of time. It uses high temperatures in the order of 1,100°C to 1,300°C with the combustion of fuel oil or natural gas in an excess of air.

inclined tube manometer An instrument used for measuring the pressure head of a gas in which one leg of the manometer is attached to a sump containing a manometric fluid and the other is a straight tube, usually made of glass, and inclined at a known angle to the horizontal. The applied differential pressure between the sump and tube gives a vertical difference between the levels. The fluid displaced from the sump moves further along the inclined tube than if the tube was vertical.

incombustible The inability of a substance to burn. *Compare* INFLAMMABLE.

incompressible fluid A fluid in which the volume or density does not change with applied pressure for a given temperature. However, truly incompressible fluids do not actually exist. Liquids are generally regarded as being incompressible to simplify calculations.

inconel A type of nickel-chromium-iron alloy used for process plant equipment, noted for its strength at high temperature and corrosion resistance. It is used for gas turbine blades, seals, and many other applications. **Incoloy** is also a nickel-chromium alloy used for process plant equipment and also noted for its strength and resistance to oxidation and carburization at high temperature. It is used in nuclear fuel reprocessing and acid production as well as for process piping, pumps, and valves.

increment (Symbol Δ) A small difference in a variable. For example, the level of a process liquid in a tank feeding to a process may change by an increment Δh over an increment of time Δt.

independent variable *See* VARIABLE.

indeterminate problem A problem that involves one or more unknown or variable quantities.

indicator 1. A substance that indicates the completion of a chemical reaction. It is often used to determine the end point in titrations, and involves a sharp colour change. **2.** A type of process controller that provides measures and controls a process variable such as temperature. On a *piping and instrumentation diagram a **TIC** is a temperature indicator controller while a **LIC** is a level indicator controller.

induction heating A means of heating an electrically conducting material by electric currents induced in the material by an alternating magnetic field. Electric heating is accomplished with an electric alternating current of high value and low magnitude voltage. It is used for melting and heat treating of certain metals as well as for welding, soldering, and in brazing. The material is heated by inducing eddy currents in the material, causing the temperature to rise.

industry An economic activity by businesses that involves the manufacture of products through the conversion of raw materials, production of goods, or supply of services. *See* CHEMICAL INDUSTRY.

inelastic collision The collision of bodies such that some of their kinetic energy is converted into internal energy and that kinetic energy is not conserved. Collisions of gas molecules may be inelastic as they cause changes in vibrational and rotational energies. In larger bodies, some of the kinetic energy is converted to vibrational energy causing a heating effect.

inert gas 1. A noble gas such as helium, neon, argon, krypton, xenon, and radon. **2.** A gas such as nitrogen or carbon dioxide, known as an *inerting agent or blanketing gas, used to protect a substance from coming into contact with air or oxygen. Blanketing gases such as carbon dioxide are used to reduce the risk of fire hazards.

inertia The tendency of a body to resist a change in the motion by an external force. A body will remain static, or travel in a straight line at a constant speed until acted upon by a force.

inerting agent An inert gas such as nitrogen or helium that can prevent the ignition and combustion of ignitable mixtures. The inert gas lowers the availability of oxygen to below the *flammability limit for combustion to occur even with an ignition source.

infinite Having no specified end, no highest or lowest value. The term *semi-infinite is sometimes used to define the geometry of an object such as in heat transfer calculations that is infinite in one or two dimensions but finite in the third. A semi-infinite cylinder has a finite radius but infinite length such that end effects can effectively be ignored. An **infinite dilution** is the concentration of a solution that corresponds to an infinite ratio of the solvent to the solute.

infinitesimal A number that is not zero but is less than any finite number. While such numbers do not exist in the conventional system of real numbers, it allows calculations to adhere to certain restrictions and requires a good understanding of limits.

inflammable A material that is combustible or has the ability to support combustion. *Compare* INCOMBUSTIBLE.

inflection A point of a curve where the gradient of the tangent changes in sign. A stationary point on a curve occurs at the point where:

$$\frac{dy}{dx}=0$$

and can be either a maximum, a minimum, or an inflection. The point is an inflection where:

$$\frac{d^2y}{dx^2}=0$$

influx The flow of a fluid into a process or across a system boundary. *Efflux is the flow out.

infranatant *See* SUPERNATANT.

infrared radiation A part of the *electromagnetic radiation spectrum that corresponds to wavelengths between those of microwaves and those of visible light (i.e. 10^{-6} and 10^{-3} m). While invisible to the naked eye, infrared radiation is perceived as heat. Infrared spectroscopy is an important technique in analytical chemistry since the infrared adsorption of molecules is characteristic of it and the spectrum can be used for molecular identification. Infrared radiation was discovered in 1800 by German-born British astronomer William Herschel (1738–1822) in the sun's spectrum.

