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

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

**ablation** See sublimation.

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

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

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

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

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

**absolute humidity** The amount of water in air expressed as the mass of water vapour per unit mass of dry air for a particular temperature and pressure condition. The SI units are kg$_{\text{water}}$ kg$_{\text{air}}$.

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

**absolute roughness** (Symbol ε) The roughness of a solid surface expressed as the average height of undulations and imperfections. It is measured using an instrument that draws a stylus over the surface. The roughness of the inner surface of a pipe wall used to transport fluids with turbulent flow has the effect of increasing frictional pressure drop. Expressed
as a ratio with internal pipe diameter, it is used in determining the friction factor of fluids flowing in pipes with turbulent flow. See RELATIVE ROUGHNESS.

**absolute temperature** See KELVIN.

**absolute viscosity** See VISCOSITY.

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

**absorbed dose** See DOSE.

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

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

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

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

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

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

\[
\frac{dv}{dt} = \frac{d^2s}{dt^2}
\]
Acheson process

where \( s \) is the distance moved by the body. In the case of motion in a circle, the acceleration is \( \frac{v^2}{r} \) and directed to the centre of the circle of radius \( r \).

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

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

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

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

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

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

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

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

- Official website of ACHEMA.

**Acheson process** A process used for the production of graphite. It involves heating coke mixed with clay to a very high temperature. At a temperature in excess of 4,000°C,
silicon carbide is formed leaving graphite. It is named after the American inventor Edward Goodrich Acheson (1856–1931) who patented the process in 1896.

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

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

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

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

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

**activated carbon** A compound of powdered or granular amorphous carbon mainly made from coconut shells. It has a very high specific surface area used to adsorb vapours and gases. With a surface area typically of around 1,000 m² per gram, it is widely used to adsorb vapours and gases. The amount of substance that can be adsorbed is proportional to the absolute temperature and pressure. The activated carbon can be reactivated for reuse using steam to strip the adsorbents and recover the carbon. Activated carbon is used in water and air purification, and used in gas masks for the removal of harmful gases. It is also known as **activated charcoal** and **active carbon**.

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

**activation energy** (Symbol $E_a$) The minimum energy required to activate one mole of a substance to cause a *chemical reaction to take place. For a chemical reaction to proceed,
the reactants are converted to products in which the energy increases to a maximum and falls to the energy of the products (see Fig. 1). The activation energy is the difference between the maximum energy and the energy of the reactants and is therefore the energy that needs to be overcome. See Arrhenius equation.

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

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

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

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

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

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

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

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

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

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

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

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

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

**adsorption isotherm** The relationship between the mass of *adsorbate* taken up per unit mass of adsorbent at constant pressure, if a gas, or at constant temperature, if in a solution. The *BET, Langmuir, Freundlich, and Temkin adsorption isotherm equations*
are empirical equations used to describe the surface available for adsorption at constant pressure for gases and constant temperature for solutions.

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

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

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

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

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

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

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

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

**aggregated fluidization** See FLUIDIZATION.

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

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

**agitation intensity** A measure of the power consumption of the shaft of an agitator used to mix a liquid in a stirred tank or *agitated vessel*. Agitation intensities are expressed
as the power supplied per unit volume of liquid. The SI units are W m$^{-3}$. The magnitude of the agitation intensity is dependent on the nature of the liquid being stirred. Biological solutions containing flocculating materials are significantly affected by the level of agitation.

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

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

**AIChE** See American Institute of Chemical Engineers.

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

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

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

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

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

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

**air pollution** The release of particles, vapours, and gases into the environment that are harmful to human health and to the environment such as plants, forests, and animals. Carbon dioxide is a product from the combustion of fossil fuels in power stations, vehicles, aeroplanes,
and numerous industrial processes, and is a greenhouse gas responsible for contributing to the warming of the Earth's atmosphere. Methane is another greenhouse gas as are chlorofluorocarbons (CFCs), which were once widely used as refrigerants and as aerosol propellants but are now banned due to their known damaging effect on the Earth's ozone layer. Sulphur dioxide is another product of the combustion of fossil fuels and is known as the cause of *acid rain.*

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

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

---

**SEE WEB LINKS**

- Official website of Environmental Protection UK.

---

### air separator

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

### air-to-close

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

### ALARA

An abbreviation for *as low as reasonably achievable,* it is a management tool used in the controlling of risks. For example, it is used to manage the exposure to chemicals and ionizing radiation doses in humans working in the nuclear industry. *Compare ALARP.*

### alarm

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

### ALARP

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

---

**SEE WEB LINKS**

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

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

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

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

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

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

**alkyne** An unsaturated aliphatic hydrocarbon that has the general formula $C_nH_{2n-2}$. These are characterized by a triple carbon–carbon bond. Alkynes that feature a single triple bond form a homologous series beginning with ethyne (acetylene) $C_2H_2$, followed by propyne (propylene) $C_3H_4$, butyne (butylene) $C_4H_6$, etc. They were formerly known as acetylenes.