Ingen-Hausz, Johannes (1730–99) A Dutch scientist and engineer who studied in four countries and made many discoveries in physics. He designed an apparatus for comparing the thermal conductivities of rods of different substances. He also noted that plants take in carbon dioxide during the day but release it out at night.

ingot A material that has been cast in moulds into a particular shape such as a bar or a block. The material is usually metal (pure or alloy) and poured in the molten state into moulds to form the ingot, which is used for further processing in order for the material to be useful as a final product. Gold ingots are used as a currency reserve. Purification of ingots can be achieved through *zone refining to remove impurities.

inherently safe A process or system that is able to operate safely without the need for external or auxiliary support. For example, a cooling water system to a process that uses heat exchangers of a sufficient duty and that are fed under gravity to ensure removal of heat is inherently safe.

inherent moisture The chemically combined and absorbed moisture of a substance; it is distinct from the surface or *free moisture.

inhibition The process of preventing or reducing a chemical reaction taking place. In enzyme kinetics, the reaction between the enzyme and substrate can be inhibited by the addition of another substance. **Competitive inhibition** is where a substance inhibits the enzyme reaction by completing with the enzyme at the active site whereas non-competitive inhibition is where a substance reduces the activity of the enzyme by binding to the enzyme whether or not it has already bound the substrate. An **inhibitor** is the substance added causing the change in rate of the chemical reaction.

initiator 1. A substance or molecule that starts a chain reaction other than a reactant. For example, peroxides are used in polymerization reactions of methyl methacrylate monomer. **2.** A small device used to start an explosive train such as a detonator. The initiator usually contains a small quantity of a sensitive explosive and receives a mechanical or electrical impulse to cause the detonation.

in-line analysis *See* OFF-LINE ANALYSIS.

in-line mixer A static device with no moving parts used in a pipeline carrying fluids that causes the fluid streamlines to cross one another thereby intimately mixing the fluid. It is used to mix fluids such as dispersing gases in liquids, assist with dissolving solids in liquids, and mixing immiscible liquids. It consists of a twisted ribbon of chemically inert and unreactive material such as metal or plastic of sufficient length to provide good mixing characteristics. It is held firmly in place. It is also known as a **static mixer**.

inoculation The injection of a small volume of liquid containing living microorganisms into a bioreactor to initiate a biochemical process such as fermentation. The microorganisms, such as yeast or bacteria, are first prepared as an inoculum by either using living cells for a previous bioreaction, or by transferring living cells from agar plates upon which they have been stored, and growing them in a shake flask. The contents of the shake flask provide the inoculum for the larger biochemical process.

input The quantity of material, energy, or power fed into a system. *Compare* OUTPUT.

insoluble A substance that is not able to dissolve in a solution.

Institution of Chemical Engineers (IChemE) A professional organization founded in 1922 representing around 38,000 (2013) members across 120 countries with its headquarters in Rugby, UK and with offices in Australia, China, Malaysia, and New Zealand. It represents benchmark standards in chemical engineering education and is licensed to award chartered chemical engineering status to qualified engineers. It also publishes research and specialist books on chemical engineering.