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

**alloy** A material that consists of two or more metals, or a metal and a non-metal such as carbon. Pewter is made from tin with lesser amounts of lead along with small amounts of antimony and copper. Steel is made from iron alloys and contains a small amount of carbon.
**alpha particle** A positively charged particle emitted by various radioactive materials such as uranium during radioactive decay. The particle consists of two neutrons and two protons, and is therefore identical to the nucleus of a helium atom. The result of this radioactive decay is that the original element is gradually converted into another element with a decreased atomic number and mass. Alpha particle emissions, or alpha decay may occur at the same time as beta decay. It can be stopped by a sheet of paper and is harmful to humans only if the substance emitting the alpha particles is ingested, inhaled, or enters the body through wounds.

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

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

\[ V = V_A + V_B + V_C + \ldots \]

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

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

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

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

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

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

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

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

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

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

**ammonia-soda process** See *Solvay process*.

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

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

$$ n = \frac{N}{N_A} $$
where \( N \) is the number of atoms and \( N_A \) is Avogadro's constant. The SI unit is the mole. It is also known as chemical amount.

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

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

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

**a.m.u.** See atomic mass unit.

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

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

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

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

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

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

**analysis** The detailed examination of something such as a mathematical problem using the theories of calculus, a chemical substance into its constituent parts, the study of a physical process and its function or operation, the economics of a chemical process or business, etc.
**analysis of variance (ANOVA)** One of a number of statistical techniques used to resolve and observe the variance between sets of statistical data into components. These techniques are used to determine whether the difference between samples is explicable as random sampling variation from within the same statistical populations. ANOVA techniques are used in *quality control.*

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

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

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

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

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

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

\[
2CH_4 + 3O_2 + 2NH_3 \rightarrow 2HCN + 6H_2O
\]

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

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

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

**angel’s share** An amount of Scotch whisky lost by evaporation during the process of maturation in wooden casks. Scotch *whisky* is stored for a minimum of three years over which time the level of whisky can drop by as much 2 per cent per year.
angström (Symbol Å) A unit of length equal to $10^{-10}$ m. It is used to measure the wavelengths of electromagnetic radiations and was formerly used for the measure of intermolecular distances. It has now been replaced by the nanometre ($10^{-9}$ m). It is named after the Swedish astronomer and professor of physics Anders Jonas Angström (1814–74).

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

angular velocity (Symbol $\omega$) The rate of change of angular displacement with time:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\text{o} \ API = \frac{141.5}{SG} - 131.5$$

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

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

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

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

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

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

Fig. 2

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

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

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

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

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

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

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

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

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

ASME See American Society of Mechanical Engineers.

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

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

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

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

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

ASTM See American Society for Testing Materials.

asymptote A straight line that is closely approached by a curve so that the perpendicular distance between them decreases to zero at an infinite distance from the origin.
ATEX An EU directive that describes the work that may be safely carried out in an explosive atmosphere. The areas or zones in a process plant are classified according to the type of hazards, the location, and size, and the likelihood of an explosion. It is applied to mining operations, offshore processing, petrochemical plants, and flour mills, where potentially explosive atmospheres may exist. The name is derived from the French title for the EU directive Appareils et systèmes de protection pour les atmosphères explosibles.

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

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

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

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

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

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

atomic energy See NUCLEAR ENERGY.

atomicity The state of being made up of atoms and is the number of atoms in molecules. For example, carbon dioxide (CO₂) has an atomicity of 3; hexane (C₆H₁₄) has an atomicity of 20, etc.

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

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

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

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

**atomic power** An alternative name for nuclear power.

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

**atomic weight** See relative atomic mass.

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

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

**auriferous** A rock or ore containing gold.

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

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

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

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

**automatic control** See feedback control.

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

**autothermal** A system, process, or reaction that is completely self-sufficient in terms of its energy requirements. Some exothermic reactions are autothermal. Some anaerobic digesters are operated in this way in which the methane liberated is used to fuel the process.
average velocity  Also known as the *mean velocity, it is the total volumetric flow rate of a fluid per unit flow area. It is a useful parameter particularly where there may be local variations in velocity and hence flow across a flow area due to the effects of turbulence or obstructions in a pipeline, duct, or stack. The SI units are m s⁻¹.

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

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

Avogadro’s constant (Symbol N_A) The number of atoms in one mole of a substance. It has the value of 6.022 1367(36) × 10²³ and was formerly known as Avogadro’s number.

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

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

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

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

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

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

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

azeotrope  A mixture of two liquids that boils at a constant composition. That is, the composition of the vapour is the same as the composition of the liquid. It is therefore not
possible to separate an azeotropic mixture by conventional distillation. Azeotropes occur due to deviations in Raoult’s law leading to either a maximum or minimum in the boiling point-composition diagram. The composition of the azeotrope is dependent on pressure.

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

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

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

**Fig. 3 Azeotropic distillation with heterogeneity**
If heterogeneity does not occur, some other means of splitting the A-entrainer azeotrope is required such as liquid–liquid extraction (see Fig. 4).

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