SEE WEB LINKS

- Official website of the Institution of Chemical Engineers.

instrument air Compressed air used in chemical and process plants to operate pneumatic instruments such as pressure controllers and air-operated control valves. The air is filtered and cleaned to prevent blockage and corrosion problems and compressed to a pressure of typically 6 bar. There are strict requirements for the quality of instrument air.

insulation A material used to limit or restrict the flow of heat, sound, noise, vibration, or electricity. Thermal insulation around pipes is known as *lagging.

intalox saddle A tradename for a type of *packing material used in *packed columns. It is shaped as a saddle and perforated, and made from inert materials such as metal or plastic.

integer A whole number. It may be positive or negative and includes zero. That is {… –3, –2, –1, 0, 1, 2, 3…}.

integral action control A mode of control used to control a process in which the change in the controller output is proportional to the time integral of the deviation. The

control action recognizes not only the magnitude of the deviation, but also the time during which the deviation occurs. Integral action is limited in application to processes of small capacitance and fast responses. It is therefore rarely used alone but instead is more frequently used in combination with proportional control. Integral action is the only mode of control that will bring the controlled variable back to the set point.

integration The continuous summing of the change in a function f(x) over an interval of the variable x. The result is known as the integral of f(x) with respect to x. An integral $\int_{x_1}^{x_2} f(x)dx$ can be considered as the area under the curve and the limits x_2 and x_1. Definite integrals have limits whereas indefinite integrals do not. The result of an indefinite integral has a constant of integration c. For example:

$$\int x^2 dx = \frac{x^3}{3} + c$$

There are lists of tables of standard integrals. The inverse process of integration is called *differentiation.

intensive variable A property of each phase in a mixture that is independent of the amount of material. It includes temperature, pressure, enthalpy, density, specific volume, specific heat capacity at constant volume, and mole fraction. For a multiphase mixture at equilibrium, both temperature and pressure are uniform throughout the mixture but the values for enthalpy and mole fraction are different for each phase. An **extensive variable** depends on the amount of material in the system such as volume, mass, and total energy.

intercooler A type of heat exchanger used to remove heat from a fluid between the stages in a process. It is used to cool liquids and gases in processes such as refrigeration, air conditioners, gas turbines, combustion engines, and some types of reactors, and in particular, to remove the heat of compression.

interface 1. The boundary between two phases such as two immiscible liquids, a liquid and vapour or gas, a gas and a solid, or a gas and a vapour or gas. The **interfacial area** is the area of the boundary between the two phases. The **interfacial tension** is the surface tension at the surfaces between two phases. **2.** The point of interaction or communication between a computer and some other device. A human–machine interface is the point of interaction by a process operator to control a process by receiving real-time data and making manual adjustments to pumps and valves.

interlock A safety control system that cuts in when unsafe conditions are detected, particularly in the operation of process machinery such as pumps and compressors.

intermediate bulk container (IBC) A rigid container used for storing and transporting liquids and bulk materials. It is generally cubic in shape and provides good storage geometry. It can be stacked and can vary in capacity ranging from 500 to 3,000 litres. It is called intermediate as its capacity is considered to be between that of a drum and a tank. IBCs are made of various materials and their use depends on their application. Plastic IBCs are commonly used for liquids. Steel and stainless steel IBCs are used for granular materials.

intermediate product A chemical product produced during a step in a process which is not the final product but may be used as the feedstock for the next step in the process. It is also known as a chemical intermediate.

internal diffusion The movement of a gas, vapour, or liquid without a change of state through a porous material.

internal energy (Symbol U) A conceptual state function whose absolute value can be neither measured nor calculated. It represents the total energy in a substance and includes the atoms and molecules and their intra-atomic, inter-atomic, and inter-molecular forces. It includes neither the kinetic energy nor the potential energy. It is used in energy balance equations in terms of its relative value to a reference state, whose internal energy is arbitrarily set to zero. For a *closed system, the change in internal energy ΔU is equal to the difference between the heat absorbed from the surroundings, Q, and the work done, W, by the system on its surroundings $\Delta U = Q - W$. The concept was proposed by American physicist Josiah Willard *Gibb (1839–1903).

internal reflux The partial condensation of liquid within a distillation column that descends down the column. The condensation does not take place in the condenser but on the walls of the column due to poor insulation. Alternatively, internal reflux is intentionally achieved using an internal heat exchanger that allows the more volatile component for separation to be separated more effectively from the top of the column.

International Council of Chemical Associations (ICCA) An organization that represents chemical manufacturers and producers all over the world. Its aims are to provide cooperation with major organizations such as the OECD, particularly in terms of chemical production management.

SEE WEB LINKS

- Official website of the International Council of Chemical Associations.

interpolation A method of obtaining data that falls between two known items of data. It is used in numerical analysis in which new data can be obtained using techniques such as curve fitting.

interstitial The space between atoms, molecules, and materials. An **interstitial element** is an impurity in metals such as hydrogen, carbon, and oxygen that affects the physical properties of the metal. These atoms are small enough to fit between the crystalline lattices of the much larger metal atoms. An **interstitial compound** is where non-metal atoms or ions fit between the spaces within a metal lattice. Examples include carbides, borides, and silicides.

intumescent paint A coating applied to a surface to protect it from flame or heat. It expands on heating thereby reducing its density and creating an insulating effect. It is used in passive fire protection for pipes and other process equipment particularly in hazardous areas. It is applied as a spray. Examples include types of hydrates, which liberate their moisture content on heating, thereby maintaining a boiling point temperature of 100°C, and protecting the metal from rising temperatures.

inventory A material stock-take or form of accountancy of materials within a process plant or equipment at a given time. It can include the raw materials, products in storage, and materials within the process.

in vitro A biochemical reaction that takes place in an apparatus, and therefore distinct from the biochemical reaction taking place within the living cell (**in vivo**). In vitro literally means 'in glass'.

I/O An abbreviation for **i**nput/**o**utput. It refers to signals entering and leaving a controlled process.

iodide process *See* VAN ARKEL–DE BOER PROCESS.

ion exchange The process involving the adsorption of ions in a solution on a surface of particles or gels accompanied by the simultaneous desorption of ions of like charge. An **ion exchange resin** is a synthetic polymeric resin that is able to exchange ions on the surface of a polymeric molecular network that possesses functional groups that carry an ionic charge. The extent of the exchange is dependent on the nature of the resin and the type of exchanging ions. Ion exchange is used in *water treatment to remove calcium and magnesium ions, and replace them with soluble sodium ions. Ion exchange equipment consists of a fixed bed of the resin down through which the water for ion exchange passes. The ion exchange resin may be naturally occurring such as *zeolites, aluminosilicates, or synthetic such as cross-linked polystyrene.

ionic bond A type of chemical bond based on the electrostatic attraction between oppositely charged ions in a compound. Sodium chloride is an ionic compound in which the sodium atom loses one of its outer electrons to the chlorine atom, resulting in the formation of a sodium cation (Na^+) and a chlorine anion (Cl^-). They are mutually attracted and therefore form an ionic bond.

ionization The process of forming ions involving the absorption or emission of electrons by atoms or molecules. It can occur in several ways such as the reaction of two neutral atoms; by the combination of an already-existing ion with other particles; by the breaking of a covalent bond in such a way that each bond is associated with one of the parts such as the dissociation of water to form a hydrogen ion and a hydroxyl ion; and by the passage of energetic charged particles through gases, liquids, and solids, such as X-rays, beta particles, gamma rays, UV radiation, and electric discharges through gases.

ionizing radiation *Radiation that either directly or indirectly causes *ionization. It includes alpha, beta, gamma, and neutron radiation.

ion leakage The concentration of unwanted ions (for example, calcium ions) left in a treated liquid within an ion exchange unit.

I/P transducer *See* TRANSDUCER.

iron (Symbol Fe) A metallic element with atomic number 26. It is widely found in the element and is extracted from ore and used to make steel and other valuable alloys. *See* CAST IRON; STEEL.

irradiance (Symbol E) The radiant flux per unit area reaching a surface. The SI units are $W\ m^{-2}$. It refers to all types of *electromagnetic radiation. Illuminance refers only to visible radiation.

irradiation A low-energy form of sterilization of certain foods using ionizing radiation. Gamma rays from cobalt-60, X-rays, and electron beams are used to kill harmful moulds, bacteria, parasites, and insects. The use of irradiation also delays the ripening and the sprouting of onions and potatoes. Its use in the US was approved in 2000. In the UK, the Food Irradiation (England) Regulations 2009 lists the seven categories of food that may be irradiated (fruit, vegetables, cereals, bulbs and tubers, dried herbs, fish and shellfish, and

poultry). For each the 'maximum overall average dose' that can be used is specified in units of kilograys (kGy).

irrational number A real number that cannot be represented as a fraction such as π.

irreversible reaction A chemical reaction which is considered to go forwards converting reactants to products. The reverse reaction is in comparison very slow to the point that it is non-existent. The process of combustion of a hydrocarbon fuel is an example of an irreversible reaction in which the fuel is reacting with oxygen to form carbon dioxide and water vapour.

irritant hazard A type of gaseous hazard that causes inflammation or irritation to the eyes, skin, and respiratory system.

isentropic A thermodynamic system in which the entropy remains constant in a reversible adiabatic process. An **isentropic process** is a process that takes place without any change in entropy. A friction-free adiabatic expansion and compression process is an example of an isentropic process.

isobar A condition representing constant pressure. Isobars are used on weather maps representing lines of constant atmospheric pressure. An **isobaric process** is a process that operates with constant pressure.

isochore A condition representing constant volume. It is also known as **isometric.**

isolated system The separation of the process plant from all forms of energy and material flows. *See* SYSTEM. An **isolation scheme** is used in such a way to ensure that hazardous substances are not released or that personnel are not exposed to risks during maintenance or equipment repair.

isomerism The existence of two or more substances having the same chemical composition but different arrangements of their atoms e.g. butane (C_4H_{10}) has two isomers: as a straight four-carbon chain and as a three-carbon chain with a methyl group ($-CH_3$) in the middle. There are two types of isomerism: structural (i.e. butane) and stereoisomerism, which includes optical and geometric isomerism.

isomerization A process used in petrochemical refineries to convert linear hydrocarbon molecules to higher-octane branched molecules used for blending into gasoline or as feed to alkylating linear alkenes to heavier hydrocarbons such as xylenes.

isometric *See* ISOCHORE.

isometric drawing A three-dimensional engineering drawing of a process plant equipment or pipe run. It is characterized by an **isometric projection** in which the plane of the projection has equal angles to the three principal axes of the object being depicted. All the dimensions are the same and there is no perspective.

isomorphism The existence of identical or similar crystalline forms in different but chemically similar compounds

isopieste A curve or line on a *psychrometric chart representing equal moisture content plotted for a constant pressure.

isopleth A vertical line used in a liquid–vapour phase diagram for two substances. The line corresponds to constant composition as the pressure changes. The isopleth is perpendicular to a *tie line.

isotherm 1. A condition representing constant temperature. **2.** The relation between the moisture content of a substance and the relative humidity in the surrounding air.

isothermal efficiency A measure of the performance of a reciprocating air compressor. It is expressed as a ratio of the isothermal work input to the actual work input. An air compressor is required to raise the pressure of the air with the minimum possible work input, which occurs with isothermal compression. Isothermal compression is an ideal case since none of the work input is absorbed in raising the temperature of the compressed air, i.e. in raising its internal energy.

isothermal process A system or process in which there is no exchange of temperature with the surroundings such that the temperature remains constant. The temperature of the system or process is maintained at a constant value by removal or addition of heat at the same rate at which it is produced or removed. The change of phase of a solid to a liquid as in the process of melting, or of a liquid to a vapour as in the process of boiling, are examples of isothermal processes. *Compare* ADIABATIC PROCESS.

isotonic The exertion of the same osmotic pull by one medium as the other on the other side of a *semi-permeable membrane. This corresponds to the same concentration of particles existing on either side of the membrane.

isotope Atoms of the same element but with a different number of protons and neutrons (i.e. **nucleon number**). They have nearly identical chemical properties. For example, the two isotopes of chlorine are chlorine-35 and chlorine-37. Both have identical atomic numbers and electron arrangements, and have the same chemical properties, but the difference of two neutrons in the nucleus produces a difference of two units of *relative atomic mass. Chlorine comprises 75 per cent chlorine-35 and 25 per cent chlorine-37 by mass, giving a combined relative atomic mass of 35.45. Most elements exhibit isotopy although some do not, such as fluorine, sodium, and aluminium. Tin with an atomic number 50 has ten isotopes, ranging in mass numbers from 112 to 124.

isotropic The condition in which the same properties exist in all directions from a point or location.

iteration A repeating calculation in which the key variables are recycled in the calculation in order eventually to reach a convergence as the solution.